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Abstract

We develop an analytical framework to investigate the competitive implications of dynamic pricing technologies (DPT), which enable precise inferring of consumers' valuations for firms' products and personalized pricing. These technologies enable first-degree price discrimination: firms charge different prices to different consumers, based on their willingness to pay. We first show that, even though the monopolist makes a higher profit with DPT, its optimal quality is the same with or without DPT. Next we show that in a duopoly setting, dynamic pricing adds value only if it is associated with product differentiation. We then consider a model of vertical product differentiation, and show how dynamic pricing on the Internet affects firms' choices of quality differentiation in a competitive scenario. We find that when the high quality firm adopts DPT both firms raise their quality. Conversely, when the low quality firm adopts DPT, both firms lower their quality. While it is optimal for the firm adopting DPT to increase product differentiation, the non-DPT firm seeks to reduce differentiation by moving closer in the quality space. Our model also points out firms' optimal pricing strategies with DPT, which may be non-monotonic in consumer valuations. Finally, we show that consumer surplus is highest when both firms adopt DPT. Thus, despite the threat of first-degree price discrimination, dynamic pricing with competing firms can lead to an overall increase in consumer welfare.

Keywords: Dynamic pricing, product differentiation, electronic retailing, information economics

1 INTRODUCTION AND RESEARCH QUESTIONS

In the near future, firms will have the wherewithal to use the waves of personal profile and consumer and supplier activity data to set personalized prices for different consumers. Retailers using the Internet as a medium for commerce can gather a remarkable wealth of information about their existing and potential consumers and hence better estimate a consumer's reservation price. As Bakos (2001) mentions, technology allows firms to identify and track individual consumers, both within an online store and across different Websites. This leads to the creation of consumer profiles through various collaborative and content filtering techniques. Based on such information, the Internet retailers' Web server can deploy complex pricebots and algorithms to determine prices to approach first degree price discrimination (Bailey 1998). Spurred partly by the low menu cost of changing prices on the Internet and partly as a response to consumer use of price-comparison bots, firms are exploring the idea of dynamic prices for goods and services that are currently sold at posted prices.

Dynamic pricing, or personalized pricing, has been defined as gauging a shopper's desire, measuring his means, and then charging accordingly. We refer to this technology as DPT, for short. A retailer that invests in DPT can identify individual consumers, infer consumer valuations, and form perfect estimations of consumers' willingness to pay for its product. This retailer can, therefore, offer a personalized price that provides greater surplus relative to the potential surplus from the competitor's product.

There are many recent examples of dynamic pricing among online retailers. A well-known example, of course, is Amazon.com, which varied prices to different consumers on its popular Diamond Rio MP3 player by up to $50 from the original $233 retail tag (Morneau 2000). Later on, over a 5-day period, Amazon offered discounts of 20 to 40 percent off the list price on 68 of its 100 most popular DVD titles, which again differed by consumer. This promotion resulted in the same title being sold at a price ranging from $24 to $39.

One way for a retailer to engage in price discrimination is through intelligent agents dynamically inserting personalized discounts on pop-up windows on a consumer's screen. Software for this is provided by, among others, iChoose, Dash, and zBubbles (Johnson 2000). In the North American long-distance telephone market, the major competitors (AT&T, MCI, and Sprint) have been able to provide specialized discounts to a majority of the population. Further, Ford plans to move toward pricing its automobile financing products dynamically, based on consumer profiles and choices, and expects to cut its $10 billion spending on non-targeted promotions significantly (Aron, et al. 2001). Calico's Dynamic Custom Price application enables sellers to offer personalized prices (see www.calico.com). Banks and airlines use modern information technology to track individual customers and make them personalized offers (Winnet 2000). Financial services companies such as Capital One use profiles based on hundreds of variables to tailor products and prices for specific clients (McDonell 2001). Travel also is a ripe area for personalized pricing because travel services change prices rapidly. Travelocity already uses data warehouse technology that enables it to tailor rates to specific customers. Bid.com claims that its software allows Internet sites to analyze their customers' shopping patterns and set prices accordingly. Amadeus, a travel booking system, says sites using its system are able to offer prices tailored for different customers (Khan 2000).

Many firms believe that the concept of making the right offer to the right consumer will be the way of the future. In this paper, we intend to examine the following questions. How does competition between online retailers, in the presence of intelligent agents and price bots that can extract buyer preferences and implement dynamic pricing, affect equilibrium outcomes in a competitive scenario? What is the impact of such technologies on product positioning when firms compete on the quality of value added services? Does the improvement in firms' knowledge of individual consumers alleviate or intensify price competition?

We consider these questions in a duopoly framework in which one or both firms can perfectly identify valuations of heterogenous consumers. Recent work on price discrimination and customization includes Ulph and Vulkan (2001), who find that a firm that first-degree price discriminates is also better off if it mass-customizes. In a monopoly setting, Aron et al. (2001) analyze the pricing, profitability, and welfare implications of agent-based technologies that price dynamically, based on product preference information revealed by consumers.

2 MODEL

We consider vertical differentiation in a dynamic pricing context. Shaked and Sutton (1982) and Gabszewicz and Thisse (1986) develop duopoly models of vertical differentiation. These papers have shown that the strategic effect of the desire to reduce price competition results in a product equilibrium where firms seek maximal product differentiation. Moorthy (1988) extends the basic model by incorporating variable production costs and allowing consumers the opportunity to not buy a product. This results in less than maximal product differentiation. Our analysis extends Moorthy's model by allowing that one or both firms be equipped with a technology that perfectly reveals the consumer's type before the price is disclosed to the consumer.

In our model, firms compete in both the quality and price of the products they offer. Formally, we model their competition as a three-stage game. At the first stage, firms simultaneously choose the quality levels of their products. At stage two, the two firms simultaneously choose their prices. Finally, at the last stage, given the quality levels and prices offered by the two firms, consumers decide which, if any, product to buy. We consider pure strategy subgame-perfect equilibria of this three-stage game using backward induction. Consumers are modelled as utility maximizers. If a consumer purchases a product of quality q at price p, his utility is $U(\theta) = \theta q - p$, where $\theta \in [0,1]$. The type parameter θ indicates a consumer's marginal valuation for quality. A consumer buys one unit of the product that maximizes his surplus. Otherwise, he chooses not to buy either product.

Consistent with prior literature, we assume that both firms have the same marginal cost function for production which is invariant with the quantity, but depends on the quality of the product. Hence depending on the quality levels they choose, their marginal costs will differ in equilibrium. The marginal cost of producing a good of quality q is $c(q) = q^2$. The quadratic functional form for the marginal costs is a pertinent way of capturing a property pivotal to our model, which is that marginal costs increase with quality and at a faster rate than consumer's willingness to pay. If the latter were untrue, then it would be optimal to supply each consumer with infinitely high quality, which would be unrealistic in real life. Quality is observed by all consumers at no extra cost.

Quality in this model is a broad notion that could include features intrinsic to the product itself (such as durability and functionality) or the service level provided by the firm (such as extended warranties, forgiving return policies on defective items, special gift services, superior customer service and support contracts, fast delivery times with low costs, and so on. In equilibrium, the chosen quality levels satisfy $0 < q_i < 1$. In practice, a dynamic pricing technology of this nature is likely to incur some fixed costs but, for simplicity, we treat these costs as zero. Adding a fixed cost does not change the qualitative nature of our results. We assume that consumers cannot practice arbitrage among themselves.

2.1 Monopoly Case

Consider first a monopoly with uniform pricing. Let q^n_m and p^n_m be the quality and price, respectively, offered by the firm in this case where the superscript **n** refers to the fact that the firm does not have DPT and the subscript **m** denotes the fact that it is a monopolist. Next, define q^d_m and $p^d_m()$ as the quality level and price, respectively, offered by a monopolist with DPT where the superscript ***d*** denotes the fact that the monopolist has DPT technology. Since this firm observes consumer types before choosing its price, $p^d_m(\theta)$ will be a function of consumer type θ and is given by, $p^d_m(\theta)=q\theta$. This price function is, trivially, increasing in θ: higher consumer types pay higher prices. Further, the firm is willing to price as low as marginal cost, to persuade a consumer to buy the product. At this price, the lowest consumer type willing to buy is $\theta^d_m =c/q^d_m$.

Proposition 1: *In equilibrium, regardless of DPT, a monopolist sets the same quality level, that is,* $q^{d*}_m = q^{n*}_m$ *. Further, profits are doubled by the DPT firm.* $\pi^d_m = 2\pi^n_m$ *.*

Increasing (decreasing) quality implies a trade off between increasing (decreasing) costs and decreased (increased) market penetration for the firm. By pricing at marginal cost for the threshold consumer, DPT gives it the ability to reach a previously untapped portion of the market without changing its product quality. This case provides a benchmark to the one in which one of two duopolists obtain a DPT technology. As we show in the next section, in the latter case, qualities of both firms typically change in response to the availability of DPT.

2.2 Duopoly with Dynamic Pricing: No Quality Differentiation

We next turn to the duopoly case, with two firms in the market. We first show that the ability to price discriminate, by itself, is of no value unless firms also differentiate in quality. Suppose that one or both firms have access to DPT.

Proposition 2: *Suppose both firms offer the same quality, so that* $q_1= q_2 =q$*. Then DPT offers no advantage to a firm, and both firms earn zero profit. In equilibrium,* $p_h(\theta)=p_l(\theta)=c(q)$ *and* $\Pi_h =\Pi_l = 0$*.*

Thus, even when one of the firms possesses a technology (DPT) of extracting consumer valuations and pricing accordingly, it does not have any competitive advantage in the absence of some form of product differentiation. This implies that online retailers will choose not to indulge in dynamic pricing, unless they can also provide value-added services to differentiate their product. We, therefore, turn to the case in which firms first choose the quality of their product, and then the price.

2.3 Differentiated Duopoly: Neither Firm Has DPT

As a benchmark case, we first assume that neither firm has access to DPT. We call this case the no-DPT case. When there is no access to DPT, firm *i*, (*i = h, l*), chooses a quality q^n_i and price p^n_i, where the superscript ***n*** indicates that neither firm has DPT. In equilibrium $q^n_h > q^n_l$ and $p^n_h > p^n_l$. Henceforth the superscripts ***l*****, h,** and **b** will indicate the scenarios when only one firm has

DPT and the DPT firm chooses low quality or high quality or when both firms have DPT. Firms' market shares are given by the following cut-offs.

$$\theta_h^n = \frac{p_h^n - p_l^n}{q_h^n - q_l^n} \qquad \theta_l^n = \frac{p_l^n}{q_l^n} \tag{1}$$

2.3.1 Price Competition at Stage 2

We can write the profit function of firms h and *l* as

$$\pi_h^n = (1-\theta_h^n)(p_h^n - q_h^{n^2}) \quad \text{and} \quad \pi_l^n = (\theta_h^n - \theta_l^n)(p_l^n - q_l^{n^2})$$

Now, consider stage 2 of the game, where we solve for the prices chosen by the firms at stage 2. Given these prices, we now consider firms' choices of quality levels at stage 1.

2.3.2 Quality Competition at Stage 1

At this stage, firms anticipate the prices they will choose at stage 2 (as a function of the qualities chosen at stage 1) and their resulting profits at stage 3. The first-order condition for firm *h*, $\partial\pi^n_h / \partial q^n_h = 0$ defines a reaction function for firm *h*. Similarly, the first-order condition, $\partial\pi^n_l / \partial q^n_l = 0$ denotes the reaction function of firm *l*. The equilibrium quality levels $q^{n*}_h = 0.41$, $q^{n*}_l = 0.19$, are determined by solving these two equations simultaneously.

2.4 Duopoly with Dynamic Pricing: Only One Firm Has DPT

We now consider the situation in which one firm has access to DPT, i.e., it can infer consumer valuations and form a perfect estimate of each consumer's willingness to pay for its product. There are two equilibria in this case: one in which the DPT firm chooses a lower quality than the other firm, and a second one in which the DPT firm chooses a higher quality.

2.4.1 DPT Firm Offers Low Quality

We denote the equilibrium qualities in this case as q^{l*}_h, q^{l*}_l with p^{l*}_h, $p^{l*}_l(\theta)$ denoting the equilibrium prices. In this case, firm *l* knows the type of each consumer, and hence can offer prices that depend on θ. In equilibrium, it must be willing to offer a price as low as its marginal cost, $c = q^2$, to each consumer, if necessary. Further, consistent with price discrimination, it will charge as high a price as it can from each consumer to whom it sells. At stage 3, firm *h* (which does not have DPT in this case) will operate in a market segment $[\theta^l_h, 1]$ and firm *l* in a market segment $[\theta^l_h, \theta^l_l]$.

From the stage 3 of the game, we define

$$\theta_h^l = \frac{p_h^n - q_l^{l^2}}{q_h^l - q_l^l} \qquad \theta_l^l = \frac{q_l^{l^2}}{q_l^l} \qquad \theta' = \frac{p_h^l}{q_h^l} \tag{2}$$

We show that the equilibrium price function of firm *l* is non-monotonic in consumer type; that is, it charges some high valuation consumers less than it charges some low valuation consumers.

Proposition 3: *In equilibrium, at stage 2, firm h charges,* $p_h^{l*} = \frac{(q_h^l - q_l^l + q_h^{l^2} + q_l^{l^2})}{2}$. *For consumers in the range* (θ_l^l, θ'), *firm l sets* $p_l^*(\theta) = \theta q_l$ *and for those in the range* (θ', θ_l^h), *it sets* $p_l^*(\theta) = \theta(q_l^l - q_h^h) + p_h^{l*}$.

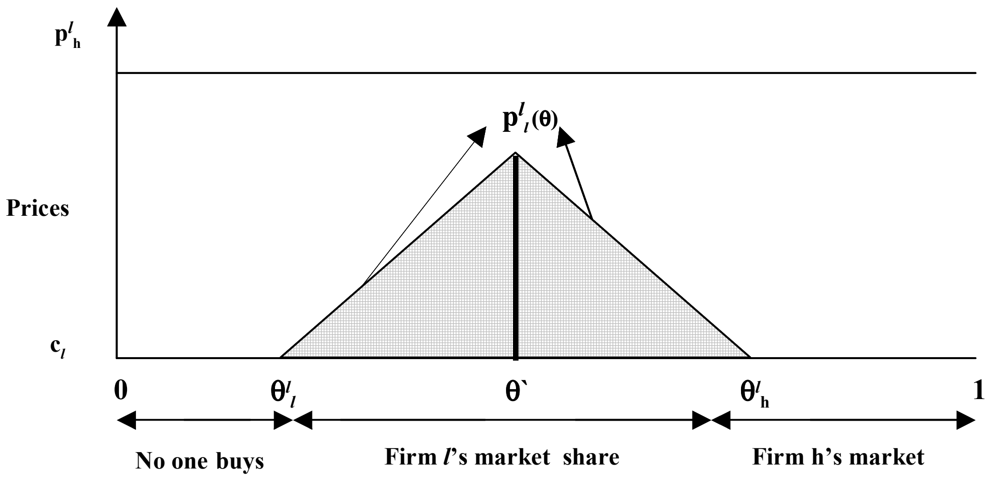

Figure 1. Prices of Firms When *l* Alone Has DPT

This situation is depicted in Figure 1. The intuition for the non-monotonicity of $p^{l}_{l}(\theta)$, is that in the market segment [0,θ'] firm *l* faces no competition from firm *h*. These consumers are not willing to buy product *h* at the offered quality and price. Hence, firm *l* is able to extract their entire consumer surplus, and consumers in this range are left with no surplus. However, consumers in the range [θ',1] obtain a positive utility from consuming product *h* as well. Hence, firm *l* faces competition in this range, and must offer consumers at least as high a surplus as firm , to induce them to buy product *l*. Thus, these consumers have a positive surplus that is monotonically increasing in consumer type. Substituting in the optimal price of firm *h*, the equilibrium price schedule for firm *l* is as given in Proposition 3.

2.4.2 DPT Firm Offers High Quality

We denote the equilibrium qualities in this case as q^{h*}_{h}, q^{h*}_{l} with p^{h*}_{l}, $p^{h*}_{h}(\theta)$ denoting the equilibrium prices. In this case, firm *h* knows the type of each consumer, and is hence willing to price as low as $p_{hh}(\theta) = c^{h}_{h}$ if need be. At stage 3, firm *l* (which does not have DPT in this case) will operate in a market segment $[\theta^{h}_{l}, \theta^{h}_{h}]$ and firm *h* in a market segment $[\theta^{h}_{h}, 1]$. The first-order condition for profit-maximization, $\partial \pi^{h}_{l} / \partial p^{h}_{l} = 0$ directly yields,

$$p^{h*}_{l} = (q^{h^2}_{h} q^{h}_{l} + q^{h^2}_{l} q^{h}_{h}) / 2q^{h}_{h} \tag{3}$$

Substituting in the optimal price of firm *l* and the quality functions, the equilibrium price schedule for firm *h* is

$$p^{h}_{h}(\theta) = \theta(q^{h}_{h} - q^{h}_{l}) + (q^{h^2}_{h} q^{h}_{l} + q^{h^2}_{l} q^{h}_{h}) / 2q^{h}_{h} \tag{4}$$

Proposition 4 : *When the lower quality firm gets DPT the optimal quality levels being offered by both firms decrease, i.e.,* $q^{d}_{l} < q^{n}_{l}$ *and* $q^{d}_{h} < q^{n}_{h}$ *. Conversely, when the higher quality firm gets DPT optimal quality levels being offered by both firms increase, i.e.,* $q^{d}_{l} > q^{n}_{l}$ *and* $q^{d}_{h} > q^{n}_{h}$.

DPT provides firm *l* with an opportunity to penetrate an untapped market segment further to the left than where it presently is, at the same time allowing it to remain competitive on the right. Hence it lowers its quality such that it can extend its reach further to the left in the direction of decreasing consumer type. Further, to remain competitive, firm *h* reduces its price. As a competitive response to differentiate itself, *h* initially moves to the right as long as moving away is relatively inexpensive due to low convexity of its costs. But when the costs start increasing at a much faster rate, the potential loss per unit of market share on the right is outweighed by the gains from moving to the left. By moving toward the low quality firm, *h* increases the uncontested portion of its market share on the right where it faces no competition from *l*. Thus, both firms reduce their qualities when the DPT firm chooses a low quality. A similar intuition holds when the high firm gets DPT.

2.4.3 Both Firms Have DPT

Suppose, as before, that firm *h* chooses h and firm *l* chooses *l*. Then, we have the market cut-offs as

$$\theta_h^b = \frac{c_h^b - c_l^b}{q_h^b - q_l^b} \qquad \theta_h^b = \frac{c_h^{b^2}}{q_h^b} \qquad \theta^` = \frac{c_l^b}{q_l^b} \tag{5}$$

Figure 2 depicts firms' pricing scedules, with the shaded triangles representing firms' profits. The maximal price firm *h* can charge any consumer θ is the price at which he is exactly indifferent between buying the low quality product at the lowest price the firm is willing to charge and the high quality product *h* at $p_h^b(\theta) = \theta(q_h^b - q_l^b) + q_l^{b^2}$.

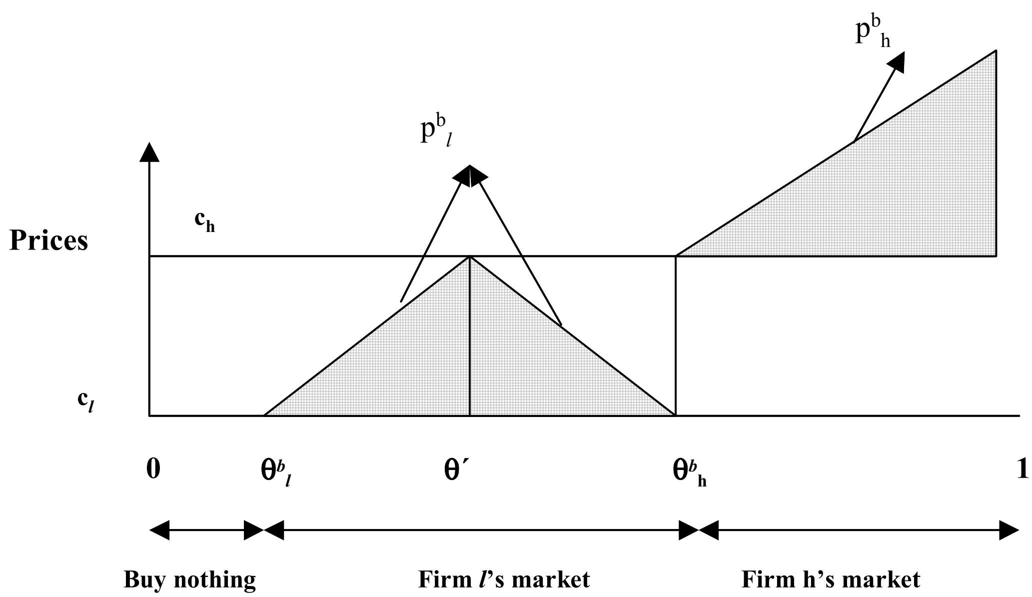

Figure 2. Pricing Schedule and Profits When Both Firms Have DPT

Proposition 5: *When both firms have DPT, the equilibrium qualities,* q^{b*}_h *and* q^{b*}_l *satisfy* $q^{l*}_h < q^{b*}_h < q^{h*}_h$ *and* $q^{l*}_l < q^{b*}_l < q^{h*}_l$*, that is, the high quality firm will lower its quality and the low quality firm will raise its quality, compared to the equilibrium situation when neither firm adopts DPT.*

Thus when both firms decide to acquire DPT, the manner in which they would change their qualities also merits attention. If the high quality firm has DPT and the low quality firm decides to deploy DPT as well, then both firms should reduce their quality levels. Conversely, if the low quality firm has DPT and the high quality firm decides to acquire it, then both firms should raise their quality levels. This implies that both firms actually come closer to each other. The intensified competition actually leaves both firms worse off than the no-DPT case. But if one firm did adopt DPT and the other did not, then the latter is much worse-off, thereby forcing them both to adopt DPT. This is a classic example of the Prisoners' Dilemma.

Proposition 6[1]: *Consumer surplus increases (decreases) when the low (high) quality firm adopts DPT and is the highest when both firms have DPT.*

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[1]Proof of proposition 6 has been excluded for brevity.

The total consumer surplus can be written as CS = $\int_{\theta_h}^{1} (\theta q_h - p_h(\theta))d\theta + \int_{\theta_l}^{\theta_h} (\theta q_l - p_l(\theta))d\theta$. When both firms have DPT, firm h charges a price $p_h^b(\theta) = \theta(q_h^b - q_l^b) + q_l^{b^2}$ to its consumers. Compare this to the price it charges when firm l does not have DPT, $p_h^h(\theta) = \theta(q_h^h - q_l^h) + (q_h^{h^2} q_l^h + q_l^{h^2} q_h^h)/2q_h^h$. If firm l now acquires DPT, the greater competition leads to a lower price for consumers of firm , and a corresponding increase in welfare.

Consumer surplus falls (compared to the no dynamic pricing case) if the DPT firm has low quality, but rises if the DPT firm has high quality. When firm l has DPT, it extends its market reach to a previously untapped segment, since it can price as low as marginal cost. However, a segment of its consumers receive no surplus, since they pay a price exactly equal to their willingness to pay. Conversely, if firm h has DPT, it faces competition from firm l throughout its market segment, and so is forced to concede some surplus to consumers. In fact, consumer surplus is highest when both firms have DPT. In that case, due to the intensified competition, the average price of both firms is the lowest of all cases. Further, their overall market coverage is at its highest since each firm can now encroach upon a hitherto untapped market segment by offering consumers their exact utility. Finally, in Table 1, we summarize our results for quadratic, cubic, and quartic cost structures with Figures 3 and 4.

Observation 1: ***(i)*** *In equilibrium, the profits of the firm with DPT, always increase, irrespective of whether it is the high or the low quality firm.*

(ii) *However, for a convex cost function of the nature $c = q^\alpha$, there exists an $\alpha \in [2,3]$ such that beyond it, the high quality firm does not benefit from DPT and hence only the low quality firm will adopt DPT.*

Table 1. Summary of Equilibrium Results

	Neither Firm Has DP	**Low Firm Has DP**	**High Firm Has DP**	**Both Firms Have DP**
	Firm h, Firm *l*	**Firm h, Firm *l***	**Firm h, Firm *l***	**Firm h, Firm *l***
Qualities (q^2)	0.409, 0.199	0.388, 0.164	0.444, 0,222	0.4, 0.2
Profits	0.0164, 0,012	0.0112, 0.0177	0.022, 0.0055	0.016, 0.008
Qualities (q^3)	0.515, 0.29	0.485, 0.242	0.358, 0.559	0.503, 0.322
Profits	0.028, 0.019	0.021, 0.025	0.0275, 0.0085	0.0209, 0.0099
Qualities (q^4)	0.582, 0.354	0.549, 0.296	0,452, 0.628	0.57, 0.41
Profits	0.0369, 0.0219	0.0284, 0.279	0.0268, 0.0097	0.0213, 0.0099

3 DISCUSSION

In this section, we derive managerial implications of our results. Electronic retailers can now gather information about consumer needs and can customize their prices to give their consumers exactly what they want, at exactly the price they are willing to bear. In a recent survey of online retailers (Johnson 2000), 57 percent of retailers surveyed planned to offer multiple prices for the same item, and 71 percent expected to have preferred pricing for regular consumers.

Our model points out certain interesting pricing strategies for firms. If the low quality firm deploys DPT, then it is optimal for it to use a non-monotonic price schedule. This implies that certain high valuation consumers are charged lower prices than some lower valuation consumers. This counterintuitive result holds because in a segment of high valuation consumers, the firm with DPT finds itself competing with a high quality firm (that does not have DPT). To induce these consumers to buy its product, the firm needs a declining price schedule. Conversely, in a segment of the market with low valuations, the DPT firm is a local monopolist, and can afford to charge consumers exactly their willingness to pay. It is important to note that given these technologies, it is easy to get into a spiralling price war. In order to avoid this, firms need to increase product differentiation either by providing some value added services or by adding features to the product to enhance its durability or functionality.

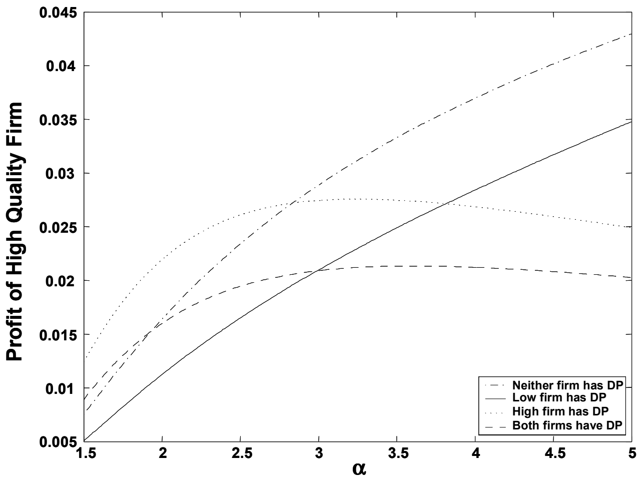

Figure 3. Firm *l*'s Profits with Convexity of Costs α

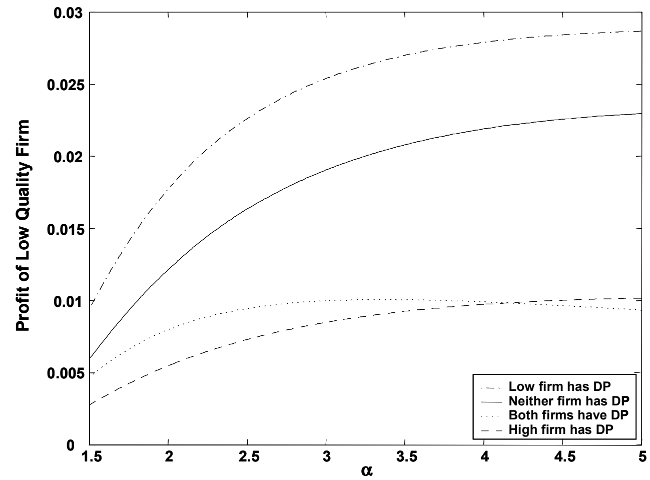

Figure 4. Firm *h*'s Profits with Convexity of Costs α

We also identify how firms should make different product quality choices, given that one firm has decided to acquire DPT. When a low quality firm acquires DPT, its best response is to lower its quality level. This can be done through removal of additional product features or value-added services. In such a scenario, the high quality firm is better off also reducing its quality level. Conversely, if the high quality firm acquires DPT, both firms should provide additional product features or services to increase their quality levels.

Finally, our model also demonstrates that consumers would benefit if higher quality firms adopt DPT. In the event that all firms adopt DPT, consumers would benefit the most. Thus we conclude that strategies approaching first degree price discrimination on the Internet should eventually lead to an overall increase in consumer welfare, which is quite in contrast to popular perceptions. Our model of vertical differentiation in the online retail business-to-consumer market shows how first degree price discrimination on the Internet will affect firms' choice of quality or service differentiation in a competitive scenario. Our paper points out many counterintutive results, which have significant real world implications. In the future, we intend to extend our setting to incorporate product customization such that firms combine DPT with customization and then tailor their products.

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Appendix

Definition of Variables

Notation	Meaning
q^n_m, q^d_m	Qualities offered by a monopolist when it does not and does have DPT
q^n_h, q^n_l	Qualities of high and low firm when neither firm has DPT
q_h^l, q_l^l	Qualities of high and low firm when Low firm has DPT
q_h^h, q_l^h	Qualities of high and low firm when High firm has DPT
q_h^b, q_l^b	Qualities of high and low firm when both firms have DPT
$p_i^j(q)$	Price of firm i as a function of consumer valuation when the firm j has DPT.
θ_i^j	Market share cutoff of firm i when firm j has DPT

Proof of Proposition 1

Define $\theta^n_m = p^n_m/q^n_m$. The monopolist's profit function, therefore, is

$$\pi^n_m = (1-\theta^n_m)(p^n_m - q^n_m{}^2) \tag{6}$$

The optimal quality level, therefore, is determined by first solving for optimal price p^* and then plugging p^* in (1) and then equating the first order condition $(\partial\pi^n_m/\partial q^n_m) = 0$. This gives $q^{n*}_m = 1/3$.

Next, the profit function of the DPT monopolist is

$$\pi^d_m(q^d_m) = \grave{o}(p^d_m() - q^d_m{}^2)d \tag{7}$$

From here we can show that the optimal quality is given by $q^{d*}_m = 1/3$. Thus we show that, regardless of the availability of DPT, a monopolist firm chooses the same quality.

Proof of Proposition 2

Suppose that $q_1 = q_2$. If neither firm has access to DPT, the proposition is immediate. Consider the case that firm 1 has DPT and firm 2 does not. Suppose $p_2 > c(q_1)$. Firm 1 will never charge $p_1(\theta) > p_2$ to any consumer θ, since the consumer will buy product 2 instead. Further, by the usual Bertrand argument, firm 1 will not charge $p_1(\theta) = p_2$ either. By charging a price ϵ below p_2, firm 1 ensures that consumer θ buys its product. Suppose $p_1(\theta) > c(q_1)$ for some consumer θ. Then, firm 2 can capture a positive market share by charging $p_2 \in (c(q_1), p_1(\theta))$. Hence, the only equilibrium is the Bertrand one, $p_1(\theta) = p_2 = c(q_1)$ for all consumers θ.

Proof of Proposition 3

Consider firm h first. Its profit at stage 2, if it charges price p_h, is

$$\pi_h^l = (1-\theta_h^l)(p_h^l - c_h^l) = \left(1 - \frac{p_h^l - c_l^l}{q_h^l - q_l^l}\right)(p_h^l - q_h^{l^2}) \tag{8}$$

The first-order condition for profit-maximization, $[(\partial\pi_h^l)/(\partial p_h^l)] = 0$, directly yields

$$p_h^{l*} = \frac{(q_h^l - q_l^l + q_h^{l^2} + q_l^{l^2})}{2}$$

Next, consider firm *l*. Firm *l* will set its price for each consumer, $p_l^l(\theta)$, as high as possible to satisfy two restrictions: (i) the consumer buys product *l* instead of product h, so that

$$\theta q_l^l - p_l^l(\theta) \geq \theta q_h^l - p_h^l$$

$$p_l^l(\theta) \leq p_h^l - \theta(q_h^l - q_l^l),$$

and (ii) the consumer buys product *l*, rather than not consume at all. That is,

$$\theta q_l^l - p_l^l(\theta) \geq 0, \quad \text{or} \quad p_l^l(\theta) \leq \theta q_l^l.$$

Further, firm *l* must set $p_l^l(\theta) \geq c_l^l = c_l^l(q_l^l)$ for each consumer, else it makes a loss on that consumer, and would prefer to not sell to him. Hence, we have $p_l^l(\theta) \geq c_l^l$, and $p_l^l(\theta) \leq \min\{\theta q_l^l, p_h^l - \underline{\ }\theta(q_h^l - q_l^l)\}$. The first term in the latter inequality is defined by the consumer's reservation utility (i.e., zero), and the second term can be interpreted as his incentive compatibility constraint: if this is violated, then he buys product h instead. Given that $\underline{\theta} = [(p_h^l)/(q_h^l)]$ as defined, it is immediate that $p_h^l - \theta(q_h^l - q_l^l) > \theta q_l^l$ for $\theta > \underline{\theta}$, and $p_h^l - \theta(q_h^l - q_l^l) < \theta q_l^l$ for $\theta < \underline{\theta}$. The pricing function for firm *l* now follows.

Proof of Propositions 4 and 5

When firm *l* has DPT, then its profit function is

$$\pi_l^l(q_h^l, q_l^l) = \int_{\theta_l^l}^{\theta'} (\theta q_l^l - q_l^{l^2}) d\theta + \int_{\theta'}^{\theta_l^h} \left(\frac{(q_h^l - q_l^l + q_h^{l^2} + q_l^{l^2})}{2} - \theta(q_h^l - q_l^l) - q_l^{l^2}\right) d\theta \tag{9}$$

The limits of the integral θ'_l, θ' and θ'_h have been defined before. Solving the integral as a closed form and replacing the optimal price of firm h and the respective cost functions we get the optimal profit equation for firm *l*. Profit function of firm h is

$$\pi_h^l(q_h^l, q_l^l) = \frac{(q_h^l - q_l^l)(q_h^l + q_l^l - 1)^2}{4} \tag{10}$$

Solving simultaneously the first order conditions $\{\partial\pi_l^l/\partial q_l^l = 0, \partial\pi_h^l/\partial q_h^l = 0\}$ we get the pure-strategy Nash equilibrium solution for optimal qualities as (0.38, 0.164).

Consider the choice of qualities at stage 1, when firm h has DPT. Suppose firm *l* chooses q_l, and firm *h* chooses q_h. Further, suppose firm *l* chooses prices optimally, given the two qualities. Then, the profit function of firm *h* is

$$\pi_h^h(q_h^h, q_l^h) = \frac{(p_l^h + q_h^h - q_l^h - q_h^{h^2})^2}{2(q_h^h - q_l^h)} \tag{11}$$

Similarly, the profit equation for firm *l* is given by

$$\pi_l^h(q_h^h, q_l^h) = \frac{q_h^h q_l^h (q_h^h - q_l^h)}{4} \tag{12}$$

Solving simultaneously the first order conditions, $\{\partial\pi_h^h / \partial q_h^h = 0, \partial\pi_l^h / \partial q_l^h = 0\}$ we get the pure-strategy Nash equilibrium solution for optimal qualities as (4/9, 2/9).

When both firms have DPT, then profit of firm h,

$$= \int_{\theta_h^b}^{1} (q_l^{b^2} + \theta(q_h^b - q_l^b) - q_h^{b^2}) d\theta = \frac{(-q_l^b + q_h^b + q_l^{b^2} - q_h^{b^2})^2}{2(q_h^b - q_l^b)} \tag{13}$$

Next, consider the profit function of firm *l*.

$$= \int_{\theta^{`}}^{\theta_h^b} (q_h^{b^2} + \theta(q_h^b - q_l^b) - q_l^{b^2}) d\theta + \int_{\theta_l^b}^{\theta^{`}} (q_l^b - q_l^{b^2}) d\theta = \frac{(q_h^b q_l^{b^2} + q_h^{b^2} q_l^b)^2}{2 q_h^b q_l^b (q_h^b - q_l^b)} \tag{14}$$

Solving simultaneously the first order conditions, $\{\partial\pi_h^b / \partial q_h^b = 0, \partial\pi_l^b / \partial q_l^b = 0\}$ we get the pure-strategy Nash equilibrium solution for optimal qualities as (2/5,1/5).