

ESSAYS IN INDUSTRIAL ORGANIZATION

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A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Economics – Doctor of Philosophy

2018

ABSTRACT

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The first essay "Tying and Platforms' R&D Incentives in Two-sided markets" analyzes how the tying arrangements can affect platforms' R&D incentives in two-sided markets under the possibility of multi-homing. The model shows that when all consumers single-home, the tying distorts platforms' R&D incentives because the tying acts as a commitment device to invest aggressively in R&D, leading to rival firm being foreclosed in the R&D decision stage even if the tying does not have exclusionary effect in the price competition. However, when exclusive contents are offered to each platform so that some of the consumers can engage in multi-homing, the tying raises the rival firm's R&D incentives as well as the tying firm's R&D incentives. This is because i) tying induces more consumers to multi-home so that total demand of consumers for both platforms can be increased and ii) the strategic effect in R&D competition disappears in the multi-homing case on the consumer side, implying that the rival firm's R&D incentives is not affected by more aggressive R&D investment of tying firm. Thus, the anti-competitiveness of tying involved with innovation can vary depending on the possibility of consumer's multi-homing.

The second essay "Information Sharing and R&D Incentives" investigates how sharing of cost information affects firms' incentives to invest in cost reduction and the role of the observability of rivals' R&D investment level. I study duopoly price competition with cost reducing R&D in three cases: the complete information case, unobservable investment case and observable investment case. The opponents' cost information is unknown in both the unobservable investment case and the observable investment case, but the investment level is unobservable and observable, respectively. I find that firms have identical incentives of investment in the complete information and the unobservable investment case, whereas they will tend to underinvest in cost reduction when the investment level is observable because a negative strategic effect makes investment less profitable. Due to this underinvestment, welfare and the consumer surplus decrease in the

observable investment case. These results have implications for the analysis of information sharing in markets where cost reduction activities are important.

The third essay "The Grandfather of Price Discrimination", coauthored with Brady Vaughan and Aleks Yankelevich, examines firms' motivations for implementing grandfather clauses that allow certain consumers to continue access to a service at a favorable, but no longer available price. We find that when consumers are fully cognizant of their valuations for available product alternatives, firms are typically better off offering all potential consumers the optimal uniform price. However, if grandfathered consumers are made complacent, failing to reevaluate the service over time, grandfather clauses may permit firms to profitably price discriminate between early adopters and new consumers in exchange for forfeiting the right to optimally set prices for early adopters.

ACKNOWLEDGEMENTS

It would not have been possible to write this doctoral thesis without the help and support of my advisors, committee members, and family.

Above all, I would like to thank my co-advisors, Prof. Jay Pil Choi and Prof. Thomas Jeitschko for their help, support, and patience. Despite all of my weaknesses, they have guided me with invaluable advice and persistent support throughout the graduate studies. I am also grateful to other members of my dissertation committee. Prof. Christian Ahlin has always given kind and detailed comments and the passionate guidance and help of Dr. Aleks Yankelevich has been invaluable.

I would like to thank to the academic, financial and technical support of the department of Economics in Michigan State University and its staffs, Lori Jean Nichols and Margaret Lynch for their friendly support.

Last but by no means least, I would like to thank my family. I am indebted to My parents, Sangmin Kim and Eunyoung Jung for their endless and unconditional love. Also my gratitude goes to my wife, Eunsun So and my son, Aaron. They are a source of motivation and encouragement throughout my grad studies. I could finish all process of this dissertation with their love and sacrifice.

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CHAPTER 1

TYING AND PLATFORMS' R&D INCENTIVES IN TWO-SIDED MARKETS

1.1 Introduction

This paper analyzes the effect of tying arrangements on platforms' R&D competition as well as price competition and social welfare in two-sided markets. Especially, I analyze how the effect of tying arrangements on platforms' R&D competition can vary across the possibility of multi-homing; that is, some of the consumers have an incentive to join multiple platforms in order to enjoy more indirect network externalities. The motivation of this analysis is particularly antitrust cases involving tying, from Microsoft to Google. Recently, Yandex, the largest search engine company in Russia, has opened the case against Google, claiming the violation of antitrust law. Yandex alleges that Google has been inhibiting smartphone manufacturers from preinstalling other competing applications in handheld devices that use Google's Android. The lawsuit explains that if smartphone manufacturers choose to preinstall other applications, instead of one of Google's applications, say YouTube, they cannot load any of Google's applications, such as Google Search and Google Maps. That is, Google has been offering all or nothing option to smartphone manufacturers and this kind of contract might be seen as a de facto tying of its applications to Android.

Google's current practice is in many ways similar to Microsoft's strategies in the late 1990s and early 2000s; especially to tying Window Media Player with its Windows operating system. Firstly, both cases concern tying in high-tech sectors where products are frequently altered and the boundaries of markets are constantly changing. Dynamic aspects are very important in high-tech sectors; one of main arguments of both plaintiff and defendant in the antitrust cases is the effect of tying on innovation. Plaintiffs claimed that tying would stifle innovation in the tied good market as it gives competitors lower incentives to innovate, while defendants argued that tying itself is a way of innovation as it improves the value of tying product to consumers and to makers of complementary goods. This debate shows that innovation plays a key role in the antitrust cases regarding tying.

Secondly, the markets of bundled product are characterized by two- sidedness, where the two sides of the market are content providers on one side and consumers on the other side. This market is characterized by indirect network externalities between two sides of the market. The utility of agents on each side depends on the number of agents on the other side. Since two types of agents participate and interact in platforms, platforms charge two prices, one on each side. According to Rochet and Tirole (2006), “the market is said to be two-sided if the volume of transaction varies with not only the overall price level but also the price structure.” Especially, one important factor when analyzing the effect of tying in two-sided markets is whether consumers single-home or multi-home. Multi-homing in the case of consumers of media players means that consumers use more than one media player and multi- homing in the case of content providers means that content providers encode their media content in several formats and offer to more than one media player. This multi-homing insures against a tipping in the market, which is a typical concern of antitrust authorities in tying issues. Moreover, Tirole (2005) concludes that if the costs of multi-homing on the tying side of the market are small, tying might induce more agents to multi-home. The literature on two-sided markets has shown that the standard economic models used in antitrust analysis often yield incorrect results and implications when applying them to two-sided markets. Thus, antitrust authorities should care about how the results from traditional economic models can vary in the two-sided market context.

In light of these distinguishing features of recent antitrust issues regarding tying, I investigate how the economic theory held in the traditional one-sided market can vary in a two-sided market context. In this paper, I examine how the effect of tying on platforms’ incentives to invest in R&D depends on the possibility of multi-homing on the consumer side. More specifically, I analyze the interaction between the price competition and R&D competition as in Choi (2004). I show that when all consumers single-home, the tying distorts platforms’ R&D incentives because the tying acts as a commitment device to invest aggressively in R&D, leading to rival firm being foreclosed in the R&D decision stage even if the tying does not have exclusionary effect in the price competition. However, when exclusive contents are offered to each platform so that some of the consumers can

engage in multi-homing, the tying can raise the rival firm's R&D incentives as well as the tying firm's R&D incentives. This is because i) tying induces more consumers to multi-home so that total demand of consumers for both platforms can be increased and ii) the strategic effect in R&D competition disappears in the multi-homing case on the consumer side, implying that the rival firm's R&D incentives is not affected by more aggressive R&D investment of tying firm. Thus, the anti-competitiveness of tying involved with innovation can vary depending on the possibility of multi-homing.

Choi (2004) shows that tying can lower the rival firm's incentives to invest and innovate when considering R&D incentives of the tying firm and the rival firm in the tied good market. The model demonstrates that tying distorts each firm's R&D incentives due to the strategic effect of the R&D competition; the tying firm's R&D investment level increases while the rival firm's R&D investment level decreases with tying. It might induce the rival firm's foreclosure with R&D competition even when it is not foreclosed in the absence of R&D competition. This effect lends weight to the argument that tying by the monopolist can stifle the rival firm's innovation incentives in the tied good market. Moreover, in the model, tying can be a profitable strategy even if the rival firm is not foreclosed with the R&D competition. It is analogous to the result in the case of the single-homing in my model. Nevertheless, I extend the mechanism to the multi-homing case, and it becomes a different story.

Choi and Stefanadis (2001) also show that tying can discourage the rival firm's R&D investment by analyzing how tying can protect the incumbent's position in the market. The model assumes that the success of stochastic R&D investment is required for potential entrants to enter the market. When the incumbent monopolist of two complementary products ties, the potential entrant in each market can enter the market only if the both entrants have to succeed in innovation. Thus, tying lowers incentives for investment and innovation of potential entrants. This model, however, focuses on the situations where one firm has monopoly power in both of two complementary goods markets whereas my model deals with the cases where one of the competing platforms is the monopolist in another market. In addition, in their paper, the success in innovation in two complementary markets

is assumed to be stochastic depending on its initial R&D investment while my model assumes that R&D outcomes in the tied good market are deterministic.

Despite the importance of innovation in high-tech sectors where two-sidedness is prevalent, the changes in platforms' incentives to invest in R&D when tying is practiced have not been analyzed before. Hagiu (2007), Belleamme and Peitz (2010), Zhao (2010), and Lin, Li, and Whinston (2011) investigate sellers' (content providers in this paper) incentives to invest in the quality of the products they sell, rather than in the platform. Casadesus and Llanes(2012) study incentives to invest in the platform's quality, but their focus is on the comparison between open-source platforms and proprietary platforms.

This paper is also related to the leverage theory of tying. Traditionally antitrust authorities had regarded tying as anti-competitive; they have mainly been concerned about the leverage effect of tying, implying that the monopolist in one market might have incentive to bundle its good to unrelated product in order to monopolize the market. While the leverage theory has been used as the ground rule in many juridical decisions since its advent as an informal concept in the law literature, it has faced heavy and influential criticism from a number of economists. According to standard economic theory argued by the Chicago school, tying would not be a profitable strategy for the monopolist if the monopolist tries to exclude rival firms from the complementary market. They explicitly show that the tying firm can obtain higher profits under separate selling if rival firms are more efficient. But from the early 1990s, the leverage theory of tying has been resurrected in many economics literatures. Whinston (1990) shows that tying can be a profitable strategy for the monopolist as tying has the exclusionary effect if the tied good market is oligopoly and characterized by economies of scale.

Li (2009) studies about tying of independent products in two-sided markets. The model concludes that tying of the CD and the magazine can be a profitable strategy for the monopolist. If the positive network externality that magazine readers exert on advertisers is large, prices are strategic substitutes. This means that the competing platform increases its price in reaction to more aggressive pricing behavior of the tying platform, implying that more magazine readers choose the

tying platform. Then, tying may be profitable strategy if gains in the magazine market outweigh losses in the CD market. Li (2009), however, considers the magazine market where there exists only one-side network externality and the model does not allow the possibility of multi-homing on the consumer's side.

Choi (2010) is closely related to this paper; he investigates the effect of tying of two complementary goods on platforms' competition and social welfare. Furthermore, the model allows consumers on both sides to multi-home. Choi (2010) creates incentives for consumers to multi-home by assuming that there exists exclusive content for each platform. In the model, if the monopolist ties the two products and captures the tied good market, the number of multi-homers on the consumer's side increases relative to the no-tying case. Given that the monopolist charges its price so that every consumer will purchase the bundle, tying is a profit-maximizing strategy. In addition, social welfare increases under tying in the model due to the increase in the number of multi-homers. However, the model is concerned only with pricing implications of tying, not with dynamic aspects in the markets.

Amelio and Jullien (2010) are also worth mentioning in relation to this paper. They analyze the rationale for bundling, especially mixed bundling, in the monopoly and duopoly context, when platforms are constrained to set non-negative prices. In the model, bundling can be a tool to introduce implicit subsidies between bundling and bundled products and hence relax the non-negativity constraints. They show that the effect on social welfare depends on the degree of asymmetry in network externalities between two sides. In the case of symmetric network externalities, for example, profits of both platforms increase under bundling while consumer surplus and social welfare decrease. However, Amelio and Jullien (2010) mainly deal with mixed bundling and hence illustrate price discrimination implemented through bundling.

The remainder of the paper is organized as follows. In section 1.2, I set up a basic model of tying in two-sided markets in the absence of consumer's multi-homing. Section 1.3 extends the analysis by allowing multi-homing. In each section, the role of tying in the R&D competition and welfare implications are discussed. Conclusion follows in Section 1.4.

1.2 Tying in Two-sided Markets with Single-Homing

The model I lay out in this paper is an extension of the model presented in Choi (2004) and Choi et al (2017). In this paper, I analyze R&D competition and price competition between two platforms when one platform ties the platform with unrelated monopoly product. As in Choi (2004), I focus on tying of independent products in order to avoid multiple equilibria problem. If one of producers is a monopolist for one of the products, price competition with complementary goods yields multiple price equilibria because the monopolist practices a price squeeze, depending on the degree of price squeeze practiced by the monopolist. As Choi (2004) points out, however, once the degree of price squeeze is assumed, the analysis and implication of this model can carry over to the case of complementary products.

Suppose that there are two symmetric platforms, $i = A, B$. Platforms deal with two distinct groups of agents; consumers on side 1 and content providers on side 2. These two groups of agents wish to interact on the platform and platforms coordinate the possible matches between the two groups. Platforms compete for market share in each agent group and charge prices p_1^i and p_2^i to consumers and content providers respectively with $i = A, B$. I further assume that marginal costs of serving another consumer and content provider are c_1 and c_2 respectively. N_1^i is the number of consumers participating in platform i , and N_2^i is the number of content providers on platform i .

In order to analyze consumers' choice of platform, I adopt a Hotelling model of horizontal product differentiation. Platforms are located at the endpoints of the Hotelling line, that is platform A is located at 0 and platform B is located at 1. Consumers are uniformly distributed on the interval $[0, 1]$. The utility that a consumer derives from participating in a platform depends on the number of content providers in the platform. Consumers obtain additional utility α_1 from each additional content provider. The utility of a consumer who is located at x from joining platform A is given by

$$u^A = \alpha_1 N_2^A - p_1^A - tx \quad (1.1)$$

where t is the transportation costs in order to reach platform i . Similarly, the utility of a consumer

who is located at x from joining platform B is given by

$$u^B = \alpha_1 N_2^B - p_1^B - t(1 - x) \quad (1.2)$$

I assume that content providers view the platforms as homogenous as in Armstrong and Wright (2007). The potential number of content providers is normalized to 1. Fixed costs for producing content are considered to be zero. Content providers obtain additional profits α_2 from each additional consumer who has access to their content. Profits for a content provider participating in platform i are hence given by $\alpha_2 N_1^i - p_2^i$. A content provider is willing to participate in platform i if $\alpha_2 N_1^i - p_2^i \geq 0$.

In this section, I focus on the single-homing case where all consumers single-home and this gives an incentive for sellers to multi-home given no fixed costs for producing content. Thus, as in “competitive bottleneck” equilibria in Armstrong and Wright (2007), the consumer side completely single-homes while the content provider side completely multi-homes.

In order to analyze the effects of tying on platform competition in two-sided markets, assume that the platform A is the monopolist for the product M with unit production cost of c_M . All consumers have valuation of v_M , which is greater than c_M , for the product M. I further assume that entry to market M is not feasible.

I analyze the following four-stage game in order to introduce the R&D investment in the platform competition. In the first stage, platform A decides whether to tie. In the second stage, the two firms engage in R&D activities for reducing the marginal cost. I assume that platform i can reduce c_1 by Δ^i with the investment costs of $I(\Delta^i)$, implying that the R&D outcomes are deterministic as long as platforms make an investment. The cost function of R&D investment, $I(\cdot)$, is characterized by $I'(\cdot)$ and $I'' > 0$. In the third stage, platforms set simultaneously their prices p_1^A and p_1^B on the consumer side and consumers decide which platform they would join. In the fourth stage, platforms set their prices p_2^A and p_2^B on the provider side and content providers decide which platform they would join. To focus on the impact of tying arrangements on R&D competition on the consumer side, I ignore the possibility of R&D activities in the market M as well as on the content provider side.

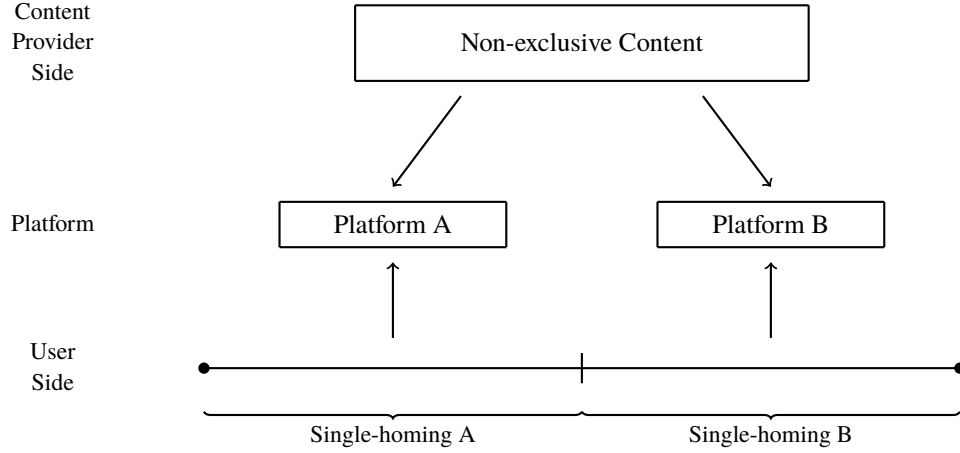


Figure 1.1: Two-sided Market with Single-homing on the Consumer Side

1.2.1 Platform Competition without Tying

If the two products, the platform and the product M , are not bundled, they can be analyzed separately. Given that all consumers have valuation of v_M for the product M , platform A can charge v_M for the product M and hence have profits of $v_M - c_M \equiv s_M$.

From the participation constraints for content providers, we have $N_2^i = 1$ as long as platform i charge the price $p_2^i \leq \alpha_2 N_1^i$. In platform competition on the consumer side, we have the Hotelling type competition. We can derive the number of consumers in platform i by considering the utility of consumers from joining each platform given above.

$$N_1^i = \frac{1}{2} + \frac{p_1^j - p_1^i}{2t} \quad (1.3)$$

Given that Δ^A , Δ^B , and the rival firm's price p_1^j , platform i chooses p_1^i to maximize its profits in the third stage.

$$\max_{p_1^i} (p_1^i - c_1 + \Delta^i) N_1^i + \alpha N_1^i - c_2 - I(\Delta^i) \quad (1.4)$$

The first order condition for platform i is given by

$$p_1^i = R_1^i(p_1^j; \Delta^i) = \frac{1}{2}(p_1^j + c_1 - \Delta^i + t - \alpha_2) \quad (1.5)$$

In Nash equilibrium, prices for platform i on each side are given by

$$\begin{aligned} p_1^{i*}(\Delta^i, \Delta^j) &= c_1 + t - \alpha_2 - \frac{2}{3}\Delta^i - \frac{1}{3}\Delta^j \\ p_2^{i*}(\Delta^i, \Delta^j) &= \alpha_2 \left(\frac{1}{2} + \frac{\Delta^i - \Delta^j}{6t} \right) \end{aligned} \quad (1.6)$$

The number of consumers joining in platform i can be written as

$$N_1^i(\Delta^i, \Delta^j) = \frac{1}{2} + \frac{\Delta^i - \Delta^j}{6t} \quad (1.7)$$

Therefore, in the second stage, platform i chooses Δ^i to maximize

$$\max_{\Delta^i} \left(t - \alpha_2 + \frac{\Delta^i - \Delta^j}{3} \right) \left(\frac{1}{2} + \frac{\Delta^i - \Delta^j}{6t} \right) + \alpha_2 \left(\frac{1}{2} + \frac{\Delta^i - \Delta^j}{6t} \right) - c_2 - I(\Delta^i) \quad (1.8)$$

The first order condition in the second stage is given by

$$I'(\Delta^i) = \frac{1}{3} + \frac{\Delta^i - \Delta^j}{9t} \quad (1.9)$$

From (1.9), we can derive the reaction function of the platform i in the R&D competition, denoted as $\Delta^i = \rho^i(\Delta^j)$. For the second order conditions for the platform's maximization problem to be satisfied, I assume that $\frac{1}{9t} - I''(\Delta^i) < 0$. In this model, cost reducing R&D activities by two competing platform have the strategic effect. We can see the strategic effect between platforms' R&D investments by totally differentiating (1.9).

$$\rho^{i'}(\Delta^j) = \left\{ 1 - \frac{1}{9t} I''(\Delta^i) \right\}^{-1} \quad (1.10)$$

which has a negative value. This implies that R&D activities of two platforms are strategic substitutes. I also assume that $|\rho^{i'}(\Delta^j)| < 1$, or $I''(\Delta^j) > \frac{2}{9t}$ for ensuring the stability of the Nash equilibrium. In symmetric equilibrium in the R&D stage, the optimal level of investment is given by $\Delta^{A*} = \Delta^{B*} = \Delta^*$ where $I'(\Delta^*) = \frac{1}{3}$.

1.2.2 Platform Competition with Tying

Under tying, platform A ties the sale of the platform and the product M and sells them for a price $\tilde{p}_1^A$.¹ In this case, consumers have two options; to purchase the bundle from platform A at the price

¹Variables corresponding to tying are denoted with a tilde.

of $\tilde{p}_1^A$, or to subscribe to platform B only. In the Hotelling line, we can derive the point $\tilde{x}$ where a consumer who is indifferent between two options is located by the following equation.

$$v_M + \alpha_1 \tilde{N}_2^A - \tilde{p}_1^A - t\tilde{x} = \alpha_1 \tilde{N}_2^B - \tilde{p}_1^B - t(1 - \tilde{x}) \quad (1.11)$$

We can derive the number of consumers joining in each platform.

$$\begin{aligned} \tilde{N}_1^A &= \frac{1}{2} + \frac{v_M + \tilde{p}_1^B - \tilde{p}_1^A}{2t} \\ \tilde{N}_1^B &= \frac{1}{2} - \frac{v_M + \tilde{p}_1^B - \tilde{p}_1^A}{2t} \end{aligned} \quad (1.12)$$

Substituting the number of consumers into each platform's profit function and maximizing with respect to $\tilde{p}_1^A$ and $\tilde{p}_1^B$, respectively, yield the following reaction function in the second stage.

$$\begin{aligned} \tilde{p}_1^A &= R_1^A(\tilde{p}_1^B; \tilde{\Delta}^A) = \frac{1}{2}(\tilde{p}_1^B + v_M + c_M + c_1 - \tilde{\Delta}^A + t - \alpha_2) \\ \tilde{p}_1^B &= R_1^B(\tilde{p}_1^A; \tilde{\Delta}^B) = \frac{1}{2}(\tilde{p}_1^A - v_M + c_1 - \tilde{\Delta}^B + t - \alpha_2) \end{aligned} \quad (1.13)$$

Then, the Nash equilibrium prices with tying and corresponding demand equations on the consumer side are given by

$$\begin{aligned} \tilde{p}_1^{A*} &= c_1 + t - \alpha_2 + \frac{1}{3}v_M + \frac{2}{3}c_M - \frac{2}{3}\tilde{\Delta}^A - \frac{1}{3}\tilde{\Delta}^B \\ \tilde{p}_1^{B*} &= c_1 + t - \alpha_2 - \frac{1}{3}v_M + \frac{1}{3}c_M - \frac{1}{3}\tilde{\Delta}^A - \frac{2}{3}\tilde{\Delta}^B \\ \tilde{p}_2^{A*} &= \alpha_2 \left(\frac{1}{2} + \frac{s_M + \tilde{\Delta}^A - \tilde{\Delta}^B}{6t} \right) \\ \tilde{p}_2^{B*} &= \alpha_2 \left(\frac{1}{2} - \frac{s_M + \tilde{\Delta}^A - \tilde{\Delta}^B}{6t} \right) \\ \tilde{N}_1^{A*} &= \frac{1}{2} + \frac{s_M + \tilde{\Delta}^A - \tilde{\Delta}^B}{6t} \\ \tilde{N}_1^{B*} &= \frac{1}{2} - \frac{s_M + \tilde{\Delta}^A - \tilde{\Delta}^B}{6t} \end{aligned} \quad (1.14)$$

Note that in the absence of R&D investment, platform B is driven out from the market if $s_M > 3t$. To emphasize the role of R&D competition under tying, I assume that $s_M < 3t$ to ensure that platform B does not exit from the market after tying.

In the second stage, platform A chooses $\tilde{\Delta}^A$ to maximize its profits.

$$\max_{\tilde{\Delta}^A} \left(t + \frac{s_M + \tilde{\Delta}^A - \tilde{\Delta}^B}{3} \right) \left(\frac{1}{2} + \frac{s_M + \tilde{\Delta}^A - \tilde{\Delta}^B}{6t} \right) - c_2 - I(\tilde{\Delta}^A) \quad (1.15)$$

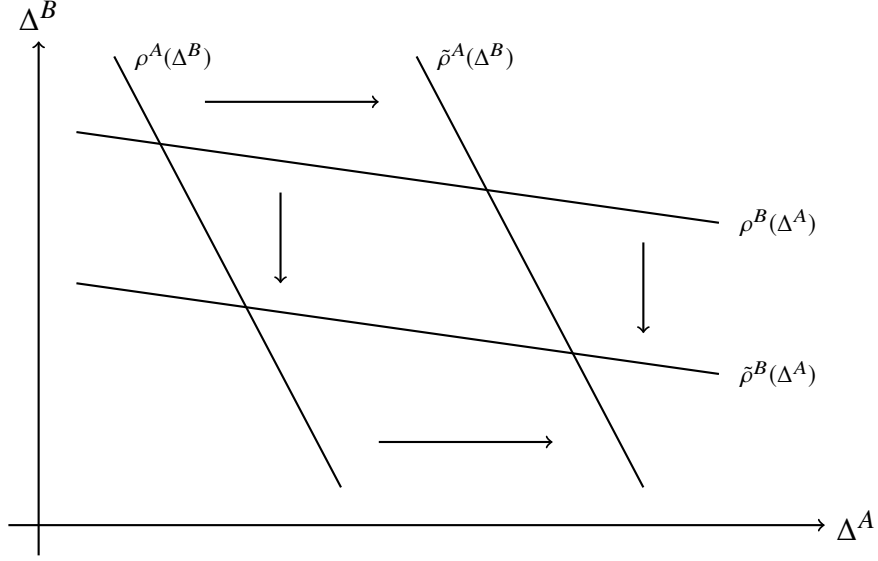


Figure 1.2: Equilibrium in R&D Investment with Single-homing

The first order condition in the second stage is given by

$$I'(\tilde{\Delta}^A) = \frac{1}{3} + \frac{s_M}{9t} + \frac{\tilde{\Delta}^A - \tilde{\Delta}^B}{9t} \quad (1.16)$$

Similarly, we have the optimal level of R&D investment for platform B.

$$I'(\tilde{\Delta}^B) = \frac{1}{3} - \frac{s_M}{9t} + \frac{\tilde{\Delta}^A - \tilde{\Delta}^B}{9t} \quad (1.17)$$

Equation (1.16) and (1.17) give each platform's reaction function in the second stage with tying, denoted as $\tilde{\Delta}^i = \tilde{\rho}^i(\tilde{\Delta}^j)$. When comparing equation (1.16) and (1.17) to equation (1.9), the assumptions on the cost structure of R&D investment, $I'(\cdot) > 0$ and $I''(\cdot) > 0$, allow us to verify easily that $\tilde{\Delta}^A > \Delta^A$ whereas $\tilde{\Delta}^B < \Delta^B$ for any given level of the rival firm's R&D investment.

Proposition 1.1. *Suppose that all consumers join a single platform. If firm A decides to tie, firm A's R&D investment level increases while firm B's R&D investment level decreases under tying.*

Figure 1.2 shows that platform A's reaction function $\tilde{\rho}^A(\tilde{\Delta}^B)$ shifts outwards while platform B's reaction function $\tilde{\rho}^B(\tilde{\Delta}^A)$ shifts inwards. The reason why tying firm's R&D incentives increase while rival firm's incentive decrease with tying is that R&D incentives in this model depend on the market share. The platform can spread out the R&D costs over more consumers as its market

share increases. As shown in equation (1.14), $\tilde{N}_1^{A*}$ increases but $\tilde{N}_1^{B*}$ decreases under tying. In this context, tying distorts R&D incentives of two competing platforms. Thus, when considering R&D competition prior to price competition to allow platforms to benefit from dynamic rent, tying arrangements might yield additional anti-competitive effects.

In the first stage, platform A decides whether to tie, comparing its profits with tying and without tying. I assume that the cost function of R&D is given by $I(\Delta) = \frac{k}{2}\Delta^2$, where k stands for the R&D cost parameter. This specific cost function of R&D gives us the closed-form solutions for the optimal level of R&D investment as well as platform's profit-maximizing prices. In the case of no tying, the optimal level of R&D investment for each platform is given by

$$\Delta^{A*} = \Delta^{B*} = \Delta^* = \frac{1}{3k} \quad (1.18)$$

The equilibrium profit for platform A is

$$\Pi^A = s_M + \frac{t}{2} - c_2 - \frac{1}{18k} \quad (1.19)$$

In the case of tying, the optimal levels of R&D investment for platform A and B are given by

$$\begin{aligned} \tilde{\Delta}^{A*} &= \frac{1}{3k} + \frac{s_M}{9tk - 2} \\ \tilde{\Delta}^{B*} &= \frac{1}{3k} - \frac{s_M}{9tk - 2} \end{aligned} \quad (1.20)$$

By substituting (1.20) with (1.14), we have

$$\begin{aligned} \tilde{p}_1^{A*} &= c_1 + t - \alpha_2 + c_M - \tilde{\Delta}^{A*} + \frac{1}{3}s_M + \frac{2s_M}{3(9tk - 2)} \\ \tilde{p}_1^{B*} &= c_1 + t - \alpha_2 - \tilde{\Delta}^{B*} - \frac{1}{3}s_M - \frac{2s_M}{3(9tk - 2)} \\ \tilde{p}_2^{A*} &= \alpha_2 \left(\frac{1}{2} + \frac{s_M}{6t} + \frac{s_M}{3t(9tk - 2)} \right) \\ \tilde{p}_2^{B*} &= \alpha_2 \left(\frac{1}{2} - \frac{s_M}{6t} - \frac{s_M}{3t(9tk - 2)} \right) \\ \tilde{N}_1^{A*} &= \frac{1}{2} + \frac{s_M}{6t} + \frac{s_M}{2t(9tk - 2)} \\ \tilde{N}_1^{B*} &= \frac{1}{2} - \frac{s_M}{6t} - \frac{s_M}{2t(9tk - 2)} \end{aligned} \quad (1.21)$$

I assumed that $s_M < 3t$ to ensure that platform B does not exit from the market after tying in the absence of R&D competition. If $\tilde{N}_1^{B*}$, or $3t - \frac{2}{3k} < s_M < 3t$, however, platform B is foreclosed

with R&D competition even in the case that it is not in the absence of R&D competition. This illustrates one of the potential anti-competitive effects of tying on platform competitions.

Since the model is set up based on Hotelling type platform competition on the consumer side and quadratic R&D cost function, the sum of two platforms' R&D investment is always equal to $\frac{2}{3k}$.

The equilibrium profit with tying for platform A is given by

$$\tilde{\Pi}^A = \frac{t}{2} + \frac{1}{3} \left(s_M + \frac{2s_M}{9tk-2} \right) + \frac{1}{18t} \left(s_M + \frac{2s_M}{9tk-2} \right)^2 - c_2 - \frac{k}{2} \left(\frac{1}{3k} + \frac{s_M}{9tk-2} \right)^2 \quad (1.22)$$

Platform A chooses to tie if either tying itself is profitable ($\tilde{\Pi}^A > \pi^A$), or tying gives rise to the exclusion of rival firm in R&D competition ($3t - \frac{2}{3k} < s_M < 3t$). One interesting fact is that, as pointed out in Choi (2004), the profitability of tying can be achieved even without the exclusionary effect.

1.2.3 Welfare Analysis

In this section, I analyze social welfare implications of tying. Social welfare without tying can be written as

$$W = s_M + (\alpha_1 - c_1) + (\alpha_2 - c_2) + \left\{ (N_1^{A*} \Delta_1^{A*} + N_1^{B*} \Delta_1^{B*}) - \frac{k}{2} [(\Delta^{A*})^2 + (\Delta^{B*})^2] \right\} - \left\{ \int_0^{N_1^{A*}} t x dx + \int_0^{N_1^{B*}} t x dx \right\} \quad (1.23)$$

Social welfare with tying can be written as

$$\tilde{W} = s_M \tilde{N}_1^{A*} + (\alpha_1 - c_1) + (\alpha_2 - c_2) + \left\{ (\tilde{N}_1^{A*} \tilde{\Delta}_1^{A*} + \tilde{N}_1^{B*} \tilde{\Delta}_1^{B*}) - \frac{k}{2} [(\tilde{\Delta}^{A*})^2 + (\tilde{\Delta}^{B*})^2] \right\} - \left\{ \int_0^{\tilde{N}_1^{A*}} t x dx + \int_0^{\tilde{N}_1^{B*}} t x dx \right\} \quad (1.24)$$

If we substitute $(\alpha_1 - c_1) + (\alpha_2 - c_2)$ by $(v_B - c_B)$, expressions above are exactly the same as in Choi (2004). He explicitly shows that $\tilde{W} < W$ unambiguously.

Proposition 1.2. *Social welfare decreases with tying when all consumers join a single platform.*

There are several reasons of this strong implication. First, asymmetric demand on each platform causes the increase in the total transportation in the Hotelling type competition. Second, as shown above, the sum of R&D investment of two platforms are constant. This implies that the distortion effect of tying on R&D investment reduces the net benefit from innovation in the market. The terms in the curly brackets in (1.23) and (1.24) represent the dynamic rents from R&D stage. We can easily check that the dynamic rents from R&D are maximized under the symmetric R&D investment. This shows a direct negative effect of tying on innovation. Lastly, some of the consumers do not choose to buy the bundled product under tying, leading to the loss of s_M .

The result in this section is the same as in Choi (2004) because if we focus on single-homing case on the consumer side in addition to no product differentiation case on the content provider side, “competitive bottleneck” equilibrium would occur and hence the platform’s maximization problem boils down to the same as in the one-sided market. This leads to same welfare implications as well as R&D investment and prices decisions of each platform.

In sum, I apply the model in Choi (2004) to the two-sided market setting and verify that the results in Choi (2004) are robust to the introduction of the two-sidedness. It shows that tying can have an anti-competitive effect that many antitrust authorities have concerned; it reduces the rival firm’s incentives to invest in R&D while strengthens the tying firm’s R&D incentives. In this section, however, I focus on the single-homing case where all consumers join in only one platform. But in reality, especially in media content markets or smartphone application markets, multi-homing equilibrium is commonly observed. Thus, I will modify the analysis to reflect this reality in the next section.

1.3 Tying in Two-sided Markets with Multi-homing

In this section, I extend the analysis of tying to the multi-homing case. As mentioned above, in the media content markets, many consumers have or subscribe to several platforms and many content providers provide multiple platforms with their content. In section 2, I assumed that

content providers regard platforms as homogenous while consumers view them as differentiated. This assumption yields a typical “competitive bottleneck” equilibrium; all consumers single-home whereas all content providers multi-home. Given that all content providers multi-home, however, consumers have no incentive to join in multiple platforms because they can meet and interact with all content providers once they subscribe to one platform. But if each platform deals with exclusive content, some of the consumers are willing to join in more than one platform to enjoy the exclusive content so that multi-homing equilibrium can occur.

As in Choi (2010), in order to introduce the possibility of multi-homing on the consumer side, I assume that there are two types of content; exclusive and non-exclusive content. $\lambda \in [0, 1]$ is defined as the amount of exclusive content available on each platform and hence $1 - \lambda$ is the amount of non-exclusive content which is available for both platforms. Let me assume that λ is exogenously given. This assumption can be justified by the fact that some content is more suitable for the specific platform while other content is easily made compatible with both platforms for technical reasons. For example, some platforms are able to support high-definition multimedia content whereas other platforms are not. Multi-homing on the content provider side in setting means that some of the non-exclusive content providers choose to offer both platforms with their content.

As in section 1.2, I assume that the cost function of R&D investment is given by $I(\Delta) = \frac{k}{2}\Delta^2$, where k stands for the R&D cost parameter. In addition, for the expositional simplicity, let me assume $c_2 = 0$ in this section.

1.3.1 Platform Competition without Tying

Since I focus on the multi-homing equilibrium on both sides, let me first assume that non-exclusive content providers multi-home and I will derive the condition for this to hold later in A1. Under this assumption, each platform has exclusive content of λ and non-exclusive content of $1 - \lambda$ available. It means that the total number of content available when users multi-home is $1 + \lambda$.

The utility of a consumer who is located at x from joining platform A and platform B is the same as (1.1) and (1.2), respectively with $N_2^A = N_2^B = 1$. In addition, the utility of a consumer who

is located at x from multi-homing can be written as

$$u^{AB} = \alpha_1(1 + \lambda) - p_1^A - p_1^B - t \quad (1.25)$$

Equation (1.25) shows that given p_1^A and p_1^B , the utility of a multi-homer is the same regardless of her location. Then the location of a consumer who is indifferent between single-homing on A and multi-homing can be obtained as

$$x = 1 - \frac{\alpha_1 \lambda - p_1^B}{t} \quad (1.26)$$

Similarly, we can derive the location of a consumer who is indifferent between single-homing on B and multi-homing.

$$y = \frac{\alpha_1 \lambda - p_1^A}{t} \quad (1.27)$$

Let's denote n_1^A and n_1^m by the number of single-homers joining in platform i and the number of multi-homers, respectively, implying that $N_1^A = n_1^A + n_1^m$. Then, the number of agents participating in platform i is given by

$$\begin{aligned} n_1^i &= 1 - \frac{\alpha_1 \lambda - p_1^j}{t} \\ n_1^m &= \frac{2\alpha_1 \lambda - (p_1^i + p_1^j)}{t} - 1 \\ N_1^i &= \frac{\alpha_1 \lambda - p_1^i}{t} \end{aligned} \quad (1.28)$$

Comparing to the single-homing case, it is a noteworthy feature in multi-homing case that there is no interaction between optimal prices of two platforms on the consumer side anymore when the consumer's demand for each platform is determined. As we can see in equation (1.28), the total number of consumers subscribing to platform i , N_1^i , depends only on its own price while the number of single-homers on platform i , n_1^i , depends only on the rival's price. It implies that the total demand for platform i is determined by its price whereas the rival's price is a determinant for the proportion of multi-homers.

Next, I look at the incentives of content providers to participate in each platform. Since profits for a content provider participating in platform i are hence given by $\alpha_2 N_1^i - p_2^i$, an exclusive content

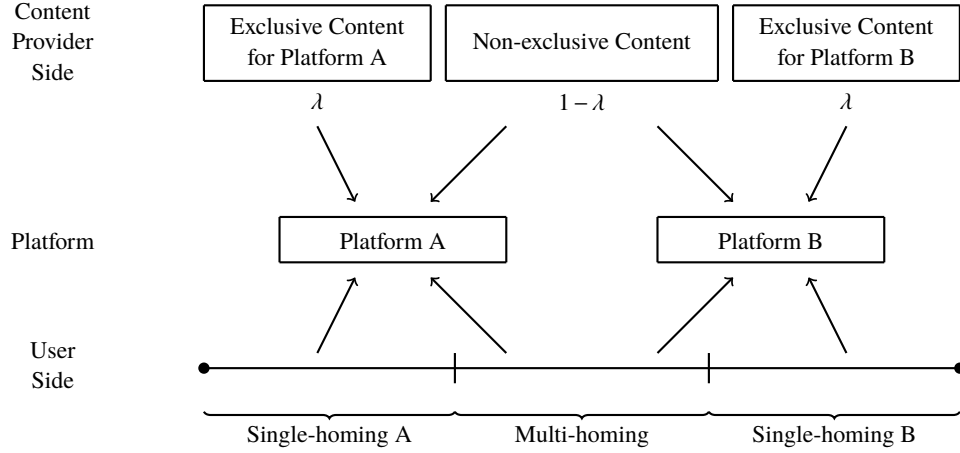


Figure 1.3: Two-sided Market with Multi-homing on Both Side

provider will participate in platform i if $\alpha_2 N_1^i - p_2^i \geq 0$. However, the incentives for non-exclusive content providers to provide platform i with their content depend on whether they already participate in platform j . If a non-exclusive provider already offers to platform j , she will provide to platform i as well only if $\alpha_2 n_1^i - p_2^i \geq 0$ due to the existence of multi-homers. If she has not provided to platform j , however, she would participate in platform i if $\alpha_2 N_1^i - p_2^i \geq 0$. Thus, platform i can attract both exclusive and non-exclusive content providers if it charges $p_2^i = \alpha_2 n_1^i$, or it can attract only exclusive content providers if it charges $p_2^i = \alpha_2 N_1^i$. Since I assumed that non-exclusive content providers multi-home, platform i will charge $p_2^i = \alpha_2 n_1^i$. Then, n_2^i , n_2^m , and N_2^i are given by

$$\begin{aligned}
 n_2^i &= \lambda \\
 n_2^m &= 1 - \lambda \\
 N_2^i &= 1
 \end{aligned} \tag{1.29}$$

Assumption 1. $\frac{\alpha_1 \lambda - c_1}{2} + \frac{1}{2k} + \frac{\lambda((2\alpha_1 + \alpha_2)\lambda - 2c_1)}{4} < t$

If $k > \frac{1}{\lambda(2(1-\lambda)\alpha_1 - \alpha_2\lambda) - 2(1-\lambda)c_1}$, the parameter space in which the multi-homing condition holds is non-empty. Assumption 1 ensures that serving both types of content providers is more profitable for each platform, which is derived in the Appendix A. In addition, it ensures that both x and y are located within Hotelling line. Assumption 2 guarantees the existence of multi-homers.

Assumption 2. $t < \alpha_1 \lambda - c_1$

Similarly to the analysis in section 1.2, given Δ^A , Δ^B , and the rival firm's price p_1^j , platform i chooses p_1^i to maximize its profit in the third stage.

$$\begin{aligned} & \max_{p_1^i, p_2^i} (p_1^i - c_1 + \Delta^i) N_1^i + p_2^i N_2^i - I(\Delta^i) \\ & = \max_{p_1^i} (p_1^i - c_1 + \Delta^i) \frac{\alpha_1 \lambda - p_1^i}{t} + \alpha_2 \left(1 - \frac{\alpha_1 \lambda - p_1^i}{t} \right) - I(\Delta^i) \end{aligned} \quad (1.30)$$

Then, the optimal prices for platform i on each side are given by

$$\begin{aligned} p_1^{i*}(\Delta^i) &= \frac{1}{2}(\alpha_1 \lambda + c_1 - \Delta^i) \\ p_2^{i*}(\Delta^j) &= \alpha_2 \left(1 - \frac{\alpha_1 \lambda - c_1 + \Delta^j}{2t} \right) \end{aligned} \quad (1.31)$$

The number of consumers joining in platform i can be rewritten as

$$\begin{aligned} n_1^i(\Delta^j) &= 1 - \frac{\alpha_1 \lambda - c_1 + \Delta^j}{2t} \\ n_1^m(\Delta^i, \Delta^j) &= \frac{2(\alpha_1 \lambda - c_1) + \Delta^i + \Delta^j}{2t} - 1 \\ N_1^i(\Delta^i) &= \frac{\alpha_1 \lambda - c_1 + \Delta^i}{2t} \end{aligned} \quad (1.32)$$

In the second stage, platform i chooses Δ^i to maximize its profits and the first order condition in the second stage is given by

$$I'(\Delta^i) = \frac{\alpha_1 \lambda - c_1 + \Delta^i}{2t} \quad (1.33)$$

Equation (1.33) shows that there is no strategic effect of R&D investment between two platforms anymore. In single-homing case, we already saw that R&D investment of two competing platforms are strategic substitutes; the increase in one platform's R&D investment leads to the decrease in the rival platform's R&D incentives. Contrary to the single-homing case, one platform's R&D investment does not affect the rival platform's incentives to invest in R&D.

1.3.2 Platform Competition with Tying

Under tying, platform A ties the sale of the platform and the product M and sells them for a price $\tilde{p}_1^A$. If platform A sells the bundled product, incentives for platform B to serve content providers

are changed. In the absence of tying, I assumed that it is more profitable for platforms to serve both exclusive and non-exclusive content providers. Under tying, however, serving both types of content providers cannot achieve equilibrium anymore. This is because under the condition in which serving both types of content providers brings more profits to platform B, tying cannot be a profitable strategy for platform A. I thus consider an equilibrium in which all non-exclusive content providers offer platform A with their content. Let me assume A3 for this equilibrium to be sustained.²

$$\text{A3} \quad s_M > 2t - \frac{1}{k} - (\alpha_1 \lambda - c_1) - \frac{\lambda[(2\alpha_1 + \alpha_2)\lambda - 2c_1]}{2}$$

In this equilibrium, platform i charges $\tilde{p}_2^i = \alpha_2 \tilde{N}_1^i$ and then, $\tilde{N}_2^i$ is given by

$$\begin{aligned} \tilde{N}_2^A &= 1 \\ \tilde{N}_2^B &= \lambda \end{aligned} \tag{1.34}$$

Let me denote the location of a consumer who is indifferent between single-homing on A and multi-homing under tying by $\tilde{x}$ and the location of a consumer who is indifferent between single-homing on B and multi-homing under tying by $\tilde{y}$. Then, $\tilde{x}$ and $\tilde{y}$ are given by

$$\begin{aligned} \tilde{x} &= 1 - \frac{\alpha_1 \lambda - \tilde{p}_1^B}{t} \\ \tilde{y} &= \frac{v_M + \alpha_1 - \tilde{p}_1^A}{t} \end{aligned} \tag{1.35}$$

Then, we have the number of consumers joining in each platform.

$$\begin{aligned} \tilde{n}_1^A &= 1 - \frac{\alpha_1 \lambda - \tilde{p}_1^B}{t} \\ \tilde{n}_1^B &= 1 - \frac{v_M + \alpha_1 - \tilde{p}_1^A}{t} \\ \tilde{N}_1^A &= \frac{v_M + \alpha_1 - \tilde{p}_1^A}{t} \\ \tilde{N}_1^B &= \frac{\alpha_1 \lambda - \tilde{p}_1^B}{t} \\ \tilde{n}_1^m &= \frac{v_M + \alpha_1(1 + \lambda) - \tilde{p}_1^A - \tilde{p}_1^B}{t} - 1 \end{aligned} \tag{1.36}$$

²The detailed derivation of A3 is in the Appendix A.

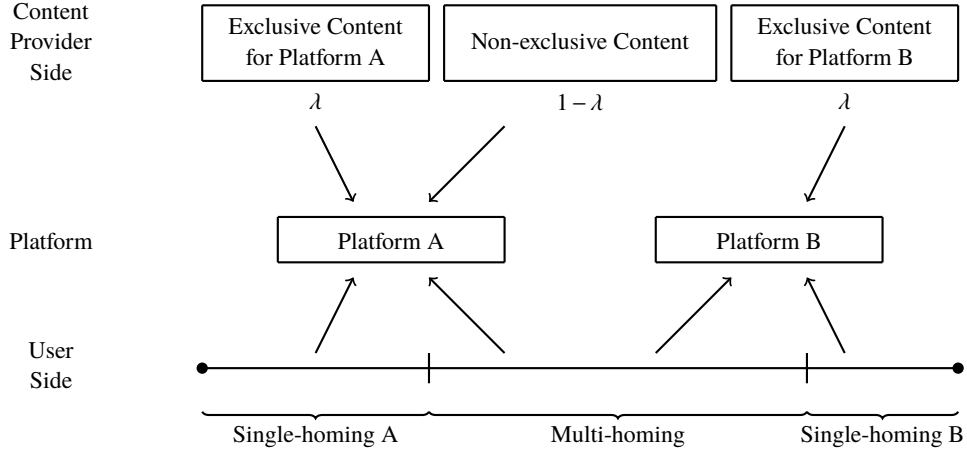


Figure 1.4: Two-sided Market with Multi-homing under Tying

Substituting the number of consumers into each platform's profit function and maximizing with respect to $\tilde{p}_1^A$ and $\tilde{p}_1^B$, respectively, yield the following optimal prices of each platform in the second stage.

$$\begin{aligned}
 \tilde{p}_1^{A*}(\tilde{\Delta}^A) &= \frac{1}{2}(v_M + c_M + \alpha_1 - \alpha_2 + c_1 - \tilde{\Delta}^A) \\
 \tilde{p}_1^{B*}(\tilde{\Delta}^A) &= \frac{1}{2}(\alpha_1\lambda - \alpha_2\lambda + c_1 - \tilde{\Delta}^B) \\
 \tilde{p}_2^{A*}(\tilde{\Delta}^B) &= \alpha_2 \left(\frac{s_M + \alpha_1 + \alpha_2 - c_1 + \tilde{\Delta}^A}{2t} \right) \\
 \tilde{p}_2^{B*}(\tilde{\Delta}^A) &= \alpha_2 \left(\frac{\alpha_1\lambda + \alpha_2\lambda - c_1 + \tilde{\Delta}^B}{2t} \right)
 \end{aligned} \tag{1.37}$$

The number of consumers participating in each platform can be rewritten as

$$\begin{aligned}
 \tilde{n}_1^A &= 1 - \frac{\alpha_1\lambda + \alpha_2\lambda - c_1 + \tilde{\Delta}^B}{2t} \\
 \tilde{n}_1^B &= 1 - \frac{s_M + \alpha_1 + \alpha_2 - c_1 + \tilde{\Delta}^A}{2t} \\
 \tilde{N}_1^A &= \frac{s_M + \alpha_1 + \alpha_2 - c_1 + \tilde{\Delta}^A}{2t} \\
 \tilde{N}_1^B &= \frac{\alpha_1\lambda + \alpha_2\lambda - c_1 + \tilde{\Delta}^B}{2t} \\
 \tilde{n}_1^m &= \frac{s_M + (\alpha_1 + \alpha_2)(1 + \lambda) - 2c_1 + \tilde{\Delta}^A + \tilde{\Delta}^B}{2t} - 1
 \end{aligned} \tag{1.38}$$

Solving the profit-maximizing problem with respect to Δ^i gives us the first order condition in

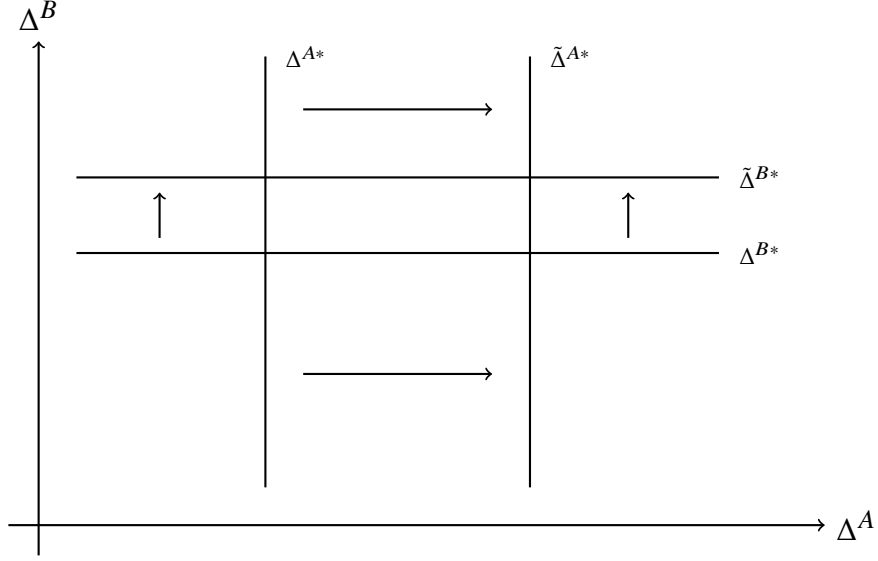


Figure 1.5: Equilibrium in R&D Investment with Multi-homing

the second stage for each platform.

$$\begin{aligned}
 I'(\tilde{\Delta}^A) &= \frac{s_M + \alpha_1 + \alpha_2 - c_1 + \tilde{\Delta}^A}{2t} \\
 I'(\tilde{\Delta}^B) &= \frac{\alpha_1 \lambda + \alpha_2 \lambda - c_1 + \tilde{\Delta}^B}{2t}
 \end{aligned} \tag{1.39}$$

Comparing equation (1.39) to equation (1.33), we can easily verify might yield additional pro-competitive effects in the multi-homing equilibrium.

Proposition 1.3. *Suppose that a part of consumers have an incentive to join multiple platforms. If firm A decides to tie, the tying decision raises the rival firm's R&D investment level as well as the tying firm's R&D investment level.*

We focus on the situation where the value of bundled product is sufficiently high. Sufficiently high value of bundled products induce more consumers to multi-homing so that not only the demand for platform A but also the demand for platform B can be increased with tying. As mentioned earlier, the benefit from innovation in this model is proportional to the demand for the platform so both platforms have more incentives to invest in R&D. Moreover, when consumers engage in multi-homing, strategic effect of investment disappears, implying that a platform's innovation incentives are not eroded by more aggressive investment by the rival.

In the first stage, platform A decides whether to tie, comparing its profits with tying and without tying. In the case of no tying, the optimal level of R&D investment for each platform is given by

$$\Delta^{A*} = \Delta^{B*} = \Delta^* = \frac{\alpha_1 \lambda - c_1}{2tk - 1} \quad (1.40)$$

The equilibrium profits for platform A and B are

$$\begin{aligned} \Pi^A &= s_M + t \left(\frac{k(\alpha_1 \lambda - c_1)}{2tk - 1} \right)^2 + \alpha_2 \left(1 - \frac{k(\alpha_1 \lambda - c_1)}{2tk - 1} \right) - \frac{k}{2} \left(\frac{\alpha_1 \lambda - c_1}{2tk - 1} \right)^2 \\ \Pi^B &= t \left(\frac{k(\alpha_1 \lambda - c_1)}{2tk - 1} \right)^2 + \alpha_2 \left(1 - \frac{k(\alpha_1 \lambda - c_1)}{2tk - 1} \right) - \frac{k}{2} \left(\frac{\alpha_1 \lambda - c_1}{2tk - 1} \right)^2 \end{aligned} \quad (1.41)$$

In the case of tying, the optimal levels of R&D investment for platform A and B are given by

$$\begin{aligned} \tilde{\Delta}^{A*} &= \frac{s_M + \alpha_1 + \alpha_2 - c_1}{2tk - 1} \\ \tilde{\Delta}^{B*} &= \frac{\alpha_1 \lambda + \alpha_2 \lambda - c_1}{2tk - 1} \end{aligned} \quad (1.42)$$

By substituting (1.42) with (1.38), we have

$$\begin{aligned} \tilde{N}_1^{A*} &= \frac{k(s_M + \alpha_1 + \alpha_2 - c_1)}{2tk - 1} \\ \tilde{N}_1^{B*} &= \frac{k(\alpha_1 \lambda + \alpha_2 \lambda - c_1)}{2tk - 1} \end{aligned} \quad (1.43)$$

Unlike the single-homing case, the aggregate level of R&D investment is not constant; the aggregate level is increased with tying. The equilibrium profit for platform A is

$$\tilde{\Pi}^A = t \left(\frac{k(s_M + \alpha_1 + \alpha_2 - c_1)}{2tk - 1} \right)^2 - \frac{k}{2} \left(\frac{s_M + \alpha_1 + \alpha_2 - c_1}{2tk - 1} \right)^2 \quad (1.44)$$

Platform A chooses to tie if $\tilde{\Pi}^A > \Pi^A$. It implies that the parameter space is not empty set for the tying arrangement to be a profitable strategy. Similarly to the single-homing case, tying can be a private optimum for the monopolist even in the absence of the exclusion of its rival.

1.3.3 Welfare Analysis

In order to analyze welfare implications, I compare total welfare under tying and no tying. Social welfare without tying can be written as

$$\begin{aligned} W &= s_M + \alpha_1(1 + \lambda n_1^{m*}) - (1 + n_1^{m*})c_1 + \alpha_2 \{ \lambda(1 + n_1^{m*}) + 1 - \lambda \} \\ &\quad + \left[(N_1^{A*} \Delta^{A*} + N_1^{B*} \Delta^{B*}) - \frac{k}{2} \{ (\Delta^{A*})^2 + (\Delta^{B*})^2 \} \right] \\ &\quad + \left[\int_0^{1-N_1^{B*}} t x dx + \int_0^{1-N_1^{A*}} t x dx + n_1^{m*} t \right] \end{aligned} \quad (1.45)$$

where $N_1^{A*} = N_1^{B*} = \frac{k(\alpha_1\lambda - c_1)}{2tk-1}$ and $n_1^{m*} = \frac{2k(\alpha_1\lambda - c_1)}{2tk-1}$.

Social welfare with tying can be written as

$$\begin{aligned}\tilde{W} = & s_M \tilde{N}_1^{A*} + \alpha_1(1 + \lambda \tilde{n}_1^{m*}) - \alpha_1 \tilde{n}_1^{B*}(1 - \lambda) - (1 + \tilde{n}_1^{m*})c_1 + \alpha_2 \{ \lambda(1 + \tilde{n}_1^{m*}) + (1 - \lambda) \tilde{N}_1^{A*} \} \\ & + \left[(\tilde{N}_1^{A*} \tilde{\Delta}^{A*} + \tilde{N}_1^{B*} \tilde{\Delta}^{B*}) - \frac{k}{2} \{ (\tilde{\Delta}^{A*})^2 + (\tilde{\Delta}^{B*})^2 \} \right] \\ & + \left[\int_0^{1-\tilde{N}_1^{B*}} t x dx + \int_0^{1-\tilde{N}_1^{A*}} t x dx + \tilde{n}_1^{m*} t \right]\end{aligned}\quad (1.46)$$

where $\tilde{N}_1^{A*} = \frac{k(s_M + \alpha_1 + \alpha_2 - c_1)}{2tk-1}$, $\tilde{N}_1^{B*} = \frac{k(\alpha_1\lambda + \alpha_2\lambda - c_1)}{2tk-1}$, and $\tilde{n}_1^{m*} = \frac{k(s_M + (\alpha_1 + \alpha_2)(1 + \lambda) - 2c_1)}{2tk-1} - 1$.

Hence, the changes in social welfare due to tying is given by

$$\begin{aligned}\Delta W = & \tilde{W} - W \\ = & (\tilde{n}_1^{m*} - n_1^{m*})(\alpha_1\lambda + \alpha_2\lambda - c_1) - (1 - \tilde{N}_1^{A*})[s_M + (\alpha_1 + \alpha_2)(1 - \lambda)] \\ & + \left[(\tilde{N}_1^{A*} \tilde{\Delta}^{A*} + \tilde{N}_1^{B*} \tilde{\Delta}^{B*}) - \frac{k}{2} \{ (\tilde{\Delta}^{A*})^2 + (\tilde{\Delta}^{B*})^2 \} \right. \\ & \left. - (N_1^{A*} \Delta^{A*} + N_1^{B*} \Delta^{B*}) + \frac{k}{2} \{ (\Delta^{A*})^2 + (\Delta^{B*})^2 \} \right] \\ & - \left[\int_0^{1-\tilde{N}_1^{A*}} t x dx + \int_0^{1-\tilde{N}_1^{B*}} t x dx + \tilde{n}_1^{m*} t \right] \\ & + \left[\int_0^{1-N_1^{A*}} t x dx + \int_0^{1-N_1^{B*}} t x dx + n_1^{m*} t \right]\end{aligned}\quad (1.47)$$

We can easily check that $\tilde{N}_1^{A*} > N_1^{A*}$ and $\tilde{N}_1^{B*} > N_1^{B*}$. From the fact that $n_1^m = N_1^A + N_1^B - 1$, we can derive $\tilde{n}_1^{m*} - n_1^{m*} > 0$, which means that tying gives rise to more multi-homers and ensures that exclusive content is exposed to more consumers. In the assumption A2, I assumed that $t < \alpha_1\lambda - c_1$. Given the positive value of transportation cost t , $\alpha_1\lambda + \alpha_2\lambda - c_1 > 0$. The first term in equation (1.47) represents net benefits from the increase in multi-homers because multi-homers are able to have access to exclusive content, and this is also beneficial to exclusive content providers. The term $(1 - \tilde{N}_1^{A*})(\alpha_1 + \alpha_2)(1 - \lambda)$ stands for the loss from changes in incentives for platform B to serve two types of content providers. Under tying, it is more profitable for platform B to serve only exclusive content providers. It reduces the chances for non-exclusive content providers to be exposed to more consumers, as well as the utility of users who single-home on platform B. The terms in the last brackets are the total transportation costs of consumers. Tying may increase overall transportation

costs due to the increase in the number of multi-homers. The terms in curly brackets represent the net benefits from R&D activities. From equation (1.40), (1.41), and (1.42), (1.43), we have $N_1^{i*} = k\Delta^{i*}$ and $\tilde{N}_1^{i*} = k\tilde{\Delta}^{i*}$. By substituting N_1^{i*} and $\tilde{N}_1^{i*}$ with $k\Delta^{i*}$ and $k\tilde{\Delta}^{i*}$, respectively, we can rewrite the net benefits from R&D as

$$\begin{aligned} (\tilde{N}_1^{A*}\tilde{\Delta}^{A*} + \tilde{N}_1^{B*}\tilde{\Delta}^{B*}) - \frac{k}{2}\{(\tilde{\Delta}^{A*})^2 + (\tilde{\Delta}^{B*})^2\} &= \frac{k}{2}\{(\tilde{\Delta}^{A*})^2 + (\tilde{\Delta}^{B*})^2\} \\ (N_1^{A*}\Delta^{A*} + N_1^{B*}\Delta^{B*}) - \frac{k}{2}\{(\Delta^{A*})^2 + (\Delta^{B*})^2\} &= \frac{k}{2}\{(\Delta^{A*})^2 + (\Delta^{B*})^2\} \end{aligned} \quad (1.48)$$

which explicitly shows that the net benefit from R&D investment increases with tying because $\tilde{\Delta}^{i*} > \Delta^{i*}$ for $i = A, B$.

In order to facilitate comparison between $\tilde{W}$ and W , let me manipulate equation (1.47) as follows:

$$\begin{aligned} \Delta W &= (\tilde{n}_1^{m*} - n_1^{m*})(\alpha_1\lambda + \alpha_2\lambda - c_1 - t) - (1 - \tilde{N}_1^{A*})[s_M + (\alpha_1 + \alpha_2)(1 - \lambda)] \\ &\quad + \left[(\tilde{N}_1^{A*}\tilde{\Delta}^{A*} + \tilde{N}_1^{B*}\tilde{\Delta}^{B*}) - \frac{k}{2}\{(\tilde{\Delta}^{A*})^2 + (\tilde{\Delta}^{B*})^2\} \right. \\ &\quad \left. - (N_1^{A*}\Delta^{A*} + N_1^{B*}\Delta^{B*}) + \frac{k}{2}\{(\Delta^{A*})^2 + (\Delta^{B*})^2\} \right] \\ &\quad - \left[\int_0^{1-\tilde{N}_1^{A*}} tx dx + \int_0^{1-\tilde{N}_1^{B*}} tx dx \right] + \left[\int_0^{1-N_1^{A*}} tx dx + \int_0^{1-N_1^{B*}} tx dx \right] \end{aligned} \quad (1.49)$$

Proposition 1.4. *The overall effects of tying on social welfare are ambiguous in the multi-homing case. But if s_M is sufficiently high so that every consumer purchases the tying product, social welfare increases with tying.*

By the assumption A2, $\alpha_1\lambda + \alpha_2\lambda - c_1 - t > 0$. The last two terms, which stand for the difference between the total transportation costs with tying and without tying, also have positive value because $1 - N_1^{i*} > 1 - \tilde{N}_1^{i*}$ for $i = A, B$. In addition, we already show that the expression in curly brackets is positive. Hence, $\Delta W > 0$ as $1 - \tilde{N}_1^{A*}$, or $\tilde{n}_1^{B*}$ goes to zero. That is, tying is welfare-enhancing in this model if the surplus of the product M is sufficiently high so that platform A can capture almost whole market on the consumer side.

1.4 Conclusion

I analyze the effects of tying on R&D incentives as well as price competition between two competing platforms in a two-sided market, especially with the possibility of multi-homing. Previous literature has discovered the role of multi-homing in anti-trust issues regarding tying. As shown in Choi (2010), it plays a role against tipping and the lock-in effects of tying, preventing the rival firm from being excluded from the market. It further makes tying welfare-enhancing because more users have an incentive to multi-home and hence have access to exclusive content in the multi-homing equilibrium. In addition to welfare-enhancing effects of tying in static analysis, my analysis may provide a new aspect of the role of multi-homing. If multi-homing is allowed, tying can be welfare-enhancing even in a dynamic setting. The fact that tying increases the number of multi-homing consumers leads to the increase in total demand of consumers for not only tying firm but also rival firm. This implies that both platforms have greater incentives to innovate under tying because they can spread out R&D costs over more units relative to no tying case. On top of that, more aggressive R&D investment by one platform does not discourage the rival's investment, as there is no strategic effect of reducing rival's incentives to invest in R&D in the multi-homing case. Hence, my model shows that tying can stimulate the rival's R&D incentives rather than stifle innovation, so consumers do not miss an opportunity to have better products or services when multi-homing is allowed. In order to highlight the importance of multi-homing, I analyze the effect of tying on innovation in the single-homing equilibrium on the consumer side as well. In the single-homing case, I show that tying has exactly the reverse effects; it has a chilling effect on innovation efforts by the rival platform and hence reduces social welfare. This contrary result suggests that competition authorities should consider the possibility of multi-homing on both sides when analyzing cases of tying in two-sided markets.

One limitation of the model in this paper is the assumption on the number of exclusive content providers. As in Choi (2010), I assume that the number of content providers, λ , is exogenously given. If content providers are allowed to choose whether to provide their content exclusively, it is likely that content providers have fewer incentives to provide exclusive content to the non-tying

platform under tying. Provided that the non-tying platform has less exclusive content available, the number of multi-homers in turn decreases on the user side. If this is the case, incentives for the non-tying platform to invest in R&D might be reduced with tying. As in Jeitschko and Tremblay (2015), the existence of duplication costs for encoding additional content in order to multi-home can allow for λ to be endogenous. This would be one possible extension of the model in this paper.

CHAPTER 2

INFORMATION SHARING AND R&D INCENTIVES

2.1 Introduction

In this paper, we study firms' incentives to invest in cost reducing R&D when information about R&D investment is shared. More specifically, we consider a situation in which firms are uncertain about opponents' R&D investment level and the outcome of R&D, i.e., reduced production cost and private information about the realized cost can be exchanged. The exchange of private information between competitors is a common practice in many industries. It is typically implemented by common agencies such as industrial trade associations which collect, aggregate, and disseminate data on behalf of their members. Another example of information exchange is the mandatory disclosure requirements by regulatory agencies, such as the SEC and FASB. Recently, regulatory agencies have increasingly emphasized disclosure requirements in addition to the financial statements.¹ In the US and Canada, for instance, publicly traded firms are required to augment GAAP mandated disclosures, referred to as Management Discussion and Analysis (MD&A). In MD&A, firms must discuss and analyze the results and trends of operations, including cost information.²

We formally study a simple duopoly model with homogeneous products to address the issues related to information sharing. Each firm first makes cost reducing R&D investment and its outcome is stochastically realized. Before setting a price, each firm has private information regarding the reduced production cost. That is, in the absence of information sharing, firms face *ex ante* uncertainty and *ex post* information asymmetry about the result of R&D investment.

Interestingly, even when private cost information is not shared, firms may observe opponents' R&D investment level, which can be a signal of the R&D outcome in many cases. For example,

¹SEC undertakes a comprehensive review of disclosure requirements on public company filings and recommend changes. MD&A is the most frequent area in the comment letter in 2014 and 2015.

²See Bryan (1997) for the details of MD&A requirement in the US.

the US Statement of Financial Accounting Standards No.2 (SFAS2) requires firms to reveal R&D expenditure in its financial statement. However, in several European countries, such as Germany, France, and Italy, public disclosure of R&D expenditure is not required.³ The observability of the R&D investment level is likely to affect strategic incentives to invest and the subsequent market outcomes. This situation leads to important questions about the effect of information sharing on technological improvement and the role of the observability of the investment level.

To answer these questions, we compare firms' investment incentives and the eventual market outcomes under three different information structures: complete information, unobservable investment, and observable investment. In the complete information case, the outcome of cost reducing investment is shared before firms choose prices. In the unobservable investment case, realized cost information is concealed and the rival's investment level is also unobservable. An intermediate case, the observable investment case, concerns a situation where realized cost information is private but firms can observe the rival's investment level prior to the price competition. We find that both investment incentives and expected market outcomes are identical in the complete information case and the unobservable investment case. In contrast, investment in cost reduction is discouraged in the observable investment case, in which both consumers and society may be hurt compared to the other two cases. This implies that the effect of information sharing on investment incentives crucially depends on the observability of opponents' investment level. The intuition for this result is as follows.

The exchange of cost information allows the most efficient firm to fully exploit the market power by choosing its price at the marginal cost of the second most efficient firm, whereas the other firm sets prices at its own marginal cost and earn zero profit. The cost uncertainty, however, moderates this concentration and every firm in the market has positive expected profits. Despite this difference of pricing between information structures, the firms' expected payoff is identical in the equilibrium for both cases as long as firms invest the same amount and the symmetry between firms is sustained.

³In these countries, government agencies or central banks collect data about R&D expenditures, but such data is kept confidential by the institutions and is not easily accessed.(see Hall and Oriani (2006))

This is analogous to the "Revenue Equivalence Theorem" in auction theory, which states that the expected revenue (which equals the expected price in this paper) is the same regardless of whether the auction is the second price or sealed-bid first price (which is in this paper interpreted as whether or not cost information is private).⁴ The implication of the Revenue Equivalence Theorem for the situation addressed here is that firms' expected payoff boils down to the probability of winning the market given c in winner-takes-all type markets. Although firms have private cost information, the symmetric firms set the same price for each realized cost and like the complete information case, the most efficient firm always captures the market and hence the probability of winning the market given c is equalized in both cases. On top of that, if opponents' investment level is unobservable, there is no room for a strategic element of R&D expenditures because firms' moves are not based on opponents' actual spending but their beliefs in the price competition stage. The equivalence of the mechanism of winning the market is sustained and thus firms have an identical incentive to invest in the complete information and the unobservable investment case.

However, the observability of opponents' investment level introduces a strategic effect in firms' equilibrium behavior. It induces firms' pricing adaptations in the price competition stage following opponents' deviation in the R&D competition stage. From the comparative statics analysis, we find that the more a firm invests in the first stage, the lower the price set by the rival in the following stage. Although the effect of one firm's additional investment on its own pricing strategy varies across specifications of R&D technology, it turns out that under the new configuration of pricing strategies, investment becomes less profitable, leading to the reduction in investment incentives.⁵ In other words, cost reducing investment has a negative strategic effect, which results in the underinvestment in the observable investment case.

Our results suggest different policy implications from those of the existing literature. Previous studies such as Sakai (1986), Sakai and Yamato (1989), and Amir et al (2010) find that if firm

⁴On the revenue equivalence theorem, see, for example, Klemperer (1999) or Krishna (2002) for the detailed explanations.

⁵In the baseline model and discrete type model in section 6.1, a investor chooses higher price given c after making investment but in the oligopoly model, the changes in the investor's pricing strategy cannot be tractable.

specific cost information is private in a price competition, firms have an incentive to conceal the information, which is beneficial to the social welfare compared to instances when firms exchange the cost information. This result justifies a laissez-faire approach to the exchange of cost information and our analysis obtains *weakly* same result when investment is unobservable. If investment is observable, however, firms' private incentives to share information are not aligned with social welfare. Firms are still willing to conceal the information while the exchange of information increases social welfare.

The economic literature has extensively studied information sharing.⁶ Previous studies have investigated firms' incentives to share information and its welfare impacts. The key elements of these analyses are the type of information shared (demand or cost), characteristics of information (common value or private value), and the type of competition (price or quantity). Most early works, such as Vives (1984) and Gal-Or (1985), investigate firms' incentives to share common value information in Cournot competition and show how the effect of asymmetric information can vary across the type of information. Gal-Or (1986), Sakai (1986), and Raith (1996) address cost information sharing in Bertrand competition, which is closely related with our paper. Gal-Or(1986) and Sakai(1986) find that concealing information is a dominant strategy for firms if each firm's cost is independently drawn from the distribution, whereas Raith(1996) shows that this result is not robust in terms of correlated costs. Sakai and Yamato (1990) and Amir et al (2010) examine the welfare implications of information sharing and show that the exchange of cost information in price competition reduces social welfare. Unlike our work, they analyze the effect of asymmetric cost information with differentiated products. Further, the present paper introduces cost-reducing investment prior to Bertrand competition so that the effect of information disclosure can be examined not only with respect to the investment outcome but also the level of investment.

Thomas (1997) and Arozamena and Cantillon (2004) study about incentives to reduce production costs in auctions and find that the firm has lower incentives to invest in cost reduction when the investment level is observable. Similar to our results, they find that less incentives to invest in cost

⁶European Commission (1995) provides an overview of theoretical literature and competition policies in various countries associated with information sharing.

reduction result from the firm's anticipation that it will face fiercer price competition.⁷ However, the analysis in Thomas and Arozamena and Cantillon assume that only one firm has an investment opportunity at a time, whereas the present paper analyzes investment incentives when investment is simultaneous.

Our paper is organized as follows: the next section describes the model; in Section 2.3, we derive the investment equilibria and compare the investment incentives in each information structure; welfare implications are analyzed in Section 2.4; in Section 2.5, we modify R&D technology in order to assess the robustness of our results; Section 2.6 discusses other concerns related to observable investment, and Section 2.7 concludes the paper.

2.2 Model

There is a mass of homogenous consumers normalized to one, each of whom wishes to purchase one unit of product from the market. Consumers have valuation $v > \bar{c}$ for the product. Two firms, labeled 1 and 2, produce homogeneous products. They compete in prices and interact only once in the market. Firms have identical marginal costs of production *ex ante*⁸, denoted by $\bar{c}$, which may be reduced through cost reducing R&D investment.⁹ Before competing in prices, the two firms engage in R&D activities to lower costs. Cost reductions are stochastic. Specifically, if firm i invests I_i , its marginal cost of production is uniformly distributed over $[\bar{c} - I_i, \bar{c}]$ and for convenience, let me denote by f_i the probability density and F_i the cumulative density, $i = \{1, 2\}$. That is, R&D investment can stretch out the lower bound of the support of distribution of marginal

⁷Interestingly, Thomas (1997) and Arozamena and Cantillon (2004) highlight the magnitude of the negative strategic effect of investment by providing numerical examples: in some parameter space, the firm which is allowed to invest may not want to reduce its cost even when the cost of investment is zero.

⁸If firms are *ex ante* asymmetric, they may signal to the rival about their initial cost type through R&D investment. Aoki and Reitman (1992) analyze the strategic use of R&D investment for signaling.

⁹Because the *ex ante* marginal cost is assumed to be $\bar{c}$, firms would earn zero profit if they do not engage in R&D investment. Therefore, in contrast to Thomas (1997) or Arozamena and Cantillon (2004), disincentives of investment is not an issue in this model.

cost. We interpret the present model as representing the shift to a more reliable technology. If $I_1 > I_2$, F_1 first order stochastically dominates F_2 and has a higher hazard rate than F_2 . In contrast to much previous literature which covers information sharing about cost, such as Gal-Or(1986) and Raith(1996), each firm's cost is drawn independently. Because our focus is on the interaction between R&D and pricing competition, not a common shock to the industry, we assume, for clarity of exposition, that firms' costs are not correlated. Additionally, the present model rules out any spillover effect of technologies. The investment cost is $\Phi(I)$, where $\Phi'(I) > 0$, $\Phi''(I) > 0$, $\Phi'''(I) > 0$, $\Phi'(0) = 0$, and $\Phi'(\bar{c}) = \infty$.

The timing of the game is as follows. In the first stage, firms simultaneously decide how much to invest. The level of investment by the rival may be observable. After observing its own cost realization, firms set prices simultaneously in the second stage. Lastly, consumers' purchase decisions are made by choosing the firm which offers the lower price. If cost information is public in the second stage, a standard two stage Nash game would be played. If cost information is private, a two stage Bayesian-Nash game would be played. That is, a noncooperative Nash game is played in the R&D stage, given that firms calculate their expected profits from the second stage. In the second stage, firms play a Bayesian-Nash game.

2.3 Basic Analysis

Three information cases are considered in this section: complete information, unobservable investment, and observable investment. In the complete information case, firms commit to share cost information at the outset of the game. We assume that the information will be truthfully revealed and all information is publicly known.¹⁰ In the unobservable investment and the observable investment case, the rival's cost information is not shared and remains unknown. In the observable investment case, however, firms can observe the rival's investment level in the first stage. For each case, we

¹⁰In the present model, we assume away partial revelation as in Gal-Or (1986) and focus only on full revelation for simplicity.

analyze how much firms choose to invest in the equilibrium. By comparing these three cases, we can examine how the effect of cost uncertainty on investment incentives depends on the observability of R&D investment.

2.3.1 Complete Information Case

When the rival's marginal cost is public, firms play the standard Bertrand game *ex post* in the second stage. That is, the lowest cost firm wins the market and sets its price at the rival's marginal cost. The other firm charges its marginal cost and earns zero profit. Thus, a firm can earn positive profits by the difference in both firms' costs, $c_j - c_i$, when it turns out that the firm is more efficient in production than the rival. The profit maximization problem for firm i in the first stage is given by

$$\max_{I_i} Pr[c_i < c_j] \cdot E[c_j - c_i | c_i < c_j] - \Phi(I_i).$$

Once a firm invests more than the rival, it is possible for the firm to have an exclusive level of efficiency that the rival cannot beat. Thus, the shape of profit function depends on the relative level of investment. Assume that $I_1 \geq I_2$. The expected profit for firm 1 is

$$E\bar{\pi}_1(I_1) = Pr[c_1 < c_2] \cdot E(c_2 - c_1 | c_1 < c_2) - \Phi(I_1).$$

Substituting $Pr[c_1 < c_2] = 1 - \frac{I_2}{2I_1}$,¹¹ firm 1's expected payoff can be rewritten as

$$E\bar{\pi}_1(I_1) = \frac{1}{2}I_1 - \frac{1}{2}I_2 + \frac{I_2^2}{6I_1} - \Phi(I_1).$$

Similarly, if $I_1 \leq I_2$, we have firm 1's expected profit as

$$E\underline{\pi}_1(I_1) = \frac{I_1^2}{6I_2} - \Phi(I_1).$$

¹¹The probability of winning the market for firm 1 can be calculated by

$$Pr[c_1 < c_2] = \int_{\bar{c}-I_2}^{\bar{c}} \int_{\bar{c}-I_1}^z dF_1(x) dF_2(z) = \begin{cases} 1 - \frac{I_2}{2I_1} & \text{if } I_1 \geq I_2 \\ \frac{I_1}{2I_2} & \text{if } I_1 \leq I_2 \end{cases}$$

$E\bar{\pi}_i(I_i)$ and $E\underline{\pi}_i(I_i)$ show that the expected profit function is continuous and differentiable at all $I_i \in [0, \bar{c}]$. The following Lemma describes firms' best responses in the first stage.

Lemma 1. Define $\bar{I}_i(I_j)$ as a function which implicitly solves $\frac{1}{2} - \frac{I_j^2}{6I_i^2} - \Phi'(I_i) = 0$ and $\underline{I}_i(I_j)$ solving $\frac{I_i}{3I_j} - \Phi'(I_i) = 0$. Then, firm i 's best response, $\Theta_i(I_j)$ is given by

$$\Theta_i(I_j) = \begin{cases} \bar{I}_i(I_j) & \text{if } I_j \leq I^o \\ \underline{I}_i(I_j) & \text{if } I_j \geq I^o \end{cases} \quad \text{where } I^o \text{ satisfies } \Phi'(I^o) = \frac{1}{3}$$

Proof. See Appendix B. □

The firm i 's best response intersects with firm j 's best response at $I_i = I_j = I^o$ and in order to ensure the stability condition at the symmetric equilibrium, we assume the following condition.

Assumption 1. $\Phi''(I^o) > \frac{2}{3I^o}$

The assumption is equivalent to $|\bar{I}'_i(I_j)| < 1$ and $|\underline{I}'_i(I_j)| < 1$ at $I_1 = I_2 = I^o$. Although the assumption above is implicitly determined by the shape of R&D cost function, it does not require the tight condition. Suppose that, for instance, the R&D cost function is given by $\Phi(I) = kI^2/(\bar{c} - I)$. Then, I^o is derived as $\bar{c}(1 - \sqrt{3k/(3k+1)})$ and we can check that the condition above is satisfied for all positive k . Also, from $\partial^2 E\bar{\pi}_i(I_i)/\partial I_i \partial I_j < 0$ and $\partial^2 E\underline{\pi}_i(I_i)/\partial I_i \partial I_j < 0$, we can confirm that firms' investments in the R&D stage are strategic substitutes.

Proposition 2.1. If information about cost is shared, there exists a symmetric equilibrium $I_1 = I_2 = I_{CI}^*$ such that $\Phi'(I_{CI}^*) = \frac{1}{3}$.

Proof. Without loss of generality, assume $I_1 > I_2$. The stability condition guarantees that $\bar{I}_1$ is steeper than $\underline{I}_2$ at $I_1 = I_2 = I^o$. Given this, the uniqueness of the equilibrium can be shown by looking at the changes in slope of best responses. The changes in the slope of firm 1's best response can be obtained as $\bar{I}_1''(I_2) = -\frac{3I_1^2\Phi''(I_1)+I_2^2/I_1}{(3I_1^2\Phi''(I_1)-I_2^2/I_1)^2} < 0$ and for firm 2, it can be derived as

$I_2''(I_1) = \frac{2I_2(9I_1^2\Phi''(I_2)-1)}{(3I_1^3\Phi''(I_2)-I_1)^2} > 0$. In other words, firm 1's best response gets steeper as I_2 decreases and firm 2's best response becomes flatter as I_1 increases. Therefore, the two firms' best responses do not interact in the area of $I_1 > I_2$. We can make a similar argument in the area of $I_1 < I_2$ by imposing symmetry of the two firms' reaction functions.

The symmetric equilibrium in the R&D stage is given by $I_1 = I_2 = I_{CI}^*$ where I_{CI}^* is uniquely defined by $\Phi'(I_{CI}^*) = \frac{1}{3}$. $\square$

2.3.2 Unobservable Investment Case

We next consider the unobservable investment case where information about costs is not disclosed and the rival's investment is unobservable. Firm i invests in cost-reducing R&D and privately observes the realized production cost which is drawn from the uniform distribution on $[\bar{c} - I_i, \bar{c}]$. The more a firm invests in the first stage, the greater the chance that a low production cost is realized, leading to a high probability of capturing the market. The information about cost is private, but it is commonly known that c_1 and c_2 are independently and uniformly distributed on $[\bar{c} - I_1, \bar{c}]$ and $[\bar{c} - I_2, \bar{c}]$, respectively. The equilibrium of the two stage game consists of an R&D investment strategy profile $\{I_1, I_2\}$ and a pricing strategy profile $\{P_1(c_1), P_2(c_2)\}$, where $\{I_1, I_2\}$ is a noncooperative Nash equilibrium in the first stage and $\{P_1(c_1), P_2(c_2)\}$ is a Bayes-Nash equilibrium in the second stage. On the equilibrium path, $P_i(c)$ is determined by the firm's beliefs about the equilibrium investment strategy, $\hat{I}_i$, for $i = 1, 2$. For ease of exposition, we define $\phi_i(p)$ the inverse function of firm i 's equilibrium pricing strategy and $\varphi_{ji}(c) := \phi_j(P_i(c))$ the composite function of P_i and ϕ_j . That is, $\varphi_{ji}(c)$ is firm j 's realized cost when the two firms' prices are the same, given that firm i 's cost is c . Plum(1992) shows that the equilibrium pricing strategy P_i for $i = 1, 2$ is continuous and strictly monotonically increasing on $[\bar{c} - I_i, \bar{c}]$ so the functions $\phi_i(p)$ and $\varphi_{ji}(c)$ can be defined and are continuous, strictly monotonically increasing.

Before proceeding to the equilibrium analysis, we first examine the second stage subgame where firms compete with price based on the private cost information and beliefs about the rival's price.

In the second stage, $P_i(c_i)$ solves

$$\text{Max}_p (p - c_i)(1 - F_j(\phi_j(p))) \quad \text{for each } c_i \in [\bar{c} - I_i, \bar{c}].$$

Taking logarithm and differentiating with respect to p , we obtain

$$\frac{F'_j(\phi_j(p))}{1 - F_j(\phi_j(p))} \phi'_j(p) = \frac{1}{p - \phi_i(p)}. \quad (2.1)$$

The solution to the system of differential equations gives each firm's equilibrium pricing strategy but in general, the system of differential equations above does not have an explicit solution. However, the cost distributions in the present model comes from a special class of distributions which allows for closed form solutions to the system in (2.1).

Lemma 2. *Given the beliefs on rival's investment $\hat{I}_i$ and $\hat{I}_j$, firm i 's equilibrium price strategy in the second stage is*

$$P_i(c) = \bar{c} - \frac{\bar{c} - c}{1 + \sqrt{1 - (\frac{1}{\hat{I}_i^2} - \frac{1}{\hat{I}_j^2})(\bar{c} - c)^2}} \quad (2.2)$$

Proof. See Appendix B. □

Equation (2.2) gives $P_1(\bar{c} - I_1) = P_2(\bar{c} - I_2) = \bar{c} - \frac{I_1 I_2}{I_1 + I_2} \equiv \underline{p}$ and $P_1(\bar{c}) = P_2(\bar{c}) = \bar{c}$, which means that a firm with the highest value of cost cannot expect positive profits. Given the pricing equilibrium $\{P_1(c), P_2(c)\}$, firm i 's *ex ante* expected payoff is calculated as

$$E\pi_i(P_i, c) = \int_{\bar{c} - I_i}^{\bar{c}} (P_i(c) - c)[1 - F_j(\phi_{ji}(c))]dF_i(c) - \Phi(I_i),$$

which, after integration by parts, can be rewritten as

$$E\pi_i(P_i, c) = - \int_{\bar{c} - I_i}^{\bar{c}} F_i(c) \frac{d}{dc} (P_i(c) - c)[1 - F_j(\phi_{ji}(c))]dc - \Phi(I_i).$$

Using the Envelope Theorem, we obtain

$$\frac{d}{dc} (P_i(c) - c)[1 - F_j(\phi_{ji}(c))] = -[1 - F_j(\phi_{ji}(c))]. \quad (2.3)$$

Substituting this expression into the integral, firm i 's profit maximization problem can be written as

$$\max_{I_i} \int_{\bar{c}-I_i}^{\bar{c}} F_i(c)[1 - F_j(\varphi_{ji}(c))]dc - \Phi(I_i). \quad (2.4)$$

Proposition 2.2. *Suppose that the rival's investment is unobservable. If information about cost is not disclosed, there exist a symmetric equilibrium, where i) firms invest $I_1 = I_2 = I_{UI}^*$ in the first stage and ii) use the same pricing strategy $P(c) = \frac{c+\bar{c}}{2}$ in the second stage. Moreover, I_{UI}^* is identical to I_{CI}^* .*

Proof. See Appendix B. □

The incentives to invest in the complete information and the unobservable investment case are identical because the expected payoffs in the equilibrium are the same in both cases. The reason for the same expected payoff in both cases is related to the Revenue Equivalence Theorem in auctions. Although our model considers not only of winner-takes-all type price competition, which is similar to an auction, but also the interaction of the competition with cost reducing R&D investment, the principle of the Revenue Equivalence Theorem is helpful to explain our result. The Revenue Equivalence Theorem states that, under the assumptions of a risk-neutral bidder, and a privately known type which is independently drawn from a distribution, expected payoffs are determined by a mechanism of winning the object and the expected payoff for a bidder who has the lowest feasible type regardless of the type of auctions. That is, the expected payoff depends on the winning probability of the market. To see this, refer to (3), which shows that changes in profits at c as cost increases are equal to the winning probability at c . Thus, the profit at c is the sum of the winning probability from c to $\bar{c}$.¹² Proposition 2 implies that the effect of additional investment on the winning probability is identical in both cases. The reasons for this are two-fold: first, in the equilibrium, firms invest symmetrically so that costs are drawn from identical distribution function in both cases; second, given that the cost distributions are symmetric, firms use the same pricing

¹²The expected profit in firm i 's profit maximization problem in (4) is indeed equivalent to the expected value of the sum of the winning probability from each feasible c to $\bar{c}$.

strategy for all c in the unobservable investment case. If firms' prices are the same for each c , a firm that has more efficient production technology wins the market as in the complete information case. Investment cannot affect this equilibrium pricing strategy because when competing with price, firms cannot adjust to the rival's actual investment level but instead choose a pricing strategy based on their belief about the rival's investment. Therefore, in this case, cost uncertainty does not diminish the efficiency of the investment relative to the complete information case.

We show that if firms are *ex ante* symmetric, the information structure about the investment outcome does not affect investment incentives. However, this result relies on the assumption in the unobservable investment case that the investment level is unobservable. If the investment level by the rival can be observed prior to the price competition, this equivalence of investment incentives may no longer hold. We will analyze this case in the next subsection.

2.3.3 Observable Investment Case

When cost information is private, cost reducing investment prior to the price competition has two effects in the present model - a direct effect and an indirect effect. The investment directly improves the investor's cost distribution so that the investor can obtain the advantage in production efficiency over the rival. We have shown that the complete information case and unobservable investment case have the same direct effect. If the investment level is observable, however, the investment forces firms to modify pricing in accordance with the new cost distribution. We will show that investment has a negative indirect effect, or strategic effect, in the observable investment case which results in less incentive to invest in cost reduction. This result may not be surprising because investment acts as a "tough" commitment to the rival by allowing the investor to have a higher chance of getting a low cost. With strategic complementarity of price competition, one may anticipate that investment makes the competition more fierce and harms expected profits. However, the following example shows that *pricing strategies* are not strategic complements when the rival's cost information is unknown. Suppose that two firms compete in price for a homogeneous product. The information about cost is private, but it is commonly known that each firm's cost is drawn from

a uniform distribution on $[0, 1]$. Under the symmetry, the equilibrium pricing strategy for each firm is $P_i(c_i) = \frac{1+c_i}{2}$ for $i = \{1, 2\}$. Suppose that firm 1 changes its pricing strategy: $\tilde{P}_1(c_1) = \frac{a+bc_1}{a+b}$ for all $c \in [0, 1]$, where $a > 0$, $b > 0$, and $a \neq b$. Note that if $a > b$, $\tilde{P}_1(c) > P_1(c)$ for all $c \in [0, 1]$ and *vice versa*. Then, firm 2 reacts by solving $\text{Max}_p (p - c)(1 - F_1(\tilde{\phi}_1(p)))$, or $\text{Max}_p (p - c)(1 - \frac{(a+b)p-a}{b})$. The new best response for firm 2 is still $P_2(c) = \frac{1+c_i}{2}$. Regardless of whether firm 1 changes pricing strategy more aggressively or less aggressively, firm 2's response does not change. We can also construct other examples in which a firm reacts either more aggressively or less aggressively against a change in the rival's behavior. This is because firms do not care about the expected absolute level of a rival's price, but instead, it is the responsiveness of winning probability to a change in price that matters. Thus, it is still worthwhile to analyze how observable cost-reducing investment interacts with the price competition.

In the observable investment case, the nature of equilibrium pricing strategy is similar to the one in the unobservable investment case discussed in Lemma 2, but here, firms can adjust pricing strategies based on the observed investment by the opponent after the first stage. Thus, the equilibrium pricing strategy in Lemma 2 will be used by substituting $\hat{I}$ with I . Note that firm i 's pricing strategy depends on not only its realized cost and the rival's investment level, but also its own investment level. When cost information is private, firms which play Bayes-Nash game set prices by considering the rival's equilibrium pricing strategy. Because each firm's cost distribution can affect how the rival will compete in prices, $P_i(c)$ depends on I_i .

The equilibrium pricing strategy in (2.2) shows that for all c in the common support of two firms, firm i 's price increases, whereas firm j 's price decreases in firm i 's investment level. This result may seem counterintuitive to the nature of price competition. It is not surprising that firm j 's responds to the rival's more aggressive investment by lowering its price. However, firm i 's reaction is to set a less aggressive price not merely relative to the rival, but in absolute terms. As seen in the example above, the pricing strategies in the incomplete information case are not generally strategic substitutes and are determined by how a new pricing strategy by the rival makes the winning probability responsive to price changes. To see this, refer back to (2.1). Given that c is

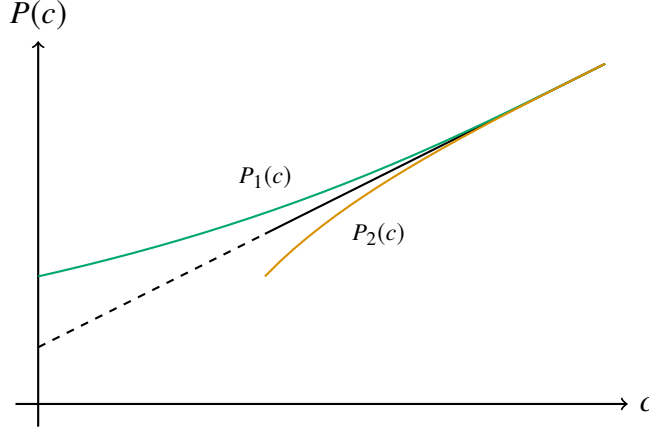


Figure 2.1: Pricing Strategy in Observed Investment Case

uniformly distributed, (2.1) can be rewritten as $\phi'_j(p)/(\bar{c} - \phi_j(p)) = 1/(p - \phi_i(p))$, which shows that changes in firm i 's pricing strategy after investment depends on how investment affects the hazard rate of firm j 's pricing. Due to the fact that the directions of the two firms' responses are different, the effect of the observability of investments on the R&D competition is not easily predictable when firms invest simultaneously.

The adjustment to the rival's deviation in the first stage is reflected through the term $\varphi_{ji}(c)$ in (2.3). Given the pricing equilibrium $(P_1(c|I_1, I_2), P_2(c|I_1, I_2))$, the first order condition with respect to I_1 in the first stage can be obtained as

$$\begin{aligned}
 \Phi'(I_1) &= \int_{\bar{c}-I_1}^{\bar{c}} \frac{\partial \{F_1(c)[1 - F_2(\varphi_{21}(c|I_1, I_2))]\}}{\partial I_1} dc - \underbrace{(-1)F_1(\bar{c} - I_1)[1 - F_2(\varphi_{21}(\bar{c} - I_1|I_1, I_2))]}_{=0} \\
 &= \int_{\bar{c}-I_1}^{\bar{c}} \left[\underbrace{\frac{\partial F_1(c)}{\partial I_1} [1 - F_2(\varphi_{21}(c|I_1, I_2))]}_{\text{direct effect}} + \underbrace{F_1(c) \frac{\partial [1 - F_2(\varphi_{21}(c|I_1, I_2))]}{\partial I_1}}_{\text{indirect effect}} \right] dc
 \end{aligned} \tag{2.5}$$

The first term and second term of RHS in (2.5) represents the direct effect and indirect effect, respectively, of additional investment on the investor's profit. In this subsection, we focus primarily on the symmetric equilibrium, where $I_1 = I_2$ and $P_1(c) = P_2(c)$.

Proposition 2.3. *Suppose that the rival's investment is observable. If information about cost is not disclosed, both firms choose to invest $I_1 = I_2 = I_{OI}^*$ in the symmetric equilibrium, where I_{OI}^* is less than the equilibrium investment level in the complete information and unobservable investment cases.*

Proof. First, we determine whether the second order condition for the firms' maximization problem is satisfied. By differentiating the profit function twice in terms of I_1 , we have

$$\frac{\partial^2 E\pi_1}{\partial I_1^2} = - \int_{\bar{c}-I_1}^{\bar{c}} \frac{(\bar{c}-c)^2(I_2^2 + (\bar{c}-c)^2)}{I_1^5 I_2^3 \sqrt{A}^5} \cdot B \, dc - \Phi''(I_1)$$

where

$$A = 1 - \left(\frac{1}{I_1^2} - \frac{1}{I_2^2}\right)(\bar{c}-c)^2 \quad \text{and} \quad B = 2I_1^2(\bar{c}-c)^2/I_2^2 + 2(I_1^2 - (\bar{c}-c)^2) - 3(\bar{c}-c)(I_1 - (\bar{c}-c))$$

Because $I_1 \geq \bar{c}-c$ for all $c \in [\bar{c}-I_1, \bar{c}]$, $2(I_1^2 - (\bar{c}-c)^2)$ is greater than $3(\bar{c}-c)(I_1 - (\bar{c}-c))$, and hence the second order condition is satisfied. It can be shown that R&D investments are strategic substitutes by looking at the sign of $\partial^2 E\pi_1 / \partial I_1 \partial I_2$.¹³ Furthermore, the slope of the best response is less than 1 at $I_1 = I_2$, implying that the stability condition of the symmetric equilibrium holds.¹⁴

By imposing symmetry, we obtain from (2.5)

$$\begin{aligned} \Phi'(I_{OI}^*) &= \int_{\bar{c}-I_{OI}^*}^{\bar{c}} \frac{(\bar{c}-c)(\bar{c}-c)}{I_{OI}^{*3}} - \frac{1}{I_{OI}^*} \left(1 - \frac{\bar{c}-c}{I_{OI}^*}\right) \frac{\partial \varphi_{21}(c|I_1, I_2)}{\partial I_1} \Big|_{I_1=I_2=I_{OI}^*} dc \\ &= \frac{1}{3} - \frac{1}{20} = \frac{17}{60} \end{aligned} \tag{2.6}$$

Because the R&D cost function, $\Phi(I)$, is assumed to be convex, I_{OI}^* is less than I_{CI}^* or I_{UI}^* . $\square$

¹³The term $\partial^2 E\pi_1 / \partial I_1 \partial I_2$ is given by

$$\frac{\partial^2 E\pi_1}{\partial I_1 \partial I_2} = \int_{\bar{c}-I_1}^{\bar{c}} (\bar{c}-c)^2 \left(\frac{3(\bar{c}-c)^3}{I_1^3 I_2^4 \sqrt{A}} + \frac{1}{I_1^2 I_2^2 \sqrt{A}} \right) \left(\frac{\bar{c}-c}{I_1} - 1 \right) dc$$

Because $\frac{\bar{c}-c}{I_1} - 1$ is negative for all $c \in [\bar{c}-I_1, \bar{c}]$, $\partial^2 E\pi_1 / \partial I_1 \partial I_2 < 0$.

¹⁴The slope of best response, $|\Theta'_1(I_{OI}^*)| = \left| \frac{\partial^2 E\pi_1}{\partial I_1 \partial I_2} / \frac{\partial^2 E\pi_1}{\partial I_1^2} \right| = \frac{13/84 I_{OI}^*}{71/84 I_{OI}^* + \Phi''(I_{OI}^*)} < 1$

The proposition states that the strategic effect of investment is negative in the symmetric equilibrium. From equation (2.2), we know that the investor's price increases in investment, whereas the rival's price decreases in investment for all c in the common support. The strategic effect of investment through firms' pricing may make the investor's markup rise but, as mentioned in the previous subsection, the expected payoff boils down to the probability of winning the market. Obviously, the probability of winning the market for the investor is lower than the rival in the common support. Moreover, unlike the situation in the complete information and unobservable investment cases, the investor cannot capture the market for sure in the stretched support because the lowest prices of their equilibrium strategies are the same.

The effect of the observability of investment information is reminiscent of the influence of the observability of contract information in vertical delegations. Fershtman and Judd (1987) and Bonanno and Vickers (1988) found that by delegating downstream pricing, firms can establish a Stackelberg leadership advantage vis-a-vis their competitors, which can lead to higher prices and profits than that present without vertical delegation. Katz (1991) and Coughlan and Wernerfelt (1989) then responded, effectively saying that this result critically depends on the level of information that competitors have about vertical contracts among their competitors. If competitors don't have any contract information about the cost and structure of how upstream divisions sell to downstream divisions, then the "Stackelberg advantage" results of Fershtman and Judd and Bonanno and Vickers are not robust.

2.4 Welfare Analysis

In the previous section, incentives to innovate were analyzed. These can be ranked as follows:

$$I_{CI}^* = I_{UI}^* > I_{OI}^*$$

If all agents have the same valuation for the product, social welfare is a function of the minimum actual cost, corresponding to the investment level. As shown above, whereas the investment level in the complete information and unobservable investment cases are the same, the observable invest-

ment case induces underinvestment. This implies that social welfare decreases in the observable investment case.

$$W_{CI} = W_{UI} > W_{OI}$$

We next analyze how consumer surplus may vary across information regimes. Because demand is assumed to be inelastic, it is sufficient to derive the expected price that consumers are charged in order to calculate consumer surplus.

Lemma 3. *If cost information is public, the expected price that consumers are charged is given by*

$$E(p) = \int_{\bar{c}-I_2}^{\bar{c}} \left[F_2(c) + cF_2'(c) - F_1(c)F_2(c) \right] dc \quad (2.7)$$

If cost information is private, the expected price that consumers are charged is given by

$$E(p) = \int_{\bar{c}-I_2}^{\bar{c}} \left[F_2(c) + cF_2'(c) + F_1(\varphi_{12}(c)) \{ \varphi_{12}(c)F_2'(c) - F_2(c) - cF_2'(c) \} \right] dc \quad (2.8)$$

Proof. See Appendix B. □

At the symmetric equilibrium, (2.7) can be rewritten as

$$E(p^*) = \int_{\bar{c}-I^*}^{\bar{c}} \left[F_2(c) + cF_2'(c) - F_1(c)F_2(c) \right] dc = \bar{c} - \frac{I^*}{3} \quad (2.9)$$

And because $\varphi_{12}(c) = c$ in the symmetric equilibrium, (2.8) becomes

$$E(p^*) = \int_{\bar{c}-I^*}^{\bar{c}} \left[F_2(c) + cF_2'(c) - F_1(c)F_2(c) \right] dc = \bar{c} - \frac{I^*}{3} \quad (2.10)$$

Equations (2.9) and (2.10) show that if firms are symmetric, expected prices depend on investment. Because $I_{CI}^* = I_{UI}^*$, the expected prices in the complete information and unobservable investment cases are identical, implying that consumer surplus in both cases is the same as well. Due to underinvestment, however, the expected price in the observable investment case is greater than in the other two cases, leading to higher profits but lower consumer surplus.

$$E\pi_{CI} = E\pi_{UI} < E\pi_{OI}$$

$$CS_{CI} = CS_{UI} > CS_{OI}$$

Proposition 2.4. *In the complete information and unobservable investment cases, total welfare is identical. In the observable investment case, each firm's expected profit increases but both social welfare and consumer surplus decrease.*

Proposition 2.4 contrasts the implication of asymmetric information about costs and investment. The asymmetric information about costs does not affect competition at all in this environment. Of course, it should be kept in mind that this implication results from the features of the model of inelastic demand and independently drawn costs. Nonetheless, this strong result about the implication of cost uncertainty highlights the impact of observability of investment. Even in an environment where asymmetric information about costs plays no role in competition, welfare implications can vary depending on whether information about investment is revealed.

This is an important point. As noted above, previous research dealing with cost information sharing concluded that a firm's private incentive to share the information is aligned with social welfare. Specifically, if firms compete in prices, cost information sharing harms social welfare, but firms also do not have an incentive to share the information about costs. This implies that there is no reason to forbid cost information sharing if it is not part of a collusive agreement. However, our result suggests that an additional criterion – observability of investment – should be considered when the anti-competitiveness of cost information sharing practices in industries where R&D activities for reducing costs play a significant role in competition.

2.5 Robustness

In the baseline model, we analyze cost reducing R&D incentives and other market outcomes under each information structure. Yet, notwithstanding the attractive feature of the baseline model that it yields a closed-form solution to the system of differential equations in (1), the model has some limitations: its applicability is limited to duopoly competition between symmetric firms with specific R&D technology. In this section, we extend the baseline model to another R&D specification so that we can check the robustness of our main results.

Suppose that n firms compete with prices in the market and they have *ex ante* the same level of efficiency in production, i.e, $c_i = \bar{c}$ for $\forall i$. To analyze the oligopoly competition, we modify the R&D technology as follows. Suppose that every firm has the same support of the cost distribution, say $[\underline{c}, \bar{c}]$ after making investment. For convenience, define $\Delta := \bar{c} - \underline{c}$. The cost distribution after R&D investment is assumed to be

$$G(c; I) = 1 - \left[1 - \frac{c}{\Delta}\right]^I \quad (2.11)$$

This is a common specification of modeling R&D in previous literature. In this specification, I can be interpreted as the number of R&D activities and c is the lowest number among independently drawn R&D results. The result of investment is bounded at a certain level, but the cost distribution of a firm with greater I first-order stochastically dominates rivals' distributions. All other settings, including the assumptions on R&D cost function, the timing of the game and the equilibrium concepts in each case, are the same as in the baseline model. The following proposition presents the comparison of investment incentives in each case.¹⁵

Proposition 2.5. *In oligopoly competition, there exists a symmetric equilibrium in the complete information and unobservable investment cases. The symmetric investment equilibrium in the complete information and unobservable investment cases are identical. However, in the symmetric investment equilibrium in the observable investment case, firms invest less compared to complete information and unobservable investment case.*

As with the baseline model, if investment is unobservable, firms choose to invest symmetrically in the unobservable investment case and hence the equivalence between the complete information case and unobservable case holds. Observable investment also induces underinvestment in the equilibrium, implying that investment has a negative strategic effect. Unlike the baseline model, however, the direction of strategic effect can clearly be derived. Recall Lemma 2 in the previous section: if a firm engages in additional investment, it always makes the rival price lower, whereas

¹⁵The detailed derivation is in Appendix B.

the investor prices less aggressively given any c in the common support. The effect of investment on each firm's pricing strategy is not tractable here. But what we do know from the proposition above is that the marginal benefit of investment is reduced due to the adjustment of firms' pricing strategies to investment. In other words, if a firm invests more in the first stage, it will have a lower chance to win the market. This shows the robustness of our main result and yields the same welfare implications as in the baseline model.

Proposition 2.6. *In oligopoly competition, the complete information case and unobservable investment case implement the socially optimum level of total welfare. In the observable investment case, however, both social welfare and consumer surplus decrease compared to the complete information and unobservable investment case.*

2.6 Discussion

2.6.1 Asymmetric Equilibria

In previous sections, we have focused on the symmetric equilibrium in the analysis. Indeed, the complete information and unobservable investment case in both models have a unique symmetric equilibrium¹⁶ and as mentioned in section 2.3.2, this is the crucial reason why market outcomes are identical in those cases. However, considering the nature of a negative strategic effect, we can anticipate that the post-investment symmetry between firms can be broken when investment is observable. Specifically, firms may have an incentive to deviate to a lower level of investment because, compared to the unobservable investment case, a strategic effect allows the firm to have a relatively higher chance of winning the market. This explanation can be confirmed by modifying R&D technology as follows.

¹⁶The uniqueness of the symmetric equilibrium is sustained even under a wider class of cost distributions than the one used in our model.

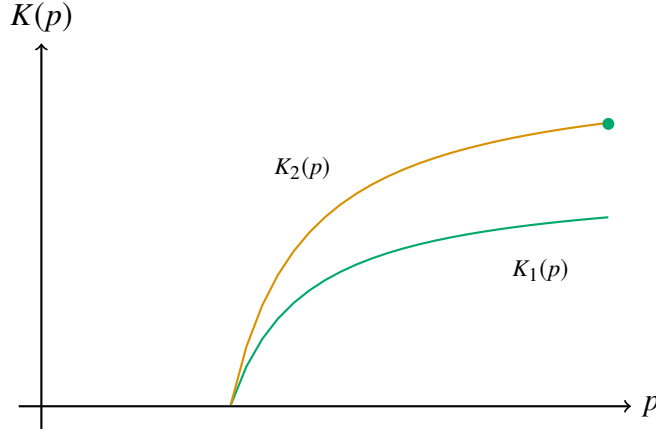


Figure 2.2: Mixed Pricing Strategy in Observed Investment Case

As is the case in the baseline model, firm 1 and 2 compete with price for a homogeneous product. Two firms are initially symmetric, that is, $c_i = \bar{c}$ for $i = \{1, 2\}$. Consider the following simple R&D technology. In the R&D stage, a firm can engage in R&D activities to reduce costs to the lower level, $\underline{c}$. Specifically, if a firm invests $I \in [0, 1]$, its marginal costs can be lowered to $\underline{c}$ with probability of I . Let's denote a firm's monopoly profits as $\hat{\pi}$ and assume that the R&D cost function is $\Phi(I) = \frac{k}{2}I^2$, where k represents the R&D cost parameter. The detailed analysis can be found in appendix B.¹⁷

In the complete information and unobservable investment cases, there exists a unique symmetric equilibrium for investment and they are identical. Furthermore, they achieve the socially optimal level as the baseline model. The interesting case is the observable investment case. In the discrete type case, firms face two types of payoff functions in the price competition stage, depending on whether they invest more or less than the rival. This induces two strategies for firms in the R&D stage: the aim to invest more than the rival or, inversely, less than the rival. In the equilibrium, one firm chooses the former strategy, while the other firm chooses the latter, implying that only asymmetric equilibria exist in the R&D stage.

As noted above, this is due to a strategic effect of investment. Suppose that $I_1 > I_2$. When

¹⁷The implications for private incentives of information sharing and investment are present in the case where firms face a general form of downward sloping demand.

cost information is private, pure pricing equilibrium does not exist and firms use mixed strategies in the equilibrium. Unobservable investment cannot break the symmetry between firms, and firms therefore use the identical pricing strategy. If firms can observe the rival's investment level, however, firm 2 uses the same mixed strategy, $K_2(p)$ as in the unobservable investment case, whereas firm 1 modifies the pricing strategy, $K_1(p)$ by putting more weight on high prices. Specifically, there exists a mass point at the highest price in order to prevent more fierce competition as shown in Figure 2. It can be interpreted as a mixed strategy version of the strategic effect of investment. The strategic effect enables firm 2 to deviate from the symmetric equilibrium in the unobservable investment case. Due to this strategic effect, firm 2 can earn more profit at the lower level of investment because the reduction in the probability of winning the market is lower than in an environment without the strategic effect. Coupled with the savings in R&D cost, asymmetric equilibria arises in the observed investment case. This is another possible effect of observable investment.

2.6.2 Asymmetric Firms

Up until now, we have assumed that the costs of firms are drawn from the identical distribution. If we focus on price competition between symmetric firms without the consideration of cost reducing investment, information disclosure plays no role in the competition and expected value of market outcomes are identical regardless of information structures. However, if firms' production efficiencies are *ex ante* heterogeneous, information disclosure could induce additional effects on market outcomes. In order to explore this possibility, we will study an asymmetric version of the baseline model, using numerical methods.

The model we lay out in this subsection is the same as the baseline model, except for firms' initial production technologies. Specifically, before engaging in cost reducing investment, firm i 's cost is drawn from a uniform distribution on $[\bar{c} - \delta_i, \bar{c}]$. If $\delta_1 > \delta_2$, firm 1 is more efficient from an *ex ante* perspective. For convenience, define $\delta_i + I_i := \tilde{\delta}_i$. Then, $\bar{c} - \tilde{\delta}_i$ is the lower bound of firm i 's cost distribution after the investment. The c.d.f of firm i 's cost after the investment are denoted $\tilde{F}_i(c)$.

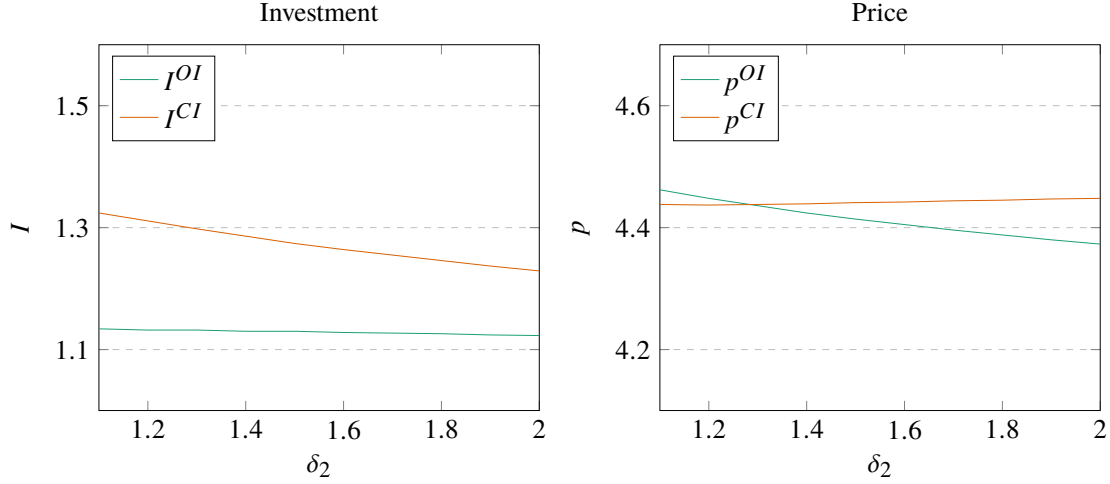


Figure 2.3: Investment Level and Price Level in Competition between Asymmetric Firms

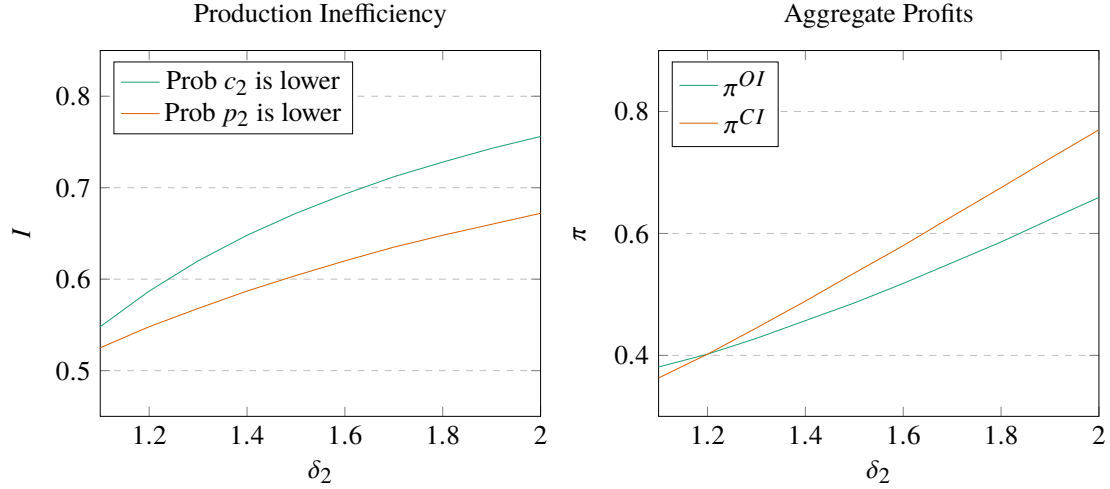


Figure 2.4: Production Inefficiency and Profits in Competition between Asymmetric Firms

The model is analyzed by using numerical methods, assuming $v = 6$, $\bar{c} = 5$, and $\Phi(I) = I^2/(\bar{c} - I)$. The results show changes in outcomes when firm 1's efficiency is increased from $\delta_1 = 1.1$ to $\delta_1 = 2$, whereas firm 2's efficiency is fixed at $\delta_2 = 1$. We compare results under the complete information and observable investment cases so that we can confirm whether the anti-competitiveness of incomplete cost information can be carried over to the asymmetric firms' case. The details can be found in appendix B.

Figure 2.3 shows asymmetric firms' investment level and price level. The solid curves represent the aggregate level, whereas dotted and dot-dashed curves graph the individual level in the observ-

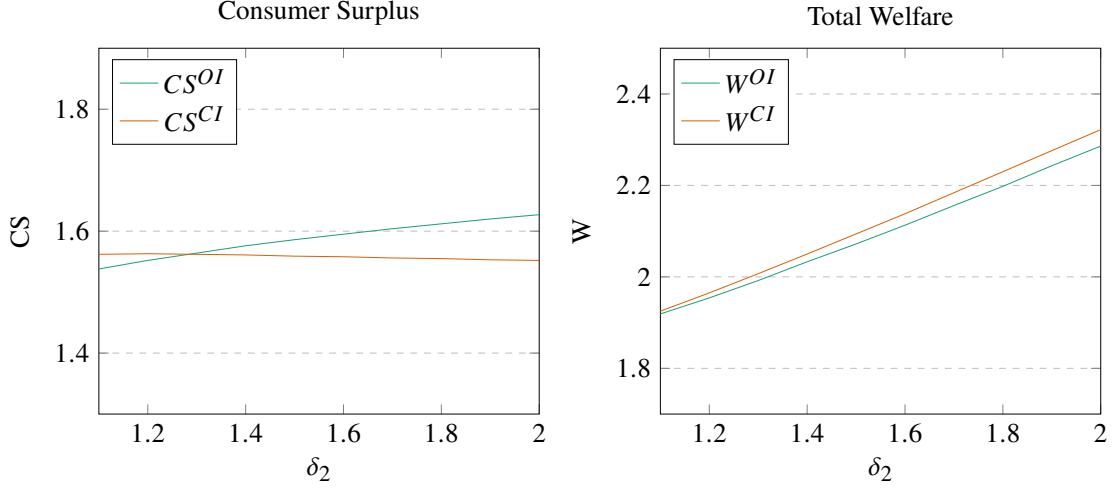


Figure 2.5: Consumer Surplus and Total Welfare in Competition between Asymmetric Firms

able investment case and complete information case, respectively. As in the symmetric firm case, complete information provides the socially optimal level of investment incentives to both firms, but the aggregate level of investment in the observable investment case is consistently lower than in the complete information case. This result mainly comes from the underinvestment by firm 1 which is *ex ante* more efficient.

When cost information is public, the expected prices of firm 1 and firm 2 are the same, but they are different in the observable investment case. At any initial degree of asymmetry, firm 1's price is lower than firm 2's, implying that firm 1 sets the price more aggressively in a stochastic sense, although firm 2 sets the price lower at any given c in the common support.

Figure 2.4 graphs the probabilities that firm 1 has a lower price and lower cost in the observable investment case and aggregate profits. The fact that those curves are not identical indicates that the market is sometimes served by a firm which has a higher cost. This is because firm 2 prices more aggressively than the rival at $\forall c \in [\bar{c} - \tilde{\delta}_2, \bar{c}]$. Thus, the difference between the two curves in the first figure in figure 2.4 represents the product inefficiency due to incomplete information.

Figures 2.5 compares consumer surplus and welfare in the observable investment case and complete information case. The second figure in Figure 2.5 shows that the information disclosure has a positive effect on total welfare, which is consistent with the symmetric case. However, our

main result about consumer surplus and industry profits is not sustained under the assumption of *ex ante* asymmetry. In the asymmetric firm case, there are two effects of cost uncertainty in addition to the underinvestment. On the one hand, if cost information is private, it is possible for a firm with higher cost to win the market in the asymmetric case, as shown in figure 2.4. Taken together with the underinvestment as in the symmetric case, this possibility induces additional welfare loss. On the other hand, the more efficient firm cannot fully exploit the market power and set a price less than the rival's cost in the observable investment case because the advantage on efficiency does not guarantee capture of the market. This effect becomes larger as the degree of asymmetry is greater, and most surplus is taken by the more efficient firm as shown in figure 2.4.

The result implies that there is no clear cut policy implications when firms are *ex ante* asymmetric. When firms are somewhat symmetric, our main results are robust. That is, when the degree of asymmetry between firms is small, information disclosure increases both consumer surplus and social welfare. When one firm is much stronger than the rival, however, information disclosure may hurt consumers, whereas it remains beneficial to society. Therefore, judgments about information disclosure depends on whether authorities give greater priority to consumer or society when the difference in initial technology between firms is huge.

2.7 Conclusion

This paper explores the effect of information sharing practices on R&D investment incentives and implications of observability of the investment level. Although the assumption of investment observability is appropriate in many situations, our understanding of its effect has been largely limited to date.

In sections 2.3 and 2.4, we analyzed a pure Bertrand duopoly model in a situation where firms have private information about the stochastic R&D outcome and showed that market outcomes are identical when the investment level is unobservable regardless of whether or not cost information is private. If, however, firms can observe the opponents' investment level, we show that this

observability of investment distorts firms' pricing strategy and it induces a negative strategic effect when cost information is not shared. Firms in turn invest less than in the complete information case, leading to lower consumer surplus and total welfare. We found in section 2.5 that this effect is robust in another type of R&D technology and oligopoly competition. However, under the assumption of asymmetry between firms prior to R&D competition, our results about industry profits and consumer surplus are reversed when the production efficiency of one firm initially dominates the rival's.

In this paper, we constructed a simple model with inelastic demand on homogeneous product which induces identical market outcomes when investment level is not observable. However, this result can be altered if the model embraces downward-sloping demand and/or horizontal differentiated product. It would be interesting to investigate how market outcomes are changed under each information structure when assumptions on demand and product type are relaxed. Nevertheless, the present paper formalizes the mechanism through which the observability of R&D investment introduces strategic incentives to invest in a situation where firms face *ex ante* uncertainty and *ex post* information asymmetry about the R&D outcome. It also highlights what the crucial elements to consider in evaluating the welfare effects of information sharing are. Furthermore, beyond the observability of the investment level, the degree of *ex ante* asymmetry between competitors should be an important criterion.

CHAPTER 3

THE GRANDFATHER OF PRICE DISCRIMINATION

3.1 Introduction

A grandfather clause exempts certain groups of people from a wider change in circumstances. Historically, grandfather clauses were found in a variety of legal contexts.¹ However, as we discuss in greater detail below, grandfather clauses have become common in retail, particularly in online and telecommunications services. In retail, grandfather clauses typically exempt existing subscribers of a service from a price hike or allow them to continue consuming a discontinued service. Thus, grandfather clauses permit firms to discriminate between early adopters and new consumers of their service, albeit at a cost: discrimination prevents the firm from pricing optimally to early adopters.

Grandfather clauses substantially fall into two categories: (i) clauses where grandfathered customers are permitted to continue to pay the same price that they paid in the past, possibly for a product generally viewed as an improvement, whereas new customers are forced to pay a higher price, and (ii) clauses where grandfathered customers end up consuming a distinctly different product from that made available to new consumers. In this manuscript we focus primarily on the profit and welfare implications of the former category with the aim of understanding when businesses might be able to profitably rely on grandfather clauses and whether doing so makes consumers better off. The advantage of focusing on category (i) is that it enables us to hone in on the direct ramifications of offering a grandfather clause rather than on potential consumer switching behavior between products produced by the same firm.² Our model of grandfather clauses is

¹For instance, at the turn of the twentieth century, grandfather clauses were used to circumvent the fifteenth amendment. The grandfather clauses exempted poor whites from poll taxes and literacy requirements used to disenfranchise Southern blacks (Schmidt 1982). Grandfather laws were also occasionally used following state increases in the legal minimum drinking ages to exempt those already permitted to drink from the change in law (Williams et al. 1983).

²From a modeling perspective, category (i) only differs from category (ii) insofar that grandfathered consumers might opt to purchase a product that they value differently (the product made

motivated by the seminal qualitative choice frameworks of McFadden (1974) and Perloff and Salop (1985). This modeling framework is apt for the analysis of grandfather clauses, which are generally found in product categories that can reasonably be categorized by oligopolistic competition and discrete choice: for instance, the markets for mobile wireless service, health insurance, and certain on-line content. To make the application of grandfather clauses meaningful within our framework, we allow products and consumer tastes to evolve over time. Thus, a consumer who subscribed to one service in the past might choose a different service today, especially if faced with a higher relative price. In this case, grandfather clauses have bite: they may allow firms to retain existing customers while raising prices for product variants generally viewed as improvements over previous versions.

We find that when consumers are fully cognizant of their valuations for available product alternatives, a firm would prefer to offer all of its potential consumers a uniform price rather than price discriminate via grandfather clauses. In our setting, we suppose that individual consumers' idiosyncratic preferences for products are independent over time. In such a setting, a firm faces the same maximization problem for both, its fully informed existing customers, and potential, but likewise fully informed consumers and should therefore charge both groups of customers the same price. Thus, a grandfather clause, which is by design intended to allow a firm to charge different prices to these two groups of customers would not serve.

This negative result begs the question, "what must a business believe about its customers to want to offer them a grandfather clause?" Although, we consider a number of potential explanations, our primary focus in this manuscript is on an environment in which consumers are complacent with regard to their idiosyncratic preference and alternative price discovery. That is, suppose that because potential consumers are engaged in hundreds or thousands of markets, they do not necessarily make the effort to reconsider their individual specific preferences for products or to price shop, even if general changes in their previously chosen product suggest that idiosyncratic preferences and alternative product prices should have changed as well. However, consumers might available to new consumers) for a different price from the same firm.

be induced to preference and price discovery if their attention to a market is drawn by say a price increase for the service they subscribe to or a general, relative improvement to a competitor's product. We find that in an environment where consumers are complacent, a firm might prefer to offer grandfather clauses in order to prevent preference and price discovery if doing so outweighs the potential gain from charging a higher uniform price to grandfathered customers who would remain with the firm anyway. Even though prevention of preference and price discovery can be detrimental to consumers, consumer surplus goes up if grandfathered customers pay a low enough price for a sufficiently improved product. Yet, even if consumers benefit, total welfare is bound to fall because some consumers don't end up purchasing from the firm that would have left them with a product they value more.

To motivate our analysis, we present various recent examples where grandfather clauses have been used in a retail setting. We suspect that an example that is familiar to most readers is in the U.S. mobile wireless industry, where nationwide service providers have been known to grandfather customers into previously contracted plans that are not made available to new customers. For instance, both AT&T and Verizon Wireless have previously grandfathered existing customers on unlimited data plans.³ Moreover, in its 2014 Open Internet Order, the U.S. Federal Communications Commission pointed to its concern over Verizon Wireless attempts to limit the speeds of customers on grandfathered unlimited plans in its discussion of exceptions to its "bright line" anti-discrimination rules (see U.S. FCC 2014). Although in the case of these unlimited plans, grandfathered mobile wireless customers end up consuming what is effectively a different product from those marketed to new customers, other customers are simply locked into a lower price for plans that remain on the market. Although some such customers may have initially purchased what is now deemed a slower service, as long as they upgrade their handsets to those capable of operations within the

³See Bea, F. "AT&T Permitting iPhone 5 Buyers to Grandfather in Existing Unlimited Data Plans." *Digital Trends*. September 12, 2012. Retrieved August, 2015. <<http://www.digitaltrends.com/mobile/att-letting-iphone-5-owners-keep-their-old-dataplans/#ixzz3XsSqKJNp>>; Dragani, R. "Verizon Nixes Unlimited Data Grandfather Clause." *E-Commerce Times*. May 17, 2012. Retrieved August, 2015. <<http://www.ecommercetimes.com/story/75141.html>>.

latest technology, grandfathered customers end up with an improved product at a lower price.

Netflix presents another well publicized example of a grandfather clause where existing consumers retained access to the same service available to new customers at a discounted price. In May 2014, Netflix announced plans to raise prices to subscribers receiving HD quality service by \$1 a month while allowing existing customers to keep their current price for two years.⁴ In September 2014, Apple offered certain existing iCloud storage customers the opportunity to keep their current storage plan, which is priced very closely to the lowest paid storage plan available to new customers, but with an additional 5GB of storage.⁵ Yet another example of retail grandfather clauses occurs when a retailer begins charging for a service that was previously free. For instance, in 2012 Google ceased offering the free edition of its cloud computing Google Apps software and e-commerce platform Ecwid decreased its product sales limit for new users of its free plan, while permitting prior registered users to retain their existing level of service.⁶

In the U.S., grandfathering in retail has also been the consequence of legislative mandate. The 2010 Patient Protection and Affordable Care Act permitted health insurance providers to continue to offer service to consumers enrolled in certain individual grandfathered plans while discontinuing further enrollment as long as the insurer updated certain provisions of the plans in accordance with the act and notified consumers of these plans that they may not get some rights and protections that new plans satisfying the requirements of the act offer.⁷ These grandfathered plans were allowed to

⁴See Fung, B. “Netflix Prices are Rising Today. But Existing Subscribers Will Get a 2-Year Reprieve.” *The Washington Post*. May 9, 2014. Retrieved August, 2015. <<https://www.washingtonpost.com/news/the-switch/wp/2014/05/09/netflix-prices-are-rising-today-but-existing-subscribers-will-get-a-2-year-reprieve/>>.

⁵See Campbell, M. “Apple Offering Existing iCloud Storage Customers Grandfathered Capacities, Cheaper Rates.” *AppleInsider*. September 10, 2014. Retrieved August, 2015. <<http://appleinsider.com/articles/14/09/10/apple-offering-existing-icloud-storage-customers-grandfathered-capacities-cheaper-rates>>.

⁶See Google, Google Apps Administrator Help. *Google Apps Free edition (legacy)*. December 6, 2012. Retrieved August, 2015. <<https://support.google.com/a/answer/2855120?hl=en&ref=topic=6043588>>; Ecwid, Blog. *Ecwid announces new service plans. No price changes for our existing users*. September 5, 2012. Retrieved August, 2015. <<http://www.ecwid.com/blog/ecwid-news/ecwid-announces-new-service-plans-no-price-changes-for-our-existing-users.html>>.

⁷See Pub.L. 111148, 124 Stat. 119; HealthCare.gov, Health Coverage Rights and Pro-

persist as long as they were not changed in ways that would substantially cut benefits or increase costs to consumers.

To our knowledge, this is the first study that attempts to explicitly analyze the profitability and welfare consequences of using grandfather clauses in retailing. Unlike many other price discrimination strategies commonly used in retail (e.g., sales, coupons, quantity discounts, price-matching guarantees, and add-on pricing⁸) grandfather clauses are best characterized by direct market segmentation—a firm knows precisely who its grandfathered customers will be and can segment the market accordingly.

More precisely, grandfather clauses segment the market based on past purchase history. Previous studies have shown that when it is possible to discriminate among customers according to purchase history, rather than offer existing customers lower prices, firms may use information inherent in past purchase behavior to induce rivals' customers to switch by offering them lower prices instead (Villas-Boas 1999, Fudenberg and Tirole 2000).⁹ A related form of pricing sometimes results when consumers face switching costs. When consumers must pay (either implicitly or explicitly) to switch to a rival producer, firms may exercise market power over their existing consumers by charging them more than they paid as new customers—so called “bargains-then-ripoffs” pricing (see for instance Klemperer 1987a, 1987b, 1995; Padilla 1992)—and more than to the existing customers of rival firms—“poaching” (see Chen 1997, Taylor 2003).¹⁰ These models entail vigorous competition for market share through bargains early on followed by ripoffs to customers who would have to pay to

tections. *Grandfathered health insurance plans*. March 23, 2010. Retrieved August, 2015. <<https://www.healthcare.gov/health-care-law-protections/grandfathered-plans/>>. Job-based grandfathered plans could continue to enroll individuals.

⁸The formulation of the price discrimination inherent in these strategies is well described in respectively: Varian (1980), Narasimhan (1984), Dolan (1987), Png and Hirshleifer (1987), and Ellison (2005).

⁹Acquisti and Varian (2005) also examine firms' ability to condition prices on past purchase history via a purchase tracking technology (e.g., HTTP cookies and related devices). As in Fudenberg and Tirole (2000), firms may induce switching behavior, albeit via service personalization instead of through lower prices. Fudenberg and Villas-Boas (2006) survey the literature on price discrimination according to customer recognition.

¹⁰Farrell and Klemperer (2007) provide a detailed overview of the literature on switching costs.

switch brands (potentially with inducements offered to rivals' customers).

A closely related literature considers endogenous switching costs via loyalty or reward programs. As in the case with grandfather clauses, and unlike in the literature on exogenous switching costs, loyalty programs allow existing customers to pay lower prices than newcomers. For instance Banerjee and Summers (1987) examine loyalty inducements in a homogenous good setting with sequential pricing and find that loyalty programs can facilitate collusion. In their model, firms benefit from increases in a rival's "loyalty coupon" because the coupon deters the rival from undercutting. In contrast, working in a horizontally differentiated model with simultaneous pricing, Caminal and Matutes (1990) find that precommitments to charge returning customers lower prices lead to a declining price path for all consumers and lower profits than without precommitments.¹¹

A driving feature of most exogenous and endogenous switching cost models is forward looking strategic behavior whereby firms use foresight of future prices and market shares in setting prices before the market matures. Instead, in this manuscript, rather than treat grandfather clauses as a strategic device that firms anticipate when setting prices early on, we focus on whether grandfather clauses should be used in a mature market setting. In contrast to much of the literature on exogenous switching costs, Shaffer and Zhang (2000) find that when the customers of a firm are substantially more loyal to that firm than the rival's customers are to that rival, both firms should offer inducements to the rival firm's customers, which entails the rival offering its own customers a lower price than to newcomers. As in Shaffer and Zhang (2000), our model takes past behavior as given and asks how competition today is affected if firms can price-discriminate. However, aside from focusing on a particular form of price discrimination not expressly contemplated by Shaffer and Zhang, our model neither relies on switching costs nor on aggregate differences in preferences or costs across groups of consumers who frequent particular firms.

The remainder of this manuscript is organized as follows. In Section 3.2 we present a baseline model in which we introduce grandfather clauses in a setting where consumers are perfectly

¹¹Caminal and Matutes (1990) also examine a framework where firms can reward returning customers using coupons instead of precommitments, but find that coupons do not survive when the choice of precommitment or couponing is endogenized.

informed about their preferences and the prices for product alternatives. In Section 3.3 we model grandfather clauses when consumers are complacent and show that in this setting a higher quality firm might wish to grandfather. Section 3.4 concludes with a discussion of alternative settings in which grandfather clauses might raise profits.

3.2 Baseline Model

3.2.1 Firms and Consumers

Two firms, labeled 1 and 2, offer differentiated, competing subscription services. Firms face no capacity constraints and have an identical constant cost of 0 of offering one unit of their respective services. There is a unit mass of consumers with idiosyncratic tastes over these services described as follows. Each consumer values consumption of a unit of service i according to some nonstochastic average quality μ_i combined with a stochastic preference parameter $\epsilon_i \in [\underline{\epsilon}_i, \bar{\epsilon}_i]$ that represents the consumer's idiosyncratic preference for brand i .¹²

Consumers freely observe both firms' prices and each consumer subscribes to a single unit of the service that maximizes his utility, or:

$$u_i = \mu_i + \epsilon_i - p_i \tag{3.1}$$

where p_i is the price of service i and u_i is the consumer's utility. Following Perloff and Salop (1985), we exclude "outside services" from the analysis by assuming that each consumer purchases that service among those offered by firms 1 and 2 that gives him the highest utility regardless of the actual cardinal level of utility.

We assume that individual consumers' idiosyncratic preferences are distributed independently and identically with mean zero within brands and that aggregate preferences for the two brands are distributed independently according to density f_i .¹³

¹²We do not explicitly rule out the possibility that $\underline{\epsilon}_i = -\infty$ or that $\bar{\epsilon}_i = \infty$.

¹³Perloff and Salop (1985) also assume that preferences are symmetric across brands whereas

For a given consumer, $u_1 \geq u_2$ if and only if $\mu_1 - \mu_2 - p_1 + p_2 + \epsilon_1 \geq \epsilon_2$. Then, letting differentiable function F_i represent the distribution associated with density f_i , the probability that $u_1 \geq u_2$ is given by $F_2(\mu_1 - \mu_2 - p_1 + p_2 + \epsilon_1)$. We can now represent the proportion of consumers who purchase from brand i —alternatively, the quantity of services ordered from firm i —as a function of firm prices and average qualities by:

$$Q_i(p_1, p_2; \mu_1, \mu_2) = \int_{\epsilon_i}^{\bar{\epsilon}_i} F_j(\mu_i - \mu_j - p_i + p_j + \epsilon_i) f_i(\epsilon_i) d\epsilon_i \quad (3.2)$$

and because there is no outside option, $Q_j(p_1, p_2; \mu_1, \mu_2) = 1 - Q_i(p_1, p_2; \mu_1, \mu_2)$.

For ease of exposition, define $\epsilon \equiv \epsilon_2 - \epsilon_1$ and let $\epsilon \sim F(\epsilon)$ where F is a differentiable distribution function with a density that is symmetric about zero to which we assign additional restrictions as necessary throughout the manuscript. If, for instance, aggregate preferences are distributed identically and independently according to the Type I extreme value distribution, then F becomes the widely used logistic distribution. An example that we will turn to throughout the manuscript will assume that ϵ is distributed uniformly.¹⁴

Define $\Delta \equiv \mu_1 - \mu_2$. Then, the quantity of services ordered from firm 1 is simply $F(\Delta + p_2 - p_1)$ and firm expected profit functions are given by:

$$\pi_1(p_1; p_2, \Delta) = p_1 F(\Delta + p_2 - p_1) \quad (3.3)$$

$$\pi_2(p_2; p_1, \Delta) = p_2 (1 - F(\Delta + p_2 - p_1)) \quad (3.4)$$

Assumption 1. *Suppose that firms engage in single-period differentiated Bertrand competition. Then there exists a unique interior equilibrium of the duopoly game described above.*

A necessary condition for existence of equilibrium is that both first order conditions are satisfied. Suppose that $\Delta = 0$. Then if a single price equilibrium exists, it is readily shown that the equilibrium

Chen and Riordan (2008), who use a related model to study price-increasing competition, assume that aggregate preferences are symmetric, but not necessarily independent across brands. Chen and Riordan (2008) additionally permit consumers to have an outside option.

¹⁴Note that in this case, aggregate preferences for individual brands cannot be identically distributed. We impose additional assumptions as necessary (e.g., to calculate welfare).

price equals, $p = 1/(2f(0))$ where f is the density associated with F . Perloff and Salop (1985) show that when aggregate preferences are distributed symmetrically across brands, a unique single price equilibrium exists and there are no multi-price equilibria (see Perloff and Salop Proposition 4). However, as seen in the example below, because we allow average quality to differ across firms (so that Δ does not necessarily equal zero), a unique interior equilibrium need not result in a single price.

Example. Suppose that ϵ is distributed uniformly on $[-a, a]$. Solving for equilibrium in our baseline model yields prices p_i , quantities q_i , and profits π_i as follows:

$$p_1 = a + \frac{\Delta}{3}, \quad p_2 = a - \frac{\Delta}{3} \quad (3.5)$$

$$q_1 = \frac{1}{2a} \left(1 + \frac{\Delta}{3}\right), \quad q_2 = \frac{1}{2a} \left(1 - \frac{\Delta}{3}\right) \quad (3.6)$$

$$\pi_1 = \frac{1}{2a} \left(1 + \frac{\Delta}{3}\right)^2, \quad \pi_2 = \frac{1}{2a} \left(1 - \frac{\Delta}{3}\right)^2 \quad (3.7)$$

Importantly, the prices, quantities, and profits of firm 1 increase and those of firm 2 decrease as firm 1's average quality advantage relative to firm 2 increases.

Even when $\Delta \neq 0$, this framework allows us to place reasonable bounds on prices in a single-period differentiated Bertrand game, which we rely on later in the manuscript. In particular, as we show below, in equilibrium, a firm with higher average quality will not set a lower price than its competitor. Moreover, that price cannot exceed the price of its competitor by more than the difference in average qualities.

Lemma 1. *Suppose that $\Delta > 0$. Then $0 \leq p_1 - p_2 \leq \Delta$.*

Proof. The first order conditions for firms 1 and 2 respectively are:

$$F(\Delta + p_2 - p_1) - p_1 f(\Delta + p_2 - p_1) = 0 \quad (3.8)$$

$$1 - F(\Delta + p_2 - p_1) - p_2 f(\Delta + p_2 - p_1) = 0 \quad (3.9)$$

Solving Equations (3.8) and (3.9) for $f(\Delta + p_2 - p_1)$ and rearranging yields:

$$1 = F(\Delta + p_2 - p_1) + \frac{p_2}{p_1 + p_2} \quad (3.10)$$

Because $F(0) = 1/2$, it follows that if $p_2 > p_1$, then both terms on the right-hand side of Equation (3.10) are greater than $1/2$, a contradiction. If instead $p_1 - p_2 > \Delta$, then both terms on the right-hand side of Equation (3.10) are less than $1/2$, which is likewise a contradiction. $\square$

Inspection of Equation (3.5) in our uniform distribution example will show that $p_1 - p_2 = 2\Delta/3$. Thus, both bounds hold.

3.2.2 Grandfather Clauses

We study grandfather clauses using a single-period mature market in which half of all consumers have previously subscribed to firm 1's service and the other half subscribed to that of firm 2. The idea that both firms initially hold half the market may be justified by supposing that prior to market maturity, firms provided services with the same initial quality at the same initial price. We further suppose that the initial price prior to market maturity, p^o , equaled the single-period, single price equilibrium price, $p^o = 1/(2f(0))$.¹⁵ Thus, if a firm wishes to grandfather its existing consumers, it must offer them a price of p^o that is different from the price charged to potential new customers. Going forward, we refer to the time prior to market maturity as the initial period and we refer to the stage to be studied as the mature market period.

If neither consumer tastes nor firm quality changes between the initial and mature market periods, then the use of grandfather clauses does not have a real world counterpart in the following sense: grandfathered customers must be made to feel that they are consuming a better product than that available to newcomers or they must be able to obtain a better price than what newcomers would have to pay. Thus, suppose that between the initial and mature market periods, firm 1 announces an average quality improvement of $\nu > 0$. As a result, Δ rises from 0 to ν . Because our focus in this manuscript is on grandfather clauses, we suppose that the quality improvement is exogenous and costless for firm 1.

¹⁵We note that because we are not solving a two-stage pricing game, equal market shares in this setting imply that the actual (not just expected) realization of idiosyncratic preferences was such that half of consumers initially preferred each service.

For simplicity, we suppose that only firm 1 can offer grandfather clauses. The game proceeds as follows: at the outset of the mature market period, firm 1 decides whether or not it will grandfather its existing consumers and simultaneously chooses a new price while firm 2 simultaneously sets its own price.¹⁶ Neither firm can engage in any other form of price discrimination and grandfathered consumers are free to choose the rival firm's product.¹⁷ Moreover, grandfathered consumers benefit from the average quality improvement, and will choose the new price if that price is lower. After firms set prices, consumers make their purchasing decisions and profits and welfare are realized.

At this juncture, the astute reader may ask why we do not study grandfather clauses in a rational expectations framework in which firms account for the potential competitive effects of grandfather clauses when setting prices in the initial period. As discussed in Section 1, such frameworks are common in the switching cost literature. In the subgame perfect Nash equilibrium of such a game, there is no a priori reason to think that initially symmetric firms would set the same price and end up with the same market share in the initial period if grandfather clauses stipulate that these prices will directly impact profitability in the mature market period. However, mathematical tractability aside,¹⁸ there are two reasons to fix initial prices and market shares regardless of whether grandfather clauses will be used in the mature market period. First, we interpret the time that passes between the initial and mature market periods as sufficiently lengthy to allow for average quality to change and to justify price adjustment. However, without investigating investment in quality in greater detail, it is difficult to determine which of two initially symmetric firms will end up with the relative quality improvement in the mature market period, and consequently, how resulting price

¹⁶The simultaneous move structure of our game is motivated by various of our examples in Section 1, where a mature market firm simultaneously resets its price while grandfathering existing consumers. However, within the setting of our main model in the next section, it will become apparent that the results are robust to a setting where firm 1 informs its rival and consumers of its intent to grandfather prior to setting its price.

¹⁷So, for instance, we suppose that firm 2 cannot specifically offer firm 1's existing, potentially grandfathered, customers incentives to switch.

¹⁸In a rational expectations framework, subgame perfection would require us to calculate mature market period prices for any level of initial market shares, and in light of grandfather clauses, it would additionally require prices to be contingent on any initial period price that might be offered to grandfathered consumers.

adjustments and the application of grandfather clauses in the future should affect prices in the initial period. Second, our primary interest is in informing managers of firms in mature markets who are contemplating implementing a grandfather clause rather than in any gaming (e.g., for the purposes of collusion or exclusion) that grandfather clauses may permit firms to undertake.¹⁹

In this subsection, we assume that consumers are always cognizant of prices, average qualities, and their idiosyncratic preferences for both brands. We suppose that individuals' idiosyncratic preferences are independent over time—effectively positing that enough time has passed such that the initial period preferences do not convey any idiosyncratic information to the individual when the market has matured. Moreover, we suppose that the ϵ_i are redrawn in the mature market period according to the same distribution as in the initial period—that is, we suppose that individual preferences may have changed, but that aggregate preferences have not.²⁰

It turns out that under the assumptions in this section, firm 1's optimal strategy is to offer a uniform price to both its initial period customers and to potential consumers that it could poach from firm 2. As shown in Proposition 1, because this is the case for any potential price that firm 2 may offer, grandfather clauses are not played in equilibrium.

Proposition 3.1. *Suppose that consumers are aware of firm prices, average qualities, and their idiosyncratic preferences prior to choosing which service to purchase. Then, in equilibrium, firm 1 will choose to offer a uniform price rather than to grandfather its initial period customers by offering them a lower price than to potential consumers.*

Proof. Suppose that firm 2 chooses price p_2 . When setting prices, by offering a grandfather clause, firm 1 can price discriminate between its initial period customers and those of firm 2. Given a

¹⁹It seems to us sensible that firms would account for say potential consumer switching in the future when setting present prices. However, unlike switching costs, which are estimable in the present, the decision to apply grandfather clauses is contingent on changing firm, consumer and overall market characteristics that appear to us very difficult to predict up front, so that we believe that firms do not necessarily account for the possibility that they may choose to grandfather certain customers in the future when setting their prices in the present.

²⁰Thus, our setting is similar to the independent preference setting of Fudenberg and Tirole (2000), who also separately look at fixed preferences. In a future manuscript, we hope to study preferences that are either fixed, or in some sense correlated over time.

price p_1 , firm 1's initial period customers will remain with firm 1 if $v - p_1 + p_2 \geq \epsilon$. Thus, firm 1's expected profit in the mature market period from its initial period customers is given by:

$$\frac{p_1}{2}(v + p_2 - p_1) \quad (3.11)$$

Because idiosyncratic preferences for firm 2's initial period customers are redrawn from the same distribution, Expression (3.11) likewise represents firm 1's expected profit from poaching firm 2's initial period customers. Consequently, the value of p_1 that maximizes expected profits from former customers is the same as the value that maximizes expected profits from new customers. As a result, firm 1 will not wish to price discriminate by offering returning customers one price and new customers a higher price.²¹ $\square$

When preferences are independent over time, under the assumptions above, knowing whether a potential customer had previously purchased from firm 1 or 2 does not convey any useful information to firm 1 at either the individual consumer level or at any level of consumer aggregation. Because in our setup, firm 1 has no other means of price discrimination at its disposal, it prefers to set a uniform price. In fact, this straightforward result is more broad. Because firm 1's profit maximizing price for the two groups of customers does not depend on initial period market shares or prices, firm 1 would prefer a uniform price even if the initial period equilibrium were asymmetric—that is, when preferences are independent over time, under Assumption 1, uniform pricing turns out to be the outcome of the unique subgame perfect Nash equilibrium of an alternative rational expectations, two-stage pricing game.

3.3 Consumer Complacency

Our findings in Proposition 1 suggest that when consumers are perfectly informed about prices charged by firms 1 and 2 as well as regarding their own idiosyncratic preferences, then in the

²¹More broadly, this proof also rules out price discrimination whereby returning customers are asked to pay a higher price than new customers.

mature market setting being studied here, a firm would not be compelled to grandfather returning customers. This leads us to wonder why various firms facing oligopoly competition in a real world mature market setting would offer grandfather clauses. In this section, we set up a simple model of complacent consumers to offer one potential explanation. In the next section, we contemplate some alternative explanations.

Suppose that consumers are complacent in the following sense: they do not reevaluate their idiosyncratic preferences for the service that they consume, nor seek updated price information from other firms unless one of two things happens: (i) they are faced with a higher price for the service they currently consume or (ii) they discover that a rival service provider offers a higher relative quality alternative.²² As such, complacency here is not interpreted so much as a cost to uncover additional price and idiosyncratic product match information (as in Wolinsky 1986 or Anderson and Renault 1999), but as a failure to contemplate that this information changed after some period of time.

As in the previous section, we suppose that idiosyncratic preferences are independently and identically distributed in the initial and mature market periods. We also suppose that consumers are perfectly informed of all average quality improvements—that is, all consumers learn ν at the outset of the mature market game. One way to think about this is to suppose that quality improvements that are expected to affect all consumers are broadly advertised by the firms, but that it is more difficult to convey concrete price and individual preference information via advertising.²³

Assumption 2. *Consumers are complacent in the mature market period.*

Proceeding with our model from Section 2, modified by Assumption 2, we now see that if

²²For a firm i , this happens if μ_j rises relative to μ_i .

²³Because our core interest is in grandfather clauses, we do not explicitly model the process by which firms convey average quality information to consumers. A standard approach would be to suppose that the cost of advertising is increasing and strictly convex in the proportion of the population that receives an update of average quality (see for instance the price advertising models of Butters 1977 and Robert and Stahl 1993). Alternatively, we could suppose that there is a fixed cost to advertise to the entire population (e.g., Janssen and Non 2008). Our model implicitly presumes that advertising quality is costless.

firm 1 offers to grandfather its initial period consumers, these consumers will not reevaluate their idiosyncratic preferences nor prices for the two service alternatives and remain with firm 1. They will continue to pay $p^o = 1/(2f(0))$ for firm 1's service, but also benefit from firm 1's general quality improvement ν . Conversely, because firm 1 offers a higher quality product in the mature market period, firm 2's initial period customers will undertake price and idiosyncratic preference discovery (even if they were grandfathered). Thus, under Assumption 2, firm 1 can either choose a uniform price, in which case a price above p^o will lead both firms to compete for the entire market, or it can grandfather its initial period consumers and restrict competition in the mature market period to firm 2's initial period customers, but sacrifice potential profit gains from raising its price to its initial period customers.

As we show in Proposition 2, under some reasonable assumptions on f , firm 1 will want to offer a grandfather clause as long as ν is not “too high.” The intuition is straightforward. If firm 1's relative quality advantage over firm 2 is sufficiently large, firm 1 does not need to worry that its initial period customers will engage in information discovery following a price increase because firm 1's quality advantage will bring most of these customers back. On the other hand, if ν is relatively low, firm 2 remains competitive for firm 1's initial period customers and firm 1 can improve its profit by using a grandfather clause to prevent firm 2 from poaching its customers. Recall that this would not have worked in the previous section—what is crucial is that grandfather clauses may prevent information discovery.

Proposition 3.2. *Suppose that F is twice continuously differentiable and that f is symmetric about zero and single-peaked. Then under Assumption 2, there exists $\hat{\nu}$ such that for any average quality improvement $\nu < \hat{\nu}$, firm 1 will wish to offer a grandfather clause, and for any $\nu > \hat{\nu}$ it will not.*

Let $\pi_1^*(\nu)$ represent firm 1's equilibrium expected profit when it chooses a uniform price in the mature market period and let $\pi_2^*(\nu)$ represent firm 2's equilibrium expected profit when it believes that firm 1 will play a uniform price (and these beliefs are correct). The key to the proof of Proposition 2 is that under Assumption 2 the firms' expected profit functions when firm 1 chooses to grandfather its initial period customers are simply affine transformations of profits under uniform

pricing.²⁴ In particular, because firms' initial period profits equaled $1/(4f(0))$, firm 1's and 2's respective equilibrium expected profits in the mature market period when firm 1 does grandfather are $1/(4f(0)) + \pi_1^*(\nu)/2$ and $\pi_2^*(\nu)/2$. Thus for firm 1, expected profit when it offers to grandfather exceeds non-grandfathered expected profit if and only if $\pi_1^*(\nu) < 1/(2f(0))$. In the Appendix, we show that $\pi_1^*(\nu)$ is continuously increasing in ν and that there are values of ν low enough to satisfy and high enough to reverse the previous inequality, completing the proof.

In Proposition 2, we placed a number of restrictions on the forms of F and f in order to derive our “cut-off” result. However, as the following example shows, the single-peakedness condition (which we rely on to assure continuity of $\pi_1^*(\nu)$) is not necessary.

Example. Suppose that ϵ is distributed uniformly on $[-a, a]$. In this case, $\pi_1^*(\nu)$ is given by replacing Δ in Equation (3.7) with ν . Similarly, letting $\pi_1^{GFC}(\nu)$ represent firm 1's expected profit when it chooses to grandfather its initial period customers in the mature market period, we obtain:

$$\pi_1^{GFC}(\nu) = \frac{a}{2} + \frac{1}{4a} \left(a + \frac{\nu}{3} \right)^2 \quad (3.12)$$

Firm 1 will want to offer a grandfather clause whenever $\pi_1^{GFC}(\nu) > \pi_1^*(\nu)$, which simplifies to:

$$\nu < 3a(\sqrt{2} - 1) \quad (3.13)$$

That is, as in Proposition 2, firm 1 will want to offer a grandfather clause as long as its average quality advantage relative to firm 2 does not exceed $3a(\sqrt{2} - 1)$.

Observe that in the example above, the higher a —that is, the greater the variance of the distribution of the difference in idiosyncratic preferences—the greater the range of ν for which firm 1 would want to offer a grandfather clause under consumer complacency. This suggests that grandfather clauses are more likely to prove useful if tastes are more dispersed. In the next proposition, we explore this result in a more general setting.

For any distribution F consider the family of distributions G_α such that $G_\alpha(\epsilon) = F(\alpha\epsilon)$. Observe that G_α is a distribution for any $\alpha \in (0, \infty)$. When $\alpha < 1$, G_α stretches F horizontally, behaving

²⁴Thus, as suggested in footnote 16, it does not matter if firm 1 informs everyone that it will commit to grandfather before firms set prices or not because under Assumption 2, the prices that solve firms' first order conditions will be the same with or without grandfathering.

similarly to the original distribution, but with larger variance. Conversely, when $\alpha > 1$, G_α horizontally compresses F .

Proposition 3.3. *Suppose that F is twice continuously differentiable and that f is symmetric about zero and single-peaked. Then under Assumption 2, if the distribution of the difference in idiosyncratic preferences is given by G_α , for a fixed improvement ν , there exists some $\alpha^*(\nu) > 0$ such that firms will wish to offer a grandfather clause if and only if $\alpha \leq \alpha^*(\nu)$.*

Proposition 3.3 states that for any $\nu > 0$, there always exists a level of dispersion in idiosyncratic preferences (α low enough) that justifies offering a grandfather clause under Assumption 2. Greater dispersion in tastes in the manner defined above makes ν less effective in retaining customers. Thus, using grandfather clauses to make customers complacent becomes that much more valuable.

Together Propositions 3.2 and 3.3 characterize sufficient conditions for a firm to wish to offer a grandfather clause. The firm wishes to grandfather when either the quality improvement it offers is slight enough so as to keep it from having an overwhelming competitive advantage, or if consumer tastes are so dispersed as to make the quality improvement relatively insignificant. Corollary 1 relates these two propositions by telling us that the larger the improvement in quality, the more taste dispersion is needed to justify offering a grandfather clause.

Corollary 1. *$\alpha^*(\nu)$ is decreasing in ν .*

3.3.1 Welfare

Under Assumption 2, grandfather clauses are unambiguously bad for total welfare. This can be seen without any explicit calculation. Recall that because we have assumed that consumers have no outside option, the price paid for each consumer's chosen service is a pure transfer and may be discounted in total welfare calculations. Thus, only the realizations of idiosyncratic preferences and whether or not a consumer ends up purchasing from the firm that offers the best match (accounting for average quality) matter. When consumers are complacent, grandfather clauses distort optimal matching by keeping firm 1's customers from potentially realizing a better match with firm 2.

As discussed earlier in this section, grandfather clauses are beneficial for firm 1 as long as ν is not too high relative to the level of dispersion in idiosyncratic preferences. Conversely, grandfather clauses are also unambiguously bad for firm 2 because they effectively reduce its market share. Perhaps of greater interest is whether or not grandfather clauses increase consumer surplus. On the one hand, grandfather clauses reduce the average price paid by consumers. On the other hand, they cause some consumers to be matched poorly and to receive a service that they might not enjoy as much relative to the price paid. As shown in a continuation of our uniform distribution example below, the effect is ambiguous and depends on the value of ν relative to the level of dispersion in tastes.

Example. Suppose that ϵ is distributed uniformly on $[-a, a]$. In order to calculate consumer surplus, we additionally need to know how ϵ_i is distributed for each individual firm along with firms' initial period average service quality levels. Thus, for the purpose of this example, suppose that ϵ_1 is distributed uniformly on $[-a, a]$ whereas ϵ_2 is a point mass at zero and suppose that $a > \nu/3$. As will become evident in Equation (3.14), the inequality states that there is sufficient taste dispersion relative to the value of ν for some customers to find it worthwhile to frequent firm 2 in the absence of grandfather clauses. Additionally, suppose that initially, $\mu_1 = \mu_2 = \mu$. Then, if firm 1 chooses not to offer a grandfather clause in the mature market period, from Equation (3.5), we know that consumer surplus is given by:²⁵

$$CS = \int_{-\frac{\nu}{3}}^a \left[\mu + \nu + \epsilon_1 - \left(a + \frac{\nu}{3} \right) \right] \frac{1}{2a} d\epsilon_1 + \int_{-a}^{-\frac{\nu}{3}} \left[\mu - \left(a - \frac{\nu}{3} \right) \right] \frac{1}{2a} d\epsilon_1 \quad (3.14)$$

where the first integral is for firm 1's consumers and the second is for firm 2's. This expression simplifies to:

$$CS = \mu - \frac{3a}{4} + \frac{\nu}{2} + \frac{\nu^2}{36a} \quad (3.15)$$

Under Assumption 2, if firm 1 offers a grandfather clause, it retains the half of the market that it possessed in the initial period. Firm 1's initial period customers then pay it a price of a for a product

²⁵Note that the bounds of integration follow because consumers strictly prefer to purchase from firm 1 if and only if $\epsilon_1 > -\nu/3$.

with mature market average quality of $\mu + \nu$. Although these consumers are complacent when firms reset their mature market prices, these consumers ultimately realize idiosyncratic preferences as distributed above. Consumer surplus for the other half of the market is represented by Equation (3.14). Thus, when firm 1 offers a grandfather clause, consumer surplus is represented by:

$$CS^{GFC} = \frac{\mu + \nu - a}{2} + \frac{CS}{2} \quad (3.16)$$

Clearly, $CS^{GFC} > CS$ if and only if $\mu + \nu - a > CS$, which occurs whenever $\nu > 3a(3 - 2\sqrt{2}) \approx 0.51a$. That is, when ν is sufficiently large relative to a , the price savings to grandfathered customers (which are proportional to ν) are larger than the foregone gains from price and idiosyncratic preference discovery (which are proportional to a). Recall that firm 1 will only wish to offer a grandfather clause when $\nu \leq 3a(\sqrt{2} - 1) \approx 1.24a$. Thus, given some level of idiosyncratic preference dispersion and considering the range of ν under which firm 1 would find it profitable to offer a grandfather clause, consumers are worse off when $\nu \in (0, 0.51a)$ and better off when $\nu \in (0.51a, 1.24a)$.

3.4 Price Unfairness

An alternative explanation for the use of grandfather clauses is that they may serve as a useful mechanism to mitigate adverse consumer reactions to perceived price unfairness over increases in prices (e.g., see Bolton et al. 2003). When customers view a price increase by their existing firm as unfair, they may be more inclined to try a rival service. Grandfather clauses allow firms to avoid angering former customers using lower prices while offering newcomers (who might direct their anger at a rival firm) a higher price.²⁶

In this section, we return to the baseline model in Section 3.2, but modify consumer utility to suppose that any individual who encounters a price increase from their current service provider

²⁶We suspect that the Netflix decision to grandfather their existing subscribers in 2014 may have been driven in part by adverse subscriber reactions to an earlier substantial price increase in 2011. See Fung, B. “Netflix Prices are Rising Today. But Existing Subscribers Will Get a 2-Year Reprieve.” *The Wall Street Journal*. September 16, 2011. Retrieved October, 2011. <<http://www.wsj.com/articles/SB10001424053111904060604576572322651549428/>>.

finds the increase unfair and faces a reduction in utility equal to $\phi > 0$. To simplify, we suppose that individuals only perceive price unfairness when subjected to a price increase from their current service provider, and not from a provider with which they have no experience. Moreover, we suppose that all consumers who perceive price unfairness face the same exogenously given level of disutility. We can now rewrite the mature market utility for service i of a consumer who consumed service i in the initial period as:

$$u_i = \begin{cases} \mu_i + \epsilon_i - p_i - \phi & \text{if } p_i > a \\ \mu_i + \epsilon_i - p_i & \text{otherwise} \end{cases} \quad (3.17)$$

Assumption 3. *consumers perceive price increases as “unfair”.*

As in Section 3.2, suppose that firm 1 announces an average quality improvement of $\nu > 0$. Moreover, for ease of exposition, in this section and the next, let us suppose that ϵ_1 is distributed uniformly on $[-a, a]$ whereas ϵ_2 is a point mass at zero, meaning that ϵ is distributed uniformly on $[-a, a]$. Thus, from Equations (3.5) to (3.7) it follows that firm 1 is the only one that would want to offer a grandfather clause.

Throughout this section, we will assume that $\phi < 2\nu$: that is, the level of disutility from price unfairness that consumers perceive is not so high as to induce firm 1 to set its price equal to or below a for the purpose of avoiding an adverse reaction from consumers whenever it opts not to offer a grandfather clause. In other words, in equilibrium, firm 1 sets $p_1 > a$ even when it does not offer a grandfather clause (whereas firm 2 sets $p_2 < a$). In the appendix, we conduct the analysis for the case $\phi \geq 2\nu$. When $\phi < 2\nu$, firms' mature market period profit maximization problems when firm 1 does not offer a grandfather clause are:

$$\max_{p_1} \underbrace{\frac{p_1}{2} \left[\frac{\nu + p_2 - p_1 - (-a)}{2a} \right]}_{\text{profit from new customers}} + \underbrace{\frac{p_1}{2} \left[\frac{\nu + p_2 - p_1 - \phi - (-a)}{2a} \right]}_{\text{profit from existing customers}} \quad (3.18)$$

$$\max_{p_2} \underbrace{\frac{p_2}{2} \left[1 - \frac{\nu + p_2 - p_1 - (-a)}{2a} \right]}_{\text{profit from existing customers}} + \underbrace{\frac{p_2}{2} \left[1 - \frac{\nu + p_2 - p_1 - \phi - (-a)}{2a} \right]}_{\text{profit from new customers}} \quad (3.19)$$

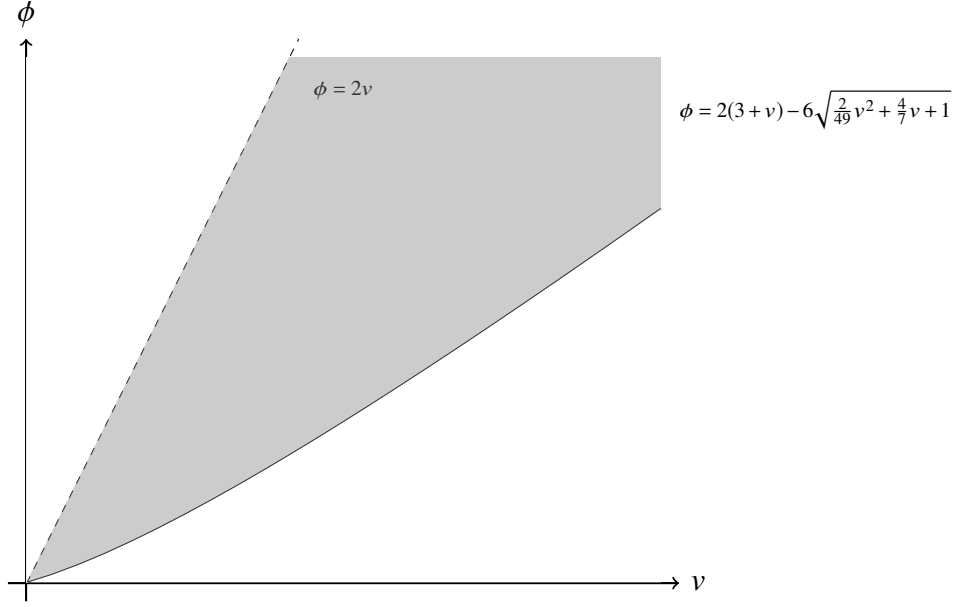


Figure 3.1: Area where Grandfather Clause is Useful ($a = 1$)

Simultaneously solving profit maximization problems (3.18) and (3.19) yields mature market period prices, quantities, and profits:

$$p_1 = a + \frac{v}{3} - \frac{\phi}{6}, \quad p_2 = a - \frac{v}{3} + \frac{\phi}{6} \quad (3.20)$$

$$q_1 = \frac{1}{2a} \left(a + \frac{v}{3} - \frac{\phi}{6} \right), \quad q_2 = \frac{1}{2a} \left(a - \frac{v}{3} + \frac{\phi}{6} \right) \quad (3.21)$$

$$\pi_1 = \frac{1}{2a} \left(a + \frac{v}{3} - \frac{\phi}{6} \right)^2, \quad \pi_2 = \frac{1}{2a} \left(a - \frac{v}{3} + \frac{\phi}{6} \right)^2 \quad (3.22)$$

As Equations (3.20) through (3.22) show, price unfairness dampens firm 1's price, quantity, and profit while increasing those of firm 2 relative to the baseline. This is because when $\phi < 2v$, in equilibrium, only firm 1's initial period consumers face disutility from price unfairness; firm 2's initial period consumers face a lower price in the mature market period and so do not perceive any additional disutility by purchasing from firm 2 again.

This result suggests that firm 1 may be able to raise its profit by offering a grandfather clause in order to avoid upsetting its initial period consumers while charging firm 2's initial period consumers a higher price for its higher quality. When firm 1 offers a grandfather clauses by charging its initial period customers price a in the mature market period, in equilibrium, no consumer perceives price

unfairness because firm 2 also sets a price $p_2 < a$ and firm 2's initial period customers who switch to firm 1 do not perceive unfairness concerning a product with which they had no prior experience. Firms' mature market period profit maximization problems when firm 1 offers a grandfather clause are therefore:

$$\max_{p_1} \underbrace{\frac{a}{2} \left[\frac{v + p_2 - a - (-a)}{2a} \right]}_{\text{profit from existing customers}} + \underbrace{\frac{p_1}{2} \left[\frac{v + p_2 - p_1 - (-a)}{2a} \right]}_{\text{profit from new customers}} \quad (3.23)$$

$$\max_{p_2} \underbrace{\frac{p_2}{2} \left[1 - \frac{v + p_2 - a - (-a)}{2a} \right]}_{\text{profit from new customers}} + \underbrace{\frac{p_2}{2} \left[1 - \frac{v + p_2 - p_1 - (-a)}{2a} \right]}_{\text{profit from existing customers}} \quad (3.24)$$

Simultaneously solving profit maximization problems (3.23) and (3.24), we can confirm that the price that firm 1 charges firm 2's initial period customers, $p_1 = a + 2v/7$, is greater than a , whereas firm 2's price, $p_2 = a - 3v/7$, is lower than a . Substituting p_1 and p_2 into firm 1's profit equation yields mature period profit:

$$\pi_1^{\text{GFC}} = \frac{a}{2} + \frac{2v}{7} + \frac{v^2}{49a} \quad (3.25)$$

Comparing Equation (3.25) with firm 1's equilibrium profit from Equation (3.22) yields the following set of inequalities:

$$\begin{aligned} \pi_1^{\text{GFC}} - \pi_1 &> 0 \\ \Leftrightarrow \underbrace{2(v + 3a) - 6\sqrt{a^2 + \frac{4}{7}av + \frac{2}{49}v^2}}_{\hat{\phi}} &< \phi < \underbrace{2(v + 3a) + 6\sqrt{a^2 + \frac{4}{7}av + \frac{2}{49}v^2}}_{\tilde{\phi}} \end{aligned} \quad (3.26)$$

Because $\tilde{\phi} > 2v$, $\tilde{\phi} > \phi$ always holds when, as assumed, $\phi < 2v$. In other words, when $\phi < 2v$, grandfather clauses are profitable whenever consumer disutility from price unfairness exceeds threshold $\hat{\phi}$. In fact, as Proposition 3.4 indicates, this is also the case when $\phi > 2v$.

Proposition 3.4. *Suppose that $\epsilon \sim U[-a, a]$. Then, when consumers perceive price unfairness, there exists $\hat{\phi}$ such that for any average quality improvement v , firm 1 will wish to offer a grandfather clause if and only if $\phi > \hat{\phi}$.*

3.4.1 Welfare

Unlike the case in which consumers are complacent, the effect of grandfather clauses on welfare is not obvious. As mentioned earlier, grandfather clause induces bad matching between firms and consumers but under Assumption 3, grandfather clause can mitigate disutility from consumers' negative perception against price increases. The following example with a continuation of our uniform distribution shows that the latter effect may exceed the former effect so that grandfather clause can increase welfare.

Example. As in the example in section 3.3.1, suppose that ϵ is distributed uniformly on $[-a, a]$. Also, suppose that ϵ_1 is distributed uniformly on $[-a, a]$ whereas ϵ_2 is a point mass at zero. Given that $\phi < 2v$, if firm 1 chooses to set the uniform price in the mature market period, we know that consumer surplus is given by:

$$CS = \int_{-\frac{v}{3} + \frac{\phi}{6}}^a \left[\mu + v + \epsilon_1 - \left(a + \frac{1}{3}v - \frac{1}{6}\phi \right) \right] \frac{1}{2a} d\epsilon_1 + \int_{-a}^{-\frac{v}{3} + \frac{\phi}{6}} \left[\mu - \left(a - \frac{1}{3}v + \frac{1}{6}\phi \right) \right] \frac{1}{2a} d\epsilon_1 \quad (3.27)$$

where the first integral is for firm 1's consumers and the second is for firm 2's. This expression can be written as:

$$CS = \mu - \frac{3a}{4} + \frac{v}{2} + \frac{v^2}{36a} + \frac{v\phi}{18a} - \frac{5\phi^2}{144a} \quad (3.28)$$

If firm 1 chooses to offer a grandfather clause, we know that consumer surplus is given by:

$$CS^{GFC} = \frac{1}{2} \left\{ \int_{-\frac{4}{7}v}^a \left[\mu + v + \epsilon_1 - a \right] \frac{1}{2a} d\epsilon_1 + \int_{-a}^{-\frac{4}{7}v} \left[\mu - \left(a - \frac{3}{7}v \right) \right] \frac{1}{2a} d\epsilon_1 \right. \\ \left. + \int_{-\frac{2}{7}v}^a \left[\mu + v + \epsilon_1 - \left(a + \frac{2}{7}v \right) \right] \frac{1}{2a} d\epsilon_1 + \int_{-a}^{-\frac{2}{7}v} \left[\mu - \left(a - \frac{3}{7}v \right) \right] \frac{1}{2a} d\epsilon_1 \right\} \quad (3.29)$$

where the first integral is for those who remain firm 1 among firm 1's original consumers and the second integral is for those who move to firm 2 among firm 1's original consumers. Similarly, the third integral is for those who move to firm 1 among firm 2's original consumers and the last integral is for those who remain firm 2 among firm 2's original consumers. Equation (3.27) simplifies to:

$$CS^{GFC} = \mu - \frac{3a}{4} + \frac{9v}{14} + \frac{5v^2}{98a} \quad (3.30)$$

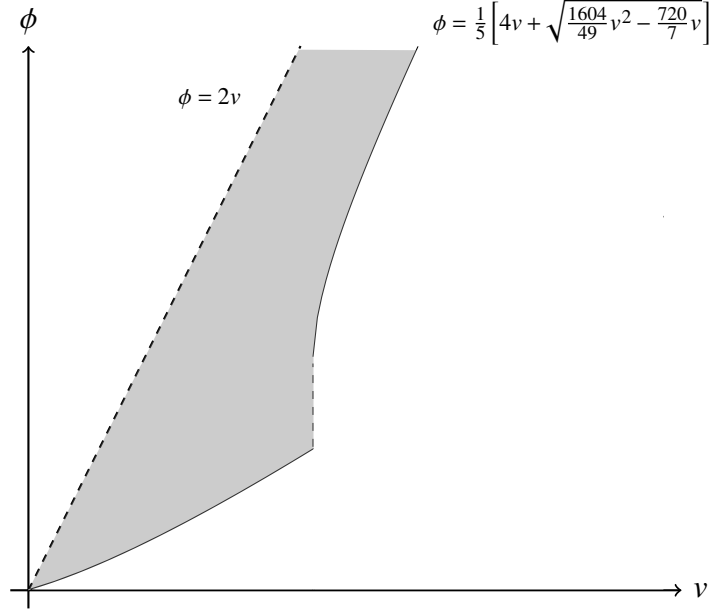


Figure 3.2: Area where Consumers are Better Off under GFC ($a = 1$)

Then, we know that $CS^{GFC} > CS$ if and only if

$$\phi > \frac{1}{5} \left\{ 4av + \sqrt{\left(16a^2 + \frac{820}{49} \right) v^2 - \frac{720}{7} av} \right\} \quad (3.31)$$

Given the level of idiosyncratic preference dispersion and considering the range of v and ϕ , figure 3.2 depicts the parameter space for v and ϕ in which consumers are better off.

Whether or not offering the grandfather clause improves social welfare can also be confirmed. Let me denote W^{GFC} social welfare when the grandfather clause is offered and W social welfare when firms use uniform prices. When $\phi < 2v$, the difference between W^{GFC} and W is given by

$$\begin{aligned} W^{GFC} - W &= \left\{ \sum_{i=1}^2 (\pi_i^{GFC} - \pi_i) \right\} + (CS^{GFC} - CS) \\ &= \left(-\frac{1}{7}v - \frac{\phi^2}{36a} + \frac{v\phi}{9} + \frac{v^2}{882a} \right) + \left(\frac{1}{7}v + \frac{41v^2}{1764} - \frac{v\phi}{18a} + \frac{5\phi^2}{144} \right) \\ &= \frac{\phi^2}{144a} + \frac{v\phi}{18a} + \frac{43v^2}{1764a} > 0 \end{aligned} \quad (3.32)$$

for all positive a, v , and ϕ . Contrary to the consumer complacency case, social welfare increases with grandfather clause, implying that the effect of mitigating consumers' disutility from the negative perception outweighs welfare loss from bad matching between firms and consumers.

3.5 Conclusion

In this manuscript we seek to understand firm price discrimination via the use of grandfather clauses. Using a discrete choice setting in which consumer preferences for individual alternatives can vary over time, we found that when individual consumers are perfectly informed, a firm that achieves a relative quality improvement will not find it profitable to grandfather its former customers while charging potential new customers a higher price. Our finding was observed in a setting in which individual preferences were distributed independently (and identically) from one period to the next, but we suspect that this result is more general. For instance, consider a setting in which individual preferences for the same product are positively correlated over time. Then, if a price increase for individuals who consumed a different firm's product in the past is optimal, the price offered to existing customers—who hence value the product more highly in the present—should be no lower than that offered to potential consumers. We hope to formalize this point in a future draft.

Cognizant of the fact that grandfather clauses are present in various retail service settings, we consider an alternative framework in which firms might wish to offer them. Our chosen framework is a “behavioral” model in which grandfather clauses act as a potential barrier to information discovery. In this setting, we find that the higher quality firm will want to grandfather early adopters as long as its relative quality improvement is not so high that the grandfather clause keeps the firm from realizing a large gain in inframarginal profit. Moreover, the range of quality improvements that makes a grandfather clause worthwhile grows with the level of dispersion in idiosyncratic preferences.

Although we rationalize the use of grandfather clauses in a setting with consumer complacency, we believe that alternative models could also serve to explain their recent proliferation. One framework that comes to mind is a model where individual preferences are negatively correlated over time—perhaps because consumers get tired with their initially sought out service. In such a setting, we suspect that the opposite intuition conjectured in the positive correlation setting holds: that is, grandfather clauses permit firms to set a higher price to consumers who are expected to value the service more highly.

An alternative explanation for the prevalence of grandfather clauses is that they permit a firm to maintain a requisite level of market penetration to exploit potential positive network externalities. This explanation appears particularly cogent in cases where grandfathered consumers get to continue to consume a service for free. A related explanation is one where a multi-product firm allows grandfathered consumers to use its (potentially free) service as a loss leader.

APPENDICES

APPENDIX A

PROOFS IN CHAPTER 1

Derivation of Assumption 1

In an equilibrium with multi-homing on both sides, no platform should have an incentive to deviate by charging $\hat{p}_2^i = \alpha_2 N_1^i$ to content providers and serving only exclusive content.¹ Hence, assumption 1 requires that the profits from serving only exclusive content are lower than the profits from serving both exclusive and non-exclusive content.

Deviation profits $\hat{\Pi}^i$ are given by $\hat{\Pi}^i = (p_1^i - c_1 + \Delta^i)N_1^i + \alpha_2 \lambda N_1^i - I'(\Delta^i)$. Plugging in the expression for N_1^i given in equation (1.28), we have:

$$\hat{\Pi}^i = (p_1^i - c_1 + \Delta^i) \frac{\alpha_1 \lambda - c_1}{t} + \alpha_2 \lambda \frac{\alpha_1 \lambda - c_1}{t} - I'(\Delta^i) \quad (\text{A.1})$$

From the first order condition on $\hat{\Pi}^i$ with respect to p_1^i , I obtain the optimal price for platform i and the number of users on platform i :

$$p_1^{i*} = \frac{1}{2}(\alpha_1 \lambda - \alpha_2 \lambda + c_1 - \Delta^i) \quad (\text{A.2})$$

$$N_1^{i*} = \frac{1}{2t}(\alpha_1 \lambda + \alpha_2 \lambda - c_1 + \Delta^i) \quad (\text{A.3})$$

After substituting p_1^i and N_1^i in the deviation profit function with the expression in equation (A.2) and (A.3), we can derive the optimal level of R&D investment from the first order condition on $\hat{\Pi}^i$ with respect to Δ^i :

$$I'(\Delta^{i*}) = \frac{1}{2t}(\alpha_1 \lambda + \alpha_2 \lambda - c_1 + \Delta^{i*}) \quad (\text{A.4})$$

Given that $I'(\Delta) = k\Delta^2/2$, the optimal level of R&D investment Δ^{i*} is:

$$\Delta^{i*} = \frac{\alpha_1 \lambda + \alpha_2 \lambda - c_1}{2tk - 1} \quad (\text{A.5})$$

Then, the optimal deviation profits for platform i can be written as:

$$\hat{\Pi}^{i*} = \frac{k}{2(2tk - 1)}(\alpha_1 \lambda + \alpha_2 \lambda - c_1)^2 \quad (\text{A.6})$$

¹Variables corresponding to deviation are denoted with a hat.

Comparing $\hat{\Pi}^{i*}$ in equation (A.6) to Π^{i*} in equation (1.41), assumption 1 can be derived as no deviation condition ($\Pi^i > \hat{\Pi}^i$).

Derivation of Assumption 3

In an equilibrium with single-homing on the content provider side under tying, platform B should not have an incentive to deviate by charging $\hat{p}_2^B = \alpha_2 \tilde{n}_1^B$ to content providers and serving both types of content. Hence, assumption 3 requires that the profits from serving both exclusive and non-exclusive content are lower than the profits from serving only exclusive content. If platform B charges $\hat{p}_2^B = \alpha_2 \tilde{n}_1^B$ so that it can attract both types of content providers, $\tilde{n}_2^B = \lambda$ and $\tilde{N}_2^B = 1$, implying that $\tilde{n}_1^B = 1 - (v_M + \alpha_1 \lambda - \tilde{p}_1^A)/t$ and $\tilde{N}_1^B = (\alpha_1 \lambda - \hat{p}_1^B)/t$. The profit maximization problem in the price competition gives the optimal price, $\hat{p}_1^{B*} = (\alpha_1 \lambda + c_1 - \hat{\Delta}^{B*})/2$.

After solving the profit-maximizing problem with respect to $\hat{\Delta}^B$, we have the first order condition in the second stage for platform B, $I'(\hat{\Delta}^{B*}) = (\alpha_1 \lambda - c_1 + \hat{\Delta}^{B*})/(2t)$. Provided that $I'(\Delta) = (k\Delta^2)/2$, the optimal level of R&D investment, $\hat{\Delta}^{B*}$ is:

$$\hat{\Delta}^{B*} = \frac{\alpha_1 \lambda - c_1}{2tk - 1} \quad (\text{A.7})$$

Then, the optimal deviation profits for platform B can be written as:

$$\hat{\Pi}^{B*} = \frac{k}{2(2tk - 1)}(\alpha_1 \lambda - c_1)^2 - \alpha_2 \left\{ 1 - \frac{k}{2tk - 1}(s_M + \alpha_1 \lambda - c_1) \right\} \quad (\text{A.8})$$

On the other hand, from Equation (1.37) and (1.42), the optimal profits for platform B is given by:

$$\tilde{\Pi}^{B*} = \frac{k}{2tk - 1}(\alpha_1 \lambda + \alpha_2 \lambda - c_1)^2 \quad (\text{A.9})$$

From the comparison of $\hat{\Pi}^{B*}$ in Equation (A.8) to $\tilde{\Pi}^{B*}$ in Equation (A.9), we obtain assumption 3.

APPENDIX B

PROOFS AND DERIVATIONS IN CHAPTER 2

Proof of Lemma 1.

Proof. First, consider optimal I_i when $I_j \leq I^o$. Note that $\Phi'(I_j) < 1/3$ for all $I_j \in [0, I^o)$. If firm i invests less than the rival, $dE\pi_i(I_i)/dI_i = I_i/(3I_j) - \Phi'(I_i)$. Because $dE\pi_i(0)/dI_i = 0$, $dE\pi_i(I_j)/dI_i > 0$, and $\Phi'(I_i)$ is convex, $dE\pi_i(I_i)/dI_i > 0$ for all $I_i \in [0, I_j]$, implying that firm i 's profit increases as I_i increases up to $I_i = I_j$. If firm i invests more than the rival, $dE\pi_i(I_i)/dI_i = 1/2 - I_j^2/(6I_i^2) - \Phi'(I_i)$. Note that $MR = 1/2 - I_j^2/(6I_i^2)$ is concave, whereas $MC = \Phi'(I_i)$ is convex for all I_i . Coupled with $dE\pi_i(I_j)/dI_i > 0$, there exists a unique $\bar{I}_i^* = \arg\max E\pi_i \in (I_j, \bar{c})$. Therefore, firm i 's profit is maximized at $\bar{I}_i(I_j)$ when $I_j \leq I^o$.

Second, suppose $I_j \geq I^o$. Note that $\Phi'(I_j) > 1/3$ for all $I_j \in (I^o, \bar{c}]$. If firm i invests more than the rival, $MR < MC$ at $I_i = I_j$ and its profit declines further as I_i increases because of the convexity of MC and concavity of MR for all I_i . If firm i invests less than the rival, $dE\pi_i(0)/dI_i = 0$, $dE\pi_i(I_j)/dI_i < 0$. Then, there exists a unique $\underline{I}_i^* = \arg\max E\pi_i \in (0, I_j)$, implying that firm i 's best response is $\underline{I}_i(I_j)$ when $I_j \geq I^o$. $\square$

Proof of Lemma 2.

Proof. The method of derivation is mainly based on Plum(1992). Substituting $p = P_j(c)$ and rearranging Equation (2.1), we have:

$$P_j'(c) = \frac{P_j(c) - \varphi_{ij}(c)}{\bar{c} - c}$$

From the definition of φ_{ji} and $P_j'(\varphi_{ji}(c)) = \frac{P_i(c) - c}{\bar{c} - \varphi_{ji}(c)}$:

$$\begin{aligned} \varphi_{ji}'(c) &= \frac{P_i'(c)}{P_j'(\varphi_{ji}(c))} \\ &= \frac{P_i(c) - \varphi_{ji}(c)}{P_i(c) - c} \cdot \frac{\bar{c} - \varphi_{ji}(c)}{\bar{c} - c} \end{aligned} \tag{B.1}$$

The equilibrium can be described by Equation (B.1) and the following boundary value:

$$P_i(\bar{c}) = \varphi_{ji}(\bar{c}) = \bar{c}, \quad \varphi_{ji}(\bar{c} - I_j) = \bar{c} - I_j \quad (\text{B.2})$$

Taking the logarithm of Equation (B.1) and differentiating with respect to c , we have:

$$\begin{aligned} \frac{\partial}{\partial c} \ln(\varphi'_{ji}(c)) &= \frac{P'_i(c) - \varphi'_{ji}(c)}{P_i(c) - \varphi_{ji}(c)} - \frac{P'_i(c) - 1}{P_i(c) - c} + \frac{\partial}{\partial c} \ln\left(\frac{\bar{c} - \varphi_{ji}(c)}{\bar{c} - c}\right) \\ &= \frac{1}{\bar{c} - c} - \frac{\bar{c} - \varphi_{ji}(c)}{(P_i(c) - c)(\bar{c} - c)} - \frac{P_i(c) - \varphi_{ji}(c) - (\bar{c} - c)}{(P_i(c) - c)(\bar{c} - c)} + \frac{\partial}{\partial c} \ln\left(\frac{\bar{c} - \varphi_{ji}(c)}{\bar{c} - c}\right) \\ &= -\frac{P_i(c) - \varphi_{ji}(c)}{(P_i(c) - c)(\bar{c} - c)} + \frac{1}{\bar{c} - c} + \frac{\varphi_{ji}(c) - c + P_i(c) - P_i(c)}{(P_i(c) - c)(\bar{c} - c)} + \frac{\partial}{\partial c} \ln\left(\frac{\bar{c} - \varphi_{ji}(c)}{\bar{c} - c}\right) \\ &= 3 \frac{\partial}{\partial c} \ln\left(\frac{\bar{c} - \varphi_{ji}(c)}{\bar{c} - c}\right) \end{aligned}$$

Therefore, we obtain:

$$\varphi'_{ji}(c) = A \left(\frac{\bar{c} - \varphi_{ji}(c)}{\bar{c} - c} \right)^3$$

where A is some positive constant. Solving the differential equation given by (B.1) and applying the boundary condition, we derive the solution:

$$P_i(c) = \bar{c} - \frac{\bar{c} - c}{1 + \sqrt{1 - \left(\frac{1}{I_i^2} - \frac{1}{I_j^2}\right)(\bar{c} - c)^2}} \quad (\text{B.3})$$

□

Proof of Proposition 2.2.

Proof. Suppose that $I_1 > I_2$. In firm 1's profit maximization problem, the first order condition with respect to I_1 yields:

$$\Phi'(I_1) = \int_{\bar{c}-I_1}^{\bar{c}} \frac{(\bar{c} - c)(\bar{c} - \varphi_{21}(c))}{I_1^2 I_2} dc \quad (\text{B.4})$$

Similarly, the first order condition for firm 2 is given by:

$$\Phi'(I_2) = \int_{\bar{c}-I_2}^{\bar{c}} \frac{(\bar{c} - c)(\bar{c} - \varphi_{12}(c))}{I_1 I_2^2} dc \quad (\text{B.5})$$

Substituting $\varphi_{21}(c)$ with t in Equation (B.4), we have:

$$\Phi'(I_1) = \int_{\bar{c}-I_2}^{\bar{c}} \frac{(\bar{c} - \varphi_{12}(t))(\bar{c} - t)}{I_1^2 I_2} \varphi'_{12}(t) dt \quad (\text{B.6})$$

From Equation (2.2), we have $\varphi'_{12}(c) = 1/\sqrt{1 - (\frac{1}{I_2^2} - \frac{1}{I_1^2})(\bar{c} - c)^2}$. Dividing the expression inside the integral sign in right-hand side of Equation (B.5) by the one in right-hand side of Equation (B.6), we have $I_1/(I_2 \cdot \varphi_{12}(c))$. From $\varphi'_{12}(\bar{c} - I_2) = \sqrt{I_1/I_2}$ and $\varphi'_{12}(\bar{c}) = 1$, we obtain $I_1/(I_2 \cdot \varphi_{12}(\bar{c} - I_2)) = \sqrt{I_1/I_2}$ and $I_1/(I_2 \cdot \varphi_{12}(\bar{c})) = 1$. Because $\sqrt{I_1/I_2} > 1$ and $\varphi''_{12}(c) = -(\frac{1}{I_2^2} - \frac{1}{I_1^2})(\bar{c} - c)/(1 - (\frac{1}{I_2^2} - \frac{1}{I_1^2})(\bar{c} - c)^2)^{3/2} < 0$ for all $c \in [\bar{c} - I_2, \bar{c}]$, we have $I_1/(I_2 \cdot \varphi_{12}(c)) \geq 1$ for all $c \in [\bar{c} - I_2, \bar{c}]$, which implies that right-hand side of Equation (B.5) is greater than right-hand side of Equation (B.6).

Given $I_1 > I_2$, right-hand side of Equation (B.5) is greater than right-hand side of Equation (B.6) but it leads to a contradiction because $\Phi'(I_1) > \Phi'(I_2)$. Similarly, both Equation (B.5) and (B.6) cannot be satisfied if $I_1 < I_2$. Therefore, firms choose $I_1 = \hat{I}_1 = I_2 = \hat{I}_2 = I_{UI}^*$ in the equilibrium.

In the symmetric equilibrium, pricing strategy in the second stage can be derived as $P(c) = \frac{c + \bar{c}}{2}$ from Equation (2.2) and in the first stage, firms profit maximizing problem becomes:

$$\Phi'(I_{UI}^*) = \int_{\bar{c}-I_{UI}^*}^{\bar{c}} \frac{(\bar{c} - c)^2}{I_{UI}^{*3}} dc = \frac{1}{3}$$

which implies that I_{UI}^* and I_{CI}^* are identical. □

Proof of Lemma 3.

Proof. When firms' cost information is observable, the expected price when firm 1 wins the market can be calculated as:

$$\begin{aligned} E(p_1 | p_1 < p_2) \cdot Pr[p_1 < p_2] &= E(c_2 | c_1 < c_2) \cdot Pr[c_1 < c_2] \\ &= \int_{\bar{c}-I_2}^{\bar{c}} c \int_{\bar{c}-I_1}^c f_1(x) dx f_2(c) dc \\ &= \int_{\bar{c}-I_2}^{\bar{c}} F_1(c) c F_2'(c) dc \end{aligned}$$

Similarly, the expected price when firm 2 wins the market is:

$$\begin{aligned}
E(p_2|p_1 > p_2) \cdot Pr[p_1 > p_2] &= E(c_1|c_1 > c_2) \cdot Pr[c_1 > c_2] \\
&= \int_{\bar{c}-I_1}^{\bar{c}} c \int_{\bar{c}-I_2}^c f_2(x) dx f_1(c) dc \\
&= \int_{\bar{c}-I_2}^{\bar{c}} c F_2(c) f_1(c) dc \quad (\text{using integration by parts}) \\
&= \int_{\bar{c}-I_2}^{\bar{c}} \left[\{1 - F_1(c)\} \frac{d}{dc} \{c F_2(c)\} \right] dc
\end{aligned}$$

Therefore, the expected price is given by:

$$\begin{aligned}
E(p) &= E(p_1|p_1 < p_2) \cdot Pr[p_1 < p_2] + E(p_2|p_1 > p_2) \cdot Pr[p_1 > p_2] \\
&= \int_{\bar{c}-I_2}^{\bar{c}} \left[F_2(c) + c F_2'(c) - F_1(c) F_2(c) \right] dc \quad (\text{B.7})
\end{aligned}$$

When firms' cost information is private, given c , the expected price when firm 1 wins the market can be written as:

$$\begin{aligned}
E(p_1|p_1 < p_2) \cdot Pr[p_1 < p_2] &= \int_{\underline{p}}^{\bar{c}} p [1 - F_2(\phi_2(p))] dF_1(\phi_1(p)) \quad (\text{using integration by parts}) \\
&= - \int_{\underline{p}}^{\bar{c}} F_1(\phi_1(p)) \frac{d}{dp} \{p [1 - F_2(\phi_2(p))]\} dp \\
&\quad (\text{B.8})
\end{aligned}$$

From Equation (2.1), we have $\frac{d}{dp} \{p [1 - F_2(\phi_2(p))]\} = -\phi_1(p) F_2'(\phi_2(p)) \phi_2'(p)$. Equation (B.8) can be rewritten as:

$$E(p_1|p_1 < p_2) \cdot Pr[p_1 < p_2] = \int_{\underline{p}}^{\bar{c}} F_1(\phi_1(p)) \phi_1(p) F_2'(\phi_2(p)) \phi_2'(p) dp \quad (\text{B.9})$$

Substituting $p = P_2(c)$, we obtain:

$$E(p_1|p_1 < p_2) \cdot Pr[p_1 < p_2] = \int_{\bar{c}-I_2}^{\bar{c}} F_1(\phi_{12}(c)) \phi_{12}(c) F_2'(c) dc$$

Similarly, the expected price when firm 2 wins the market can be derived from Equation (B.9):

$$E(p_2|p_1 > p_2) \cdot Pr[p_1 > p_2] = \int_{\underline{p}}^{\bar{c}} F_2(\phi_2(p))\phi_2(p)F_1'(\phi_1(p))\phi_1'(p)dp$$

Substituting $p = P_2(c)$, we obtain:

$$\begin{aligned} E(p_2|p_1 > p_2) \cdot Pr[p_1 > p_2] &= \int_{\bar{c}-I_2}^{\bar{c}} cF_2(c)F_1'(\varphi_{12}(c))\varphi_{12}'(c)dc \quad (\text{using integration by parts}) \\ &= \int_{\bar{c}-I_2}^{\bar{c}} \left[\{1 - F_1(\varphi_{12}(c))\} \frac{d}{dc} \{cF_2(c)\} \right] dc \end{aligned}$$

Therefore, the expected price is given by:

$$\begin{aligned} E(p) &= E(p_1|p_1 < p_2) \cdot Pr[p_1 < p_2] + E(p_2|p_1 > p_2) \cdot Pr[p_1 > p_2] \\ &= \int_{\bar{c}-I_2}^{\bar{c}} \left[F_2(c) + cF_2'(c) + F_1(\varphi_{12}(c))\{\varphi_{12}(c)F_2'(c) - F_2(c) - cF_2'(c)\} \right] dc \end{aligned} \quad (\text{B.10})$$

□

Derivation of Equilibrium in the Baseline Model: Complete Information Case

In the complete information case, given that each firm's investment level, firm i 's expected payoff is $E\Pi_i(c_i) = E(c_j - c_i|c_i < c_j < c_k, \forall k \neq i, j) \cdot Pr[c_i < c_j < c_k, \forall k \neq i, j] - \Phi(I_i)$:

$$E(c_j - c_i|c_i < c_j < c_k, \forall k \neq i, j) = \quad (\text{B.11})$$

$$\int_0^{\bar{c}} \Delta_i \cdot g_i(\Delta_i|\Delta_k < \Delta_j < \Delta_i, \forall k \neq i, j)d\Delta_i - \int_0^{\bar{c}} \Delta_j \cdot g_j(\Delta_j|\Delta_k < \Delta_j < \Delta_i, \forall k \neq i, j)d\Delta_j$$

where $g_i(x|\Delta_k < \Delta_j < \Delta_i, \forall k \neq i, j) = g_i(x) \cdot Pr[\Delta_k < x, \forall k \neq i] / Pr[\Delta_k < \Delta_i, \forall k \neq i]$. Also, the probability of having the lowest Δ is given by:

$$\begin{aligned} Pr[\Delta_k < \Delta_i, \forall k \neq i] &= \int_0^{\bar{c}} \prod_{k \neq i} \int_0^z g_k(x)dx g_i(z)dz = \frac{I_i}{\sum_{k=1}^n I_k} \\ E(\Delta_i|\Delta_k < \Delta_i, \forall k \neq i) &= \int_0^{\bar{c}} \frac{\sum_{k=1}^n I_k}{I_i} \cdot I_i \cdot \left(\frac{z}{\bar{c}}\right)^{\sum_{k=1}^n I_k} dz = \frac{\bar{c}(\sum_{k=1}^n I_k)}{\sum_{k=1}^n I_k + 1} \end{aligned}$$

Similiarly, we have:

$$E(\Delta_j|\Delta_k < \Delta_j < \Delta_i, \forall k \neq i, j) = \frac{\sum_{k \neq i} I_k}{\sum_{k \neq i} I_k + 1} \cdot \frac{\bar{c}(\sum_{k=1}^n I_k)}{\sum_{k=1}^n I_k + 1}$$

Therefore, Equation (B.11) can be rewritten as:

$$E(c_j - c_i | c_i < c_j < c_k, \forall k \neq i, j) = \frac{\bar{c}(\sum_{k=1}^n I_k)}{(\sum_{k \neq i} I_k + 1)(\sum_{k=1}^n I_k + 1)} \quad (\text{B.12})$$

Firm i 's expected payoff is given by:

$$E\Pi_i(c_i) = \frac{\bar{c} \cdot I_i}{(\sum_{k \neq i} I_k + 1)(\sum_{k=1}^n I_k + 1)} - \Phi(I_i) \quad (\text{B.13})$$

and the first order condition for firm i is:

$$\Phi'(I_i) = \frac{\bar{c}}{(\sum_{k=1}^n I_k + 1)^2} \quad (\text{B.14})$$

Equation (B.14) implicitly solves the best response, $\Theta_i(I_j)$. From $\partial^2 E\Pi_i / \partial I_i^2 = -2\bar{c} / ((\sum_{k \neq i} I_{k+1})(\sum_{k=1}^n I_{k+1})^3)$, $\Phi''(I_i) < 0$, we can see that the second order conditions for the firm's maximization problem are satisfied. The uniqueness of symmetric equilibrium can be easily checked when $n = 2$. The slope of the reaction function is:

$$|\Theta'_i(I_j)| = \left| \frac{\partial^2 E\Pi_i / \partial I_i \partial I_j}{\partial^2 E\Pi_i / \partial I_i^2} \right| = \frac{\frac{2\bar{c}}{(I_i + I_j + 1)^3}}{\frac{2\bar{c}}{(I_i + I_j + 1)^3} + \Phi''(I_i)} < 1$$

which is a sufficient condition for the uniqueness of the equilibrium. In the symmetric equilibrium, firms' optimal R&D investment level is:

$$\Phi'(I^*) = \frac{\bar{c}}{(nI^* + 1)^2} \quad (\text{B.15})$$

In complete information case, the expected price at which the product is sold is calculated as:

$$EP_{CI}^* = E(c_j | c_i < c_j < c_k, \forall k \neq i, j) = \frac{(2n-1)I^* + 1}{((n-1)I^* + 1)(nI^* + 1)} \bar{c} \quad (\text{B.16})$$

Derivation of Equilibrium in the Baseline Model: Unobservable Investment Case

Next, we consider the situation where firms' investment and costs are unobservable. Given that firm i 's marginal cost is c_i , suppose that firm i 's pricing strategy is $P_i(c_i)$ and let ϕ_i be the inverse

pricing function. Denote $H(c) \equiv 1 - c/\bar{c}$. Firm i 's profit is given by:

$$\begin{aligned}
\pi_i &= (P_i(c_i) - c_i) \cdot \Pr[c_k > \phi_k(P_i(c_i)), \forall k \neq i] - \Phi(I_i) \\
&= \prod_{k \neq i} [1 - G_k(\varphi_{ki}(c_i))] (P_i(c_i) - c_i) - \Phi(I_i) \\
&= \prod_{k \neq i} H(\varphi_{ki}(c_i))^{I_k} (P_i(c_i) - c_i) - \Phi(I_i)
\end{aligned} \tag{B.17}$$

Then, the *ex ante* expected profit for firm i is:

$$\begin{aligned}
E\pi_i &= \int_0^{\bar{c}} \prod_{k \neq i} H(\varphi_{ki}(c_i))^{I_k} (P_i(c_i) - c_i) dG(c_i; I_i) - \Phi(I_i) \\
&= G(\bar{c}; I_i) \prod_{k \neq i} H(\varphi_{ki}(\bar{c}))^{I_k} \underbrace{(P_i(\bar{c}) - \bar{c})}_{=0} - \underbrace{G(0; I_i)}_{=0} \prod_{k \neq i} H(\varphi_{ki}(0))^{I_k} (P_i(0) - 0) \\
&\quad - \int_0^{\bar{c}} G(c; I_i) \frac{d}{dc} \prod_{k \neq i} H(\varphi_{ki}(c))^{I_k} (P_i(c) - c) dc - \Phi(I_i)
\end{aligned}$$

By using the Envelope Theorem, we have:

$$\frac{d}{dc} \prod_{k \neq i} H(\varphi_{ki}(c))^{I_k} (P_i(c) - c) = - \prod_{k \neq i} H(\varphi_{ki}(c))^{I_k} \tag{B.18}$$

So, firm i 's expect profit can be rewritten as:

$$E\pi_i = \int_0^{\bar{c}} [1 - H(z)^{I_i}] \prod_{k \neq i} H(\varphi_{ki}(z))^{I_k} dz - \Phi(I_i)$$

The first order condition for firm i in R&D investment stage follows as:

$$\Phi'(I_i) = - \int_0^{\bar{c}} H(z)^{I_i} \prod_{k \neq i} H(\varphi_{ki}(z))^{I_k} \ln H(z) dz \tag{B.19}$$

Let's consider the case of two firms. Assume that $I_1 > I_2$. Then, from Maskin and Riley (2000) (Proposition 3.5. (ii)), we have $\phi_1(p) < \phi_2(p)$ for all $p \in (\underline{p}, \bar{c})$, where $\underline{p} = P_i(0), i = \{1, 2\}$. From Equation (B.19), we obtain the following equation:

$$\Phi'(I_1) - \Phi'(I_2) = \int_0^{\bar{c}} H(z)^{I_2} H(\varphi_{12}(z))^{I_1} \ln H(z) dz - \int_0^{\bar{c}} H(z)^{I_1} H(\varphi_{21}(z))^{I_2} \ln H(z) dz$$

Since $I_1 > I_2$ and $\Phi''(\cdot) > 0$, left-hand side of the equation above is positive. But right-hand side of the equation is negative because $\varphi_{12}(c) < c < \varphi_{21}(c)$ for all $c \in (0, \bar{c})$, leading to a contradiction. The same argument can be applied when $I_1 < I_2$. Therefore, there does not exist asymmetric equilibrium in the unobservable investment case.

In the symmetric equilibrium, $I_1 = \dots = I_n = I^*$ and $P_1(c) = \dots = P_n(c), \forall c \in [0, \bar{c}]$, implying $\phi_1 = \dots = \phi_n$. Then, Equation (B.19) becomes:

$$\Phi'(I^*) = - \int_0^{\bar{c}} H(z)^{nI^*} \ln H(z) dz = - \int_0^{\bar{c}} \left(1 - \frac{z}{\bar{c}}\right)^{nI^*} \ln \left(1 - \frac{z}{\bar{c}}\right) dz = \frac{\bar{c}}{(nI^* + 1)^2} \quad (\text{B.20})$$

It implies that the symmetric equilibrium of R&D investment in the unobservable investment case is identical to the one in the complete information case.

By using standard methods in Myerson (1981), the symmetric price equilibrium can be derived as:

$$\begin{aligned} P_1(c) = P_2(c) = P^*(c) &= c + \frac{1}{H(c)^{(n-1)I^*}} \int_c^{\bar{c}} H(t)^{(n-1)I^*} dt \\ &= \frac{1}{(n-1)I^* + 1} \bar{c} + \frac{(n-1)I^*}{(n-1)I^* + 1} c \end{aligned} \quad (\text{B.21})$$

for all $c \in [0, \bar{c}]$. In the equilibrium, the expected price at which the product is sold is:

$$EP_{UI}^* = \frac{1}{(n-1)I^* + 1} \bar{c} + \frac{(n-1)I^*}{(n-1)I^* + 1} E(\underline{c}) = \frac{(2n-1)I^* + 1}{((n-1)I^* + 1)(nI^* + 1)} \bar{c} \quad (\text{B.22})$$

Compared to the complete information case, the expected price is the same in the unobservable investment case.

Derviation of Equilibrium in the Baseline Model: Observable Investment Case

In the observable investment case, only the rival's investment level is commonly known, while firms cannot observe the rival's realized cost. The observed investment level by the rival can directly affect firms' pricing strategies in the second stage. Since firms can observe rival's investment level, it can directly affect firms' pricing strategies in the second stage. Given the pricing equilibrium

$(P_1(c; \mathbf{I}), \dots, P_n(c; \mathbf{I}))$, firm i 's *ex ante* expected payoff is given by:

$$\begin{aligned} E\pi_i(P_i, c; \mathbf{I}) &= \int_0^{\bar{c}} (P_i(c; \mathbf{I}) - c) \cdot Pr[c_k > \varphi_{ki}(c; \mathbf{I}), \forall k \neq i] dG_i(c) - \Phi(I_i) \\ &= \int_0^{\bar{c}} (P_i(c; \mathbf{I}) - c) \prod_{k \neq i} [1 - G_k(\varphi_{ki}(c; \mathbf{I}))] dG_i(c) - \Phi(I_i) \end{aligned}$$

By using the same method in the unobservable investment case, we obtain the following equation:

$$E\pi_i = \int_0^{\bar{c}} [1 - H(z)^{I_i}] \prod_{k \neq i} H(\varphi_{ki}(z; \mathbf{I}))^{I_k} dz - \Phi(I_i)$$

We have the first order condition for firm i in R&D investment stage as:

$$\begin{aligned} \Phi'(I_i) &= \int_0^{\bar{c}} [-H(z)^{I_i} \prod_{k \neq i} H(\varphi_{ki}(z; \mathbf{I}))^{I_k} \ln H(z) \\ &\quad + \sum_{j \neq i} [1 - H(z)^{I_i}] \frac{\partial H(\varphi_{ji}(z; \mathbf{I}))^{I_j}}{\partial I_i} \prod_{k \neq i, j} H(\varphi_{ki}(z; \mathbf{I}))^{I_k}] dz \end{aligned} \quad (\text{B.23})$$

Equation (B.23) implicitly defines firm i 's reaction function $I_i = \Theta_i(I_j)$. The first term in right-hand side of Equation (B.23) shows the benefit from the R&D investment. The investment gives the firm i a higher probability of having the cost advantage over rivals so that it can win the market. The second term is an additional effect compared to the unobservable investment case.

Since the firms are *ex ante* homogeneous, there exists a unique symmetric Nash equilibrium in the R&D competition stage if the stability condition is satisfied. Throughout the analysis, we assume that the stability condition is satisfied and focus on the symmetric equilibrium. In fact, we cannot rule out the possibility of the existence of asymmetric Nash equilibria in the first stage due to the additional effect mentioned above. The stability condition is assumed for analytical tractability but since there exists a unique symmetric investment equilibrium in the unobservable investment case, the direct comparison between the two cases can be achieved under this assumption.

We cannot apply the standard theorems regarding differentiability with respect to the parameters of the solution of a differential system because, in general, explicit forms of pricing functions and inverse pricing functions cannot be derived. We can circumvent this difficulty by defining functions

$\alpha_i(q; \mathbf{I}) = P_i(G_1^{-1}(q; I_i); \mathbf{I})$ and $\beta_{ji}(q; \mathbf{I}) = G_j(\phi_j(P_i(G_1^{-1}(q; I_i); \mathbf{I}); \mathbf{I}); I_j)$, that is, $\alpha_i(q; \mathbf{I})$ is firm i 's price as a function of its cost quantile and $\beta_{ji}(q; \mathbf{I})$ is firm j 's cost quantile when firm i and firm j set the same price given firm i 's cost quantile.

From the first order condition in the price competition stage, we have the following equations:

$$\sum_{k \neq i} \frac{d \log(1 - G_k(\phi_k(p; \mathbf{I}); I_k))}{dp} = \frac{1}{p - \phi_i(p; \mathbf{I})}$$

Summing up all equations except the one for firm i and subtracting the equation for firm i , we find:

$$-\frac{G'_i(\phi_i(p); I_i) \cdot \phi'_i(p)}{1 - G_i(\phi_i(p))} = \frac{1}{n-1} \left\{ \frac{-(n-2)}{p - \phi_i(p; \mathbf{I})} + \sum_{k \neq i} \frac{1}{p - \phi_k(p; \mathbf{I})} \right\} \quad (\text{B.24})$$

Similiarly, we obtain the equation for firm j .

$$-\frac{G'_j(\phi_j(p); I_j) \cdot \phi'_j(p)}{1 - G_j(\phi_j(p))} = \frac{1}{n-1} \left\{ \frac{-(n-2)}{p - \phi_j(p; \mathbf{I})} + \sum_{k \neq j} \frac{1}{p - \phi_k(p; \mathbf{I})} \right\} \quad (\text{B.25})$$

By multiplying Equation (B.25) by the inverse of Equation (B.24), we obtain:

$$\begin{aligned} \frac{d}{dq} \beta_{ji}(q; \mathbf{I}) = & \frac{1 - \beta_{ji}(q; \mathbf{I})}{1 - q} \frac{\frac{-(n-2)}{\alpha(q; \mathbf{I}) - G_j^{-1}(\beta_{ji}(q; \mathbf{I}); I_j)} + \frac{1}{\alpha(q; \mathbf{I}) - G_i^{-1}(q; I_i)} + \sum_{k \neq i, j} \frac{1}{\alpha(q; \mathbf{I}) - G_k^{-1}(\beta_{ki}(q; \mathbf{I}); I_k)}}{\frac{-(n-2)}{\alpha(q; \mathbf{I}) - G_i^{-1}(q; I_i)} + \frac{1}{\alpha(q; \mathbf{I}) - G_j^{-1}(\beta_{ji}(q; \mathbf{I}); I_j)} + \sum_{k \neq i, j} \frac{1}{\alpha(q; \mathbf{I}) - G_k^{-1}(\beta_{ki}(q; \mathbf{I}); I_k)}} \end{aligned} \quad (\text{B.26})$$

The initial conditions are $\beta_{ji}(0; \mathbf{I}) = 0$ and $\beta_{ji}(1; \mathbf{I}) = 1$ and we can use the former condition to solve the differential equation.

Let $\hat{\alpha}_i(q) = \frac{\partial \alpha_i(q; \mathbf{I})}{\partial I_i} \big|_{I_k = I^* \forall k}$ and $\hat{\beta}_{ji}(q) = \frac{\partial \beta_{ji}(q; \mathbf{I})}{\partial I_i} \big|_{I_k = I^* \forall k}$. Differentiating Equation (B.26) with respect to I_i , setting all I_k equal to I^* , we have:

$$\begin{aligned} \hat{\beta}'_{ji}(q) + \left[\frac{n-1}{\alpha_i(q; \mathbf{I}^*) - G_i^{-1}(q; I^*)} \cdot \frac{\partial G_j^{-1}(q; I^*)}{\partial q} + \frac{1}{1-q} \right] \hat{\beta}_{ji}(q) = & \\ \frac{n-1}{\alpha_i(q; \mathbf{I}^*) - G_i^{-1}(q; I^*)} \cdot \frac{\partial G_i^{-1}(q; I^*)}{\partial I_i} & \end{aligned} \quad (\text{B.27})$$

In the symmetric investment level, each firm's pricing function $\alpha_k(q; \mathbf{I}^*)$ is given by:

$$\alpha_k(q; \mathbf{I}^*) = G_k^{-1}(q; I^*) + \frac{\int_{G_k^{-1}(q; I^*)}^c (1 - G_k(t; I^*))^{n-1} dt}{(1-q)^{n-1}}$$

Substituting this expression into Equation (B.27), we have:

$$\begin{aligned} \hat{\beta}'_{ji}(q) + \left[\frac{(n-1)(1-q)^{n-1}}{\int_{G_k^{-1}(q; I^*)}^{cH} (1-G_k(t; I^*)^{n-1}) dt} \cdot \frac{\partial G_j^{-1}(q; I^*)}{\partial q} + \frac{1}{1-q} \right] \hat{\beta}_{ji}(q) \\ = \frac{(n-1)(1-q)^{n-1}}{\int_{G_k^{-1}(q; I^*)}^{cH} (1-G_k(t; I^*)^{n-1}) dt} \cdot \frac{\partial G_i^{-1}(q; I^*)}{\partial I_i} \end{aligned} \quad (\text{B.28})$$

From Equation (B.28) and the initial condition $\hat{\beta}_{ji}(0) = 0$, we obtain:

$$\hat{\beta}_{ji}(q) = -A \cdot (1-q) (((n-1)^2 + 2)I^* + n-1) \log(1-q) - I^* - A \cdot I^* (1-q) \frac{((n-1)^2 + 1)I^* + n-1}{I^*} \quad (\text{B.29})$$

where $A = \frac{(n-1)((n-1)I^* + n-1)}{I^*(((n-1)^2 + 2)I^* + n-1)^2}$. By the definition of $\varphi_{ji}(c; \mathbf{I})$ and $\beta_{ji}(q; \mathbf{I})$, we have:

$$\begin{aligned} \frac{\partial \varphi_{ji}(c; \mathbf{I})}{\partial I_i} \Big|_{I_k = I^* \forall k} &= \frac{\partial G_j^{-1}(G_i(c; I_i); I_j)}{\partial q} \Big|_{I_k = I^* \forall k} \\ &= \left(\frac{\partial \beta_{ji}(G_i(c; I_i); \mathbf{I})}{\partial q} \cdot \frac{\partial G_i(c; I_i)}{\partial I_i} + \underbrace{\frac{\partial \beta_{ji}(G_i(c; I_i); \mathbf{I})}{\partial I_i}}_{=\hat{\beta}_{ji}(q)} \right) \Big|_{I_k = I^* \forall k} \end{aligned} \quad (\text{B.30})$$

Substituting the expression for $\hat{\beta}_{ji}(q)$ in Equation (B.29) into Equation (B.30), $\partial \varphi_{ji}(c; \mathbf{I}) / \partial I_i \Big|_{I_k = I^* \forall k}$ can be rewritten as:

$$\begin{aligned} \frac{\partial \varphi_{ji}(c; \mathbf{I})}{\partial I_i} \Big|_{I_k = I^* \forall k} &= \frac{\bar{c}}{I^*} \left(1 - \frac{c}{\bar{c}} \right)^{1-I^*} \\ &\quad \left[-B \cdot \left(1 - \frac{c}{\bar{c}} \right)^{I^*} (((n-1)^2 + 2)I^* + n-1) \log \left(1 - \frac{c}{\bar{c}} \right) \right. \\ &\quad \left. + B \cdot \left\{ \left(1 - \frac{c}{\bar{c}} \right)^{I^*} - \left(1 - \frac{c}{\bar{c}} \right)^{((n-1)^2 + 1)I^* + n-1} \right\} - \left(1 - \frac{c}{\bar{c}} \right)^{I^*} \log \left(1 - \frac{c}{\bar{c}} \right) \right] \end{aligned} \quad (\text{B.31})$$

where $B = A \cdot I^*$.

This implies that $\partial \varphi_{ji}(c; \mathbf{I}) / \partial I_i \Big|_{I_k = I^* \forall k} > 0$, $\forall c \in [0, \bar{c}]$. Coupled with $\partial H(c)^{I_j} / \partial c < 0$, $\partial H(\varphi_{ji}(c; \mathbf{I}))^{I_j} / \partial I_i \Big|_{I_k = I^* \forall k} < 0$, $\forall c \in [0, \bar{c}]$. We know that left-hand side and the first term in right-hand side in Equation (B.23) are the same as the one in unobservable investment case but the

second term in right-hand side is negative for all $c \in [0, \bar{c}]$. Given the convexity of the R&D cost function, $\Phi(\cdot)$, symmetric level of R&D investment in the observable investment case cannot be greater than the one in the unobservable investment case.

Welfare Analysis in Baseline Model

Under the box demand, the results above are ready to be applied to the welfare analysis. First, the R&D investment level in the equilibrium in each case can be compared:

$$I_{CI}^* = I_{UI}^* > I_{OI}^*$$

If all agents have the same valuation of the product, social welfare is a function of minimum actual cost, corresponding to the investment level. As shown above, whereas the investment level in complete information and unobservable investment case is the same, the observable investment case induces underinvestment. This finding implies that social welfare decreases in the observable investment case, compared to the complete information and unobservable investment case.

The symmetric investment equilibrium gives rise to the standard pricing function (analogous to the bidding function in auction theory):¹

$$P^*(c; I) = c + \frac{1}{H(c)^{(n-1)I^*}} \int_c^{\bar{c}} H(t)^{(n-1)I^*} dt = \frac{1}{(n-1)I^* + 1} \bar{c} + \frac{(n-1)I^*}{(n-1)I^* + 1} c$$

Thus, the expected price of the product is given by:

$$EP^*(I) = \frac{1}{(n-1)I^* + 1} \bar{c} + \frac{(n-1)I^*}{(n-1)I^* + 1} E(\underline{c}) = \frac{(2n-1)I + 1}{((n-1)I + 1)(nI + 1)} \bar{c}$$

Since $\frac{\partial EP^*(I)}{\partial I} = -\frac{n(n-1)I((2n-1)I+2)\bar{c}}{(((n-1)I+1)(nI+1))^2} < 0$ and $I_{UI}^* > I_{OI}^*$, we obtain $EP_{OI}^* > EP_{UI}^*$. We already showed that $EP_{UI}^* = EP_{CI}^*$. Therefore, the expected price of the product under each regime is ranked as:

$$EP_{OI}^* > EP_{UI}^* = EP_{CI}^*$$

The comparison of consumer surplus under each regime follows as:

$$CS_{CI} = CS_{UI} > CS_{OI}$$

¹See Myerson (1981) for the detailed derivation.

Derviation of Equilibrium in the Oligopoly Model: Complete Information Case

In complete information case, given that each firm's investment level, firm i 's expected payoff is $E\Pi_i(c_i) = E(c_j - c_i | c_i < c_j < c_k, \forall k \neq i, j) \cdot Pr[c_i < c_j < c_k, \forall k \neq i, j] - \Phi(I_i)$.

$$\begin{aligned}
 E(c_j - c_i | c_i < c_j < c_k, \forall k \neq i, j) &= E(\bar{c} - \Delta_j - (\bar{c} - \Delta_i) | \bar{c} - \Delta_i < \bar{c} - \Delta_j < \bar{c} - \Delta_k, \forall k \neq i, j) \\
 &= E(\Delta_i - \Delta_j | \Delta_k < \Delta_j < \Delta_i, \forall k \neq i, j) \\
 &= \int_0^{\bar{c}} \Delta_i \cdot g_i(\Delta_i | \Delta_k < \Delta_j < \Delta_i, \forall k \neq i, j) d\Delta_i \\
 &\quad - \int_0^{\bar{c}} \Delta_j \cdot g_j(\Delta_j | \Delta_k < \Delta_j < \Delta_i, \forall k \neq i, j) d\Delta_j
 \end{aligned} \tag{B.32}$$

$$g_i(x | \Delta_k < \Delta_j < \Delta_i, \forall k \neq i, j) = \frac{g_i(x) \cdot Pr[\Delta_k < x, \forall k \neq i]}{Pr[\Delta_k < \Delta_i, \forall k \neq i]}$$

$$\begin{aligned}
 Pr[\Delta_k < \Delta_i, \forall k \neq i] &= \int_0^{\bar{c}} \prod_{k \neq i} \int_0^z g_k(x) dx g_i(z) dz \\
 &= \int_0^{\bar{c}} \prod_{k \neq i} G_k(z) \cdot g_i(z) dz \\
 &= \int_0^{\bar{c}} \left(\frac{z}{\bar{c}}\right)^{\sum_{k \neq i} I_k} \cdot \frac{I_i}{\bar{c}} \left(\frac{z}{\bar{c}}\right)^{I_i - 1} dz \\
 &= \frac{I_i}{\sum_{k=1}^n I_k}
 \end{aligned}$$

$$\begin{aligned}
 E(\Delta_i | \Delta_k < \Delta_i, \forall k \neq i) &= \int_0^{\bar{c}} \frac{\sum_{k=1}^n I_k}{I_i} \cdot I_i \cdot \left(\frac{z}{\bar{c}}\right)^{\sum_{k=1}^n I_k} dz \\
 &= \frac{\bar{c}(\sum_{k=1}^n I_k)}{\sum_{k=1}^n I_k + 1}
 \end{aligned}$$

Similiarly, we have:

$$E(\Delta_j | \Delta_k < \Delta_j < \Delta_i, \forall k \neq i, j) = \frac{\sum_{k \neq i} I_k}{\sum_{k \neq i} I_k + 1} \cdot \frac{\bar{c}(\sum_{k=1}^n I_k)}{\sum_{k=1}^n I_k + 1}$$

Therefore, equation (B.32) can be rewritten as:

$$E(c_j - c_i | c_i < c_j < c_k, \forall k \neq i, j) = \frac{\bar{c}(\sum_{k=1}^n I_k)}{(\sum_{k \neq i} I_k + 1)(\sum_{k=1}^n I_k + 1)} \quad (\text{B.33})$$

Firm i 's expected payoff is given by:

$$E\Pi_i(c_i) = \frac{\bar{c} \cdot I_i}{(\sum_{k \neq i} I_k + 1)(\sum_{k=1}^n I_k + 1)} - \Phi(I_i) \quad (\text{B.34})$$

and the first order condition for firm i is:

$$\Phi'(I_i) = \frac{\bar{c}}{(\sum_{k=1}^n I_k + 1)^2} \quad (\text{B.35})$$

From $\partial^2 E\Pi_i / \partial I_i^2 = -2\bar{c} / \{(\sum_{k \neq i} I_k + 1)(\sum_{k=1}^n I_k + 1)^3\} - \Phi''(I_i) < 0$, we can see that the second order conditions for the firm's maximization problem are satisfied. In the symmetric equilibrium, firms' optimal R&D investment level is:

$$\Phi'(I^*) = \frac{\bar{c}}{(nI^* + 1)^2} \quad (\text{B.36})$$

In the complete information case, the expected price at which the product is sold is:

$$\begin{aligned} EP_{CI}^* &= E(c_j | c_i < c_j < c_k, \forall k \neq i, j) = E(\bar{c} - \Delta_j | \Delta_k < \Delta_j < \Delta_i, \forall k \neq i, j) \\ &= \frac{(2n-1)I^* + 1}{((n-1)I^* + 1)(nI^* + 1)} \bar{c} \end{aligned} \quad (\text{B.37})$$

Derivation of Equilibrium in Oligopoly Model: Unobservable Investment Case

Next, we consider the situation where firms' investment and costs are unobservable. Given that firm i 's marginal cost is c_i , suppose that firm i 's pricing strategy is $P_i(c_i)$ and let ϕ_i be the inverse pricing function. Suppose further that $H(c) \equiv 1 - c/\bar{c}$. Firm i 's profit is given by:

$$\begin{aligned} \pi_i &= (P_i(c_i) - c_i) \cdot \Pr[c_k > \phi_k(P_i(c_i)), \forall k \neq i] - \Phi(I_i) \\ &= \prod_{k \neq i} [1 - G_k(\phi_{ki}(c_i))] (P_i(c_i) - c_i) - \Phi(I_i) \\ &= \prod_{k \neq i} H(\phi_{ki}(c_i))^{I_k} (P_i(c_i) - c_i) - \Phi(I_i) \end{aligned} \quad (\text{B.38})$$

Then, the *ex ante* expected profit for firm i is:

$$\begin{aligned}
E\pi_i &= \int_0^{\bar{c}} \prod_{k \neq i} H(\varphi_{ki}(c_i))^{I_k} (P_i(c_I) - c_i) dG(c_i; I_i) - \Phi(I_i) \\
&= G(\bar{c}; I_i) \prod_{k \neq i} H(\varphi_{ki}(\bar{c}))^{I_k} \underbrace{(P_i(\bar{c}) - \bar{c})}_{=0} - \underbrace{G(0; I_i)}_{=0} \prod_{k \neq i} H(\varphi_{ki}(0))^{I_k} (P_i(0) - 0) \\
&\quad - \int_0^{\bar{c}} G(c; I_i) \frac{d}{dc} \prod_{k \neq i} H(\varphi_{ki}(c))^{I_k} (P_i(c) - c) dc - \Phi(I_i)
\end{aligned}$$

By using the Envelope Theorem, we have:

$$\frac{d}{dc} \prod_{k \neq i} H(\varphi_{ki}(c))^{I_k} (P_i(c) - c) = - \prod_{k \neq i} H(\varphi_{ki}(c))^{I_k} \quad (\text{B.39})$$

So, firm i 's expect profit can be rewritten as:

$$E\pi_i = \int_0^{\bar{c}} [1 - H(z)^{I_i}] \prod_{k \neq i} H(\varphi_{ki}(z))^{I_k} dz - \Phi(I_i)$$

The first order condition for firm i in R&D investment stage follows as:

$$\Phi'(I_i) = - \int_0^{\bar{c}} H(z)^{I_i} \prod_{k \neq i} H(\varphi_{ki}(z))^{I_k} \ln H(z) dz \quad (\text{B.40})$$

Let's consider two firms case. Assume that $I_1 > I_2$. Then, from Maskin and Riley(2000b) (Proposition 3.5. (ii)), we have $\phi_1(p) < \phi_2(p)$ for all $p \in (\underline{p}, \bar{c})$, where $\underline{p} = P_i(0), i = \{1, 2\}$. From (B.40), we obtain the following equation:

$$\Phi'(I_1) - \Phi'(I_2) = \int_0^{\bar{c}} H(z)^{I_2} H(\varphi_{12}(z))^{I_1} \ln H(z) dz - \int_0^{\bar{c}} H(z)^{I_1} H(\varphi_{21}(z))^{I_2} \ln H(z) dz$$

Since $I_1 > I_2$ and $\Phi''(\cdot) > 0$, left-hand side of the equation above is positive. But right-hand side of the equation is negative because $\varphi_{12}(c) < c < \varphi_{21}(c)$ for all $c \in (0, \bar{c})$, leading to a contradiction. The same argument can be applied when $I_1 < I_2$. Therefore, there dose not exist asymmetric equilibrium in the unobservable investment case.

In the symmetric equilibrium, $I_1 = \dots = I_n = I^*$ and $P_1(c) = \dots = P_n(c), \forall c \in [0, \bar{c}]$, implying $\phi_1 = \dots = \phi_n$. Then, (B.40) becomes:

$$\begin{aligned}\Phi'(I^*) &= - \int_0^{\bar{c}} H(z)^{nI^*} \ln H(z) dz \\ &= - \int_0^{\bar{c}} \left(1 - \frac{z}{\bar{c}}\right)^{nI^*} \ln \left(1 - \frac{z}{\bar{c}}\right) dz \\ &= \frac{\bar{c}}{(nI^* + 1)^2}\end{aligned}\tag{B.41}$$

It implies that the symmetric equilibrium of R&D investment in the unobservable investment case is identical to the one in the complete information case.

By using standard methods, the symmetric price equilibrium can be derived as:

$$\begin{aligned}P_1(c) = P_2(c) = P^*(c) &= c + \frac{1}{H(c)^{(n-1)I^*}} \int_c^{\bar{c}} H(t)^{(n-1)I^*} dt \\ &= \frac{1}{(n-1)I^* + 1} \bar{c} + \frac{(n-1)I^*}{(n-1)I^* + 1} c\end{aligned}\tag{B.42}$$

for all $c \in [0, \bar{c}]$. In the equilibrium, the expected price at which the product is sold is:

$$\begin{aligned}EP_{UI}^* &= \frac{1}{(n-1)I^* + 1} \bar{c} + \frac{(n-1)I^*}{(n-1)I^* + 1} E(\underline{c}) \\ &= \frac{1}{(n-1)I^* + 1} \bar{c} + \frac{(n-1)I^*}{(n-1)I^* + 1} \cdot \frac{\bar{c}}{nI^* + 1} \\ &= \frac{(2n-1)I^* + 1}{((n-1)I^* + 1)(nI^* + 1)} \bar{c}\end{aligned}\tag{B.43}$$

Compared to the complete information case, the expected price is the same in the unobservable investment case.

Derivation of Equilibrium in Oligopoly Model: Observable Investment Case

Under the observable investment case, only rival's investment level is commonly known, while firms cannot observe rival's realized cost. Since firms can observe rival's investment level, it can directly affect firms' pricing strategies in the second stage. Since firms can observe rival's investment level, it can directly affect firms' pricing strategies in the second stage. Given the pricing

equilibrium $(P_1(c; \mathbf{I}), \dots, P_n(c; \mathbf{I}))$, firm i 's *ex ante* expected payoff is given by:

$$\begin{aligned} E\pi_i(P_i, c; \mathbf{I}) &= \int_0^{\bar{c}} (P_i(c; \mathbf{I}) - c) \cdot \Pr[c_k > \varphi_{ki}(c; \mathbf{I}), \forall k \neq i] dG_i(c) - \Phi(I_i) \\ &= \int_0^{\bar{c}} (P_i(c; \mathbf{I}) - c) \prod_{k \neq i} [1 - G_k(\varphi_{ki}(c; \mathbf{I}))] dG_i(c) - \Phi(I_i) \end{aligned}$$

By using the same method in the unobservable investment case, we obtain the following equation:

$$E\pi_i = \int_0^{\bar{c}} [1 - H(z)^{I_i}] \prod_{k \neq i} H(\varphi_{ki}(z; \mathbf{I}))^{I_k} dz - \Phi(I_i)$$

We have the first order condition for firm i in R&D investment stage as:

$$\begin{aligned} \Phi'(I_i) &= \int_0^{\bar{c}} [-H(z)^{I_i} \prod_{k \neq i} H(\varphi_{ki}(z; \mathbf{I}))^{I_k} \ln H(z) \\ &\quad + \sum_{j \neq i} [1 - H(z)^{I_i}] \frac{\partial H(\varphi_{ji}(z; \mathbf{I}))^{I_j}}{\partial I_i} \prod_{k \neq i, j} H(\varphi_{ki}(z; \mathbf{I}))^{I_k}] dz \end{aligned} \tag{B.44}$$

The equation (B.44) implicitly defines firm i 's reaction function $I_i = R_i(I_j)$. The first term in right-hand side of (B.44) shows the benefit from the R&D investment. The investment gives the firm i higher probability of having the cost advantage over rivals so that it can win the market. The second term is an additional effect compared to the complete information case.

Since the firms are *ex ante* homogeneous, there exists a unique symmetric Nash equilibrium in R&D competition stage if the stability condition is satisfied. Throughout the analysis, we assume that the stability condition is satisfied and focus on the symmetric equilibrium. In fact, we cannot rule out the possibility of the existence of asymmetric Nash equilibria in the first stage due to the additional effect mentioned above. The stability condition is assumed for analytical tractability but since there exists a unique symmetric investment equilibrium in the unobservable investment case, the direct comparison between two cases can be achieved under this assumption.

We cannot apply the standard theorems regarding differentiability with respect to parameters of the solution of a differential system because in general explicit forms of pricing functions and inverse pricing functions cannot be derived. We can circumvent this difficulty by defining functions

$\alpha_i(q; \mathbf{I}) = P_i(G_1^{-1}(q; I_i); \mathbf{I})$ and $\beta_{ji}(q; \mathbf{I}) = G_j(\phi_j(P_i(G_i^{-1}(q; I_i)); \mathbf{I}); \mathbf{I}; I_j)$, that is, $\alpha_i(q; \mathbf{I})$ is firm i 's price as a function of its cost quantile and $\beta_{ji}(q; \mathbf{I})$ is firm j 's cost quantile when firm i and firm j set the same price given that firm i 's cost quantile.

From the first order condition in the price competition stage, we have the following equations:

$$\sum_{k \neq i} \frac{d \log(1 - G_k(\phi_k(p; \mathbf{I}); I_k))}{dp} = \frac{1}{p - \phi_i(p; \mathbf{I})}$$

Summing up all equations except the one for firm i and subtracting the equation for firm i , we find:

$$-\frac{G'_i(\phi_i(p); I_i) \cdot \phi'_i(p)}{1 - G_i(\phi_i(p))} = \frac{1}{n-1} \left\{ \frac{-(n-2)}{p - \phi_i(p; \mathbf{I})} + \sum_{k \neq i} \frac{1}{p - \phi_k(p; \mathbf{I})} \right\} \quad (\text{B.45})$$

Similiarly, we obtain the equation for firm j :

$$-\frac{G'_j(\phi_j(p); I_j) \cdot \phi'_j(p)}{1 - G_j(\phi_j(p))} = \frac{1}{n-1} \left\{ \frac{-(n-2)}{p - \phi_j(p; \mathbf{I})} + \sum_{k \neq j} \frac{1}{p - \phi_k(p; \mathbf{I})} \right\} \quad (\text{B.46})$$

By multiplying (B.46) by the inverse of (B.45), we obtain:

$$\begin{aligned} \frac{d}{dq} \beta_{ji}(q; \mathbf{I}) = & \frac{1 - \beta_{ji}(q; \mathbf{I})}{1 - q} \frac{\frac{-(n-2)}{\alpha(q; \mathbf{I}) - G_j^{-1}(\beta_{ji}(q; \mathbf{I}); I_j)} + \frac{1}{\alpha(q; \mathbf{I}) - G_i^{-1}(q; I_i)} + \sum_{k \neq i, j} \frac{1}{\alpha(q; \mathbf{I}) - G_k^{-1}(\beta_{ki}(q; \mathbf{I}); I_k)}}{\frac{-(n-2)}{\alpha(q; \mathbf{I}) - G_i^{-1}(q; I_i)} + \frac{1}{\alpha(q; \mathbf{I}) - G_j^{-1}(\beta_{ji}(q; \mathbf{I}); I_j)} + \sum_{k \neq i, j} \frac{1}{\alpha(q; \mathbf{I}) - G_k^{-1}(\beta_{ki}(q; \mathbf{I}); I_k)}} \end{aligned} \quad (\text{B.47})$$

The initial conditions are $\beta_{ji}(0; \mathbf{I}) = 0$ and $\beta_{ji}(1; \mathbf{I}) = 1$ and we can use the former condition to solve the differential equation.

Let $\hat{\alpha}_i(q) = \frac{\partial \alpha_i(q; \mathbf{I})}{\partial I_i} |_{I_k = I^* \forall k}$ and $\hat{\beta}_{ji}(q) = \frac{\partial \beta_{ji}(q; \mathbf{I})}{\partial I_i} |_{I_k = I^* \forall k}$. Differentiating (B.47) with respect to I_i , setting all I_k equal to I^* , we have:

$$\begin{aligned} \hat{\beta}'_{ji}(q) + \left[\frac{n-1}{\alpha_i(q; \mathbf{I}^*) - G_i^{-1}(q; I^*)} \cdot \frac{\partial G_j^{-1}(q; I^*)}{\partial q} + \frac{1}{1-q} \right] \hat{\beta}_{ji}(q) = & \\ \frac{n-1}{\alpha_i(q; \mathbf{I}^*) - G_i^{-1}(q; I^*)} \cdot \frac{\partial G_i^{-1}(q; I^*)}{\partial I_i} & \end{aligned} \quad (\text{B.48})$$

In the symmetric investment level, each firm's pricing function $\alpha_k(q; \mathbf{I}^*)$ is given by:

$$\alpha_k(q; \mathbf{I}^*) = G_k^{-1}(q; I^*) + \frac{\int_{G_k^{-1}(q; I^*)}^c (1 - G_k(t; I^*))^{n-1} dt}{(1-q)^{n-1}}$$

Substituting this expression into the equation (B.48), we have:

$$\begin{aligned} \hat{\beta}'_{ji}(q) + \left[\frac{(n-1)(1-q)^{n-1}}{\int_{G_k^{-1}(q; I^*)}^{cH} (1-G_k(t; I^*)^{n-1}) dt} \cdot \frac{\partial G_j^{-1}(q; I^*)}{\partial q} + \frac{1}{1-q} \right] \hat{\beta}_{ji}(q) \\ = \frac{(n-1)(1-q)^{n-1}}{\int_{G_k^{-1}(q; I^*)}^{cH} (1-G_k(t; I^*)^{n-1}) dt} \cdot \frac{\partial G_i^{-1}(q; I^*)}{\partial I_i} \end{aligned} \quad (\text{B.49})$$

From the equation (B.49) and the initial condition $\hat{\beta}_{ji}(0) = 0$, we obtain:

$$\begin{aligned} \hat{\beta}_{ji}(q) = \\ -A \cdot (1-q) (((n-1)^2 + 2)I^* + n-1) \log(1-q) - I^* - A \cdot I^* (1-q) \frac{((n-1)^2 + 1)I^* + n-1}{I^*} \end{aligned} \quad (\text{B.50})$$

where $A = \frac{(n-1)((n-1)I^* + n-1)}{I^*(((n-1)^2 + 2)I^* + n-1)^2}$. By the definition of $\varphi_{ji}(c; \mathbf{I})$ and $\beta_{ji}(q; \mathbf{I})$, we have:

$$\begin{aligned} \frac{\partial \varphi_{ji}(c; \mathbf{I})}{\partial I_i} \Big|_{I_k = I^* \forall k} = \frac{\partial G_j^{-1}(G_i(c; I_i); I_j)}{\partial q} \Big|_{I_k = I^* \forall k} \\ \left(\frac{\partial \beta_{ji}(G_i(c; I_i); \mathbf{I})}{\partial q} \cdot \frac{\partial G_i(c; I_i)}{\partial I_i} + \underbrace{\frac{\partial \beta_{ji}(G_i(c; I_i); \mathbf{I})}{\partial I_i}}_{=\hat{\beta}_{ji}(q)} \right) \Big|_{I_k = I^* \forall k} \end{aligned} \quad (\text{B.51})$$

Substituting (B.50) into (B.51), $\frac{\partial \varphi_{ji}(c; \mathbf{I})}{\partial I_i} \Big|_{I_k = I^* \forall k}$ can be rewritten as:

$$\begin{aligned} \frac{\partial \varphi_{ji}(c; \mathbf{I})}{\partial I_i} \Big|_{I_k = I^* \forall k} = \frac{\bar{c}}{I^*} \left(1 - \frac{c}{\bar{c}} \right)^{1-I^*} \\ \left[-B \cdot \left(1 - \frac{c}{\bar{c}} \right)^{I^*} (((n-1)^2 + 2)I^* + n-1) \log \left(1 - \frac{c}{\bar{c}} \right) \right. \\ \left. + B \cdot \left\{ \left(1 - \frac{c}{\bar{c}} \right)^{I^*} - \left(1 - \frac{c}{\bar{c}} \right)^{((n-1)^2 + 1)I^* + n-1} \right\} - \left(1 - \frac{c}{\bar{c}} \right)^{I^*} \log \left(1 - \frac{c}{\bar{c}} \right) \right] \end{aligned} \quad (\text{B.52})$$

where $B = A \cdot I^*$. It implies that $\frac{\partial \varphi_{ji}(c; \mathbf{I})}{\partial I_i} \Big|_{I_k = I^* \forall k} > 0$, $\forall c \in [0, \bar{c}]$. Coupled with $\frac{\partial H(c)}{\partial c} \frac{I_j}{I_j} < 0$, $\frac{\partial H(\varphi_{ji}(c; \mathbf{I}))}{\partial I_i} \frac{I_j}{I_j} \Big|_{I_k = I^* \forall k} < 0$, $\forall c \in [0, \bar{c}]$. We know that left-hand side and the first term in right-hand side in the equation (B.44) are the same as the one in the unobservable investment case but the

second term in right-hand side is negative for all $c \in [0, \bar{c}]$. Given the convexity of R&D cost function, $\Phi(\cdot)$, symmetric level of R&D investment in the observable investment case cannot be greater than the one in the unobservable investment case.

Welfare Analysis in Oligopoly Model

Under the box demand, the results above are ready to be applied to welfare analysis. First, R&D investment level in the equilibrium under each regime can be compared.

$$I_{CI}^* = I_{UI}^* > I_{OI}^* \quad (\text{B.53})$$

If all agent have the same valuation on the product, social welfare is a function of minimum actual cost, corresponding to the investment level. As shown above, whereas the investment level in the complete information case and the unobservable investment case are the same, the observable investment case induces underinvestment. It implies that social welfare decreases in the observable investment case.

The symmetric investment equilibrium gives rise to standard pricing function (analogous to bidding function in auction theory):

$$\begin{aligned} P^*(c; I) &= c + \frac{1}{H(c)^{(n-1)I^*}} \int_c^{\bar{c}} H(t)^{(n-1)I^*} dt \\ &= \frac{1}{(n-1)I^* + 1} \bar{c} + \frac{(n-1)I^*}{(n-1)I^* + 1} c \end{aligned}$$

Thus, expected price of the product is given by:

$$\begin{aligned} EP^*(I) &= \frac{1}{(n-1)I^* + 1} \bar{c} + \frac{(n-1)I^*}{(n-1)I^* + 1} E(c) \\ &= \frac{(2n-1)I + 1}{((n-1)I + 1)(nI + 1)} \bar{c} \end{aligned}$$

Since $\frac{\partial EP^*(I)}{\partial I} = -\frac{n(n-1)I((2n-1)I+2)\bar{c}}{(((n-1)I+1)(nI+1))^2} < 0$ and $I_{UI}^* > I_{OI}^*$, we obtain $EP_{OI}^* > EP_{UI}^*$. We already showed that $EP_{UI}^* = EP_{CI}^*$. Therefore, the expected price of the product under each regime is ranked as:

$$EP_{OI}^* > EP_{UI}^* = EP_{CI}^*$$

The comparison of consumer surplus under each regime follows as:

$$CS_{CI} = CS_{UI} > CS_{OI}$$

Derivation of Equilibrium in Discrete Cost Model: Complete Information Case

As mentioned in the footnote in section 2.6.1, when possible realizations of the R&D result are simplified to two discrete types, all results except social welfare are sustained in the broad class of demand function. Therefore, in this section, we analyze the model under the assumption of general downward-sloping demand. $D(p)$ is a market demand with $D'(p) < 0$ and define profits of a firm with low cost, excluding R&D cost, as $\pi(p) = (p - \underline{c})D(p)$. We assume that $\pi(p)$ is strictly concave in price. In order to simplify the result, denote the monopoly price for the firm with low cost as $p^* = \underset{p}{argmax} \pi(p)$ and define $\hat{p} = \min\{\bar{c}, p^*\}$. Let's further denote the maximized profit with low cost as $\hat{\pi} = \pi(\hat{p})$. The timing of the game is the same as the baseline model.

Given firms' R&D investment level, firm i can earn positive profit, $\hat{\pi}$, only if firm i succeeds in reducing its cost whereas the rival fails in full disclosed case. Therefore, firm i 's expected payoff is given by $E\Pi_i = I_i(1 - I_j)\hat{\pi} - \Phi(I_i)$. Then, the first-order condition in the R&D stage is $(1 - I_j)\hat{\pi} - kI_i = 0$ and, by symmetry, the equilibrium of R&D investment is given by:

$$I_{CI}^* = \frac{\hat{\pi}}{\hat{\pi} + k}$$

Derivation of Equilibrium in Discrete Type Model: Unobservable Investment Case

When cost information is private, a two stage Bayesian game is considered. We first show strategies of firms in equilibrium and then show that firms have no incentive to deviate from the strategy. In the second stage, high cost firms would set price at the marginal cost. For privately informed low cost firms, however, there does not exist a pure strategy equilibrium in the second stage subgame because it has two motivations under cost uncertainty. On the one hand, the firm is tempted to enjoy market power given that the rival remains at high cost. On the other hand, the firm try to undercut and capture the market if it believes the rival also succeeds in R&D. Regardless of which strategy the rival uses in the second stage, the low cost firm i for sure expects to earn

$(1 - I_j)\hat{\pi}$ so two moves of the low cost firm should be balanced at the expected profit. Let $K_i(p)$ be the distribution function of firm i which describes the mixed strategy the low cost firm plays. Then, it requires:

$$\begin{aligned}(1 - I_j)\hat{\pi} &= (1 - I_j)(p - \underline{c})D(p) + I_j \cdot Pr(p < p_j)(p - \underline{c})D(p) \\ &= (1 - I_j)(p - \underline{c})D(p) + I_j(1 - K_j(p))(p - \underline{c})D(p)\end{aligned}\tag{B.54}$$

in the support of $[\underline{p}, \hat{p}]$, where $\underline{p}$ satisfies $\pi_i(\underline{p}) = (1 - I_j)\hat{\pi}$. From Equation (B.54), we obtain:

$$K_j(p) = \frac{1}{I_j} - \frac{(1 - I_j)\hat{\pi}}{I_j(p - \underline{c})}\tag{B.55}$$

Suppose that (I_i^*, I_j^*) is a Nash equilibrium in the first stage. If firm i deviates from I_i^* , firm j still believes that the rival plays I_i^* and invests by I_j^* . Then, firm j plays the mixed strategy describes in Equation (B.55) over $[\underline{p}_j^*, \hat{p}]$ where $\underline{p}_j^*$ satisfies $\pi(\underline{p}_j^*) = (1 - I_j^*)\hat{\pi}$. No matter how firm i sets price in the second stage, its expected profit is given by $E\Pi_i = I_i(1 - I_j^*)\hat{\pi} - \Phi(I_i)$ which gives the same shape of best response in the complete information case if replacing I_j^* with I_j . It implies that $I_{UI}^* = \frac{\hat{\pi}}{\hat{\pi} + k}$ is a Nash equilibrium in R&D stage.

Derivation of Equilibrium in Discrete Type Model: Observable Investment Case

In the observable investment case, there does not exist pure strategy pricing equilibrium because firms compete with prices under cost uncertainty. The nature of mixed strategy in the second stage is similar to the one in the unobservable investment case. However, we should consider the case where firms invest asymmetrically as well because of the observability of investment level in this case. Let us assume that firm 1 invests more than firm 2 in the first stage. Suppose that both firms use the same pricing strategy as in the unobservable investment case. Then, it turns out that firm 1's minimum price level in the support of pricing strategy would be less than the rival's minimum price level and obviously firm 1 does not have any incentive to set price less than rival's minimum price. So this equilibrium cannot be sustained anymore.

Rather, firm 1 would set prices at higher level as it can expect that it is more likely to have the market power. And for firm 2, it would set prices aggressively relative to the rival because it knows

its investment level is lower than the rival. Thus in equilibrium, the expected payoff to the low cost firm is equalized for both firms even when firms invest asymmetrically. Given that $I_1 > I_2$, the distribution used in mixed strategy for firm 1 is:

$$K_1(p) = \frac{1}{I_1} - \frac{(1 - I_2)\hat{\pi}}{I_1(p - \underline{c})}$$

and the distribution describing the strategy for firm 2 is:

$$K_2(p) = \frac{1}{I_2} - \frac{(1 - I_2)\hat{\pi}}{I_2(p - \underline{c})}$$

The distributions show that firm 1 sets price less aggressively compared to the rival and note that $K_1(p)$ has a mass point on $\hat{p}$. In the observable investment case, therefore, firms have two types of investment strategy: aggressive investment and passive investment. Firms' expected profit for each investment strategy is given by:

$$\Pi_i = \begin{cases} I_i(1 - I_i)\hat{\pi} - \Phi(I_i) & \text{if } I_i \leq I_j \\ I_i(1 - I_j)\hat{\pi} - \Phi(I_i) & \text{if } I_i \geq I_j \end{cases}$$

If a firm choose the aggressive investment strategy, the optimal investment level is:

$$I_i = \begin{cases} I_j & \text{if } I_j \leq \frac{\hat{\pi}}{2\hat{\pi} + k} \\ \frac{\hat{\pi}}{2\hat{\pi} + k} & \text{if } I_j \geq \frac{\hat{\pi}}{2\hat{\pi} + k} \end{cases}$$

And if a firm choose the passive investment strategy, the optimal investment level is:

$$I_i = \begin{cases} I_j & \text{if } I_j \geq \frac{\hat{\pi}}{\hat{\pi} + k} \\ \frac{1}{k}(1 - I_j)\hat{\pi} & \text{if } I_j \leq \frac{\hat{\pi}}{\hat{\pi} + k} \end{cases}$$

Denote Π_i^A the expected profit of firm i when it chooses the aggressive investment strategy and Π_i^P the expected profit when firm i chooses the passive investment strategy. Lemma A.1 says how firms use these two investment strategy given the rival's R&D level.

Lemma 1. *There exists $\tilde{I} \in (\frac{\hat{\pi}}{2\hat{\pi} + k}, \frac{\hat{\pi}}{\hat{\pi} + k})$ such that $\Pi_i^A > \Pi_i^P, \forall I_i < \tilde{I}$ and $\Pi_i^A < \Pi_i^P, \forall I_i > \tilde{I}$.*

If the rival's R&D level is very low, then a firm would be willing to invest aggressively so that it can effectively increase the chance to hold a dominant position in the market in terms of cost. But as the rival increases its investment level, switching the strategy would be profitable because as shown above, once the rival observes that its own investment level is greater than the other, the rival tends to set price at $\hat{p}$. Then, this firm may want to invest passively and enjoy the undercutting chance.

The fact that $\tilde{I} < \frac{\hat{\pi}}{\hat{\pi}+k}$ implies that there is no symmetric equilibrium in R&D stage in the observable investment case. The equilibrium of investment in the observable investment case is:

$$(I_{1OI}^*, I_{2OI}^*) = \left(\frac{\hat{\pi}}{2\hat{\pi}+k} \left(1 + \frac{\hat{\pi}}{k}\right), \frac{\hat{\pi}}{2\hat{\pi}+k} \right) \text{ or } \left(\frac{\hat{\pi}}{2\hat{\pi}+k}, \frac{\hat{\pi}}{2\hat{\pi}+k} \left(1 + \frac{\hat{\pi}}{k}\right) \right)$$

Comparing the investment equilibrium with the one in previous cases, the aggregate level of investment in the observable investment case is less(greater) than the one under other cases if $\hat{\pi} < (>) k$. Interestingly, regardless of value of parameters, both firms earn more profits in the observable investment case. This is because unlike the baseline model, one firm's additional investment does not affect the rival's pricing strategy. So the firm with passive investment strategy does not price aggressively and, in turn, price competition becomes softened.

If we assume that demand is inelastic and the valuation of all consumer on the product is v , we can easily see that $I_{CI}^* = I_{UI}^*$ achieves socially desirable level and the observable investment case induces over- or under-investment, depending on the value of parameters. Moreover, considering that firms capture more surplus in the observable investment case, it hurts consumers as well.

Derivation of Equilibrium in Asymmetric Firms Model

I first consider the complete information case. The lower bound of firm i 's cost distribution is reduced by I_i after the investment, i.e, the support of firm i 's cost distribution is changed to $c \sim U[\bar{c} - \delta_i - I_i, \bar{c}]$, or $U[\bar{c} - \tilde{\delta}_i, \bar{c}]$. Let $\tilde{F}_i(c) = 1 - \frac{\bar{c}-c}{\tilde{\delta}_i}$ be the c.d.f of firm i 's cost after R&D activities.

In price competition stage, if $c_i < c_j$, firm i sets price at rival's marginal cost and its profit is $c_j - c_i$. Otherwise, firm i would charge its marginal cost and earn zero profit. Thus, firm i 's

expected payoff $E\pi_i$ is equal to $E[c_j - c_i | c_i < c_j]Pr[c_i < c_j]$. If $\tilde{\delta}_1 > \tilde{\delta}_2$, firm 1's expected payoff can be written as:

$$\begin{aligned}
E\pi_1(c; \mathbf{I}) &= \int_{\bar{c}-\tilde{\delta}_2}^{\bar{c}} c[1 - \tilde{F}_2(c)]d\tilde{F}_2(c) - \int_{\bar{c}-\tilde{\delta}_1}^{\bar{c}} c[1 - \tilde{F}_2(c)]d\tilde{F}_1(c) - \Phi(I_i) \\
&= \int_{\bar{c}-\tilde{\delta}_2}^{\bar{c}} c[1 - \tilde{F}_2(c)]d\tilde{F}_2(c) - \int_{\bar{c}-\tilde{\delta}_1}^{\bar{c}-\tilde{\delta}_2} c d\tilde{F}_1(c | c < \bar{c} - \tilde{\delta}_2) \\
&\quad - \int_{\bar{c}-\tilde{\delta}_2}^{c^H} c[1 - \tilde{F}_2(c)]d\tilde{F}_1(c | c > \bar{c} - \tilde{\delta}_2) - \Phi(I_i) \\
&= \frac{1}{2}(\tilde{\delta}_1 - \tilde{\delta}_2) + \frac{\tilde{\delta}_2^2}{6\tilde{\delta}_1} - \Phi(I_i)
\end{aligned} \tag{B.56}$$

If $\tilde{\delta}_1 < \tilde{\delta}_2$, firm 1's expected payoff is:

$$\begin{aligned}
E\pi_1(c; \mathbf{I}) &= \int_{\bar{c}-\tilde{\delta}_2}^{\bar{c}} c[1 - \tilde{F}_2(c)]d\tilde{F}_2(c) - \int_{\bar{c}-\tilde{\delta}_1}^{\bar{c}} c[1 - \tilde{F}_2(c)]d\tilde{F}_1(c) - \Phi(I_i) \\
&= \frac{\tilde{\delta}_1^2}{6\tilde{\delta}_2} - \Phi(I_i)
\end{aligned} \tag{B.57}$$

Define I_i^* such that $\Phi'(I_i^* + \delta_i) = 1/3$. Then, firm i 's best response in R&D competition stage is given by:

$$\Phi'(I_i) = \begin{cases} \frac{1}{2} - \frac{\tilde{\delta}_j^2}{6\tilde{\delta}_i^2} & \text{if } I_i < I_i^* \\ \frac{\tilde{\delta}_i}{3\tilde{\delta}_j} & \text{if } I_i \geq I_i^* \end{cases} \tag{B.58}$$

which gives the equilibrium in R&D competition stage at the intersection of best responses. By using the same method in the section 2.4, the expected price in the complete information case is given by:

$$E(\tilde{p}^{CI}) = \int_{\bar{c}-\tilde{\delta}_2}^{\bar{c}} \tilde{F}_2(c) + c\tilde{F}_2'(c) - \tilde{F}_1(c)\tilde{F}_2(c)dc \tag{B.59}$$

and consumer surplus is derived by $CS = v - E(\tilde{p}^{CI})$, followed by total welfare, $W = CS + \sum E\pi_i$.

In the observable investment case, by applying the same method in section 2.3.3, the pricing strategy for firm i can be derived as:

$$P_i(c; \mathbf{I}) = \bar{c} - \frac{\bar{c} - c}{1 + \sqrt{1 - (\frac{1}{\delta_i^2} - \frac{1}{\delta_j^2})(\bar{c} - c)^2}} \quad (\text{B.60})$$

and the inverse pricing function is:

$$\phi_i(p; \mathbf{I}) = \bar{c} - \frac{2(\bar{c} - p)}{1 + (\frac{1}{\delta_i^2} - \frac{1}{\delta_j^2})(\bar{c} - p)^2} \quad (\text{B.61})$$

Given the pricing equilibrium $(P_1(c; \mathbf{I}), P_2(c; \mathbf{I}))$, firm 1's *ex ante* expected payoff is given by:

$$\begin{aligned} E\pi_1(P_1, c; \mathbf{I}) &= \int_{\bar{c}-\tilde{\delta}_1}^{\bar{c}} (P_1(c; \mathbf{I}) - c) \cdot Pr[c_2 > \varphi_{21}(c; \mathbf{I})] d\tilde{F}_1(c) - \Phi(I_1) \\ &= \int_{\bar{c}-\tilde{\delta}_1}^{\bar{c}} (P_1(c; \mathbf{I}) - c) \{1 - \tilde{F}_2(\varphi_{21}(c; \mathbf{I}))\} d\tilde{F}_1(c) - \Phi(I_1) \quad (\text{by using integration by parts}) \\ &= - \int_{\bar{c}-\tilde{\delta}_1}^{\bar{c}} \tilde{F}_1(c) \frac{d}{dc} (P_1(c; \mathbf{I}) - c) \{1 - \tilde{F}_2(\varphi_{21}(c; \mathbf{I}))\} dc - \Phi(I_1) \end{aligned}$$

By using Envelope Theorem, we obtain:

$$\frac{d}{dc} (P_1(c; \mathbf{I}) - c) \{1 - \tilde{F}_2(\varphi_{21}(c; \mathbf{I}))\} = - \{1 - \tilde{F}_2(\varphi_{21}(c; \mathbf{I}))\}$$

Substituting this expression into the integral, we then have:

$$E\pi_1(P_1, c; \mathbf{I}) = \int_{\bar{c}-\tilde{\delta}_1}^{\bar{c}} \tilde{F}_1(c) \{1 - \tilde{F}_2(\varphi_{21}(c; \mathbf{I}))\} dc - \Phi(I_1) \quad (\text{B.62})$$

The first order condition with respect to I_1 is:

$$\begin{aligned} \Phi'(I_1) &= \int_{\bar{c}-\tilde{\delta}_1}^{\bar{c}} \frac{\partial \tilde{F}_1(c) \{1 - \tilde{F}_2(\varphi_{21}(c; \mathbf{I}))\}}{\partial I_1} dc - \underbrace{(-1) \tilde{F}_1(\bar{c} - \tilde{\delta}_1) \{1 - \tilde{F}_2(\varphi_{21}(\bar{c} - \tilde{\delta}_1; \mathbf{I}))\}}_{=0} \\ &= \int_{\bar{c}-\tilde{\delta}_1}^{\bar{c}} \left[\frac{\partial \tilde{F}_1(c)}{\partial I_1} \{1 - \tilde{F}_2(\varphi_{21}(c; \mathbf{I}))\} + \tilde{F}_1(c) \frac{\partial}{\partial I_1} \{1 - \tilde{F}_2(\varphi_{21}(c; \mathbf{I}))\} \right] dc \end{aligned} \quad (\text{B.63})$$

From the fact that $\frac{\partial}{\partial I_1} \{1 - \tilde{F}_2(\varphi_{21}(c; \mathbf{I}))\} < 0$ for all $c \in [\bar{c} - \tilde{\delta}_1, \bar{c}]$, cost-reducing investment has a negative strategic effect as in the symmetric model. Applying the same method in the section

2.4, the expected price in the observable investment case is:

$$E(\tilde{p}^{PD}) = \int_{\tilde{c}-\tilde{\delta}_2}^{\tilde{c}} \tilde{F}_2(c) + c\tilde{F}_2'(c) + \tilde{F}_1(\varphi_{12}(c; \mathbf{I}))\{\varphi_{12}(c; \mathbf{I})\tilde{F}_2'(c) - \tilde{F}_2(c) - c\tilde{F}_2'(c)\}dc \quad (\text{B.64})$$

The equation (B.64) and the corresponding equation for firm 2 give the industry profits and consumer surplus is derived by $CS = v - E(\tilde{p}^{PD})$. Total welfare follows as $W = CS + \sum \pi_i$.

APPENDIX C

PROOFS IN CHAPTER 3

Proof of Proposition 3.2.

Proof. This proof proceeds in three steps. First, we show that there exists some positive value of ν for which firm 1 would want to offer a grandfather clause. Second, we show that if firm 1 wants to offer a grandfather clause for some value ν , it must also want to offer a grandfather clause for any average quality improvement lower than that value. Conversely, we show that if firm 1 does not want to offer a grandfather clause for some value of ν , it will not want to offer one for any larger average quality improvement. Finally, we show that there exists a value of ν for which firm 1 does not want to offer a grandfather clause.

Step 1. To show existence of a ν for which firm 1 would want to offer a grandfather clause, we must first show that prices and consequently, firm 1's profit, are continuous in ν . This requires a continuous implicit function that gives the equilibrium prices in terms of ν . First, suppose that firm 1's equilibrium price is increasing in ν when firm 1 does not offer a grandfather clause. This assumption will be confirmed in Step 2. Let

$$H(\nu, p_1, p_2) := \left(\frac{\partial}{\partial p_1} [p_1 F(\nu + p_2 - p_1)], \frac{\partial}{\partial p_2} [p_2 (1 - F(\nu + p_2 - p_1))] \right) \quad (\text{C.1})$$

Note that under Assumption 2, $p_1 F(\nu + p_2 - p_1)$ represents either firm 1's expected profit under uniform pricing, or double the non-constant component of expected profit when it offers a grandfather clause. Similarly, $p_2 (1 - F(\nu + p_2 - p_1))$ represents either firm 2's expected profit when it believes that firm 1 will set a uniform price, or double that amount when firm 1 is expected to offer a grandfather clause.¹

¹Thus, the price that satisfies firm 2's first order condition is invariant to its beliefs regarding firm 1's decision to grandfather.

Let $J(\nu, p_1, p_2)$ represent the matrix of the partials of $H(\nu, p_1, p_2)$:

$$\frac{\partial H(\nu, p_1, p_2)}{\partial(p_1, p_2)} := J(\nu, p_1, p_2) = \begin{bmatrix} -2f(\gamma) + p_1 f'(\gamma) & f(\gamma) - p_1 f'(\gamma) \\ f(\gamma) + p_2 f(\gamma) & -2f(\gamma) - p_2 f(\gamma) \end{bmatrix} \quad (\text{C.2})$$

where we define $\gamma \equiv \nu + p_2 - p_1$. In equilibrium, it must be that $H(\nu, p_1, p_2) = 0$. Thus, we need to find a continuous implicit function $g(\gamma) = (p_1, p_2)$ such that $H(\nu, g(\nu)) = 0$. Such a g exists if $H(\nu, p_1, p_2)$ is continuously differentiable and $J(\nu, p_1, p_2)$ is invertible. The first condition is satisfied by assumption. The second follows if the determinant of $J(\nu, p_1, p_2)$,

$$|J(\nu, p_1, p_2)| = 3f(\gamma)^2 + (p_2 - p_1)f(\gamma)f'(\gamma) \quad (\text{C.3})$$

is non-zero. The first term on the right-hand side of Equation (C.3) is clearly positive. Our assumption that idiosyncratic preferences are independently and identically distributed in the initial and mature market periods together with Assumption 2 imply that Lemma 1 applies. Therefore, $p_2 - p_1 < 0$ and $\gamma > 0$. Then, single-peakedness and symmetry imply that $f'(\gamma) < 0$, such that the second term on the right-hand side of Equation (C.3) is likewise positive, as is $|J(\nu, p_1, p_2)|$. Thus, $J(\nu, p_1, p_2)$ is invertible and the implicit function theorem guarantees the existence of a continuously differentiable g . Therefore, the function that gives firm 1's equilibrium expected profit in terms of ν is likewise continuous. Note that if firm 1 chooses to set a uniform price in the mature market period, its equilibrium expected profit is given by $\pi_1^*(\nu) \equiv g_1(\nu)F(\nu + g_2(\nu) - g_1(\nu))$ where $g(\nu) = (g_1(\nu), g_2(\nu))$.

Recall that when $\nu = 0$, firm 1's expected profit in the mature market period under uniform pricing is $1/(4f(0))$ (this was also its realized profit in the initial period). Under Assumption 2, if firm 1 chooses to offer a grandfather clause at some positive ν , its expected profit is $1/(4f(0)) + \pi_1^*(\nu)/2$. This will exceed firm 1's non-grandfathered expected profit if and only if $\pi_1^*(\nu) < 1/(2f(0))$. Continuity of π_1^* implies that for any ϵ , there exists $\underline{\nu}$ such that if $|\nu| < \underline{\nu}$, $|\pi_1^*(\nu) - 1/(4f(0))| < \epsilon$. By choosing $\epsilon < 1/(4f(0))$, we can ensure that for any $\nu < \underline{\nu}$, firm 1's profits will be higher with a grandfather clause than without one.

Step 2. For the proof of this step, it suffices to show that $\pi_1^*(\nu)$ is increasing in ν . This follows immediately if p_1 and γ are increasing in ν .

According to the implicit function theorem the derivative of prices with respect to ν is $-(J(\nu, p_1, p_2))^{-1} D_\nu H(\nu, p_1, p_2)$, where $D_\nu H(\nu, p_1, p_2)$ represents the derivative of $H(\nu, p_1, p_2)$ with respect to ν . After some algebraic manipulation, we find that:

$$\frac{dp_1}{d\nu} = \frac{f(\gamma)(f(\gamma) - p_1 f'(\gamma))}{3f(\gamma)^2 + (p_2 - p_1)f(\gamma)f'(\gamma)} \quad (\text{C.4})$$

$$\frac{d\gamma}{d\nu} = \frac{f(\gamma)^2}{3f(\gamma)^2 + (p_2 - p_1)f(\gamma)f'(\gamma)} \quad (\text{C.5})$$

Note that the denominator in Equations (C.4) and (C.5) equals $|J(\nu, p_1, p_2)|$, which is already established to be positive. Likewise, both numerators are positive. In particular, with regard to Equation (C.4), as established in the previous step, $f'(\gamma)$ is negative because of Lemma 1, single-peakedness, and symmetry. Therefore, because price is increasing and quantity is non-decreasing in ν , $\pi_1^*(\nu)$ is increasing in ν .

Because $\pi_1^*(\nu)$ is increasing, $\pi_1^*(\hat{\nu}) < 1/(2f(0))$ implies that $\pi_1^*(\nu) < 1/(2f(0))$ whenever $\nu < \hat{\nu}$. That is, if firm 1 wants to offer a grandfather clause for some $\hat{\nu}$, it will want to offer a grandfather clause for all $\nu < \hat{\nu}$. Conversely, whenever $\pi_1^*(\hat{\nu}) > 1/(2f(0))$, this will also be the case for all $\nu > \hat{\nu}$. Thus, if firm 1 does not want to offer a grandfather clause at $\hat{\nu}$, it will not want to offer one for any $\nu > \hat{\nu}$.

Step 3. To complete the proof we must show that there exists some $\bar{\nu}$ such that $\pi_1^*(\bar{\nu}) > 1/(2f(0))$. Because quantity is bounded above by 1, to guarantee this, we need to show that price is unbounded in ν —or alternatively, that its derivative provided in Equation (C.4) is bounded away from zero. Using the first order conditions that $f(\gamma) = 1/(p_1 + p_2)$, Equation (C.4) can be rewritten as:

$$\frac{dp_1}{d\nu} = \frac{1}{3 - (p_1^2 - p_2^2)f'(\gamma)} + \frac{-p_1 f'(\gamma)}{3f(\gamma) - (p_1 - p_2)f'(\gamma)} \quad (\text{C.6})$$

Lemma 1, single-peakedness, and symmetry imply that both terms on the right-hand side are positive. Thus, it suffices to show that the first term is unbounded. Because single-peakedness implies that $f'(\gamma)$ goes to zero as ν approaches infinity, the first term could only go to zero if

$(p_1^2 - p_2^2)$ were unbounded. But if that were true, p_1 would be unbounded. Thus, p_1 is unbounded in ν and it must be the case that there exists some $\bar{\nu}$ such that $\pi_1^*(\bar{\nu}) > 1/(2f(0))$. Finally, because $\pi_1^*(\nu)$ is strictly increasing, there exists $\hat{\nu}$ such that $\pi_1^*(\hat{\nu}) = 1/(2f(0))$ and for any average quality improvement $\nu < \hat{\nu}$, firm 1 will wish to offer a grandfather clause, whereas for any $\nu > \hat{\nu}$ it will not. $\square$

Proof of Proposition 3.3.

Proof. We first show that prices and firm 1's profits are continuous in ν and α . However, because we fix ν for the duration of this proof, going forward, we will suppress ν as an argument in functions. Suppose that the distribution of the difference in idiosyncratic preferences is given by G_α . Additionally, suppose that firm 1's equilibrium price is increasing in ν when firm 1 does not offer a grandfather clause. It is possible to confirm that this assumption does indeed hold in equilibrium following the same methodology used in the proof of Proposition 2 (see Equation (C.4)). Define the vector

$$H(\alpha, p_1, p_2) := \left[\frac{\partial}{\partial p_1} [p_1 F(\alpha(\nu + p_2 - p_1))], \frac{\partial}{\partial p_2} [p_2 (1 - F(\alpha(\nu + p_2 - p_1)))] \right] \quad (C.7)$$

and let $J(\alpha, p_1, p_2)$ represent the matrix of the partials of $H(\alpha, p_1, p_2)$:

$$J(\alpha, p_1, p_2) = \begin{bmatrix} -2\alpha f(\alpha\gamma) + p_1 \alpha^2 f'(\alpha\gamma), & \alpha f(\alpha\gamma) - p_1 \alpha^2 f'(\alpha\gamma) \\ \alpha f(\alpha\gamma) + p_2 \alpha^2 f'(\alpha\gamma), & -2\alpha f(\alpha\gamma) - p_2 \alpha^2 f'(\alpha\gamma) \end{bmatrix} \quad (C.8)$$

where we again define $\gamma \equiv \nu + p_2 - p_1$.

As in the proof of Proposition 3.2 we need to find a continuous implicit function $g(\alpha) = (p_1, p_2)$ such that $H(\alpha, g(\alpha)) = 0$. Such a g exists if $H(\alpha, g(\alpha))$ is continuously differentiable and $J(\alpha, p_1, p_2)$ is invertible. The first condition is satisfied by assumption. The second follows if the determinant of $J(\alpha, p_1, p_2)$,

$$|J(\alpha, p_1, p_2)| = 3\alpha^2 f(\alpha\gamma)^2 + \alpha^3 (p_2 - p_1) f(\alpha\gamma) f'(\alpha\gamma) \quad (C.9)$$

is non-zero. As in Proposition 3.2, this follows from Assumption 2, Lemma 1, as well as our single-peakedness and symmetry assumptions. Therefore, the function that gives firm 1's equilibrium

expected profit in terms of α and ν is likewise continuous. Note that if firm 1 chooses to set a uniform price in the mature market period, its equilibrium expected profit is given by $\pi_1^*(\alpha) \equiv g_1(\alpha)F(\alpha(\nu + g_2(\alpha) - g_1(\alpha)))$ where $g(\alpha) = (g_1(\alpha), g_2(\alpha))$.

Under this new specification, when $\nu = 0$, it is readily shown that firm 1's expected profit in the mature market period under uniform pricing is:

$$\bar{\pi}_1(\alpha) \equiv \frac{1}{4\alpha f(0)} \quad (\text{C.10})$$

Moreover, under Assumption 2, if firm 1 chooses to offer a grandfather clause at some positive ν , its expected profit is $\bar{\pi}_1(\alpha) + \pi_1^*(\alpha)/2$ so that its profit when it grandfathers exceeds its profit when it doesn't if and only if $\pi_1^*(\alpha) < 2\bar{\pi}_1(\alpha)$. Define:

$$r_\pi \equiv \frac{\pi_1^*(\alpha)}{\bar{\pi}_1(\alpha)} \quad (\text{C.11})$$

Thus, firm 1 wants (doesn't want) to offer a grandfather clause if $r_\pi(\alpha) < 2$ ($r_\pi(\alpha) > 2$). Then to complete our proof it suffices to show that (i) $r_\pi(\alpha)$ is increasing in α , (ii) $\lim_{\alpha \rightarrow 0} r_\pi(\alpha) = 1$, and (iii) $\lim_{\alpha \rightarrow \infty} r_\pi(\alpha) = \infty$.

For (i), using the implicit function theorem together with the first order condition $p_1 f(\alpha\gamma) = F(\alpha\gamma)/\alpha$, we find that the derivative of $r_\pi(\alpha)$ with respect to α is:

$$\frac{\partial r_\pi(\alpha)}{\partial \alpha} = \frac{4\nu f(0)F(\alpha\gamma)(2f(\alpha\gamma) - \alpha p_1 f'(\alpha\gamma))}{3f(\alpha\gamma) - \alpha(p_1 - p_2)f'(\alpha\gamma)} \quad (\text{C.12})$$

In the numerator, ν , $f(0)$, $F(\alpha\gamma)$, α , and p_1 are all positive, whereas $f'(\alpha\gamma)$ is negative (Assumption 2, Lemma 1, single-peakedness and symmetry). Additionally, in the denominator, $f(\alpha\gamma)$ and $p_1 - p_2$ are positive (Lemma 1). Thus, both the numerator and denominator are positive, so that $r_\pi(\alpha)$ is increasing in α .

In proving (ii), we note that as α approaches zero, $\bar{\pi}_1(\alpha)$ increases to infinity, and because $\pi_1^*(\alpha)$ is bounded below by $\bar{\pi}_1(\alpha)$ (this follows because we assume that $\nu > 0$ and because $\pi_1^*(\alpha)$ is increasing in ν —see Step 2 in the proof of Proposition 2) $\pi_1^*(\alpha)$ likewise approaches infinity. Therefore, we can use L'Hopital's Rule to evaluate the limit of $r_\pi(\alpha)$ as it approaches zero. Again

using the implicit function theorem together with firm 1's first order condition, we have:

$$\frac{\partial \pi_1^*(\alpha)}{\partial \alpha} \bigg/ \frac{\partial \bar{\pi}_1(\alpha)}{\partial \alpha} = \frac{4\alpha f(0)F(\alpha\gamma)[(3p_1 - 2\nu)f(\alpha\gamma) + \alpha p_1 \gamma f'(\alpha\gamma)]}{3f(\alpha\gamma) - \alpha(p_1 - p_2)f'(\alpha\gamma)} \quad (\text{C.13})$$

Using firm 1's first order condition, the numerator in Equation (C.13) can be written:

$$12f(0)F(\alpha\gamma)^2 - 8\alpha\nu f(0)f(\alpha\gamma)F(\alpha\gamma) + 4\alpha\gamma f(0)f'(\alpha\gamma)f(\alpha\gamma)^{-1}F(\alpha\gamma) \quad (\text{C.14})$$

Using the fact that $p_1 - p_2 \leq \nu$ (Lemma 1) and $F(0) = 1/2$, we see that the first term in Expression (C.14) equals $3f(0)$ in the limit whereas the remaining two terms equal zero. Similarly, the limit of the first term in the denominator of Equation (C.13) equals $3f(0)$ and that of the second term equals zero, such that $r_\pi(\alpha)$ goes to 1 as α approaches zero.

Finally, for the proof of (iii), assuming that prices are restricted to being non-negative, it suffices to show that firm 1 can always make a profit of at least $\nu/2$. Because $\pi_1^*(\alpha)$ increases in p_2 , at worst, when $p_2 = 0$, firm 1 can name a price of ν to earn profit of $\nu F(\alpha \times 0) = \nu/2$. Therefore, $r_\pi(\alpha) \geq 2\alpha\nu f(0)$ and as α goes to infinity, so does $r_\pi(\alpha)$. $\square$

Proof of Corollary 1.

Proof. Consider $\alpha^*(\nu)$ for some $\nu > 0$. From the proof of Proposition 3.3, we know that $\alpha^*(\nu)$ is the value of α that satisfies $\pi_1^*(\alpha)/\bar{\pi}_1(\alpha) = 2$. Next, consider some $\nu' > \nu$. Using Step 2 in the proof of Proposition 3.2, we know that holding α fixed, $\pi_1^*(\alpha)$ rises, but that $\bar{\pi}_1(\alpha)$ remains unchanged. Thus, $r_\pi(\alpha^*(\nu)) > 2$ at ν' . Because $r_\pi(\alpha)$ is increasing in α , $\alpha^*(\nu') < \alpha^*(\nu)$. $\square$

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