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Periodic Price Reduction as a Way to Boost Diminishing Demand

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Abstract

In this paper, I offer a new theory for why price reductions take place on a regular basis in some industries. I suggest that the demand for a firm’s product drops over time because of the erosion of consumers’ brand recall, and that price discounts are utilized to boost the diminishing demand. A dynamic model is then constructed to demonstrate the theory for both monopoly and duopoly competition. I show that it is optimal for a monopolist to alternate between a constant high (normal) price and a constant low (discount) price with fixed frequency, and that competing firms offer discounts at the same time in duopoly competition.

Keywords: Price discounts; Intertemporal pricing; Dynamic oligopoly; Dynamic programming; Shifting demand

Introduction

Price discounts are pervasive in the business world. At the retailing level, various forms of price reductions exist for various reasons. This paper focuses on a particular form of price discounts, namely a periodic price reduction that consists of long periods of a constant (high) price and short periods of a discounted (low) price. This kind of intertemporal pricing is typical in the fast food and service industries. For a time in Durham, North Carolina, all Burger King Customers could enjoy burgers at $0.99 a piece on Wednesdays, while the normal price was $2.99. More interestingly, during that same time, Wendy’s also offered its price discounts every Wednesday. Another example is the discount price of HK $40 that all movie theatres in Hong Kong simultaneously charge on Tuesdays, vis-a-vis a regular ticket price of HK $60 on any other days. Free admission is available each Wednesday in public museums in Hong Kong. In many European countries, public transportation is free on particular days each year. Similar pricing patterns exist for durable goods. Figure 1 shows the daily price time path of color TVs at Sears, San Diego [1].

Figure 1: Daily price time path of color TVs at Sears, San Diego [1].

Existing literature has several explanations for why price discounts are offered. Some models focus on spatial price dispersion, while some others study price variations over time. Spatial price dispersion cannot persist unless there is market friction, otherwise a store charging a higher price than its competitors would not have any sales. Market friction, in the form of consumer searching costs or switching costs, typically leads to mixed strategy equilibria, which generates intertemporal price variation for any given store [2-4]. The variation, however, does not display any regularity. Price discounts on selected items may serve the purpose of generating store traffic. The familiar marketing tactic of the “loss leader” or the “bait and switch” strategy is meant to use the low price of one good to lure consumers into buying the complements [5,6] or substitutes [7] for that good. However, fast food restaurants and movie cinemas are both highly specialized stores that would find it difficult to offer a great variety of complements and substitutes.

More relevant to this paper are models with a clear time dimension.

Lazear [8] suggests that in the presence of demand uncertainty, a good strategy is to start with a high price and eventually lower the price if the item has not been sold. While Lazear’s model explains well the “clearance sale” of fashion clothing, for which demand uncertainty plays a central role, it is hardly applicable to generic goods such as fast foods, for which demand is relatively predictable. Besides, an auction-type downward pricing is quite different from a cyclic price movement. Intertemporal price discrimination could happen when consumers have differential costs for holding inventories, which makes periodic price discounts optimal [9,10].

But, obviously, people do not buy large amounts of fast food to save for future consumption. Fast food, like services, is not storable. Finally, price discounts could be a store’s optimal response to a changing demand or cost. In Conlisk et al. [11], Sobel [12], and Pesendorfer [13], a new cohort of consumers enters the market each period so that cyclic pricing is optimal for the firms. These models are mainly suitable for durable goods: Once a consumer buys the good, she vanishes forever from the market; if a consumer does not buy at some time, she stays in the market until the next sale. Clearly, fast foods are not durable. It is also hard to believe there are new customers who enter the market every day.

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In this paper, I am interested in the regular intertemporal price movement of a non-durable, non-storable good exemplified by fast food and other industries. There is clearly a cycle: a store charges a constant regular price most of the time, and a constant discounted price every now and then. The timing of discounts is fixed and predictable, and the pricing pattern exists in both monopoly and oligopoly, with all stores offering discounts at the same time. In this paper, I offer a new theory for why price reductions take place on a regular basis. A dynamic model is then constructed to show that the pricing pattern observed in reality is indeed optimal for the firms.

When people think of periodic price reductions such as those by Burger King and Wendy's on Wednesdays, the first response might be "peak-load pricing" such as the "Happy Hours" studied by Varian [15], the seasonal price variation described by Gerstner [16], or the well-known pricing pattern for electricity, car rentals, telephone calls, etc., in which fixed capacity plays an important role. Presumably, the mid-week demand for dining (or movie) services is smaller than that during weekends, which justifies differential and cyclic prices. It is then optimal for a monopolist to charge a low price in the mid-week when demand is low. But, then, why does the price reduction not appear on Tuesdays or Thursdays? It is hard to believe that the demand stays the same for six days of the week, and then sharply drops on Wednesdays, as implied by a discount price of $0.99 versus a normal price of $2.99. A more fundamental problem with this explanation, though, is the requirement of market power. When there is competition, peak-load pricing is simply not sustainable. In fact, Warner and Barsky [17] document strong empirical evidence of lower prices when demand is higher, for example, during weekends and holidays.

Another plausible explanation for periodic price reduction is intertemporal price discrimination—high valuation consumer's purchase on the spot, while price-sensitive customers wait until the price is lowered. In order for them to make intertemporal choices, however, consumers need to have unit demand each week, not every day. While this might be true for movies and video tape rentals, it is hardly the case with fast food or mass transportation, for which people make daily purchases. One more problem with the price discrimination theory is that it cannot explain why the seller offers the good for free (e.g., museums and European mass transportation). Price discrimination is meant to raise profits. A zero price is obviously not optimal if price discrimination is the only purpose: the seller would have been better off closing the business on that day rather than offering the product or service for free.

In summary, I believe the existing literature is not able to explain fully the price cycles in the fast food and other industries. I attempt to give a new explanation for the phenomenon in this paper. My argument consists of two major points. First, without any stimulation, the demand for a particular product diminishes over time, as consumers eventually forget about this product. A person might not remember the good taste of a Big Mac if there is nothing to remind her, so she just brings her lunch from home. In fact, a declining demand is one of the major reasons behind the need for continuous and endless advertising. Why does Nike repeatedly promote itself? Why because otherwise people will go away. A new product may need advertising to inform people of its existence and of the function of the product, or to signal its quality [18], but for well-established brand names such as McDonald's, Nike or Intel, persistent advertising campaigns can only be explained by one purpose: keeping consumers hooked. Without any reminder, a firm's consumer base will gradually erode away. The second point of my argument is that periodic price discounts can be used to boost diminishing demands. A price reduction will certainly lead to a higher quantity demanded in the current period. But a higher current consumption implies a higher demand in the future. This positive relationship has been well established in the habit persistence literature [21-24]. If a consumer's utility is a function of past consumption as well as current consumption, then the marginal utility of current consumption, and hence the demand function, would be increasing in past consumption. Blattberg and Neslin [25] point out: "... any purchase of a brand has implications beyond the immediate purchase occasion: The consumer forms a habit toward purchasing the brand, sustains that habit, or learns about the performance of the brand". Slade [26] expresses a similar idea in her empirical formulation of price changes. The demand function in her model contains a term for consumer goodwill, which erodes over time and reacts positively to price cuts.

Given the basic idea of a shrinking demand and the possibility for a firm to use price discounts to boost the demand, I study the optimal and equilibrium choice of price discounts under both monopoly and duopoly settings. In the model, firms have a large set of choice variables at their disposal: the normal and discount prices as well as the duration, frequency, and timing of discounts. I find that it is indeed optimal for firms to offer a constant normal (high) price most of the time, and a constant discounted (low) price occasionally with the same frequency. In duopoly equilibrium, each firm seeks the longest lasting effect of its boosted demand before the demand is eroded by its rival's next discount. As a result, in equilibrium, the two firms offer discounts at the same time.

It has been well established in consumer psychology [27] and social psychology [28] literature that consumers' memory declines over time and the memory can be stimulated by sales promotions such as price discounts. For example, Wyer's [27] Principle 2 states that "The accessibility of a unit of knowledge in memory is an increasing function of both the recency with which it has been activated and the frequency with which it has been activated. The effect of recency decreases over time." Adaval and Monroe [29] demonstrated the relation between knowledge accessibility and pricing. Nedungadi [30] found that changes in a brand's accessibility may affect the probability that it is retrieved and considered for choice. Alba and Chattopadhyay [31] demonstrated that consumers have difficulties recalling brands (brand inhibition), and that exposure to promotion activities induces positive responses from consumers. "Frequent or recent exposure to a brand increases its salience (i.e., the prominence or 'level of activation' of a brand in memory), thereby increasing the ability of a consumer to recall it. Marketing variables that enhance the salience of a brand have been shown to be related directly to recall." Banerjee [32,33] presented two models to explain how people are influenced by others' opinions. Behavioral learning theory suggests that rewarded behavior tend to persist [34,35]. Promotions such as price discounts can serve as such a reward, thereby increasing subsequent purchases. Bouling et al. [36], Mela et al. [37], Papatla and Krishnamurthi [38], Shankar and Krishnamurthi [39] all found that promotion purchasing changes price sensitivity. Gedenk and Neslin [40] demonstrated that promotion had long-term effects on consumer

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1Doyle [19] claims that "most stores seem to hold sales simultaneously".  
2A slightly different story is offered by Villas-Boas [20]: Consumers live for two periods. A monopolist firm price discriminates against consumers who have bought in the previous period. Cyclical pricing occurs in equilibrium.

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behavior. Price promotions have been demonstrated to be profitable in the long run [41,42]. Sellers usually employ two types of promotion tactics [43]: A flat, low price (everyday low pricing), and an alternation between a relatively high price and frequent price discounts (hi-lo pricing). Tsioros and Hardesty [44] have suggested a new discounting strategy, which requires a seller to return the discounted price to the regular level in several steps rather than at once. They argue that consumers will be tricked into purchasing more because they observe an upward time trend of the price and may conclude that the price will keep rising. To the extent that word of mouth (WOM) or consumer and professional reviews help establish a positive relation between present consumption and future consumption, these channels are consistent with the theory presented here. I have mainly used the habit persistence theory to explain the positive relation, but WOM and reviews will lead to the same prediction. Of course WOM and reviews will mainly affect the consumption choice by potential buyers rather than existing buyers, but at the aggregate level they would still lead to a positive relation. Marketing scholars have long established the importance of WOM and reviews. The advance of the internet has made it much easier to collect and quantify such information [45-51]. Many firms regard online consumer reviews as an important marketing tool [52]. They regularly post product information and sponsor promotional chats on online forums [53], and may even manipulate online reviews [54].

The paper is organized as follows. The basic monopoly model is set up in Section 2. The next three sections study the optimal choice of the normal price and the depths and frequencies of discounts. Section 6 extends the basic model to duopoly competition and derives the equilibrium timing of discounts. Finally, Section 7 concludes the paper.

The Model: Monopoly

Time is discrete with an infinite horizon. A time unit is called a period. Consider a monopolist who sells a standard product in each period. Consumers are distributed uniformly with density 1 along a straight line, one end of which is occupied by the monopolist firm. In each period, every consumer demands at most one unit of the product. Consumers’ willingness to pay is µ, and the unit transportation cost in period t is (1/xt) for all consumers. In period t, the marginal consumer, xt, changes in the following way: given xt−1 in the previous period and the depth of the price discount, dt, in the current period,

\[ xt = (xt−1) − δ + λ dt, \]

Where 0 < δ < 1, λ > 0 the depth of the discount, dt, is defined as

\[ dt = \max(0, r_t − p_t), \]

Where p_t is the actual price charged in period t and r_t is the reference price for that period.

Assumption 1 describes the transition of consumer memory between two consecutive periods. The memory erodes at a fixed rate, δ, and can be boosted by λ for every dollar of price cuts6. For simplicity, the effect of price discounts on xt is assumed to be linear and is separable from that of xt−1. This assumption can be relaxed without changing the basic features of the model6.

The monopolist is said to offer a price discount in period t if the actual price, p_t, is strictly lower than the reference price, r_t. Otherwise, the price is normal (p_t ≥ r_t). The depth of the discount, dt, is defined to be the difference between r_t and p_t. When the firm charges the normal price, dt = 0.

Assumption 2

The reference price in period t is

\[ r_t = \min(p_t, p_{t−1}), \]

where p_t is the long-term regular price, which is obtained by taking the average of normal prices over a long time span.

Consumers determine their reference price in period t, r_t, as the lower value between the price in the previous period, p_{t−1}, and the long-term regular price, p_r. They will not be fooled by two possible tricks used by the firm. On the one hand, there is a general regular price, p_r. The firm is not able to cheat by raising p_{t−1}, charging a p_t that is lower than p_r, and then claiming that it is having a “discount” in period t. On the other hand, consumers have fresh memory about the price in the previous period. They do not think any price that is lower than the regular price is always a discount7. The demand is not stimulated if today’s price is higher than or equal to yesterday’s price, even if both are lower than the regular price. In other words, a lower price is thought to constitute a discount only when it is lower than both the long-term regular price, p_r, and the last period price, p_{t−1}.

Consumers take the average of “normal” prices to form the long-term regular price, p_r. It should be emphasized that the average is taken over non-discount prices, not the price in every period. For example, $2.99 is both the long-term regular price of a burger and the “normal” price that is charged each day except Wednesdays. Consumers have a

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1. The fixed percentage drop in memory should be more realistic than a fixed absolute drop: x_t = 0.5 * x_{t−1} + x_{t−1}, where there is nothing to prevent the memory stock from dropping below zero.
2. A more general specification is to let x_t asymptotically approach a certain level, say, x_0. That is, x_t = x_0 + (x_0 - x_t) * e^(-t).
3. This can also be understood from the angle of reputation. As part of brand equity, reputation may be adversely affected by price discounts because low prices may deliver the image of low quality [55].
clear understanding that $0.99 is a discount price and should not be included when they determine the long-term regular price.8

Finally, the firm is assumed to have a constant marginal production cost, $c \in (0, \mu)$; a fixed cost, $F$, in the discount period (the cost of, say, advertising and changing price tags); and a time discount factor, $\beta \in (0, 1)$. The monopolist chooses the price in each period to maximize the total present value of profit.

### Normal Prices and Long-Term Regular Price

We first determine the optimal choice of normal prices. A normal price, $p_i$ (i.e., no discount is offered in this period) affects the firm’s objective function directly and indirectly. The direct effect is on the current-period profit, while the indirect effect is on the next-period profit through the formation of the reference price9. The profit of period $t$ is $\pi_t = q_t(p_t-c) = x_t(\mu-p_t)(p_t-c)$. Since $d_t = 0$, the coefficient $x_t = \delta x_{t-1} + \lambda d_t = \delta x_{t-1}$ is not affected by the choice of $p_t$. Then, the single-period profit, $\pi_t$, is maximized at the monopoly price, $p_m = (\mu+c)/2$, which does not depend on the time index, $t$. Therefore, although the demand changes over time, the change is in such a way that the single period profit is maximized at the same price. When prices deviate from this optimal level, $\pi_t$ monotonically increases in $p_t$ when $p_t < p_m$ and monotonically decreases in $p_t$ when $p_t > p_m$.

For the indirect effect, because $r_{t+1} = \min(p_{t+1}, p_t)$, the current price $p_t$ can become the reference price for the next period. This is relevant only when a discount is offered in $t + 1$. We can show that the indirect effect does not distort normal prices from $p_m$.9

Therefore,

**Proposition 1:** In equilibrium, every normal price is the same, and they all equal $p_m = (\mu + c)/2$. Consequentially, the long-term regular price is $p_t = p_m = (\mu+c)/2$.

The driving force behind the uniform pricing in normal periods is that the single period monopoly price is the same despite changing demand coefficients. One may think that a uniform normal price that is slightly higher than $p_m$ should be beneficial to the firm, as a higher reference price means a smaller distortion in the discounted periods. This is not true, because when there are two consecutive normal periods, the optimal price for the first period should be $p_m$, as it does not have any direct or indirect effect on the next period profit.

Proposition 1 greatly simplifies the firm’s choice: When it is not offering any discount, the firm should always charge the same normal price. Nevertheless, the firm still faces complicated choices: the duration of discounts (i.e., whether or not it wants several consecutive discounts), the depth of every discount, and the frequency of discounts.

### Depth of Discount

For a wide range of parameter values, it can be shown that the firm should choose at most one discount period between any two must be lower than the preceding price in order to constitute a discount. If the preceding price is already discounted, offering a further discount in the next period would be more costly, as the price would be farther away from the single-period-profit-maximizing price. Most of the time, the firm would rather wait for at least one period after a discount before the next is offered.

In principle, the firm has the freedom of never offering any discounts, but in most cases this is not optimal10. Basically, the cost of offering a discount includes the fixed cost, $F$, and a lower current profit, while the benefit is higher demands in the future. If, the firm never offers any discount, the demand would eventually drop to zero, in which case offering discounts at least once is beneficial, given that the fixed cost, $F$, is not prohibitively high.

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8Blattberg and Neslin [25] present empirical findings on how the long-term regular price is formed: if the current price differs substantially from the normal price, then the observed price will be seen as “exceptional” and the regular price will not be updated. “This essentially tells the consumers that the reduced price is temporary and should not be used to decrease the consumers reference price” (p. 46). I should point out that the “reference price” in Blattberg and Neslin [25] is in fact the “long-term regular price” in this paper.

9In principle, there could be a third effect: the firm’s profit may be affected by normal prices through a change in the long-term regular price, $p_m$, which is the average of normal prices. The average, however, is taken over a long time span, so the impact of a single normal price on $p_m$ is negligible.

10The sufficient condition is that $z$ or $F$ is large enough, where $z = (\mu + c)/2$, or that both $\delta$ and $\beta$ are close enough to 1.
It now becomes clear that the firm’s optimal strategy is to offer price discounts once at a time: a price discount for one period, then a normal price for several periods, followed by another discount for one period, and several other normal periods, and so on and so forth. I call this the price movement from one discount period to the next a cycle. Consider the case when exactly n periods form a cycle. The firm chooses n first, commits to it, and then chooses the depth of the discount in each cycle.

In what follows, I will determine the optimal depth of the discount for any given n, discuss the stability of the system, and finally find the optimal n. Making n a parameter first and then a choice variable implies that the discounts must be offered at equal pace.13

A cycle starts with (n − 1) periods of normal prices and ends with a discount price, after which a new cycle starts. Suppose that the demand coefficient is x when a cycle starts, and that the depth of the discount is d. Then, \(x_i = \delta^{i-1}x\) for \(i = 1, 2, \ldots, n-1\) and \(x_n = \delta^{n-1}x + \lambda d\). By Proposition 1, for \(i = 1, 2, \ldots, n-1\) and \(p_i = p_{n-1}\). The present value of profit is thus \(\pi_i = x_i (\mu - p_i) (p_i - c)\), where \(z = (\mu - c)/2\) is the profit margin when \(p_n\) is charged. In the last period, \(p_n = p_{n-1} - d\), which means that \(\pi_n = x_n (\mu - p_n) (p_n - c)\) and \(\pi_n = \delta^{n-1} x (\mu - c)/2\) + \(\lambda d (\mu - c)/2\). The total present value of the profits in the cycle is:

\[
\pi(x, d) = \sum_{i=1}^{n} \beta^{i-1} \pi_i = xy + \beta^{n-1} \left[ \lambda d (z^2 - d^2) - \delta^{n-1} x d^2 - F \right]
\]

Where \(y = \frac{z^2 (1 - \beta^{n-1})}{1 - \beta^2}\) > 0 at the beginning of the next cycle, the transition equation is:

\(x_{n+1} = \delta x_n + \lambda d\).

**Optimal depth of discount**

Starting from an arbitrary x, the monopolist chooses a series of d in each cycle in order to maximize lifetime profits. This is a typical dynamic programming problem. In each cycle, there is a state variable, \(x_i\), and a choice variable, \(d_i\). The time subscript has been changed from t to i, as the index is now about cycles (each consisting of n periods), not periods. The transition equation is:

\[x_{n+1} = \delta x_n + \lambda d\].

In line with standard procedures (see, for example, Stokey and Lucas, 1989) [56], define the value function as V (x). Then the value function satisfies the following Bellman equation:

\[V(x) = \max_{0 \leq d \leq 1} \left\{ \pi(x, d) + \beta V(\delta x + \lambda d) \right\}\]

Where the profit of the current cycle, \(\pi\), is given by equation (2). A unique optimal choice, \(d > 0\), is found for any given initial demand, \(x\).

**Proposition 2:** The optimal choice of discount, d, is given by:

1. \(d = d^* = \frac{x \phi - \sqrt{x^2 \phi^2 - \lambda^2 \phi^2}}{\lambda \phi}\) if \(x^2 \geq (\phi \lambda^2 y) / \phi^2\)

2. \(d = p_{n-1} = \frac{\mu + c - x}{2}\) if \(x^2 < (\phi \lambda^2 y) / \phi^2\), where \(\phi = \delta^{n-1} (1 - \beta^{n-1})^2 > 0\), \(\phi = 2 \beta^2 \delta^2 + 2 \beta^2 \delta^2 - 3\) (4)

A discount brings the following tradeoff: a positive \(d\) deviates from pm, reducing the profit in the current period; but it also boosts consumers’ brand recall, increasing the demand in the future. At \(d = 0\), the first effect is zero, so the second effect dominates.

Therefore, unless \(\lambda = 0\), the discount, \(d\), should always be positive: the firm should always offer discounts.

It is easy to verify the following comparative static properties:

\[\frac{\partial d^*}{\partial x} < 0, \frac{\partial d^*}{\partial c} < 0, \frac{\partial d^*}{\partial \lambda} > 0, \frac{\partial d^*}{\partial \delta} > 0, \frac{\partial d^*}{\partial \beta} > 0\]

These signs all make intuitive sense: the discount should be deeper when the current business is not very good, a normal price brings more profit, consumers are more sensitive to price discounts, the decline in consumer goodwill is slower, or the firm is more patient.

**Stability of the dynamic system**

Proposition 2 determines the optimal depth of discounts. For any given \(x\), there is a corresponding optimal choice, \(d^*(x)\). Then, given \(d^*\), at the beginning of the next cycle, the firm faces a new demand, \(g = \delta^{n-1} x + \lambda d^*(x)\), and needs to make another choice of d. We are interested in the stability of the dynamic system, namely whether or not such choices of \(d^*\) will eventually lead to any steady state. It will make no sense to talk about price discounts if the system explodes.

The stability of the dynamic system can be studied in the following way14. Express both \(x\) and \(g\) as functions of the optimal discount, \(d^*\). It can be shown that the two functions have a unique intersection, which, by definition, is the steady state. Both functions are decreasing in \(d^*\) at the intersection, and \(x\) is always steeper than \(g\). Moreover, \(x\) decreases in \(d^*\) over the entire range, while \(g\) can be either monotonically decreasing in \(d^*\) (case 1 in Figure 2, where \(dm\) is the largest value that \(d^*\) can take) or U-shaped (case 2 in Figure 2). Thus, the transition from \(x\) to \(g\) is determined by using \(d^*\) as a linkage. In either case, it is obvious from Figure 2 that starting from any \(x\), the system converges monotonically toward the steady state. Therefore, we have

**Table 1:** Time paths of demands and discounts under monopoly.

<table>
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<tr>
<th>x</th>
<th>100</th>
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<th>56.47</th>
<th>43.54</th>
<th>34.57</th>
<th>28.53</th>
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<td>5.15</td>
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**Table 2:** Comparative statics in the steady state.

\(z\) + + +
\(\lambda\) + + +

13There are two justifications for this implication. First, there may exist some natural choices of n, e.g. once a week. Once every other week or twice a week will be too confusing for consumers to remember. Second, the firm may need to announce and commit to the frequency of discounts. Presumably, prices can change much quicker than the frequency of discounts. The model regards price as a short-term variable and frequency as a long-term one.

14According to standard mathematics textbooks, the dynamic system is stable if and only if the eigenvalue of \(g(x) = \delta x + \lambda d^*(x)\) is less than 1 in absolute value. However, \(d^*\) as a function of \(x\) is very complicated, making it impossible to find the eigenvalue of \(g(x)\).
The system converges monotonically to a unique steady state in which
\[ x = \bar{x} = \lambda \delta \frac{\gamma}{1 - \delta^s}, \quad d = \bar{d} = \frac{z}{\sqrt{1 - \delta^s}} \]
and \( \gamma = \frac{1 - \beta^s \delta^s}{1 - \beta^s (3 - 2 \beta^s \delta^s)} > 0 \). To give an idea of how the system evolves a numerical example is constructed as follows. Let \( \lambda = 1, z = 5, \delta = \beta = 0.95, n = 6 \). Then, the steady state is given by \( \bar{x} = 18.41, \bar{f} = 5.13 \). Starting from any \( x \) that is either above or below \( \bar{x} \), the system, described by the state variable \( x \), does not depend on \( \lambda \). Starting from any \( x \) that is either above or below \( \bar{x} \), the system converges monotonically to a unique steady state. To simplify, assume \( \beta = \delta \). Let \( s = \beta n = \delta n \), then,

\[ x = \bar{x} = \lambda \delta s \left( \frac{1}{1 - \delta^s} \right), \quad d = \bar{d} = \frac{z}{\sqrt{1 - \delta^s}} \left( \frac{1 - s^2}{3 + 2 s} \right), \]

and the profit of one cycle in the steady state is:

\[ \pi = \lambda^2 \delta^s \left( \frac{1 - s}{1 - \delta^s} \right) \left( \frac{1 + s}{1 + s} \right) \left( \frac{1 + s}{3 + 2 s} \right) - \frac{s}{s} \eta \]

By direct observation, it is easy to verify the comparative statics in Table 2.

\[ \lambda \] indicates the effectiveness of a discount on the demand. Previous discussion has shown that, for fixed \( x \), \( d^* \) increases in \( \lambda \). However, when \( d \) increases, the demand coefficient of the next cycle increases so that \( d \) increases in \( \lambda \). The sign of the comparative statics is quite intuitive. When the fixed cost is higher, discounts should be offered less frequently. When either \( \lambda \) is larger (a discount is more effective in boosting demand) or \( z \) is larger (a higher demand is more profitable), the firm should offer discounts more often.

**Dynamic Duopoly Competition**

**Modification of the model**

The analysis so far has dealt with monopoly. Naturally, we would like to extend the model to oligopoly, where several firms compete by using price discounts. In addition to the depths and frequencies of discounts, the timing becomes a central issue: do the firms offer discounts at the same time? I focus on duopoly. To accommodate the interaction between firms, I modify the model as follows.

Two firms, designated a and b, sell differentiated products. The demand of firm i in period t is \( q_i = x_i (\mu - p_i) \) where \( i = a, b \), and \( \mu \) is the price and demand coefficient of firm i in period t. The interaction between the two firms is assumed to affect only the demand coefficient:

\[ x_i = \delta x_i^{*} + \lambda d_i^{*} - \theta d_i^{*} \]

where \( 0 < \delta < 1, \lambda > 0 \geq 0, j = \{ a, b \} \) i, and \( d_i^{*} \) is firm i’s depth of discount in period t. As in the model for monopoly, \( d_i^{*} > 0 \) if firm i offers a discount in period t, and \( d_i^{*} = 0 \) if the normal price is charged.

### Figure 3: Firm b overshoots when firm a’s starting demand is very high and firm b’s is very low.

---

This conclusion is sensitive to the specification of the model. For example, if \( x_i \) drops asymptotically to a level, \( x_0 \) that is greater than zero (see footnote 5), then \( \bar{d} \) will depend on \( \lambda \).
Compared to the monopoly case, there is now a new parameter, \( \theta \), that captures the interaction between the two firms. When \( \theta > 0 \), a firm’s discount boosts consumer memory for its own product but hurts the memory for its rival’s product. When \( \theta = 0 \), the two firms become two independent monopolists.

Expression (7) says that, if neither of the firms offers any discount, the demand for each firm shrinks at a constant rate, \( \delta \), but the lost consumers do not go to the firm’s competitor. When a firm offers a discount, the demands of both firms are affected: the discounting firm’s own demand is raised by a factor \( \lambda \), while its rival’s demand is reduced by a factor \( \theta \). The rival’s demand is affected because some of its customers are lured away by the discount. Finally, when both firms offer discounts at the same time, the net effect will depend on the magnitude of the two discounts. Because \( \lambda > \theta \), if the two discounts have the same depth, demands of both firms are boosted.

Since the interaction between the two firms only affects the demand coefficients, as in the case of monopoly, the normal prices should always be fixed at \( p_m = (\mu + c)/2 \) for each firm, and the profit of a normal period is

\[
\pi = (p - c)(1 - \beta \delta) - \beta \delta^2
\]

where, again, \( \beta \delta = \frac{z^2(1 - \beta^2 \delta^2)}{1 - \beta \delta} \). Given \( d_i \), firm \( a \) chooses \( d_a \) to maximize its own lifetime profits. Likewise for firm \( b \). The duopoly dynamic programming problem is thus set up as:

\[
V(x_a, x_b) = \max_{d_a, d_b} \left\{ \pi_a + \beta V(x_a, x_b) \right\}
\]

and

\[
U(x_a, x_b) = \max_{d_a, d_b} \left\{ \pi_b + \beta U(x_a, x_b) \right\}
\]

There are two state variables, \( x_a \) and \( x_b \), and a choice variable for each firm. The transition equations of the system are given by:

\[
x_a' = (x_a + \lambda d_a - \theta d_b)(y - d_a^2)
\]

\[
x_b' = (x_b + \lambda d_b - \theta d_a)(y - d_b^2)
\]

The best response function for each firm is found by dynamic programming.

Lemma 1: In the subgame with simultaneous timing, the depths of discounts in each cycle are characterized by

\[
k_a = \frac{926 \lambda^2}{1 - 6 \lambda^2} = \frac{926 \lambda^2}{1 - 6 \lambda^2}
\]

\[
k_b = \frac{926 \lambda^2}{1 - 6 \lambda^2} = \frac{926 \lambda^2}{1 - 6 \lambda^2}
\]

Figure 4: Steady state variables with different timing.

Table 3: Steady state profits for various timing combinations.

<table>
<thead>
<tr>
<th>( k )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>842, 922</td>
<td>879, 906</td>
<td>913, 898</td>
<td>945, 896</td>
</tr>
<tr>
<td>2</td>
<td>944, 802</td>
<td>944, 944</td>
<td>816, 968</td>
<td>852, 951</td>
<td>886, 942</td>
<td>916, 939</td>
</tr>
<tr>
<td>3</td>
<td>922, 842</td>
<td>968, 916</td>
<td>963, 963</td>
<td>833, 994</td>
<td>865, 983</td>
<td>895, 980</td>
</tr>
<tr>
<td>4</td>
<td>906, 879</td>
<td>951, 852</td>
<td>994, 833</td>
<td>985, 985</td>
<td>851, 1022</td>
<td>880, 1018</td>
</tr>
<tr>
<td>5</td>
<td>898, 913</td>
<td>942, 886</td>
<td>983, 865</td>
<td>1022, 851</td>
<td>1010, 1010</td>
<td>872, 1053</td>
</tr>
<tr>
<td>6</td>
<td>896, 945</td>
<td>939, 916</td>
<td>980, 895</td>
<td>1018, 880</td>
<td>1053, 872</td>
<td>1038, 1038</td>
</tr>
</tbody>
</table>

17 Basically, consumers evaluate the relative attractiveness of the two products when at least one firm is offering a discount. This is similar in spirit to the demand pattern of Rosenthal [57]: consumers start to compare the two products only when one firm raises its price. In my model, the interaction between the two firms is not through price or quantity (i.e., it is not Bertrand or Cournot), but rather through price reductions. There is implicitly an optimization problem that consumers solve, and expression (7) can be viewed as a reduced form of the demand due to consumers’ choices.
\[
\lambda \phi d_i^2 + 2\theta \phi d_i d_j - 2\rho x_i d_i + \lambda y = 0,
\]
\[
\lambda \phi d_i^2 + 2\theta \phi d_i d_j - 2\rho x_i d_i + \lambda y = 0,
\]
where \( p = 1 - \beta^n \delta^n \), \( \phi = 2\beta^n \delta^n + 2\beta^n \delta^{2n} - 3 \), and \( \eta = 1 - \beta^n \delta^n - \beta^n \delta^{2n} \).

If the two firms’ businesses are equally good (i.e., \( x_i = x_j = x \)), their discounts are of the same magnitude. Moreover, the common choice, \( d = d_i = d_j \), have the following properties:
\[
\frac{\partial d}{\partial x} < 0, \quad \frac{\partial d}{\partial z} > 0, \quad \frac{\partial d}{\partial \delta} > 0, \quad \frac{\partial d}{\partial \theta} > 0, \quad \text{while}
\]
\[
\frac{\partial d}{\partial \theta} > 0 \quad \text{if and only if} \quad \beta^n \delta^n + \beta^n \delta^{2n} < 1
\]

These signs are quite intuitive and are also consistent with the corresponding signs under monopoly. There is a new parameter, \( \theta \), under duopoly. For a large range of parameters, the depth of the discount, \( d \), increases in \( \theta \). That is, if a firm’s customers are sensitive to the rival product’s discounts, the firm should discount deeply so as to win back the leaving customers\(^{19}\).

Numerical examples show that starting from any pair of \( x_i \) and \( x_j \), the dynamic system converges to a unique steady state. The path of the convergence, however, is not necessarily monotonic. If \( x_i \) and \( x_j \) differ very much, the firm that has a lower demand may overshoot in terms of both the choice variable, \( d \), and the state variable, \( x \), before finally settling down at the steady state. Figure 3 illustrates this overshooting behavior. In this example, the parameter values are the same as in monopoly: \( \lambda = 1, z = 5, \delta = \bar{\delta} = 0.95, n = 6 \), with a new parameter, \( \theta = 0.5 \). The steady state is found to be \( \bar{x}_i = \bar{x}_j = 9.11 \) and \( \bar{d}_i = \bar{d}_j = 6.56 \). Firm a starts from \( x_i^0 = 100 \) while firm b starts from \( x_j^0 = 0 \).

The overshooting can be understood as follows. Due to its original high demand, firm a’s discount is first very small and then eventually rises. In principle, firm b should do just the opposite: decrease the depths of its discounts over time. Under duopoly competition, however, there is no interaction between the two firms. In the first several cycles, because firm a’s discounts are small, there is not much interaction, so firm b continues to decrease its discounts. Later, the interaction becomes stronger, which requires \( d_i \) and \( d_j \) to move in the same direction, so the discount depths both go up. This gives rise to firm b’s overshooting behavior.

**Proposition 5:** In the subgame with simultaneous timing, starting from any pair of \( x_i \) and \( x_j \), the dynamic system converges to a unique steady state in which
\[
\bar{x}_i = \bar{x}_j = \bar{x} = \delta^n (1 - \theta) \sqrt{\frac{\lambda y}{\sigma}} \quad \text{and} \quad \bar{d}_i = \bar{d}_j = \bar{d} = \sqrt{\frac{\lambda y (1 - \delta^n)}{\sigma}}
\]
where \( \sigma = \lambda (3 - \delta^n - 2\beta^n \delta^n) - 2\beta^n (1 - \beta^n \delta^n) \).

When the two firms start from different demand levels, the firm with the higher demand will choose a smaller discount, leading to a smaller difference between the two firms’ demands in the next cycle. Eventually they converge to the same level.

### Non-simultaneous timing

Now consider the case when the two firms offer discounts at different times. Without loss of generality, let firm a discount in the first period of each cycle and firm b in the \( k \)th period, \( 2 < k \leq n \). Following the same procedure as in the simultaneous timing case, it can be shown that the equilibrium depths of discounts, \( d_i \) and \( d_j \), are characterized by the following two best response functions:\(^{20}\)
\[
\rho d_i^2 - 2\theta \delta^{2i+1} d_i d_j - 2\rho x_i d_i + \lambda y = 0
\]
\[
\lambda \phi d_i^2 + 2\theta \phi d_i d_j - 2\rho x_i d_i + \lambda y = 0
\]
where \( \varphi, \rho \) and \( \eta \) are defined in Lemma 1.

Numerical examples show that, for every timing arrangement, the duopoly dynamic system is globally stable and converges to a unique steady state. Figure 4 shows the two firms’ steady state discounts, demands in the discount period, and per-cycle profits. Remember that \( k \) is the timing of firm b’s discount and that firm a’s discount is in the first period.

**Lemma 2:** In the subgame with non-simultaneous timing,

(i) The depths of discounts \( \bar{d}_i \) and \( \bar{d}_j \) are characterized by
\[
\lambda (3 - \delta^n - 2\beta^n \delta^n) \bar{d}_i^2 - 2\theta \delta^{2i+1} (1 - \beta^n \delta^n) \bar{d}_i \bar{d}_j - \lambda y (1 - \delta^n) = 0
\]
\[
\lambda (3 - \delta^n - 2\beta^n \delta^n) \bar{d}_j^2 - 2\theta \delta^{2j+1} (1 - \beta^n \delta^n) \bar{d}_i \bar{d}_j - \lambda y (1 - \delta^n) = 0
\]
(ii) If \( k > \frac{n}{2} + 1 \), then \( \bar{d}_i > \bar{d}_j \).

In order to understand conclusion (ii), consider the case when \( k < \frac{n}{2} + 1 \). That is, firm a’s discount is followed quickly by firm b’s. Because firm a can only enjoy the increased demand for a very short time, its incentive for offering discounts is reduced. As a result, a’s discount should be smaller than b’s. The symmetry in conclusion (ii) (and in Figure 4) around \( k = \frac{n}{2} + 1 \) should come as no surprise. After all, a cycle is defined arbitrarily in the dynamic process with an infinite time horizon. When \( k > \frac{n}{2} + 1 \), firm b’s discount is closer to firm a’s next discount than to the current one. Consequently, the starting and ending points of a cycle can be redefined so that firm b’s discount comes first in a cycle, while firm a’s discount follows in the \((n-k)\)th period. The conclusion of (ii) can therefore be restated as follows: define the

---

\(^{19}\)The Folk Theorem is not applicable here, as it is not a stage game. We can view the equilibrium as a Markov equilibrium because the strategy depends only on the state of the world when an action is taken.

\(^{20}\)Notice that \( \theta \) affects \( d \) through the demand coefficient \( x \), not through parameter \( \lambda \). Some people may think that since \( x = \delta x_i = x_j \delta \), given \( d_i = d_j \), the demand becomes \( x = \delta x_i = x_j \delta \), so the presence of \( \theta \) has the effect of reducing the discount coefficient \( \lambda \). Furthermore, since \( d \) increases in \( \lambda \), it should in turn decrease in \( \theta \). This argument is wrong, as \( d_i = d_j \) cannot be assumed a priori. When determining the optimal \( da \), firm a should regard \( d_j \) as given. Consequently, \( x = \delta x_i = x_j \delta \). The presence of \( \theta \) serves to reduce \( x \), and we know that \( d \) decreases in \( x \).

\(^{18}\)One might raise the issue of sub game perfection. For fixed \( k \), the timing of actions seems to be well defined: in each cycle, firm a moves first and firm b moves second. The Folk Theorem is not applicable here, as it is not a stage game. We can view the equilibrium as a Markov equilibrium because the strategy depends only on the state of the world when an action is taken.

\(^{20}\)The presence of \( \theta \) serves to reduce \( x \), and we know that \( d \) decreases in \( x \).
“leader” to be the firm whose discount is closer to the other firm’s next discount than to its previous discount. Then the steady state discount of the leader is smaller than that of the follower.

**First stage: Equilibrium timing of discounts**

Having derived the steady state profits with various timing arrangements, we are now ready to determine the equilibrium timing of discounts. An analytical solution for non-simultaneous timing is too complicated, so I resort to numerical simulation using the parameter values that have been used throughout the paper: \( \lambda = 1, \theta = 0.5, z = 5, \delta = \beta = 0.95, n = 6 \). Steady state profits of the two firms are calculated for every combination of the timing and the following table is constructed:21

This symmetric table has a unique pure-strategy equilibrium, in which both firms offer discounts in the last period of each cycle. Therefore, we draw the following conclusion:

In the dynamic duopoly game, in equilibrium the two firms offer discounts at the same time.

The last graph in Figure 4 reveals that when \( k_a = 1 \), firm b’s profit is maximized at \( k_b = 2 \): the best response is to offer discounts immediately after its rival does. By doing so, a firm can enjoy the boosted demand for the longest time before its rival’s next discount. This is true as long as there is a “later” period in the cycle: When \( k_a = 2, 3, 4, 5 \), \( k_b = k_a + 1 \) (see Table 3). When the rival’s discount appears in the last period \( k_a = 6 \), however, there is no period in the same cycle that is later, so firm b’s best choice is to offer a discount in the same (last) period. Since the timing game is symmetric, the above best response leads to a unique equilibrium, in which the two firms offer discounts simultaneously.

In principle, the timing game could also have mixed strategy equilibrium, but two forces make it unlikely. First, the purpose of offering discounts is to remind consumers of the existence of the products. Regularity of the discount timing is therefore important. This is different from the incentive of price discrimination, for which unpredictability is a crucial element and consequently randomized strategies fit perfectly. Second, the two firms have a collective incentive to coordinate the timing, as their total profit of \( k_a = k_b = 6 \) is the highest among all combinations of the timing and therefore is higher than any weighted average of the payoffs in Table 3. Given the symmetry between the two firms, this means that the pure strategy equilibrium of simultaneous timing Pareto dominates any mixed strategy equilibrium. As long as one firm is able to announce its choice of timing before the other firm does, which is very likely in reality, the coordination can be easily achieved.

In fact, this second force also gives us a hint as to what will happen when the two firms choose different \( n \), which is the frequency of discounts. Then their discounts will necessarily be staggered; sometimes a’s discount precedes b’s, and sometimes b’s precedes a’s. As we have seen, a firm’s discount becomes rather ineffective when followed quickly by its rival’s. Over time, the firm’s profits fluctuate, but overall, both firms should do worse than when they synchronize their discounts. This gives them strong incentive to choose the same frequency and then coordinate the timing.

Having established simultaneous timing as the only equilibrium in the duopoly dynamic game, we can now study the properties of the equilibrium. Proposition 5 characterizes the steady state of simultaneous timing. We are mainly interested in a comparison between monopoly and duopoly, which is reflected in the presence of parameter \( \theta \). We have:

**Proposition 6**: In the duopoly steady state, \( T \) increases in \( \theta \) and \( \Xi \) decreases in \( \theta \).

Parameter \( \theta \) measures the interaction between the two firms. When \( \theta \) is larger, the negative impact of one firm’s discount on the other firm’s demand is larger, so the equilibrium demand level for both firms is lower. Facing lower demands, therefore, each firm needs to offer deeper discounts to compete for consumers.

Since \( \theta = 0 \) represents the case of monopoly, the above Proposition leads to:

**Corollary**: Compared with monopoly, the duopoly demand is lower, while the discount is deeper.

**Conclusion**

This paper provides a new explanation for why price discounts are offered. I suggest that the demand for a firm’s product shrinks over time and that the firm periodically uses price discounts to boost the diminishing demand. While it is well known that demand can be stimulated by advertising, the paper’s contribution is to show that price reductions can be regarded as a special form of advertising. For a widely used business practice such as price discounts, there are naturally many different explanations. For example, the periodic price reduction in durable goods is explained well by Conlisk et al. [11] and Sobel [12], while consumers’ stockpiling behavior for storable goods is modeled by Pesendorfer [13]. I have focused in this paper on non-durable, non-storable products such as fast foods and services, because these are the places where the existing literature is not able to provide a satisfactory theory22. The model works well to explain all of the stylized facts. It also provides some insight into the interaction between firms in a dynamic setup when price discounts are the choice variables.

Notice that the model itself does not need the assumption of a non-durable, non storable good; the basic idea is applicable to any industry. The model’s prediction of the optimal pricing pattern has actually...
been found in many other industries: periodic price reductions with a long period of a constant high price and a short period of a constant low price for durable goods [1] and non-durable but storable goods [13], as well as demonstrate offerings of price discounts by competing firms [19,58]. On the other hand, it is fully possible that several forces could all play a role in generating the pricing pattern of a particular industry. For example, while my model can explain why Burger King offers deep discounts once a week, it does not exclude the element of price discrimination, and the exact timing of discounts may well reflect a concern for peak-load pricing23. If that is the case, which theory is price discrimination, and the exact timing of discounts may well reflect industry. For example, while my model can explain why Burger King could all play a role in generating the pricing pattern of a particular

[13], as well as simultaneous offerings of price discounts by competing and price discrimination simultaneously.

Although I propose that periodic price reduction is a special form of advertising, there are important differences between the two promotion strategies. Price discounts have the danger of delivering an image of inferior quality, so this strategy should not be utilized in cases when quality is a major concern (new products, fashion clothing, or industries with important vertical product differentiation). The fast food industry is a good place to execute the discounting strategy because the product quality is standard and well known. Consumers have long perceived that $2.99 is the normal price for a burger at Burger King, so discounting the price to $0.99, while stimulating the demand, will not damage the product image.

Another drawback of price discounts is that competitors are likely to respond with their own price cuts, making the first firm’s discounting less effective or even counter-productive. By contrast, advertising has the strategic effect of reducing price competition: When I promote my products with advertising, my customers are less likely to switch to your product. This will make your price cut less effective in luring my customers, so you will cut the price less often or may even raise your own prices, which in turn benefits me.

Of course promotional strategies do not have to be used exclusively. Many discounts in the real world are accompanied by heavy advertising. On the other hand, we do see various advertisements without price discounts. It will be interesting to study under what situation a firm should use advertising and under what situation the firm should use price discounts with advertising. Milgrom and Roberts [18] have analyzed the optimal combination of discounting and advertising for quality signaling. Discounting without advertising is also imaginable—for effective price discrimination.

Other promotional strategies such as public relations, personal selling, direct marketing or sponsorship may also boost consumers’ memory. But price discount may also serve the purpose of second-degree price discrimination [61]: Price-sensitive consumers are more likely to notice the regular price discounts and end up purchasing the product at the lower price, exactly what price discrimination requires. While direct marketing may target particular segments, discrimination is achieved only after the target has been identified first. The beauty of second-degree (i.e., indirect) price discrimination is that the seller does not need to identify or differentiate consumers—consumers differentiate themselves by self-selecting into different pricing deals. Although not modeled in this paper, price discrimination is likely to be a goal by store managers in real life when they choose marketing strategies, and price discounts have the advantage of achieving memory stimulation and price discrimination simultaneously.

Appendix

A Proof of Proposition 1

If a normal price, pormal, should deviate from the single-period optimal level, pr, the concern must be the indirect effect. I distinguish between two cases: pm (the next period price is also normal) and pm (the next period price is discounted). When pm = pm, the indirect effect is zero, so in equilibrium pm = pm for every t.

As for pm, if pm = pm for every t, the proof is finished. Suppose that in an equilibrium, pm ≠ pm for at least one t. Because pm is the weighted average of every pm and many pm, we have min{pm} < pm < max{pm}. Let β = [arg max{pm}] and k = [arg max{pm}].

If pj ≥ pm, then pm < p, then the monopolist can earn a higher profit by slightly lowering pm, because rk+1 = min{p, pm} is not affected by pm, and the profit in period k is decreasing in pm when pm > pm.

If pj < pm, then pm < pm < pm. Then rj+1 = min{pj, pm} = pm. The profit in period j is increasing in pm when pm < pm. The profit in the next period, pj+1 = qj+1(pm - c) - [δxj + λdj+1](m - pj) - λpj - c, is increasing in pm, for fixed dj+1 > 0. But pm = pm - dj+1 + 1 < pm = pm, in pm, so in pm also increases in pm.

Therefore the firm could have enjoyed a higher profit in both period j and period (j+1) by slightly increasing pm, while the profits in all the following periods are either not affected (when period (j+2) is a normal period) or positively affected (when period (j+2) is a discount period), as the reference price in period (j+2), pm = pm, is higher, while the demand coefficient, xj+2 = δxj+1 + λdj+2 = δxj + λdj+1 + λdj+2, is the same when dj+1 and dj+2 are both fixed.

In summary, pm must equal to pm for every t in any equilibrium. Combined with the fact that pm = pm for every t, this leads to the conclusion that all normal prices are the same. Moreover, they are all equal to pm. As a result, pm = pm.

B Proof of Proposition 2

In the dynamic programming problem (3), let g = δx + δδx. Then, the first-order condition with respect to the choice variable, d, gives:

\[ β^{-1}(δx - d) - 2δd - 2δx + \lambda δx ≥ 0 \] (14)

The envelope equation associated with the state variable, x, leads to:

\[ V'(x) = y - βx - βx - βδx - δx + δx + \lambda δx + \lambda δx + \lambda δx ≥ 0 \] (15)

From (14), solve for the expression of V'(g), which is then plugged into (15) to get:

\[ V'(x) = y - βx - βx - βx - \lambda δx + \lambda δx + \lambda δx + \lambda δx + \lambda δx + \lambda δx ≥ 0 \] (16)

Now, use variable g = δx + δδx and substitute for x in equation (16) to get the derivative of the value function evaluated at g:

\[ V'(g) = y - βx - βx - βx - \lambda δx + \lambda δx + \lambda δx + \lambda δx + \lambda δx + \lambda δx + \lambda δx ≥ 0 \] (17)

23The discounts on Tuesdays by Hong Kong movie theatres may be partly explained by the fact that many people go to horse racing on Wednesdays while new movies are always released on Thursdays.
m = (μ + c)/2. For simplicity, let us ignore the p could be either positive or negative. However, t depends only on z = (μ − c)/2 and therefore is independent of \( \delta \).

Out of the two solutions of d in equation (19), only the one given in the proposition is optimal.

One can easily verify that \( d^* > 0 \). When \( x^2 \geq (\phi \lambda y)/\phi \), the term within the square root is non-negative so that \( d^* \) is well defined. Otherwise, H(d) is positive for every d, and d should take the highest possible value, namely \( p_m \).

For the requirement that \( d^* \leq p_m \), observe that \( d^* \) depends on z, which is \( (μ − c)/2 \), while \( p_m = (μ+c)/2 \). For any \( p_m \), z can be made arbitrarily small so that \( d^* \) will be close to zero and \( d^* \leq p_m \) will always be satisfied.

C Proof of Proposition 3

In any steady state, \( x = g(x, d(x)) = δ^* x + δλ d \). Therefore,

\[
x = \frac{λ δ d}{1 − δ^*} \tag{20}
\]

By plugging (20) into the expression \( H(d) = 0 \) in equation (18), the steady states \( \bar{X} \) and \( \bar{d} \) can be found as shown in the Proposition. Notice that \( \bar{d} \) depends only on \( z = (μ − c)/2 \) and therefore is independent of the requirement \( \bar{d} \leq p_m = (μ+c)/2 \). For simplicity, let us ignore the unlikely case where \( \bar{d} > p_m \).

Recall from Proposition 2 that in order for \( d = d^* \), \( x^2 \) must be no less than \( (\phi \lambda y)/\phi \). It turns out that this requirement is always satisfied at \( x = \bar{X} : \)

\[
\bar{X} = \frac{φ\lambda y}{δ^*φ} \left( 3 + β^*δ^* − 2δ^* − 2β^*δ^* \right) ≥ 0
\]

Expression \( H(d) = 0 \) of equation (19) fully characterizes the optimal steady states.

Regarding equation (8), for firm a, there is a first-order condition with G and u(s) defined as in the proposition, the above equation becomes

\[
\prod = − − = − + − + + − + − + = \tag{21}
\]

The dynamics of the system are represented by the transition from \( x(d^*) \) to \( g(d^*) \). The two variables are brought together by \( d^* \) as a linkage. Figure 2 shows the only two possible cases of the dynamic system: \( g(d_a) < 0 \) and \( g(d_a) > 0 \).

(1) \( g(d_a) < 0 \). Both \( x(d) \) and \( g(d) \) are monotonically decreasing in \( d \), and \( x(d) \) has a steeper slope than \( g(d) \) for any valid \( d \). Starting from an arbitrary \( x_a \), the firm chooses \( d_a \), which is found on curve \( g(d) \). Then corresponding to the same \( d_a, g_a \) is found from the \( g(d) \) curve. The transition is a mapping from \( x_a \) to \( g_a \). In the next round \( g_a \) becomes \( x_a \) and the whole process repeats itself. It is clear from the picture that the system converges monotonically to \( (\bar{X}, \bar{d}) \).

(2) \( g(d_a) > 0 \). Starting from any \( x \), the system again converges monotonically to \( (\bar{X}, \bar{d}) \).

D Proof of Proposition 4

The objective function is given in equation (6), and the choice variable is \( s \). The first-order condition is

\[
\Pi (s) = \frac{2λ^2}{1 − δ^*} \left( (1+s)^2 − \frac{F}{(1-s)^2} \right) = 0
\]

With G and u(s) defined as in the proposition, the above equation becomes

\[
\frac{F}{G} ≤ \frac{2λ^2}{9(1−δ^*)} \left( (1+s)^2 − \frac{F}{(1-s)^2} \right) \tag{22}
\]

Since \( n^* \) decreases in \( s^* \), it is straightforward to verify the comparative statics from the picture.

E Proof of Lemma 1

Regarding equation (8), for firm a, there is a first-order condition with respect to the choice variable \( d_a \):

\[
λ \left( y − d_a \right) − 2 \left( x + λ d_a − α \right) d_a + β^* \left[ δ \lambda \frac{∂F}{∂x}(g_a, ε_a) − δ^* \frac{∂F}{∂x}(g_a, ε_a) \right]
\]

There are two envelope equations, corresponding to the two state
variables:
\[
\frac{\partial V}{\partial x_i}(x_i, x_j) = (y - d_i) + \beta' \delta' \frac{\partial V}{\partial x_i}(g_i, g_j)
\]  
(22)
\[
\frac{\partial V}{\partial x_k}(x_i, x_j) = \beta' \delta' \frac{\partial V}{\partial x_k}(g_i, g_j)
\]  
(23)

From equations (22) and (23), express the two partial derivatives evaluated at \((g_i, g_j)\) in terms of those evaluated at \((x_i, x_j)\), and plug the results into equation (21).

\[
\frac{\partial V}{\partial x_i}(g_i, g_j) - \frac{\partial V}{\partial x_i}(x_i, x_j) = 2\lambda d_i + 2\lambda d_j - 2\theta d_i d_j
\]  
(24)

Using \(g_j\) to substitute for \(x_j\) in the right-hand side of the above equation, we get the left-hand side expression evaluated at \((g_i, g_j)\):

\[
\frac{\partial V}{\partial x_i}(g_i, g_j) - \frac{\partial V}{\partial x_k}(g_i, g_j) = 2\lambda d_i + 2\lambda d_j - 2\theta d_i d_j
\]  
(25)

Plug (25) into equation (21), and the best response function for firm \(a\) emerges as an implicit function of \(d_a\) and \(d_b\):

\[
\lambda (-3 + 2\beta' \delta' + 2\beta' \delta^* d_a) d_a + 2\theta (1 - \beta' \delta' - \beta' \delta^*) d_a d_b = 0
\]  
(26)
which is the expression in the Lemma.

When \(x_i\) is switched with \(x_j\) in equation (26), and at the same time \(d_i\) is switched with \(d_j\), firm \(b\)'s best response function will emerge as:

\[
\lambda (-3 + 2\beta' \delta' + 2\beta' \delta^* d_j) d_j + 2\theta (1 - \beta' \delta' - \beta' \delta^*) d_a d_b = 0
\]  
(27)

F Proof of Proposition 5

The steady state should be characterized by four equations: the two best response equations, (26) and (27), and two steady state transition equations:

\[
g_a = \delta (x_a + \lambda d_a - \theta d_a) = x_a; \quad g_b = \delta (x_b + \lambda d_b - \theta d_b) = x_b
\]  
(28)

From (28), we solve

\[
x_a = \frac{\delta (3 - \delta' - 2\beta' \delta^*)}{1 - \delta^*} (\overline{d_a} - d_a)
\]  
(29)

Take the difference between equations (26) and (27) and plug in (29). We have:

\[
\frac{\lambda (3 - \delta - 2\beta' \delta^*)}{(\delta' - \delta^*)} (\overline{d_a} - d_a) = 0
\]  
(30)

thus \(\overline{d_a} = \overline{x_a}\). Consequently \(\overline{x_a} = \overline{x_b}\). Drop the subscript. Plugging (29) into either (26) or (27), we get the steady state discount and demand in the Proposition. Notice that the denominator in the expression

\[
\sigma = \lambda (3 - \delta - 2\beta' \delta^*) - 2\theta (1 - \beta' \delta^*)
\]  
(31)

Similarly,

\[
x_a = \frac{\lambda \delta' \overline{d_a} - \delta \delta^* d_a}{1 - \delta^*}
\]  
(32)

These two expressions are then plugged into equations (10) and (11) to get the expressions in the Lemma.

Taking the difference between the two equations (12) and (13), we find that \(\overline{d_a} - \overline{d_b}\) has the same sign as \(\delta^{k+1} - \delta^k\). When \(k = \frac{n}{2} + 1\delta^{k+1} - \delta^k\) so \(\overline{x} = \overline{d_a}\).

When \(k \geq \frac{n}{2} + 1\delta^{k+1} \equiv \delta^k\) so \(\overline{d_a} \geq \overline{d_b}\).

H Proof of Proposition 6

We know by direct observation that \(\overline{d_a}\) increases in \(\theta\).

\[
\overline{d_a} = \left[ \lambda (\delta' + \beta' \delta^* - 2) + \theta (1 - \beta' \delta^*) \right] \frac{\lambda \delta'}{1 - \delta^*}
\]

But

\[
\lambda (\delta' + \beta' \delta^* - 2) + \theta (1 - \beta' \delta^*) < \lambda (\delta' + \beta' \delta^* - 2) + \lambda (1 - \beta' \delta^*) = \lambda (\delta^* - 1) < 0
\]

Therefore, \(\overline{d_a}\) decreases in \(\theta\).

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