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Research Article

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Industrial Technology Boundary, Product Quality Choice, and Market Segmentation

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Abstract: This paper studies how firms in a duopoly market choose product qualities when facing two types of consumers: high-end consumers value quality more than low-end consumers. Firms' highest possible quality (referred to as industrial technology boundary) is determined by an industrial common technology. I consider price competition and show that in equilibrium, an increase in the technology boundary can induce a decrease in the equilibrium quality of one firm. In this case, the firms enlarge their quality difference, triggering a *market segmentation*. In this market segmentation, the firm with a lower quality does not serve the high-end consumers and obtains higher profits from the low-end consumers, whereas the firm with a higher quality supplies both types of consumers and obtains higher profits as well. This market segmentation causes additional mismatch costs for high-end consumers, therefore lowering both consumer and social surplus.

Keywords: quality choice; market segmentation; pricing strategy; social surplus

JEL Classification: L11; L13; L22; M21

1 Introduction

The recent decades have witnessed a great expansion of technology boundaries in many industries. For example, in telecommunications, 5G (fifth-generation technology standard for broadband cellular networks) has a peak download speed about 70

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times faster than its former generation standard, 4G.[1] In the electronic vehicle (EV) industry, CATL, a battery supplier for major automobile producers such as Tesla, BMW, and Geely, launched its new generation of battery and extends EV's travel distance for a single charge to 1000 km (Kane 2023). While high-end consumers are delighted by the expansion of industrial technology boundaries because of the relevant products' higher performance (or higher quality), there is still great demand from low-end consumers who focus more on products' basic functions. According to the prediction by IDC (International Data Corporation), the demand for low-end smartphones priced below 200 US dollars will continue to occupy over 40 % of the total in 2024 (Bicheno 2020), Also, according to the data by Jato (a globally based consulting company specialized in automobile data),[2] cars categorized below the segment-C (the compact category) occupied over 30 % of the total in the EU market in 2022. These industrial facts indicate that consumers differ evidently in how they value products. Specifically, while high-end consumers care about cutting-edge technologies or premium qualities of products that highly depend on the industrial technology boundary, low-end consumers care more about products' essential values and put much less weight on products' quality.

When more advanced technologies become available, and consumers show great heterogeneity in how they value product quality, how do firms choose product quality? How do firms' quality choices affect consumer surplus and social surplus? On the one hand, higher product quality over its rival indicates a firm's competitive advantage in the competition for high-end consumers, and the high-end consumers benefit from such a competitive advantage as well. On the other hand, since low-end consumers care less about product quality, despite the availability of cutting-edge technology at the industrial level, it is also possible for a firm to choose lower product quality that leads to a sufficient "quality disadvantage." Such a quality disadvantage ensures that the firm does not serve high-end consumers and focuses only on low-end consumers. In that case, there is a potential welfare loss because a firm may intentionally choose to offer low-quality products to avoid the head-to-head competition for high-end consumers. In other words, the expansion of industrial technology boundary may motivate firms to subtly adjust their product quality choices, eventually affecting consumer and social surplus.

In this paper, I consider a variation of the Hotelling model in which two firms choose their respective product quality from a choice set and compete in price. The higher the industrial technology boundary, the higher the upper bound of each firm's quality choice set. There are two types of consumers choosing which firm to

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1 The 5G standard has a peak download speed of 10 Gbit/s (Edwards and Hoffman 2022), whereas 4G has a speed of 150 Mbit/s (https://www.4g.co.uk/how-fast-is-4g/).

2 https://www.jato.com/h1-2022-europe-by-segments/.

buy from, based on their distance to each firm and each firm's product quality. The two types of consumers are heterogeneous in how they value product quality – high-end (type-H) consumers value product quality more than low-end (type-L) consumers.

Under the above setting, I show that a change in the quality difference of firms' products will give rise to various market regimes. When the quality difference between the two firms' products is sufficiently small, a unique pure-strategy equilibrium exists in which both firms compete for both types of consumers. When the quality difference is intermediate, there is a mixed-strategy equilibrium in which one firm (say firm 1) chooses a sufficiently high price with a positive probability such that it no longer supplies type-H consumers (referred to as a *partial* market segmentation). Moreover, when the quality difference is sufficiently large, there is a pure-strategy equilibrium in which one firm (say firm 1) always chooses a sufficiently high price such that it always supplies only the type-L consumers, whereas its rival, firm 0, always supplies both types of consumers (referred to as a *complete* market segmentation).

I use this variation of the Hotelling model to show that the industrial technology boundary determines firms' quality choices and, hence, which of the above three market regimes occurs in equilibrium. To be specific, when the industrial technology boundary is sufficiently high, given one firm (say firm 0) choosing the highest quality, it is beneficial for firm 1 to induce a sufficiently large quality difference by choosing the lowest quality such that a *partial* or *complete* market segmentation occurs. The intuition is that because type-H consumers place a high value on firm 0's quality advantage, they exclusively buy from firm 0, which, in turn, motivates firm 0 to increase its price. Firm 0's price increase makes firm 1's product relatively cheap for type-L consumers so that firm 1 can attract a larger number of type-L consumers. Therefore, although firm 1 cannot sell to type-H consumers after choosing the lowest quality, it benefits from a larger demand and milder competition for type-L consumers.

The main message of my model is that only when the industrial technology boundary is sufficiently high will a firm be motivated to lower its product quality. This message seems to be consistent with the real-world cases of Nokia (a Finnish telecommunications maker) and Wuling Motors (a Chinese automobile manufacturer). Nokia used to be a giant in the high-end mobile phone industry with its own Sabian operating system in the 1G to 3G eras. But after Verizon launched the 4G LTE network on a large scale, Nokia started only offering low-end smartphones using the Android system and retreated from the high-end market.[3] The other

3 https://www.verizon.com/about/news/what-4g-lte-and-why-it-matters.

real-world example is Wuling Motors. With a long history since 1982, Wuling Motors recently entered the electronic vehicle (EV) market with its low-price micro EV models, Air EV, Nano EV, and Mini EV, which are generally regarded as low-end models compared with the products of its rivals such as BYD and Tesla (Mihalascu 2022). According to my theoretical findings, it is possible that firms like Nokia and Wuling Motors spontaneously chose low-quality products since they had expected the industrial technology boundary to be sufficiently high such that their rivals (such as Apple for Nokia and BYD for Wuling Motors) could choose premium product quality so that the quality differences triggers a market segmentation that guarantees mild competition. Although there are other possible reasons behind why firms choose to produce low-quality products, this paper provides one theoretical explanation.

I further investigate the effects of expanding the industrial technology boundary on welfare. I find that a higher industrial technology boundary motivates one firm to choose the lowest product quality and triggers a market segmentation, which may harm both consumer surplus and social surplus. The intuition is that if the expansion of the industrial technology boundary leads to a market segmentation, all high-end consumers, including those who are located close to firm 1, have to buy from firm 0; but if the industrial technology boundary was not so high, firm 1 might also have chosen the highest quality product. This could have allowed high-end consumers to avoid transportation costs and directly purchase from firm 1, leading to a more favorable welfare outcome.

The above finding regarding welfare may have the following policy implication: while the 4G technology enhanced the product quality of Nokia's rivals, such as Apple (firm 0), Nokia (firm 1) was motivated to downgrade its own products' quality. While some high-end consumers who show brand preferences towards Apple (consumers located close to firm 0) benefit more, those who should have preferred Nokia (those located close to firm 1) lost the option of choosing Nokia and turned to Apple, from which additional mismatch costs arose. Therefore, in light of the expanding boundaries of industrial technology, it becomes crucial for policymakers to address potential welfare-reducing market segmentation caused by some firms' deliberate product downgrades. One effective approach can be the implementation of minimum quality regulations for products. By enforcing these regulations, policymakers can mitigate market segmentation and guarantee that high-end consumers have diverse options of high-quality products to choose from. This strategy aims to strike a balance between industrial progress and consumer protection, fostering innovation while upholding consumers' benefits.

1.1 Related Literature

This paper is related to the literature on vertical product differentiation where each firm sells a single product (e.g. Shaked and Sutton 1982). The general finding is that firms' profits strictly increase in their quality difference in equilibrium because a larger quality difference alleviates firms' price competition. Although not explicitly pointed out, their model also indicates that the social surplus always increases when the industrial technology boundary increases such that firms can choose a higher quality. In contrast, in my model with both horizontally and vertically differentiated products and heterogeneous consumer groups, the profit of the low-quality firm first decreases in the quality difference due to its increasing disadvantage, and then jumps upwards when a market segmentation occurs. Moreover, the social loss demonstrated here stems from the consumers' additional transportation costs, which is not included in Shaked and Sutton (1982). The non-monotonicity and continuity in firms' profits and the negative welfare impact brought by the market segmentation distinguish this paper from the existing ones that consider only vertical product differentiation and one consumer type. Another related seminal paper is Neven and Thisse (1989) who consider a model of two-dimensional vertical and horizontal differentiation. In their model, firms compete over both quality and location/variety, and in equilibrium, they maximize differentiation on one dimension and minimize differentiation on the other dimension. The model in this paper adopts a similar approach to Neven and Thisse (1989) by considering two Hotelling specifications. Important differences in my model are: (1) two heterogeneous consumer groups who value product quality differently are considered, and (2) firms cannot endogenize their locations, and the only instrument to alleviate their price competition is by triggering a market segmentation.

Ansari, Economides, and Steckel (1998) use a location model to capture firms' endogenous choices of their products with two/three attributes. In their model, all consumers value these attributes similarly. The authors show that in equilibrium, firms can only maximize their product differentiation at one attribute, depending on consumers' weights on each attribute. My model differs in that firms can only choose one attribute of their products, i.e. product quality, but there are heterogeneous consumer groups who value this attribute differently, and all of my results are driven by the market segmentation stemming from the different consumer groups, which is absent in their model.

This paper also contributes to the literature on segmented markets (e.g. Ellison 2005). Ishibashi and Matsushima (2009) show that although supplying to only high-end consumers could bring both firms higher profits, the firms sell to both consumer types in equilibrium. Amaldoss and Shin (2011) consider a similar market structure and show that an increase in the number of low-end consumers could benefit firms because it alleviates the price competition in the high-end market.

Building on – but extending – their results, I show that a firm can benefit from lowering its product quality in a similar market structure. Heidhues, Kőszegi, and Murooka (2016) consider a model in which some consumers are aware of a product's hidden price whereas others are not. Although the authors also show that a quality improvement may be detrimental to social welfare, their results stem from a different logic based on consumer naivety and shrouded attributes.

As a related topic, there is the literature on voluntary technology sharing among firms.[4] For example, considering a market with free entry and exit, Creane and Konishi (2009) show that an incumbent firm with higher efficiency could share its technology with its rival to deter potential market entrants. Yoshida and Pan (2017) show a similar result in the case of a duopoly market in which some consumers always buy from one firm. As my model allows all consumers to buy from any firm, my results are driven by entirely different mechanisms.

This paper is also related to the vast theoretical literature on health economics, which generally uses the Hotelling model to capture competition between hospitals. Gravelle and Masiero (2000) consider the market for primary care by incorporating switching costs of patients and imperfect information about the quality of medical treatment. The authors show that medical care's quality is lower and the incentive effects of the fee on quality are smaller when there is imperfect information. Brekke, Nuscheler, and Straume (2006) consider hospitals' endogenous location choices as well as their investments in healthcare quality. They show that the regulators' price commitment may cause hospitals' over-investment in quality and insufficient horizontal differentiation. Brekke, Nuscheler, and Straume (2007) further explore the role of gatekeeping in the health market which aims to increase the transparency of patients' information regarding their preferences. Interestingly, the gatekeeping service may reduce social surplus by causing over-investment in healthcare quality and too much specialization of hospitals. Although the above three papers also consider hospitals' quality competition, all of them differ from my model in that the price in the healthcare market is exogenously given (by the regulator), so firms' incentives to alleviate their price competition – which is the core of this paper – is absent. Barros and Martinez-Giralt (2002) consider two healthcare providers' competition over quality and price. The difference in our models is that Barros and Martinez-Giralt (2002) capture one type of patient group who value healthcare quality similarly, whereas my model considers two heterogeneous consumer groups, so the effect of market segmentation is absent in their model.

Two papers in health economics consider heterogeneous patient groups and discuss market segmentation. Brekke, Siciliani, and Straume (2008, 2011) consider

4 In my model, decreasing one's product quality is essentially equivalent to making the rival's product more advantageous through technology sharing.

the competition among n hospitals. There are two groups of consumers: type-H patients who highly value healthcare services and always get medical care, and type-L patients with lower values, among whom some choose not to have medical care. Brekke, Siciliani, and Straume (2008) focus on patients' waiting times (which are endogenously decided by hospitals) and show that intensifying hospital competition may lead to patients' longer waiting times. Brekke, Siciliani, and Straume (2011) study patients' incentives to choose healthcare quality and show that the intensity of hospital competition may ambiguously affect the equilibrium healthcare qualities. The main difference between the above two papers and this paper is that they assume each hospital always monopolizes a specific segment of type-L consumers, so the market segmentation is exogenously given. In contrast, the market segmentation in this paper endogenously arises as a result of the price competition.

This paper also relates to literature that studies the effect of product market competition on firms' managerial incentives where quality is improved (or cost is reduced) through the effort of employees. Similar to my paper, competition is captured in a modified Hotelling model where products are vertically differentiated through different levels of quality. Raith (2003) studies the effect of competition on firms' managerial incentives to reduce costs and shows that competition incentivizes employees to increase their efforts, but the marginal effect diminishes as the rival loses market share. Baggs and Bettignies (2007) further explore the situation when firms are subject to agency costs. Manna (2017) shows that, in a competitive environment, consumer-oriented employees (who care about the well-being of consumers) can hurt firms' profit in a prisoner's dilemma situation. Although we adopt a similar model to capture firms' competition, one major difference is that my model incorporates heterogeneous consumer groups, which is absent in theirs. Besides, my research focuses on how firms' competition outcome is affected by heterogeneous consumer groups, whereas the above three papers focus on how that is affected by the managerial structure of firms.

1.2 Organization of the Paper

This paper is organized as follows. Section 2 introduces the model. Section 3 shows the main results. Section 4 analyzes extensions and discusses the robustness of the main results. Section 5 concludes. The appendix provides the proofs. Mathematical details are provided in the online Supplementary Material.

2 Model

Consider Hotelling's linear-city model along the real line [0,1]. Two firms $i \in \{0,1\}$ have their two retail stores located at the endpoints l_i (firm 0's at $l_0 = 0$, firm 1's at $l_1 = 1$); each firm offers a differentiated product of quality $s_i \in [\underline{s}, \underline{s} + \Delta] \subset \mathbb{R}_+$, where $\Delta > 0$ represents industrial technology boundary, which is given by an industrial common technology between firms. The larger Δ becomes, the higher the industrial technology boundary is. I assume each firm's marginal cost of production is independent of quality and set the marginal cost to be zero.[5] I also assume each firm's fixed cost to improve its own product quality to be zero.[6] Each firm (say firm $i = 0, 1$) offers a uniform price $p_i \geq 0$ to both markets.

Regarding the demand side, there are two types of consumers: high-end and low-end consumers (denoted by type-H consumers and type-L consumers, respectively).[7] Type-H consumers value firm i's product quality by $v + \alpha^H s_i$ while type-L consumers value it by $v + \alpha^L s_i$, where v is the common intrinsic value of a product, and $\alpha^H > \alpha^L \geq 0$ capture these two types of consumers' heterogeneous tastes towards product quality.[8] I assume that v is sufficiently large such that both types of consumers must buy from either firm. I also assume the type-H and type-L consumers are uniformly distributed over $[0, 1]$ and that they have the same size – each with a mass of $\frac{1}{2}$.[9]

Each consumer buys up to one unit of the product. For simplicity, I assume $\alpha^H = 1$ and $\alpha^L = 0$. A consumer located at $x \in [0, 1]$ will incur a cost $d(x, l_i) \cdot t$ to buy from firm i, where $d(x, l_i) = |l_i - x|$ and $t > 0$. Notice that the products here are both horizontally and vertically differentiated.

The utility of a consumer of type $j \in \{H, L\}$ located at x is given by $u^j(x) = \max_i \left\{ v + \alpha^j s_i - d(x, l_i)t - p_i, 0 \right\}$. The location of the indifferent consumer of each type is given by $\hat{x}^H(p_0, p_1) = \frac{1}{2} + \frac{\Delta^s + p_1 - p_0}{2t}$ and $\hat{x}^L(p_0, p_1) = \frac{1}{2} + \frac{p_1 - p_0}{2t}$, where $\Delta^s \equiv s_0 - s_1$. Without loss of generality, let $\Delta^s \geq 0$, that is, firm 1's product quality cannot be higher than firm 0's. I also assume $0 \leq \Delta < 2t$.[10]

I consider the following 2-stage game:

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5 This assumption refers to the textbook setting in Belleflamme and Peitz (2015, pp. 120–122), which helps us focus on how the industrial technology boundary affects firms' product quality choices and the corresponding market regime. All results hold if we consider a positive production cost.

6 Results remain to hold if there is a positive cost to increase s_i.

7 Technically, we can consider two separated Hotelling lines, comprised of the two types of consumers respectively.

8 In Tirole (1988, pp. 143–144), the consumer taste parameter can be denoted by the inverse of the "marginal utility of income." Thus, consumers with different incomes have varying willingness to pay.

9 This assumption is for simplicity in calculation. All of the results hold qualitatively in the general case where type-H and type-L consumers have masses of $\lambda \in (0, 1)$ and $1 - \lambda$, respectively.

10 I impose the upper bound of Δ to ensure the possibility that both firms will supply to both types of consumers. When both firms supply to H consumers, $\hat{x}^H(p_0, p_1) \in (0, 1)$, from which $p_1 - p_0 \in (-t - \Delta^s, t - \Delta^s)$. When both firms supply to L consumers, $\hat{x}^L(p_0, p_1) \in (0, 1)$, from which

1. Each firm chooses its quality level $s_i \in [\underline{s}, \underline{s} + \Delta]$;
2. Each firm chooses its price $p_i \geq 0$.

The solution concept is subgame-perfect Nash equilibrium (SPNE). The assumption that firms choose their qualities before prices captures the idea that quality choices always involve firms' R&D investments in the long run, which are longer-term decisions compared with the price decisions that can be adjusted more flexibly.[11]

3 Analysis

3.1 Benchmark: Only Type-H Consumers

To see how firms choose their product quality in the presence of heterogeneous consumer groups, I first consider the benchmark case in which there are only type-H consumers. I skip the analysis of the case where there are only type-L consumers because type-L consumers do not value product quality, so firms' profits are irrelevant to their quality choices. When there are only type-H consumers, firms' demand functions are

$$d_0(p_0, p_1) = \frac{1}{2}\min\left\{\max\{\hat{x}^H(p_0, p_1), 0\}, 1\right\} \text{ and } d_1(p_0, p_1) = \frac{1}{2} - d_0(p_0, p_1).$$

Solving $\max_{p_0} d_0(p_0, p_1)p_0$ and $\max_{p_1} d_1(p_0, p_1)p_1$ yields firms' equilibrium prices and profits

$$p_0^* = \frac{3t + \Delta^s}{3},\ p_1^* = \frac{3t - \Delta^s}{3};\ \pi_0^* = \frac{(3t + \Delta^s)^2}{36t},\ \pi_1^* = \frac{(3t - \Delta^s)^2}{36t}.$$

Here, firm 1 with a weakly lower product quality (from the assumption that $\Delta^s \geq 0$) has its profit π_1^* strictly decreasing in the quality difference Δ^s, whereas firm 0's profit is strictly increasing in Δ^s. Therefore, in stage 1, given any of firm

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$p_1 - p_0 \in (-t, t)$. If $\Delta^s > 2t$, these two conditions do not simultaneously hold. Since Δ^s must be smaller than Δ, $\Delta^s > 2t$ can be avoided by assuming $\Delta < 2t$.

11 For example, before the first iPhone was unveiled in 2007, Apple started the iPhone's development in 2005 (Shetty 2012), meaning that the iPhone's R&D decisions, which eventually decided its quality, were made before its price was announced. In the literature on firms' strategic investment in product quality, it is also standard to assume quality choices to be made before firms' price/quantity decisions (e.g., D'Aspremont and Jacquemin 1988).

0's quality, firm 1 will choose the same level, and both firms end up choosing the highest quality $\underline{s} + \Delta$. I summarize the above finding in the proposition below:

Observation 1. *If only type-H consumers exist, in any SPNE, both firms choose the highest quality level* $\underline{s} + \Delta$.

Without heterogeneity in consumer types, no firm would reduce its quality level. Hence, the finding by Shaked and Sutton (1982) that firms' profits increase in quality difference because a large quality difference reduces firms' price competition doesn't hold as products are both vertically and horizontally differentiated in this paper.

3.2 With Heterogeneous Consumer Types

Now, let both types of consumers exist. Each firm's demand function $D_i(p_0, p_1)$ is

$$D_0(p_0, p_1) = \frac{1}{2}\min\{\max\{\hat{x}^H(p_0, p_1), 0\}, 1\} + \frac{1}{2}\min\{\max\{\hat{x}^L(p_0, p_1), 0\}, 1\},$$

$$D_1(p_0, p_1) = 1 - D_0(p_0, p_1).$$

Note that the indifferent consumer's location can be outside the linear city, implying that one type of consumers can be monopolized by one firm. Let h and l be the indicators of type-H and type-L consumers, which are, respectively, being supplied by both firms (B), only firm 0 (0), only firm 1 (1), or none of them (N). Superscript hl specifies the realized market regime where $h, l \in \{B, 0, 1, N\}$. For example, $0B$ means that type-H consumers are supplied by only firm 0, and type-L consumers are supplied by both firms. Using the above notations, the demand system becomes

$$D_0(p_0, p_1) = \begin{cases} D_0^{00}(p_0, p_1) = 1 & if\ \ p_1 - p_0 \in [t, \infty), \\ D_0^{0B}(p_0, p_1) = \frac{1}{2}\hat{x}^L(p_0, p_1) + \frac{1}{2} & if\ \ p_1 - p_0 \in \left[t - \Delta^s, t\right), \\ D_0^{BB}(p_0, p_1) = \frac{1}{2}\hat{x}^H(p_0, p_1) + \frac{1}{2}\hat{x}^L(p_0, p_1) & if\ \ p_1 - p_0 \in (-t, t - \Delta^s), \\ D_0^{B1}(p_0, p_1) = \frac{1}{2}\hat{x}^H(p_0, p_1) & if\ \ p_1 - p_0 \in \left(-t - \Delta^s, -t\right], \\ D_0^{11}(p_0, p_1) = 0 & if\ \ p_1 - p_0 \in \left(-\infty, -t - \Delta^s\right], \end{cases}$$

and $D_1(p_0, p_1) = 1 - D_0(p_0, p_1)$. Each firm chooses p_i to maximize its profit $\pi_i = D_i(p_0, p_1)p_i$. The lemma below summarizes the equilibrium outcomes:

Lemma 1.

(1) *If* $\Delta^s \in [0, \underline{\Delta}]$, *there exists a unique pure-strategy Nash equilibrium in which the regime BB prevails. In this equilibrium,* $\left(p_0^{*BB}, p_1^{*BB}\right) = \left(\frac{6t+\Delta^s}{6}, \frac{6t-\Delta^s}{6}\right)$;

(2) *If* $\Delta^s \in \left(\underline{\Delta}, \overline{\Delta}\right)$, *there exists a mixed-strategy Nash equilibrium in which both the regime BB and 0B could prevail with a positive probability. In this equilibrium, firm 0 chooses* $p_0^{mix} = \frac{t(6+\beta)+\Delta^s-\beta\Delta^s}{6-3\beta}$, *and firm 1 chooses* $\overline{p}_1^{mix} = \frac{2t(6-\beta)+(1-\beta)\Delta^s}{6(2-\beta)}$ *with probability* β *and* $\underline{p}_1^{mix} = \frac{4t(6-\beta)-(4-\beta)\Delta^s}{12(2-\beta)}$ *with probability* $1-\beta$;

(3) *If* $\Delta^s \in \left[\overline{\Delta}, 2t\right)$, *there exists a unique pure-strategy Nash equilibrium in which firm 0 monopolizes type-H consumers, and both firms supply to type-L consumers (0B). In this equilibrium,* $\left(p_0^{*0B}, p_1^{*0B}\right) = \left(\frac{7t}{3}, \frac{5t}{3}\right)$,

where $\underline{\Delta} \equiv \frac{12(5-3\sqrt{2})t}{7}$, $\overline{\Delta} \equiv \frac{5}{3}t$, *and* $\beta \equiv \frac{24(\sqrt{2}-1)t-2(1+2\sqrt{2})\Delta^s}{4(\sqrt{2}-1)t-(2+\sqrt{2})\Delta^s)}$.

I depict the three types of market regimes in Figure 1 below. The real line denotes the equilibrium price of firm 0, whereas the dashed line denotes that of firm 1. Firms' equilibrium profits corresponding to the above three cases in Lemma 1 are provided in Appendix.

Under regime BB, an increase in Δ^s increases firm 0's price but decreases firm 1's. Intuitively, when firm 0's quality advantage becomes more prominent, given the prices, firm 0's demand from the type-H consumers increases whereas firm 1's decreases. Therefore, firm 0 raises its price to explore a positive marginal revenue, whereas firm 1 decreases its price to reduce its loss.

When Δ^s becomes larger than $\underline{\Delta}$, the regime labeled by "mix" prevails. Given firm 0's price, firm 1 chooses a high price $\overline{p}_1^{mix}$ with a probability β such that it does

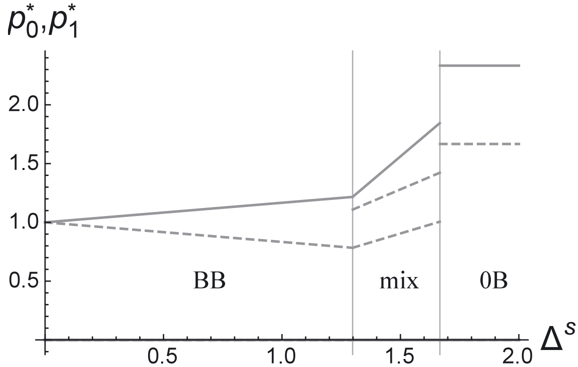

Figure 1: Equilibrium prices under different market regimes.

not serve type-H consumers but a low price $\underline{p}_1^{mix}$ with the remaining probability such that it still serves both types of consumers, which I call a *partial* market segmentation. Notice that an increase in Δ^s increases both $\overline{p}_1^{mix}$ and $\underline{p}_1^{mix}$. With firm 1's quality disadvantage becoming more prominent, it has a stronger incentive to increase $\overline{p}_1^{mix}$ so that it does not serve the type-H consumers. Firm 1's such incentive motivates firm 0 to increase its price through strategic complementarity. Remember that firm 1 still has the probability $1-\beta$ to set $\underline{p}_1^{mix}$ and compete with firm 0 for type-H consumers. In this case, firm 0's higher price adversely motivates firm 1 to increase $\underline{p}_1^{mix}$.

When Δ^s is larger than $\overline{\Delta}$, the market regime becomes $0B$ in which firm 1 drastically increases its price such that it does not serve the type-H consumers for sure, which I call a *complete* market segmentation. In this case, type-H consumers will be monopolized by firm 0, so its price is higher than those under regime BB and the mixed regimes of BB and $0B$.

To summarize, when the quality difference Δ^s grows from zero to $2t$, firm 1 will first compete with firm 0 for both types of consumers, and then begin to stop supplying the type-H consumers with a positive possibility, and finally, completely stop doing so. In other words, a larger Δ^s strengthens firm 1's incentive to trigger a *partial* market segmentation (Lemma 1-(2)) or a *complete* market segmentation (Lemma 1-(3)).

Now, given Lemma 1, let us characterize firms' quality choices in stage 1. How firms' equilibrium profits are affected by their quality difference Δ^s is depicted in Figure 2 below, where the real line denotes the equilibrium profit of firm 0 whereas the dashed line denotes that of firm 1. A change in Δ^s may switch the equilibrium market regime among the three cases, and such a switch may consequently determine the firms' product quality. Since $\Delta^s \in [0, \Delta]$, the switch among different market regimes does not necessarily happen unless Δ is sufficiently large, say, at least larger than $\underline{\Delta}$ such that there is potentially a partial or complete market segmentation.

I summarize my findings in the following proposition:

Proposition 1. *Given the outcomes in the second-stage subgames in Lemma* 1,

(1) *when* $\Delta \in \left[0, \hat{\Delta}\right]$, *there exists an SPNE outcome in which both firms choose the highest quality* $\underline{s} + \Delta$;

(2) *when* $\Delta \in \left(\hat{\Delta}, 2t\right)$, *there exists an SPNE outcome in which firm 0 chooses the highest quality* $\underline{s} + \Delta$ *whereas firm 1 chooses the lowest quality* $\underline{s}$,

where $\hat{\Delta} \equiv \left(4\sqrt{3-2\sqrt{2}}\right)t$.

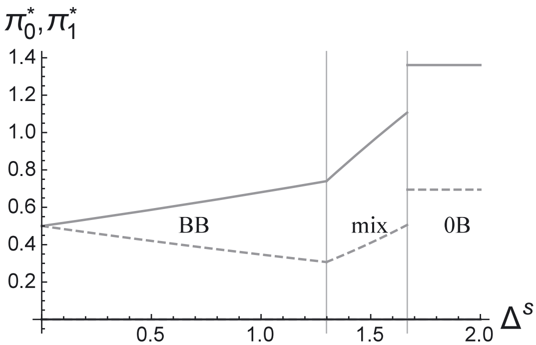

Figure 2: Equilibrium profits under different market regimes.

The intuition behind Proposition 1 can be explained by considering the following three cases:

First, consider the case when $\Delta \in [0, \underline{\Delta}]$. Since $\Delta^s \in [0, \Delta]$, only the equilibrium characterized by Lemma 1-(1) can be realized. In this case, both firms compete for both types of consumers (regime BB), and a larger quality difference strictly increases firm 0's profit while decreasing firm 1's. Therefore, following the logic from the benchmark case, both firms end up choosing the highest quality level $\underline{s} + \Delta$.

Next, consider the second case when $\Delta \in \left(\underline{\Delta}, \overline{\Delta}\right)$. Here, both the equilibria characterized by Lemma 1-(1) and -(2) can be realized. In the second equilibrium, there is a *partial* segmentation in which firm 1 chooses a high price $\overline{p}_1^{mix}$ with a probability β such that it does not serve type-H consumers. Since firm 0 is still possible to compete with firm 1 for type-H consumers, its profit π_0^{mix} is increasing in Δ^s. Surprisingly, firm 1's profit is also increasing in Δ^s. This is because, as firm 1's quality disadvantage becomes larger, it has a stronger incentive to raise the probability of choosing the high price $\overline{p}_1^{mix}$ so that a *partial* market segmentation is more likely to happen (i.e. β is an increasing function of Δ^s). Hence, firm 1's profit first decreases in Δ^s for $\Delta^s \in [0, \underline{\Delta}]$, and then increases in Δ^s for $\Delta^s \in \left(\underline{\Delta}, \overline{\Delta}\right)$.[12] Then, firm 1's problem becomes a comparison between (1) having the smallest quality difference ($\Delta^s = 0$) such that it can compete with firm 1 for type-H consumers, and (2) having the largest quality difference ($\Delta^s = \Delta$) such that a *partial* market segmentation happens with some probability. The first consequence results when Δ is such that $\pi_1^{*BB}\big|_{\Delta^s=0} > \pi_1^{mix}\big|_{\Delta^s=\Delta}$, from which $\Delta \in \left(\underline{\Delta}, \hat{\Delta}\right]$. This means that the quality difference Δ^s is not sufficient to guarantee a *partial* market segmentation

12 Note that $\pi_1^{*BB}\big|_{\Delta^s=\underline{\Delta}} = \lim_{\Delta^s \to \underline{\Delta}} \pi_1^{mix}$, so firm 1's profit is continuous and becomes the lowest at $\Delta^s = \underline{\Delta}$.

as it happens with a relatively low probability. The second consequence dominates when the opposite happens.

In the third case when $\Delta \in \left[\overline{\Delta}, 2t\right)$, all three types of the equilibria characterized by Lemma 1 can be realized. In the third equilibrium, there is *complete* market segmentation in which firm 1 does not serve the type-H consumers. Firm 1 prefers having a *complete* market segmentation to having no market segmentation or a *partial* one. The intuition is as follows. On one hand, firm 1 is completely excluded from supplying type-H consumers and loses profits from them. On the other hand, since type-H consumers highly value firm 0's quality advantage, firm 0 can increase its price from p_0^{*BB} or p_0^{mix} to p_1^{*0B} to further exploit their surplus. Due to strategic complementarity, firm 1's price also increases from either p_1^{*BB} or $\beta\overline{p}_1^{mix} + (1-\beta)\underline{p}_{-1}^{mix}$ to p_1^{*0B}. Consequently, becoming sufficiently asymmetric in product quality enables both firms to escape from the price competition in the type-H consumers.

To summarize, when facing heterogeneous consumer groups, firm 1 will reduce its product quality to trigger a *partial* or *complete* market segmentation only when its rival, firm 0, can produce a product of sufficiently high quality, which can only happen when the industry's technology boundary is sufficiently high. Regime 0B in Figure 2 can correspond to the real-world example regarding telecommunications mentioned in the introduction. Specifically, only after the 4G technology standard for broadband cellular networks was widely adopted did Nokia find it profitable to downgrade its product line and not serve the high-end consumers, i.e. Δ is larger than $\overline{\Delta}$ such that the quality difference Δ^s can induce regime 0B. Nokia chose to supply the high-end consumers in the 2G and 3G eras because, at that time, its rival(s)' product quality was not high enough to trigger a market segmentation, i.e. Δ is smaller than $\underline{\Delta}$ such that the quality difference Δ^s can only induce regime BB. It was then profitable for Nokia to choose high-quality products as well. Notice that Nokia's incentives of not serving high-end consumers can be due to various reasons. My model provides one theoretical explanation from the strategic perspective.

3.3 Welfare Analysis

Now, I turn to welfare analysis. Consumer surplus (CS) is given by the total utility from each group of consumers, and producer surplus (PS) is the summation of both firms' profits. Social surplus (SS) is the summation of CS and PS.[13]

One might think that pushing the industrial technology boundary should benefit all social members. However, this does not necessarily hold in the presence

13 The welfare formulas are given in Appendix.

of heterogeneous consumer groups described in this paper. The next proposition summarizes my finding (Note that $\Delta \in [0, 2t)$ by the assumption):

Proposition 2. *Both the consumer surplus and the social surplus are maximized at* $\Delta = \hat{\Delta} < 2t$.

Notice that the level of Δ that maximizes the consumer surplus and social surplus is below the maximum level allowed, meaning that any policy that facilitates a more advanced industry such that the industrial technology boundary Δ is beyond $\hat{\Delta}$ may make the consumers suffer and cause a social loss as well. The intuition is explained as follows: When Δ passes $\hat{\Delta}$, according to the SPNE characterized in Proposition 1, firm 1 adjusts its quality decision to the lowest level $\underline{s}$. Such an adjustment consequently gives rise to a partial market segmentation (a mixture of regimes BB and 0B), and then a complete market segmentation (regime 0B). The increase in Δ and the subsequent changes in the market regime have the following welfare impacts: Firm 0 sets the highest quality and all type-H consumers value this quality improvement. Although firm 1 lowers its quality to $\underline{s}$, since type-L consumers do not value product quality, the quality reduction does not bring any negative impact on welfare.[14] However, when there is either a partial market segmentation or a complete one, the type-H consumers who locate close to firm 1 need to incur a higher transportation cost to access firm 0, whereas they should have bought from firm 1 and avoided the unnecessary transportation costs when the market regime is BB. Then, the additional transportation costs incurred on some type-H consumers cause a significant welfare loss such that the social surplus is maximized only when Δ is at the level such that the market regime is still BB. Regarding the consumer surplus, in both a partial market segmentation and a complete one, both firms charge a higher price compared with that when the market regime is BB, meaning that the firms exploit more producer surplus from the social surplus. Then, the consumer surplus is maximized only when the type-H consumers can enjoy the highest possible quality but the market regime is still BB.

Proposition 2 has the following corresponding policy implication: policies that intend to push the industrial technology boundary may lower both consumer surplus and social surplus, as it can lead to welfare-decreasing market segmentation. This policy conclusion is reminiscent of Heidhues, Kőszegi, and Murooka (2016) who show a similar welfare implication that quality improvement may not necessarily increase social welfare, but comes from a completely different mechanism based on consumer naivety and shrouded attributes. Proposition 2 of this paper shows that

14 The above consequences are based on the analysis of a complete market segmentation. When there is a partial segmentation, these consequences happen with a positive probability β.

both social and consumer welfare are maximized at a medium level of the industrial technology boundary that maintains the market regime as BB. From the above observations, we can argue that to mitigate negative welfare effects from intentional product downgrades due to expanding industrial technology boundaries, policymakers can enforce minimum quality regulations to avoid market segmentation and ensure quality choices for high-end consumers while balancing technology progress and consumer protection.

4 Extensions

In this section, I will discuss four extensions to investigate the robustness of the above results. That is, in the presence of consumers' heterogeneity regarding product quality, one firm may spontaneously choose the lowest quality to trigger market segmentation in order to alleviate market competition. The following extensions will be considered: (1) firms' quality-dependent costs, including both marginal costs and fixed costs; (2) quality spillover between firms; (3) firms' endogenous location choice; (4) type-H consumers' valuation depending on the technology boundary.

4.1 Quality-dependent Costs

4.1.1 Marginal Costs

Now, I assume each firm i faces marginal cost $c_i \in \mathbb{R}_+, i = 0, 1$ so that each firm's profit function becomes $D_i(p_0, p_1)(p_i - c_i)$. I assume the asymmetry in marginal costs is sufficiently small.[15] Then, following the logic of a standard Hotelling model, it is the relative price/cost that affects profits, so the introduction of marginal costs (with sufficiently small asymmetry) only leads to changes in equilibrium prices, but not profits. Accordingly, the quality thresholds Δ^s in all three cases are the same as those in Lemma 1, and the equilibrium outcomes for the stage-1 game is still that given firm 0 choosing the highest quality, firm 1 benefits by choosing the lowest when the industrial technology boundary is sufficiently large such that a market segmentation occurs. See the Supplementary Materials for details.

15 If the asymmetry in marginal costs becomes sufficiently large, then both the asymmetries of qualities and marginal costs would affect the market regimes, which would make the piecewise discussions overly complex, for both on and off-equilibrium path.

4.1.2 Fixed Costs

Now we consider the case where firm i incurs a fixed quality-dependent cost $\frac{1}{2}s_i^2$. Since this cost is sunk in the competition stage, the equilibrium outcome is the same as summarized in Lemma 1. Specifically, I have that for sufficiently small Δ^s both firms supply both groups; for intermediate Δ^s, firm 1 mix its prices such that a market segmentation occurs with a positive probability; for sufficiently large Δ^s, firm 1 does not serve the type-H group such that the market segmentation always occurs.

Firms' net profits are denoted by $\pi_0^{*BB} - \frac{1}{2}s_0^2$ and $\pi_1^{*BB} - \frac{1}{2}s_1^2$ under regime BB, $\pi_0^{mix} - \frac{1}{2}s_0^2$ and $\pi_1^{mix} - \frac{1}{2}s_1^2$ under the mixed regimes of BB and 0B, and $\pi_0^{*0B} - \frac{1}{2}s_0^2$ and $\pi_1^{*0B} - \frac{1}{2}s_1^2$ under regime 0B. Notice that fixed costs make firms' profits no longer depend on only the quality difference Δ^s, which makes the derivation of firms' optimal product qualities mathematically complicated. To simplify the analysis, let $\underline{s} = 0$. Despite the presence of fixed cost, I confirm that regime 0B, in which firm 1 spontaneously chooses the lowest quality, can be obtained as an SPNE outcome when the transportation cost is smaller than approximately 0.715. Details are relegated to the Supplementary Material.

4.2 Spillovers

Now, we look into how the equilibrium results change if firms' quality improvement has spillover effects. Following Spence (1984), I assume each firm benefits from the other firm's quality improvement and let parameter $\theta \in (0,1)$ capture spillovers. Then firm i's quality is $s_i + \theta s_j$, where $i, j \in \{0,1\}$, and the effective quality difference between firm 0 and firm 1 is $\Omega^s \equiv (1-\theta)\Delta^s$. All the results are the same except that replacing Δ^s with Ω^s. Similarly, by solving $\pi_1^{*BB}\Big|_{\Omega^s=0} = \pi_1^{*mix}\Big|_{\Omega^s=\Omega}$, I obtain the optimal level of quality difference $\Omega = 4\sqrt{3-2\sqrt{2}}$ (i.e. technology boundary $\Delta = \frac{4\sqrt{3-2\sqrt{2}}}{1-\theta}$) in stage 1. Notice that the cutoff value of the technology boundary becomes higher compared to Proposition 1, meaning that market segmentation becomes less likely to occur. Due to the existence of spillovers, given firm 1 choosing the lowest quality, firm 0 is required to choose a higher quality to guarantee a sufficiently large effective quality difference to trigger market segmentation.

4.3 Endogenous Location Choice

Here, we briefly discuss the case in which firms can endogenously choose their locations. When there are no firms' quality variables (that is, when consumers choose whether to buy a firm's product purely depending on the transportation cost and the price charged by that firm), endogenizing firms' location choices will motivate both firms to locate apart from each other to alleviate their price competition, compared with the case of fixed locations. Even with endogenous location choices, facing consumer heterogeneity, firms still have the incentive to enlarge their quality difference to trigger a market segmentation, but endogenously setting their locations away from each other should play a similar role in alleviating competition. Therefore, market segmentation becomes less likely to occur compared with my main model.

4.4 Type-H Consumers' Valuation Depending on the Technology Boundary

In the main model, for simplicity, I have assumed type-H's valuation to be one. This assumption can be relaxed by considering a valuation function that depends on the technology boundary, say $\alpha^H = \alpha(\Delta)$. Then, the effective quality difference for type-H consumers becomes $\alpha(\Delta)(s_0 - s_1)$ instead of $s_0 - s_1$ in the main model. This adjustment in the model does not change the essence of Lemma 1, since I can take $\alpha(\Delta)(s_0 - s_1)$ as a whole, and the conditions for each type of equilibrium to exist are now based on $\alpha(\Delta)(s_0 - s_1)$. Regarding firms' choices on product equality, the presence of type-H consumers' technology-boundary-based valuation $\alpha(\Delta)$, which is exogenous, will not change the logic behind Observation 1. Given firm 0 choosing the highest product quality $\underline{s} + \Delta$, firm 1 finds it profitable to choose the lowest quality $\underline{s}$ when the technology boundary is sufficiently large such that firms' quality difference is large enough to trigger a market segmentation.

5 Conclusions

This paper studies how firms choose their product qualities when facing different levels of industrial technology boundary and heterogeneous consumers. Consumers' heterogeneity in how they value products' quality plays a crucial role. I assume there are two consumer groups – one consumer group values products' quality more (type-H) than the other (type-L). I show that when one firm chooses a low-quality product, it is excluded from type-H consumers, which is then monopolized by its rival. However, since type-H consumers highly value the rival's products, the rival optimally raises its price, which alleviates the price competition for type-L consumers, therefore benefiting the firm with low-quality products who obtains a larger demand there. This mechanism can only happen when the industrial technology boundary is sufficiently high. This is because only under this condition can a firm provide a sufficiently high-quality product and can its rival reduce product quality such that the quality difference becomes sufficiently large to trigger the market segmentation. This finding helps explain why some firms find it profitable to decrease their product quality in practice, even when the industrial technology boundary is high. The corresponding welfare analysis shows that a regulator may incentivize firms to push the technology boundary at the industrial level, but not too much as it may lead to undesirable welfare-decreasing market segmentation.

Notice that my model captures a static situation where a firm that faces heterogeneous consumer groups chooses a low-quality product to trigger market segmentation, which is detrimental to consumer surplus and social surplus. This logic applies in the short run, but market entries, in the long run, may imitate and adopt the industrial boundary-level technology, therefore weakening the welfare-reducing effect of the market segmentation and reinforcing a socially optimal outcome. Moreover, if we consider repeated interactions between firms, the firm with a low product quality has less incentive to unilaterally increase the quality because doing so induces head-to-head competition in the high-end market. Then, firms' incentives to sustain a market segmentation in the static game in each period are even stronger. Analyzing interactions between innovation dynamics and market segmentation would be meaningful, but this is beyond the scope of this paper and left for future research.

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Appendix

Proof of Lemma 1

(1) The BB equilibrium

Under BB, firms solve

$$\max_{p_0} \frac{1}{2}(\hat{x}^H(p_0, p_1) + \hat{x}^L(p_0, p_1))p_0, \ \max_{p_1}\left(1 - \frac{1}{2}(\hat{x}^H(p_0, p_1) + \hat{x}^L(p_0, p_1))\right)p_1,$$

subject to $p_1 - p_0 \in (-t, t - \Delta^s)$, which has an interior solution $\left(p_0^{*BB}, p_1^{*BB}\right) = (\frac{6t+\Delta^s}{6}, \frac{6t-\Delta^s}{6})$ with $\left(\pi_0^{*BB}, \pi_1^{*BB}\right) = (\frac{(6t+\Delta^s)^2}{72t}, \frac{(6t-\Delta^s)^2}{72t})$ if and only if $0 \le \Delta^s < \frac{3}{2}t$.

Given $p_0 = p_0^{*BB}$, if firm 1 induces 0B, it solves $\max\limits_{p_1} \frac{1}{2}\left(1 - \hat{x}^L\left(p_0^{*BB}, p_1\right)\right)p_1$, subject to $t - \Delta^s \le p_1 - p_0^{*BB} < t$, which has an interior solution $p_1 = \frac{12t+\Delta^s}{12}$ with profits $\frac{(12t+\Delta^s)^2}{576t}$ when $\Delta^s \in [\frac{12t}{11}, 2t)$ and a corner solution $p_1 = \frac{12t-5\Delta^s}{6}$ with profits $\frac{\Delta^s(12t-5\Delta^s)}{24t}$ when $\Delta^s \in [0, \frac{12t}{11})$. The profits under the interior solution are weakly less than π_1^{*BB} if $\frac{12t}{11} \le \Delta^s \le \frac{12(5-3\sqrt{2})}{7}t$, while the profits under the corner solution are always strictly less than π_1^{*BB} when $\Delta^s \in [0, \frac{12t}{11})$. It is straightforward to check that neither firm will have an incentive to deviate to other situations, 00, B1, and 11, and that no situation other than BB will happen in an equilibrium. See the Supplementary Material for detailed derivations.

(2) The mixed equilibrium

Between the range of Lemma (1) and (3) when $\Delta^s \in (\underline{\Delta}, \frac{5t}{3})$, there exists a mixed-strategy equilibrium (p_0, σ_1) constructed as follow,

1. Firm 0 takes a pure strategy p_0;
2. Firm 1 mixes between (1) p_1^h such that $\hat{x}^H > 1$ and $0 < \hat{x}^L < 1$ and (2) p_1^l such that $0 < \hat{x}^H < 1$ and $0 < \hat{x}^L < 1$ (denoted as σ_1). Let β be the probability that p_1^h is chosen, and $1 - \beta$ be the probability that p_1^l is chosen.

Now I verify if (p_0, σ_1) constitutes a mixed Nash equilibrium.
First, write down firm 0's expected profit from (p_0, σ_1),

$$\pi_0 = p_0 \cdot \frac{1}{2}\left(\beta \cdot 1 + (1-\beta)\frac{p_1^l - p_0 + t + \Delta^s}{2t}\right) + p_0 \cdot \frac{1}{2}\left(\beta\frac{p_1^h - p_0 + t}{2t} + (1-\beta)\frac{p_1^l - p_0 + t}{2t}\right).$$

When choosing p_1^h, firm 1 obtains $\pi_1^h = p_1^h\left(\frac{1}{2} \cdot 0 + \frac{1}{2}\left(1 - \frac{p_1^h - p_0 + t}{2t}\right)\right)$; when choosing p_1^l, firm 1 obtains $\pi_1^l = p_1^l\left(\frac{1}{2}\left(1 - \frac{p_1^l - p_0 + t + \Delta^s}{2t}\right) + \frac{1}{2}\left(1 - \frac{p_1^l - p_0 + t}{2t}\right)\right)$. Thus, firm 1 obtains the following expected profit from (p_0, σ_1),

$$\pi_1 = \beta\pi_1^h + (1-\beta)\pi_1^l = \beta \cdot p_1^h\left(\frac{1}{2} \cdot 0 + \frac{1}{2}\left(1 - \frac{p_1^h - p_0 + t}{2t}\right)\right) + (1-\beta) \cdot p_1^l\left(\frac{1}{2}\left(1 - \frac{p_1^l - p_0 + t + \Delta^s}{2t}\right) + \frac{1}{2}\left(1 - \frac{p_1^l - p_0 + t}{2t}\right)\right).$$

Then, I solve for p_0, p_1^l and p_1^h respectively by first-order conditions,

$$p_0^* = \frac{t(6+\beta)+\Delta^s-\beta\Delta^s}{6-3\beta};$$

$$p_1^{h*} = \frac{2t(\beta-6)+(\beta-1)\Delta^s}{6(\beta-2)};$$

$$p_1^{l*} = \frac{4t(\beta-6)-(\beta-4)\Delta^s}{12(\beta-2)}.$$

Substituting p_0^*, p_1^{h*} and p_1^{l*} into the expected profits, we can obtain

$$\pi_1^{h*} = \frac{(2t\beta-12t-\Delta^s+\beta\Delta^s)^2}{144t(\beta-2)^2};$$

$$\pi_1^{l*} = \frac{(4t\beta-24t+4\Delta^s-\beta\Delta^s)^2}{288t(\beta-2)^2}.$$

If (p_0, σ_1) is a mixed Nash equilibrium, firm 1 should be indifferent between choosing p_1^h and p_1^l. That is

$$\pi_1^{h*} = \pi_1^{l*}.$$

By $\pi_1^{h*} = \pi_1^{l*}$, we can solve for β and obtain

$$\beta = \frac{24(\sqrt{2}-1)t-2(1+2\sqrt{2})\Delta^s}{(4\sqrt{2}-4)t-(2+\sqrt{2})\Delta^s}.$$

Substituting β into π_0 and π_1, I obtain $\left(\pi_0^{mix}, \pi_1^{mix}\right) = \left(\frac{(\Delta^s-8t)(2(\sqrt{2}-1)t-\sqrt{2}\Delta^s)^2}{8(\sqrt{2}-1)(4(\sqrt{2}-1)t-(2+\sqrt{2})\Delta^s))t}, \frac{(\Delta^s)^2}{32(\sqrt{2}-1)^2 t}\right)$.

To verify if (p_0, σ_1) constitutes a mixed Nash equilibrium, I examine if $\beta \in (0,1)$ under the assumptions on t and Δ^s i.e. $t \in (0,1)$ and $\Delta^s \in (0, 2t)$. We can find that $\beta \in (0,1)$ if

$$\frac{12(5-3\sqrt{2})}{7}t < \Delta^s < \frac{10(2-\sqrt{2})}{3}t.$$

Recall that the range gap between Lemma 1 (1) and (3) is

$$\frac{12(5-3\sqrt{2})}{7}t < \Delta^s < \overline{\Delta}.$$

Since $\overline{\Delta} < \frac{10(2-\sqrt{2})}{3}t$, I confirm that $\beta \in (0,1)$ is true for $\frac{12(5-3\sqrt{2})}{7}t < \Delta^s < \overline{\Delta}$.

Therefore, I confirm that (p_0, σ_1) constitutes a mixed-strategy Nash equilibrium. By substituting the value of β in (2) back into (1), I confirm that the following mixed Nash equilibrium exists when $\frac{12(5-3\sqrt{2})}{7}t < \Delta^s < \overline{\Delta}$:

1. Firm 0 takes a pure strategy $p_0 = \frac{2+\sqrt{2}}{2}\Delta^s - t$;

2. Firm 1 takes $p_1^h = \frac{2+\sqrt{2}}{4}\Delta^s$ with probability $\beta = \frac{24(\sqrt{2}-1)t-2(1+2\sqrt{2})\Delta^s}{(4\sqrt{2}-4)t-(2+\sqrt{2})\Delta^s}$ and takes $p_1^l = \frac{1+\sqrt{2}}{4}\Delta^s$ with probability $1-\beta = \frac{20(\sqrt{2}-1)t-3\sqrt{2}\Delta^s}{(4\sqrt{2}-4)t-(2+\sqrt{2})\Delta^s}$.

It is straightforward to check that the above p_1^h is a price such that $\hat{x}^H > 1$ and $0 < \hat{x}^L < 1$, and p_1^l is a price such that $0 < \hat{x}^H < 1$ and $0 < \hat{x}^L < 1$.

(3) The 0B equilibrium

Under 0B, firms solve

$$\max_{p_0} \frac{1}{2}(1 + \hat{x}^L(p_0, p_1))p_0, \ \max_{p_1} \frac{1}{2}(1 - \hat{x}^L(p_0, p_1))p_1,$$

subject to $p_1 - p_0 \in [t - \Delta^s, t)$, which has an interior solution $\left(p_0^{*0B}, p_1^{*0B}\right) = (\frac{7t}{3}, \frac{5t}{3})$ with $\left(\pi_0^{*0B}, \pi_1^{*0B}\right) = (\frac{49t}{36}, \frac{25t}{36})$ if and only if $\overline{\Delta} \le \Delta^s < 2t$.

Given $p_0 = p_0^{*0B}$, if firm 1 induces B1, it solves $\max_{p_1} \frac{1}{2}((1 - \hat{x}^A\left(p_0^{*0B}, p_1\right)) + 1)p_1$, subject to $-t - \Delta^s < p_1 - p_0^{*0B} \le -t$, which always has a corner solution $p_1 = \frac{4t}{3}$ with profits $\frac{4t-\Delta^s}{3}$ that are less than π_1^{*0B} if $\overline{\Delta} \le \Delta^s < 2t$. It is straightforward to check that neither firm will have an incentive to deviate to other situations, 00, BB, and 11, and that no situation other than BB will happen in an equilibrium. See the Supplementary Material for this. ■

Proof of Proposition 1

Proposition 1-(1). *When $\Delta \in [0, \underline{\Delta}]$, only the BB equilibrium in Lemma 1-(1) can be realized. In this equilibrium, firm 0's profit increases in Δ^s, whereas firm 1's profit decreases in it. Given firm 0 chooses the highest quality level $s_0 = \underline{s} + \Delta$, firm 1's profits decrease if it deviates from choosing the same level $s_1 = \underline{s} + \Delta$. Also, given firm 1 chooses the highest level $s_1 = \underline{s} + \Delta$, firm 0 cannot further increase its quality from $s_0 = \underline{s} + \Delta$.*

When $\Delta \in (\underline{\Delta}, \hat{\Delta}]$, both the BB equilibrium in Lemma 1-(1) and the mixed equilibrium in Lemma 1-(2) can be realized. Since firm 1's profit decreases in Δ^s when $\Delta^s \in [0, \underline{\Delta}]$ and then increases in Δ^s when $\Delta^s \in (\underline{\Delta}, \Delta]$, I only need to compare the two local maxima $\pi_1^{*BB}\Big|_{\Delta^s=0}$ and $\pi_1^{mix}\Big|_{\Delta^s=\Delta}$. As $\pi_1^{*BB}\Big|_{\Delta^s=0} \ge \pi_1^{mix}\Big|_{\Delta^s=\Delta}$ for $\Delta \in (\underline{\Delta}, \hat{\Delta}]$, given firm 0's quality level $s_0 = \underline{s} + \Delta$, firm 1 prefers to following the same quality strategy $s_1 = \underline{s} + \Delta$ as above to have the BB equilibrium. Since I have assumed $\Delta^S = s_0 - s_1 \ge 0$, firm 0 will follow with the same quality level $s_0 = \underline{s} + \Delta$.

Proposition 1-(2). *When $\Delta \in (\hat{\Delta}, \overline{\Delta})$, both the BB equilibrium in Lemma 1-(1) and the mixed equilibrium in Lemma 1-(2) can be realized. Since $\pi_1^{*BB}\big|_{\Delta^s=0} < \pi_1^{mix}\big|_{\Delta^s=\Delta}$, firm 1 prefers to having the largest Δ^s. In the mixed equilibrium, both firms' profits increase in Δ^s so that $\Delta^s = \Delta$ maximizes both firms' profits. Then, by assumption $\Delta^s = s_0 - s_1 \geq 0$, firm 0 chooses the highest quality level $s_0 = \underline{s} + \Delta$ while firm 1 chooses the lowest quality level $s_1 = \underline{s}$.*

When $\Delta \in [\overline{\Delta}, 2t)$, all the three equilibria in Lemma-(1), -(2) and -(3) are all possible. When the 0B equilibrium exists ($\Delta^s \in [\overline{\Delta}, 2t)$), $\pi_0^{*0B} = \frac{49}{36}t$, $\pi_1^{*0B} = \frac{25}{36}t$. Firm 1's maximum profit is $\pi_1^{*BB}\big|_{\Delta^s=0}$ in the BB equilibrium (for $\Delta^s \in [0, \underline{\Delta}]$) and $\lim_{\Delta^s \to \overline{\Delta}} \pi_1^{mix}$ in the mixed equilibrium (for $\Delta^s \in (\underline{\Delta}, \overline{\Delta})$). It can be confirmed that $\pi_1^{*0B} > \pi_1^{*BB}\big|_{\Delta^s=0}$ and $\pi_1^{*0B} > \lim_{\Delta^s \to \overline{\Delta}} \pi_1^{mix}$. For firm 0, its maximum profit is $\pi_0^{*BB}\big|_{\Delta^s=\underline{\Delta}}$ in the BB equilibrium (for $\Delta^s \in [0, \underline{\Delta}]$) and $\lim_{\Delta^s \to \overline{\Delta}} \pi_0^{mix}$ in the mixed equilibrium (for $\Delta^s \in (\underline{\Delta}, \overline{\Delta})$). It can be confirmed that $\pi_0^{*0B} > \pi_0^{*BB}\big|_{\Delta^s=\underline{\Delta}}$ and $\pi_1^{*0B} > \lim_{\Delta^s \to \overline{\Delta}} \pi_0^{mix}$. Then, both firm 0 and firm 1 prefer to have the 0B equilibrium. Since both firms' profits are independent of Δ^s in the 0B equilibrium, neither firm can get better off by deviating from $(s_0, s_1) = (\underline{s} + \Delta, \underline{s})$ so that $(s_0, s_1) = (\underline{s} + \Delta, \underline{s})$ constitute the equilibrium in the first stage.[16] ■

Proof of Proposition 2

The welfare formulas are given by

$$CS = \frac{1}{2}\left(\int_0^{\hat{x}^H} (v + s_0 - xt - p_0)\mathrm{d}x + \int_{\hat{x}^H}^1 (v + s_1 - (1-x)t - p_1)\mathrm{d}x\right)$$
$$+ \frac{1}{2}\left(\int_0^{\hat{x}^L} (v - xt - p_0)\mathrm{d}x + \int_{\hat{x}^l}^1 (v - (1-x)t - p_1)\mathrm{d}x\right),$$

$$PS = \pi_0 + \pi_1,$$

16 Notice that $(s_0, s_1) = (\underline{s} + \Delta, \underline{s})$ is not the unique equilibrium when $\Delta \in (\overline{\Delta}, 2t)$. Since π_0^{*0B} and π_1^{*0B} are independent of Δ^s, there might exist other equilibrium quality choices such that $s_0 - s_1 \in [\overline{\Delta}, \Delta)$.

$$SS = CS + PS = \frac{1}{2}\left(\int_0^{\hat{x}^H} (v + s_0 - xt)\mathrm{d}x + \int_{\hat{x}^H}^{1} (v + s_1 - (1-x)t)\mathrm{d}x\right)$$
$$+ \frac{1}{2}\left(\int_0^{\hat{x}^L} (v - xt)\mathrm{d}x + \int_{\hat{x}^l}^{1} (v - (1-x)t)\mathrm{d}x\right).$$

I calculate and compare the social surplus and consumer surplus under the three cases in Lemma 1.

(1) The BB equilibrium

By Lemma 1-(1), in the BB equilibrium, the equilibrium locations of the indifferent consumers are $\hat{x}^L = \hat{x}^H = \frac{1}{2}$. By Proposition 1-(1), in the BB equilibrium, both firms choose the highest possible quality level i.e. $s_0 = s_1 = \underline{s} + \Delta$ so that $\Delta^s = 0$. Then the social surplus SS^{BB} and consumer surplus CS^{BB} under the BB equilibrium can be calculated as follow:

$$SS^{BB} = \frac{1}{2}\left(\int_0^{\frac{1}{2}} (v + \underline{s} + \Delta - xt)\mathrm{d}x + \int_{\frac{1}{2}}^{1} (v + \underline{s} + \Delta - (1-x)t)\mathrm{d}x\right)$$
$$+ \frac{1}{2}\left(\int_0^{\frac{1}{2}} (v - xt)\mathrm{d}x + \int_{\frac{1}{2}}^{1} (v - (1-x)t)\mathrm{d}x\right) = \frac{1}{4}(2\underline{s} + 4v + 2\Delta - t),$$

$$CS^{BB} = SS^{BB} - \pi_0^{*BB} - \pi_1^{*BB} = SS^{BB} - \frac{1}{2}t - \frac{1}{2}t = \frac{1}{4}(2\underline{s} + 4v + 2\Delta - 5t).$$

(2) The mixed equilibrium

By Lemma 1-(2), in this mixed equilibrium, firm 0 chooses $p_0^{mix} = \frac{t(6+\beta)+\Delta^s-\beta\Delta^s}{6-3\beta}$, and firm 1 chooses $\overline{p}_1^{mix} = \frac{2t(6-\beta)+(1-\beta)\Delta^s}{6(2-\beta)}$ with probability β and $\underline{p}_1^{mix} = \frac{4t(6-\beta)-(4-\beta)\Delta^s}{12(2-\beta)}$ with probability $1-\beta$, where $\beta = \frac{24(\sqrt{2}-1)t-2(1+2\sqrt{2})\Delta^s}{4(\sqrt{2}-1)t-(2+\sqrt{2})\Delta^s)}$, $\left(\pi_0^{mix}, \pi_1^{mix}\right) = \left(\frac{(\Delta^s-8t)(2(\sqrt{2}-1)t-\sqrt{2}\Delta^s)^2}{8(\sqrt{2}-1)(4(\sqrt{2}-1)t-(2+\sqrt{2})\Delta^s))t}, \frac{(\Delta^s)^2}{32(\sqrt{2}-1)^2t}\right)$. Therefore, the equilibrium locations of indifferent consumers are: $\hat{x}^H = 1$ and $\hat{x}^L = 1 - \frac{\Delta}{8t-4\sqrt{2}t}$ when firm 1 takes strategy $\overline{p}_1^{mix}$; $\hat{x}^H = 1 + \frac{\Delta-\sqrt{2}\Delta}{8t}$ and $\hat{x}^L = 1 - \frac{(3+\sqrt{2})\Delta}{8t}$ when firm 1 takes strategy $\underline{p}_1^{mix}$. By Proposition 1-(2), firm 0 chooses the highest quality level $s_0 = \underline{s} + \Delta$ whereas firm

1 chooses the lower level $s_1 = \underline{s}$ so that $\Delta^s = s_0 - s_1 = \Delta$. Then the social surplus SS^{mix} and consumer surplus CS^{mix} under the BB equilibrium can be calculated as follow:

$$\begin{aligned}
SS^{mix} &= \beta\left(\frac{1}{2}\left(\int_0^1 (v+\underline{s}+\Delta-xt)\mathrm{d}x + \int_1^1 (v+\underline{s}-(1-x)t)\mathrm{d}x\right)\right. \\
&\quad + \frac{1}{2}\left(\int_0^{1-\frac{\Delta}{8t-4\sqrt{2}t}} (v-xt)\mathrm{d}x + \int_{1-\frac{\Delta}{8t-4\sqrt{2}t}}^1 (v-(1-x)t)\mathrm{d}x\right) \\
&\quad + (1-\beta)\left(\frac{1}{2}\left(\int_0^{1+\frac{\Delta-\sqrt{2}\Delta}{8t}} (v+\underline{s}+\Delta-xt)\mathrm{d}x\right.\right. \\
&\quad \left.\left.+ \int_{1+\frac{\Delta-\sqrt{2}\Delta}{8t}}^1 (v+\underline{s}-(1-x)t)\mathrm{d}x\right)\right) \\
&\quad + \frac{1}{2}\left(\int_0^{1-\frac{(3+\sqrt{2})\Delta}{8t}} (v-xt)\mathrm{d}x + \int_{1-\frac{(3+\sqrt{2})\Delta}{8t}}^1 (v-(1-x)t)\mathrm{d}x\right) \\
&= \frac{\begin{array}{l} 64(-4+3\sqrt{2})t^3 - 32\underline{s}t((-8+6\sqrt{2})t-\Delta) + 7(3-2\sqrt{2})\Delta^3 \\ -16t^2(8(-4+3\sqrt{2})v + (-30+23\sqrt{2})\Delta) \\ +2t\Delta(32v + (-112+89\sqrt{2})\Delta) \end{array}}{64t((8-6\sqrt{2})t+\Delta)}, \\
CS^{mix} &= SS^{mix} - \pi_0^{*mix} - \pi_1^{*mix} \\
&= SS^{mix} - \frac{(\Delta^s - 8t)(2(\sqrt{2}-1)t - \sqrt{2}\Delta)^2}{8(\sqrt{2}-1)(4(\sqrt{2}-1)t-(2+\sqrt{2})\Delta)\big)t} - \frac{(\Delta)^2}{32(\sqrt{2}-1)^2 t}.
\end{aligned}$$

(3) The 0B equilibrium

By Lemma 1-(2), in the 0B equilibrium, $\left(p_0^{*0B}, p_1^{*0B}\right) = \left(\frac{7t}{3}, \frac{5t}{3}\right)$, $\left(\pi_0^{*0B}, \pi_1^{*0B}\right) = \left(\frac{49}{36}t, \frac{25}{36}t\right)$, so that the equilibrium location of the indifferent consumers are $\bar{x}^H = 1$

and $\bar{x}^L = \frac{1}{6}$. By Proposition 1-(1), in the 0B equilibrium, firm 0 chooses the highest quality level $s_0 = \underline{s} + \Delta$ whereas firm 1 chooses the lower level $s_1 = \underline{s}$.

$$\begin{aligned}
SS^{0B} &= \frac{1}{2}\left(\int_0^1 (v + \underline{s} + \Delta - xt)\mathrm{d}x + \int_1^1 (v + \underline{s} - (1-x)t)\mathrm{d}x\right)\Bigg) \\
&\quad + \frac{1}{2}\left(\int_0^{\frac{1}{6}} (v - xt)\mathrm{d}x + \int_{\frac{1}{6}}^1 (v - (1-x)t)\mathrm{d}x\right) \\
&= \frac{1}{72}(36\underline{s} - 31t + 72v + 36\Delta),
\end{aligned}$$

$$CS^{0B} = SS^{0B} - \pi_0^{*0B} - \pi_1^{*0B} = SS^{0B} - \frac{49}{36}t - \frac{25}{36}t = \frac{1}{72}(36\underline{s} - 179t + 72v + 36\Delta).$$

(4) Comparison of SS and CS

Since the social surplus increase in Δ for all the above three cases (i.e. $SS^{BB\prime}(\Delta)$, $SS^{mix\prime}(\Delta), SS^{0B\prime}(\Delta) > 0$ with conditions on Δ), I only need to compare three local maxima $SS^{BB}|_{\Delta=\hat{\Delta}}$, $SS^{mix}|_{\Delta=\overline{\Delta}}$ and $SS^{0B}|_{\Delta=2t}$. Substituting the value of Δ, I have $SS^{BB}|_{\Delta=\hat{\Delta}} = v + \frac{1}{2}\underline{s} + (2\sqrt{3-2\sqrt{2}} - \frac{1}{4})t$, $SS^{mix}|_{\Delta=\overline{\Delta}} = v + \frac{1}{2}\underline{s} + \frac{289\sqrt{2}-65}{576(47\sqrt{2}-65)}t$ and $SS^{0B}|_{\Delta=2t} = v + \frac{1}{2}\underline{s} + \frac{41}{72}t$. A simple comparison shows that $SS^{BB}|_{\Delta=\hat{\Delta}} > SS^{0B}|_{\Delta=2t} > SS^{mix}|_{\Delta=\overline{\Delta}}$ for any $t \in (0,1)$.

Similarly, I compare $CS^{BB}|_{\Delta=\hat{\Delta}}, CS^{mix}|_{\Delta=\overline{\Delta}}$ and $CS^{0B}|_{\Delta=2t}$. Substituting the value of Δ, I have $CS^{BB}|_{\Delta=\hat{\Delta}} = v + \frac{1}{2}\underline{s} + (2\sqrt{3-2\sqrt{2}} - \frac{5}{4})t$, $SS^{mix}|_{\Delta=\overline{\Delta}} = v + \frac{1}{2}\underline{s} + \frac{-223244+149127\sqrt{2}}{576(-2088+1489\sqrt{2})}t$ and $SS^{0B}|_{\Delta=2t} = v + \frac{1}{2}\underline{s} - \frac{107}{72}t$. A simple comparison shows that $CS^{BB}|_{\Delta=\hat{\Delta}} > CS^{mix}|_{\Delta=\overline{\Delta}} > CS^{0B}|_{\Delta=2t}$ for any $t \in (0,1)$. ■

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