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Essays on Timing of Firm Actions in Industrial Economics

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Essays on Timing of Firm Actions in Industrial Economics

A Dissertation Presented for the
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DEDICATION

To my parents, Meichu Li and Fangjun Yao.

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ABSTRACT

The timing of actions by firms plays an important role in industrial economics. It is key to strategic advantage in oligopoly models whether firms compete on quantity or on price. In a vertical relationship between input suppliers and final-good manufacturers, a firm which chooses a strategy first will take into account the response by those firms moving second and different sequence of play leads to different market outcomes. In my dissertation, I study the determinants and implications of the timing of firm actions in a variety of scenarios. In my first two essays, I examine how market leadership may arise endogenously in oligopoly models and focus on the effect of information about uncertain market demand. My first essay studies a quantity game and I identify the circumstance under which a perishable information asymmetry regarding stochastic demand causes market leadership. In an information acquisition game, I show that Stackelberg equilibrium in the full game is supported only when firms have different costs of information. My second essay considers a duopoly in which firms supply a differentiated product and compete on price. I find that different equilibrium outcomes arise under different information structures. Under asymmetric information, a firm's information advantage leads to a strategic disadvantage of leading in the price game. The time value of information may well be negative, contrasting with results in the first essay. In my third essay, I consider a vertical relationship in which a supplier sets the price of an input and the firm that produces the final good must choose how much to invest in some complementary input or process. Two models with different sequence of firm actions are studied and yield different pricing strategies for the upstream monopolist. Interestingly, a

change of the sequence from one model (the upstream firm commits to input prices first) to the other (the upstream firm sets input prices after investments are made) benefits all parties including the upstream monopolist, the downstream firms and the consumers.

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CHAPTER I

GENERAL INTRODUCTION

A critical part of market competition in industrial economics is the timing of actions by firms. When firms interact strategically in an oligopoly, an important consideration is whether they act simultaneously or sequentially (and if so, in what sequence). It was first emphasized by von Stackelberg (1934) that a sequential play equilibrium (which is later referred to as Stackelberg equilibrium) differs from the simultaneous play outcome (which is referred to as Cournot equilibrium for quantity competitions and Bertrand equilibrium for price competitions). In a linear quantity oligopoly with constant marginal production cost, the Stackelberg leader payoff is higher than the Cournot payoff which is again higher than the Stackelberg follower payoff. In other types of industrial relations such as interactions between input suppliers and final-good manufacturers, the sequence of play also affects the strategic interaction between the firms. A firm which chooses a strategy first will take into account the response by those firms moving second. Different sequence of play leads to different market outcomes.

The timing of firm actions is key to strategic advantage in oligopoly models whether firms compete on quantity or on price. Gal-Or (1985) studied first- and second-mover advantages in general duopoly models. He showed that the relative magnitudes of equilibrium payoffs, being a leader or a follower, depend on the slope of the reaction curves. With downward sloping reaction curves, leading is preferred to being a follower and there is first-mover advantage. Usually a quantity game falls into this category and commitment is valuable. With upward sloping reaction curves, being a follower is preferred and there is second-mover advantage. Usually a price game falls into this category and flexibility, instead, has a value. The comparison of firm payoffs between a simultaneous play equilibrium and a sequential play equilibrium is less straightforward. Hamilton and Slutsky (1990) showed that a player's leadership payoff exceeds his payoff in simultaneous play because one can choose any point on the other player's reaction curve including the simultaneous moving point. This apparently applies to duopoly models in which firms use their output levels or product prices as strategies. However, all these results are derived assuming that firms have perfect information about market demand. They may fail to hold when market demand is stochastic and firms have to make a choice based on a distribution instead of each realization of the market demand.

A vertical relationship between an upstream firm and a downstream firm differs in nature from firms in a duopoly. The actions taken by the firms are in different spaces. Suppose the upstream firm sets the price of the intermediate good, while the downstream firm chooses the output level and how much to invest in a complementary process that transform the intermediate good into the final good. The sequence of these actions significantly affects the strategic interaction between the firms. Although the choice of output level by the downstream firm is determined in the last stage, the order of upstream firm's input price setting and the downstream firms' investment choice can be in either way. For example, an upstream monopolist can either commit to an input price schedule before the downstream firms undertake an investment to lower production cost, or the upstream monopolist may remain flexible and set the input price after observing downstream firm's chosen production technology. How will market outcome be changed under different timing and how it impacts the profits of the firms?

In my dissertation, I study the determinants and implications of the timing of firm actions in a variety of scenarios in industrial economics. In my first two essays, I examine how market leadership may arise endogenously in oligopoly models and focus on the effect of information about uncertain market demand. My first essay studies a quantity game in which firms choose to produce in one of two periods. The circumstance under which a perishable information asymmetry regarding stochastic demand causes market leadership is identified. In the duopoly case, the firm that knows its competitor has a temporary information advantage may choose to act as the follower. A tradeoff is made between the strategic value of timing and the information value of choosing a quantity with knowledge of realized demand. High demand volatility leads to Stackelberg competition with the information advantaged firm leading. In the N-firm case, a Generalized-Stackelberg-Nash-Cournot (GSNC) equilibrium[1] (with multiple leaders and multiple followers) emerges endogenously. In a duopoly information acquisition game, I find the time value of information is strictly positive. Both symmetric and asymmetric outcomes are possible when information is costly. However, Stackelberg equilibrium in the full game is supported only when firms have different costs of information.

My second essay studies a price game in which firms supply a differentiated product and compete on price. Price competition differs from quantity competition in that following is usually preferred to leading since the follower can undercut the leader's

[1] Sherali (1984) defined a GSNC equilibrium by extending the simple Stackelberg structure into multiple simultaneously playing leaders and multiple simultaneously playing followers.

price. Different from the result under no uncertainty that only sequential play is a pure strategy equilibrium, with both firms uninformed in the first period, simultaneous play in the second period emerges as the unique equilibrium when the variance of the demand shock is high. With firms asymmetrically informed, the sequential play with the information advantaged firm leading may be the unique equilibrium. Even when both sequential moves are equilibria, I show the equilibrium with the advantaged firm leading risk dominates the other. A firm's information advantage leads to a strategic disadvantage of leading in the price game. I then consider an information acquisition stage in which firms can choose either to buy or not to buy information. I find both firms buying information is not an equilibrium even if information is free. The time value of information may well be negative, given the other firm's information choice. This contrasts with the result in the first essay.

In my third essay, I consider a vertical relationship in which a supplier sets the price of an input and the firm that produces the final good must choose how much to invest in some complementary input or process. Greater investment reduces the production cost of the final good. I then analyze two models with alternative timing, whether the investment occurs prior to the time the input price is set, or afterward. The upstream firm and the downstream firms strategically choose the input price and investment level, and this interaction depends crucially on the timing of their actions. Interestingly, not only the downstream firms but also the upstream monopolist prefers the sequence of play in the latter model, i.e. it benefits from committing to prices before investments are undertaken. Considering that consumer surplus is also improved due to higher output, a change of sequence of play from the first model to the second constitutes a strict Pareto improvement.

My first essay contributes to the literature in that it studies the effect of a perishable (instead of a permanent) information advantage on firms' timing choices. Clear-cut equilibrium results are obtained in the duopoly model and are extended to the general oligopoly case. Demand uncertainty in price games have not been modeled in the endogenous timing literature and my second essay fits this gap. Many of the results are quite interesting and contrast with previous findings. In both the quantity and price competition setting, I find that a perishable information advantage may give rise to market leadership with the information advantaged firm leading. However, since leading is preferred to following in the quantity game but not in the price game, the time value of information is different in these models. This further advances our understanding about the two forms of market competition in industrial organization. The results in my third essay that different sequence of firm actions in the vertical structure leads to substantially different market outcomes and one sequence Pareto dominates the other are new to the literature. Many related topics are open for future researches.

The rest of the dissertation is organized as follows. Essay 1 is presented in Chapter II, Essay 2 is presented in Chapter III and Essay 3 is presented in Chapter IV. Chapter V concludes all the findings from the essays. To facilitate reading, all proofs of the lemmas and propositions are put in the Appendix.

CHAPTER II

ESSAY 1: INFORMATION VALUE UNDER DEMAND UNCERTAINTY AND ENDOGENOUS STACKELBERG COMPETITION

In an oligopoly model with firms choosing to produce in one of two periods, I identify the circumstance under which a perishable information asymmetry regarding stochastic demand causes market leadership. In the duopoly case, the firm that knows its competitor has a temporary information advantage may choose to act as the follower. A tradeoff is made between the strategic value of timing and the information value of choosing a quantity with knowledge of realized demand. High demand volatility leads to Stackelberg competition with the information advantaged firm leading. In the N-firm case, a Generalized-Stackelberg-Nash-Cournot (GSNC) equilibrium (with multiple leaders and multiple followers) emerges endogenously. In a duopoly information acquisition game, I find the time value of information is strictly positive. Both symmetric and asymmetric outcomes are possible when information is costly. However, Stackelberg equilibrium in the full game is supported only when firms have different costs of information.

1.1 Introduction

Two critical ways that a firm may have an advantage over competitors are superior information (regarding uncertain demand, for example), and the strategic value of market leadership. An important question is, can an information advantage enable a firm to achieve leadership in a market? Put differently, if a firm that is known to be better informed than competitors leads a market, will its competitors choose to follow? How then does this impact the value of information?

As I discuss below, this question has been studied in some earlier work, but a key assumption has been that the information known by an informed firm (e.g. the realization of an uncertain market demand) is never directly revealed to uninformed firms regardless of the timing of their actions. Consequently, a signaling game arises with uniformed firms possibly able to infer some information from the actions of the informed firm if they act as a follower in the market. This signaling dynamic is interesting but generates a complex strategic environment which limits the analysis and does not lead unambiguously to leadership by an informed firm in equilibrium. I assume instead that any information advantage is perishable. That is, a firm may "get a jump" on competitors, becoming informed about realized demand earlier than others and thus have the possibility of acting in the market based on this information at a time when other firms can only act based only on expectations. However, if those competitors choose to act as followers, they can act after also becoming fully informed.

To understand my model, consider that in many markets firms may make a choice whether to be "close" to the market, which may entail geographic or other proximity that gives the firm an early signal of market demand. If this proximity comes at a cost, some firms may choose to incur it, while others do not. For example, a domestic producer may have this advantage of proximity relative to a foreign producer of a good, but the foreign producer may have lower production costs. Information advantage may also be obtained simply through more extensive and costly effort at forecasting demand. In either of these cases the information advantage would likely be perishable—an advantage of timing in the receipt of information.

I study firm behavior in a quantity-setting model with stochastic demand. In my setting, an information advantaged firm has a dominant strategy of playing first, while a disadvantaged firm faces a tradeoff between the strategic value of acting earlier (not ceding leadership to the informed firm) and the value of acting while fully informed. It prefers being an informed Stackelberg follower to being an uninformed Cournot player when the variance of the demand shock is high, and Stackelberg competition therefore arises endogenously. The *time value of information* lies in confronting other firms with a choice between a strategic disadvantage and an information disadvantage.

One advantage of my assumption that an information advantage is perishable is that, unlike previous papers that studied endogenous market leadership arising with an information asymmetry, I am able to model the quantity competition game for an N-firm oligopoly. I show that a Generalized-Stackelberg-Nash-Cournot (GSNC) equilibrium arises for $N > 2$ firms, with all informed firms acting as leaders and some (but not necessarily all) uniformed firms acting as followers.

Finally, I am able to identify equilibrium information acquisition for the duopoly case. The value of knowledge of realized demand increases with the variance of the distribution of possible demand shocks. As is intuitive, I find that when this variance is sufficiently high both firms will incur the cost of an early signal of demand, when the variance is low neither firms will obtain this information, and an intermediate range exists where only one firm becomes informed in equilibrium. It is interesting, however, that if both firms face the same cost of obtaining information, market leadership never arises endogenously. This is because in those circumstances where information is asymmetric (only one firm obtains the information), the equilibrium of the game involves the uninformed firm choosing not to act as a follower but rather as an uniformed Cournot competitor. Endogenous market leadership may arise, but only when the cost of information differs between firms.

Market leadership may have value if a firm benefits by committing to a particular action (output) and compelling other firms to react to it. Gal-Or (1985) showed that if the reaction function of the follower is downward sloping the leader earns higher profits than the follower. In a quantity duopoly with linear demand and constant marginal costs, a firm's payoff from playing Stackelberg leader is higher than the payoff from playing Cournot, which is again higher than that from playing Stackelberg follower. In this essay I will refer it as the *strategic value* of timing. Hamilton and Slutsky (1990) modeled what they termed "extended games with observable delay" to study endogenous sequencing games. Extended games entail players making a choice of the timing of their action, in addition to the underlying action choice (e.g., quantity or price in models of firm competition). In this model, firms announce at which time they will choose an action and are committed to it in the game of action choices that follows. Hamilton and Slutsky showed that the equilibrium has a simultaneous play subgame unless payoffs in sequential play Pareto dominate those in a simultaneous play.[2] In their discussion, information is complete and there is no uncertainty.

Several subsequent papers incorporate demand uncertainty into models of endogenous sequencing. Typically the intercept term of market demand has a random component. Because a firm's profit function is convex in the demand intercept, the expected payoff from acting with knowledge of the realization of the random shock is higher than that from acting based on expected demand. This is the *information value* of acting with knowledge of demand. Spencer and Brander (1992) consider a duopoly setting in which one firm has the option of choosing a quantity before the demand uncertainty is resolved. They show that when the variance of the random intercept is low, the firm would choose to pre-commit. But if both firms have this option, only Cournot equilibrium could possibly arise.

Mailath (1993) was the first to analyze a signaling game based on asymmetric information about market demand. He assumed demand could take on three possible values (low, medium, high). The informed firm in this model can choose either to move earlier than the uninformed firm at the cost of possibly revealing its private information, or move simultaneously. He gave an example of a patent expiring firm's capacity choice when facing the entry of another firm. The incumbent may choose a quantity before the entrant or simultaneously with the entrant. It was shown that in the unique stable outcome, the informed firm moves first regardless of its private information. Note that here the uninformed firm does not have the option to move early (i.e. only the choice to

[2] In another model called extended games with action commitment (firms can play early only by selecting an action to which it is then committed), Stackelberg equilibria are the only equilibria in undominated strategies. See Hamilton and Slutsky (1990) for more discussion about the differences between these two models.

lead is studied, not the choice to follow). Normann (2002) extended Mailath's model by allowing both the informed firm and the uninformed firm to move early.[3] He found that although Stackelberg equilibrium with either firm being the leader may emerge, Cournot equilibrium results endogenously for most parameters. These papers basically focus on how asymmetric information leads to endogenous timings of firm actions. A natural question is, considering how the sequence of play may be affected by information asymmetry, is information valuable and will firms buy information? The only paper that has addressed this is Daughety and Reinganum (1994). Instead of the intercept term having several types, they let the demand slope take two types and allowed firms to acquire information. They showed that if acquiring information is costly, the typical equilibrium involves only one firm acquiring information. Both firms acquiring information is an equilibrium if and only if information is free.

In these signaling models, at most three types of demand are considered. By focusing on different timing of information, my analysis avoids the complication and the possibility of no separating equilibrium in signaling games with too many types.[4] A general random demand intercept is assumed. Also, I assume it may cost a firm a lump-sum expenditure or a higher marginal production cost (or both) to obtain timely information. Examples of the former include firms buying information from some market research agency or doing forecasting on their own. For the latter, having earlier information may require a firm's locating close to the end market. For instance, a steel company which locates near a city, and thus is better informed, may have higher

[3] In his earlier paper (Normann 1997), a similar analysis was done using the model of extended game with action commitment. Cournot equilibrium is eliminated in undominated strategies.
[4] As was noted by Gal-Or (1987), there is no separating equilibrium if the second mover does not have any private information about the demand, which is generally stochastic.

production cost than if locating near iron ore mines or cheap labor. Another example arises if an international firm's having fast access to demand information in a foreign market requires its presence in that country.

The remainder of this essay is organized as follows. In section 1.2, I study firms' timing and output choices in a duopoly under information asymmetry, that is, one firm has earlier knowledge of the realization of the demand than the other firm. The result is then extended to the N-firm case. In section 1.3, I analyze firms' information acquisition decisions. I find both symmetric and asymmetric information acquisitions may arise when information is costly. The time value of information is strictly positive. In section 1.4, I conclude this essay and discuss future work.

1.2 The Model

I model a homogeneous product market in which firms compete in quantities, and initially assume a duopoly. Inverse market demand is linear with a stochastic intercept: $P = a + \varepsilon - Q$. Aggregate output is the sum of two firms' outputs, $Q = q_1 + q_2$, and $a > 0$ is the expected value of demand intercept and $\varepsilon \sim F(\cdot)$ is a random shock with mean 0 and variance $\sigma^2 > 0$. Without loss of generality, I set the coefficient on Q to one by the appropriate adjustment of units of output. Also, I assume the support of ε is such that every firm produce a strictly positive quantity throughout my considerations.[5]

I adopt the model of extended games with observable delay in Hamilton and Slutsky (1990). Extended games entail players making a choice of the timing of their

[5] As we will see, this requires $\varepsilon > -(A - 3k)$. It simplifies analysis by avoiding shut-down considerations. However, $F(\cdot)$ may still be symmetric or asymmetric around 0.

action, in addition to the underlying action choice (i.e. output). In this model, firms announce at which time they will choose an action and are committed to it in the game of action choices that follows. The basic quantity game is played in two periods, T_1, T_2. At a prestage, both firms make a decision either to produce in period T_1 or T_2 and this becomes common knowledge. If one firm chooses to produce in T_1 and the other T_2, Stackelberg equilibrium arises in the basic game. If both firms choose to produce in the same period, T_1 or T_2, a Cournot equilibrium obtains. I assume that an information asymmetry exists in the following way. Firm 1 learns the demand shock at the beginning of period T_1, while Firm 2 learns it at the beginning of period T_2. As discussed in the introduction, Firm 1 has a perishable information advantage because the demand uncertainty that Firm 2 faces at T_1 is resolved at T_2.

I assume Firm 1's information advantage is obtained through information acquisition activities (that incur a fixed cost $f \geq 0$, or a higher marginal production cost $k \geq 0$, or both). I will discuss in the next section an information acquisition stage, but here simply assume that Firm 1 alone has this information and incurs the associated cost. Denote Firm 1's marginal cost of production as $(c + k)$, where $c > 0$, while Firm 2 has marginal cost c. I define $A \equiv a - c$ to simplify notation. To ensure that both firms produce a positive quantity for any sequence of play, I assume $k < \frac{1}{3}A$. Note a fixed cost would be sunk in the analysis of timing and output choices. The parameters, a, c, k, and σ^2 are common knowledge.

Absent demand uncertainty, a firm earns greater profit as a Stackelberg leader than as a Cournot player, which in turn yields greater profit than being a Stackelberg follower. This is the *strategic value* of timing (i.e. the value of leading or not following). On the other hand, knowledge of the demand shock is directly valuable because a firm's profit function is convex in the demand intercept $(a+\varepsilon)$. Without information regarding realized demand, a risk-neutral firm's optimal output is determined by the expected value of the demand intercept. For any sequence of play, a firm's expected payoff (taking expectations of the distribution of possible demand shocks) is greater when output will be chosen with knowledge of demand than if output will be chosen based on expected demand. This is the *information value* of acting with knowledge of demand. In the extended game with two production periods, both values will be relevant to Firm 2's timing choice, because in choosing the time of its action it determines whether it will act with or without knowledge of the demand shock.

Restricting attention to subgame perfect equilibrium (SPE), the extended game can be solved backward by first solving four basic games corresponding to each possible choices of timing of the two firms. Denote firm i's output and profit as q_i and π_i. With a superscript, q_i^j and π_i^j, they represent firm i's output and profit when production is done in period T_j, $j=1,2$. For Firm 1, since the shock is known in both periods, the objective is simply:

$$\max_{q_1} \left(A+\varepsilon_0-q_1-q_2^{'}-k\right)q_1,$$

where ε_0 is the realized value of ε, and $q_2^{'}=\begin{cases} q_2(q_1), & \text{if Firm 2 moves after him} \\ q_2\,, & \text{otherwise} \end{cases}$.

For Firm 2, without knowledge of ε_0 in period T_1, the objective is:

$$\max_{q_2} \int \left(A+\varepsilon-q_1^{'}-q_2\right)q_2\, dF(\varepsilon),$$

$$\text{where } q_1' = \begin{cases} q_1(q_2), & \text{if Firm 1 moves after him} \\ q_1, & \text{otherwise} \end{cases}.$$

If Firm 2 chooses to produce in T_2, with knowledge of ε_0, then the objective is:

$$\max_{q_2} (A + \varepsilon_0 - q_1 - q_2) q_2.$$

Given risk neutral firms, only the expected value (0) and variance (σ^2) of the distribution $F(\cdot)$ affect expected payoffs. I obtain the equilibrium payoffs in each subgame of the extended game, the expectation of which gives us the payoffs of the prestage game of timing choice as shown in Table 1:

Table 1.1 The Reduced Game of Timing Choice

		Firm 2	
		T_1	T_2
Firm 1	T_1	$\frac{(A-2k)^2}{9}+\frac{\sigma^2}{4}, \frac{(A+k)^2}{9}$	$\frac{(A-2k)^2}{8}+\frac{\sigma^2}{8}, \frac{(A+2k)^2}{16}+\frac{\sigma^2}{16}$
	T_2	$\frac{(A-3k)^2}{16}+\frac{\sigma^2}{4}, \frac{(A+k)^2}{8}$	$\frac{(A-2k)^2}{9}+\frac{\sigma^2}{9}, \frac{(A+k)^2}{9}+\frac{\sigma^2}{9}$

From the payoff matrix, we can see the strategic value of timing by comparing the payoffs in two periods, given the other firm's timing choice. The information value is represented by the component with σ^2.[6] The higher the variance of the demand shock, the more valuable to a firm is being informed while choosing a quantity. Note that the SPE of the extended game are in one-to-one correspondence with equilibria in the reduced game. While Firm 1 has a dominant strategy of producing early, Firm 2's behavior in equilibrium depends on the variance of the demand shock. Define condition (1) as follows:

[6] If Firm 2 produces in $T1$, it does not observe ε and its expected profit does not have this component. Note that the magnitudes of information values are different with different sequences of play, not surprisingly.

$$\sigma^2 \geq \frac{7A^2 - 4Ak - 20k^2}{9}. \tag{1}$$

Then the equilibrium of this game is characterized by Proposition 1.1. (All proofs are in the Appendix.)

Proposition 1.1: It is a strictly dominant strategy for the informed firm (Firm 1) to act in period T_1. The uniformed firm (Firm 2) will choose to follow, acting in period T_2, if the variance of demand is sufficiently high satisfying condition (1) above. In this case, Stackelberg equilibrium in the output subgame with the information advantaged firm leading emerges endogenously. If condition (1) does not hold, both firms act in period T_1 and Cournot equilibrium arises.

The dominant strategy of Firm 1 is intuitive: it gains no information by waiting to produce in T_2 and loses a possible timing advantage. Given that Firm 1 will produce in T_1, Firm 2's choice is then between being a Cournot player in T_1 and being a Stackelberg follower in T_2. If producing in T_1, it gains the strategic value of not following, but must choose a quantity without knowing the shock. If producing in period T_2, it learns the shock at the cost of being a Stackelberg follower. The magnitudes of these two values depend on the parameters, A, k, σ^2, as well as the sequence of movement he chooses. By comparing the expected payoffs from two periods, I obtain the condition under which Firm 2 prefers being a Stackelberg follower to being a Cournot player, which is condition (1) above.

Using S to denote Stackelberg and C to denote Cournot, I have the following equilibrium quantities when firms produce sequentially:

$$q_1^{1S} = \frac{A-2k}{2} + \frac{\varepsilon_0}{2}, \;\; q_2^{2S} = \frac{A+2k}{4} + \frac{\varepsilon_0}{4}, \tag{2}$$

and the Cournot equilibrium quantities:

$$q_1^{1C} = \frac{A-2k}{3} + \frac{\varepsilon_0}{2}, \;\; q_2^{1C} = \frac{A+k}{3}. \tag{3}$$

The expected payoffs for the two firms are:

$$E(\pi_1^{1S}) = \frac{(A-2k)^2}{8} + \frac{\sigma^2}{8} - f, \;\; E(\pi_2^{2S}) = \frac{(A+2k)^2}{16} + \frac{\sigma^2}{16}, \tag{4}$$

$$E(\pi_1^{1C}) = \frac{(A-2k)^2}{9} + \frac{\sigma^2}{4} - f, \;\; E(\pi_2^{1C}) = \frac{(A+k)^2}{9}. \tag{5}$$

A higher volatility of demand, implying a higher information value, makes Firm 2 more willing choose to delay production until the demand shock is observed. At the same time as Firm 2 switches production to T_2, Firm 1 will benefit from taking a leadership at the cost of a lower information value.[7] Note that given σ^2, the higher the cost difference between the two firms, k, the more likely Firm 2 plays Stackelberg follower. Put differently, the greater the cost disadvantage that the information advantaged firm has, the more likely a Stackelberg equilibrium occurs.

It is perhaps counterintuitive that greater cost advantage for Firm 2 increases the range of circumstances under which it will choose to be a Stackelberg follower. This occurs because the strategic disadvantage of following diminishes with Firm 2's cost

[7] In the Cournot competition, only Firm 1earns an information value (which is $\sigma^2/4$); in the Stackelberg competition, both firms earn it (firm 1 gets $\sigma^2/8$ and firm 2 gets $\sigma^2/16$).

advantage. As a result, Firm 2 becomes more likely to wait to capture the information value of acting with knowledge of the demand shock.

Another interesting result following Proposition 1.1 is the relative performance of the two firms. Firm 2 may be better off than Firm 1, *ex post*, especially when the realized demand is low.[8]

Proposition 1.2: The information disadvantaged firm earns a higher market share and a higher profit, *ex post*, than the information advantaged firm if: (i) (1) holds and $\varepsilon_0 \leq 6k - A$, or, (ii) (1) does not hold and $\varepsilon_0 \leq 2k$.

Consequently, when $6k - A \geq 0$, Firm 2 outperforms Firm 1 under a negative shock ($\varepsilon_0 \leq 0$), no matter whether (1) holds or not. If the competition is Cournot, Firm 1 internalizes the negative shock alone, since Firm 2 will produce based on expected demand. Ignorance of the true state of demand gives Firm 2 a strategic advantage when the realized demand is low. If the competition is Stackelberg, Firm 1 internalizes a major part of it, and is further harmed by a cost disadvantage. In other words, knowing "bad" news first is "bad". However, it is not to say that Firm 1 would rather not know this information earlier. It is still better off, compared with not knowing it, in which case both firms would produce too much.[9]

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[8] From (4) and (5), we can see that Firm 2 may be better off than Firm 1 *ex ante* as well, when *k* is positive. More will be discussed in the next section of information acquisition.

[9] A comprehensive study of the value of this information advantage will be done in the next section. Here, given the sequence of play, knowing this negative shock is still valuable.

□ $N > 2$ **firms.** The result of endogenous sequencing in the two-firm model can be extended to an N-firm oligopoly. Suppose instead there are $n_1 \geq 1$ information advantaged firms and $n_2 = N - n_1 \geq 1$ information disadvantaged firms. I call a firm learning the demand shock in period T_1 an $I1$ firm, and call a firm learning information until period T_1 an $I2$ firm. With $N > 2$ firms, there will be more than one firm producing in the same period. For tractability I now assume equal marginal costs among all firms, that is $k = 0$, so the cost of being informed is fixed.

As in the duopoly case, those information advantaged firms have a dominant strategy to produce early. The information disadvantaged firms need make a tradeoff between a strategic value and an information value in selecting a period of production. What is different in this N-firm case is that the relative magnitude of these two values also depends on the number of firms playing in each period, and the number of information advantaged firms in the game. For a given level of uncertainty, σ^2, as more $I2$ firms delay production to period two, the information value (which has to be shared in some way among all the $I1$ firms and the delaying $I2$ firms) for each $I2$ firm decreases. At the equilibrium, changing the timing of production would yield a bigger loss than gain. Define $\theta(N, n_1, x) \equiv \frac{(n_1+1)^2(N-n_1-x+1)^2}{(n_1+x+2)^2(N-n_1-x)} - \frac{(n_1+1)^2}{(n_1+x+1)^2}$, the following is proved:

Proposition 1.3: When $k = 0$, the following is pure strategy equilibrium to the extended game in the N-firm oligopoly:

(i) All the $I1$ firms leading and all the $I2$ firms following, if and only if $\sigma^2 \geq \theta(N, n_1, 0)A^2$;

(ii) All the $I1$ firms and x of the $I2$ firms leading and the rest $I2$ firms following, if and only if $\theta(N, n_1, x)A^2 \leq \sigma^2 < \theta(N, n_1, x-1)A^2$, where $x = 1, 2, \ldots, n_2 - 1$;

(iii)All N firms playing Cournot in period T_1, if and only if $\sigma^2 < \theta(N, n_1, n_2 - 1)A^2$.

For any $\sigma^2 > 0$, the number of leading (and following) firms in pure strategy equilibrium is uniquely determined.

Endogenous sequencing results in the more general case of N firms under asymmetric information. Following the notion of Sherali (1984), a Generalized-Stackelberg-Nash-Cournot (GSNC) equilibrium (with multiple firms acting simultaneously as leaders and multiple firms acting simultaneously as followers) emerges endogenously, when the variance of the demand shock is not too low. For example, suppose there are $N = 4$ firms in the market, and only one firm has information advantage. A GSNC equilibrium with 2 leaders and 2 followers emerges if $0.68A^2 \leq \sigma^2 < 1.37A^2$, and there would be 3 leaders and 1 follower in the equilibrium if $0.39A^2 \leq \sigma^2 < 0.68A^2$. Instead, if the variance of the demand shock is such that $\sigma^2 < 0.39A^2$, delaying production for any $I2$ firm is not optimal and Cournot equilibrium with all firms producing in $T1$ arises.

Thus by introducing a random demand shock and focusing on asymmetric timing of information, I have obtained some results which are quite different from those in models with no uncertainty and signaling games in the endogenous timing literature as well. Earlier access to information about a demand shock grants a firm an information value and possibly also a strategic leadership if the other firm chooses to delay production. The information value is increasing with the variance of demand shock. The interesting tradeoff is: if the variance is low it enjoys the information value alone as the other firms choose to produce early; if the variance is high such that information value is big, it earns a smaller portion, but with the compensation of a strategic leadership. These results may have rich implications on firm decisions in a world where demand uncertainty is a fact of life. A firm need decide not only when and how much to produce, but also whether to acquire better information. I will next study the firms' information acquisition strategies.

1.3 Information Acquisition

The literature on endogenous sequencing focuses almost entirely on how an assumed asymmetry in information or costs leads to endogenous timing in competition. The circumstances under which such an asymmetry could arise have not received much attention. Given how the strategic interactions between firms in both timing and output decisions are affected by asymmetric information, I can now address firms' willingness to pay for costly information. Moreover, I can determine under what circumstances asymmetric information is an equilibrium outcome when both firms have the option of buying information.

Here I add an information acquisition stage before the extended game I analyzed for the duopoly case. At this stage, firms simultaneously choose either to buy information or not. Information acquisition entails any costly activities enabling a firm to learn the demand shock at the beginning of period $T1$ in the quantity competition game. Following the previous section, I assume the cost of information takes the form (k, f), where $0 \le k < \frac{A}{3}$ is the increase to a firm's marginal production cost, and $f \ge 0$ is the fixed cost part. Initially I will assume (k, f) is the same to both firms. As is common in the literature on endogenous sequencing, I consider only pure strategy equilibria.[10] The full game can be solved backward by first solving the extended games corresponding to each possible information outcome arising from the information acquisition stage.

In the duopoly model I consider, there are four possible outcomes in the information acquisition stage: (*B*, *B*), (*B*, *NB*), (*NB*, *B*) and (*NB*, *NB*), where (*B*, *B*) represents both firms buying information, (*NB*, *NB*) represents both firms not buying, (*B*, *NB*) represents Firm 1 buying and Firm 2 not, (*NB*, *B*) represents Firm 2 buying and Firm 1 not. Each of these outcomes is associated with an extended game with both timing and quantity choices. I have studied the two outcomes with asymmetric information acquisition in the previous section, to complete the analysis I must characterize the symmetric equilibria as well.

If both firms buy information, (*B*, *B*), then both will learn the realized value of the demand shock ε_0 in T_1 and produce $q_i^1(B,B) = \frac{A-k}{3} + \frac{\varepsilon_0}{3}$ without delaying. This is analogous to the case without uncertainty. The expected profit is then $E(\pi_i^1(B,B)) = \frac{1}{9}(A-k)^2 + \frac{1}{9}\sigma^2 - f$ for each of the firms.

If both firms do not buy information, there are possibly two pure strategy equilibria existing depending on the variance of the demand shock.

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[10] Daughety and Reinganum (1994), among others, also focused on pure strategy equilibria. As we will see later, when either firm acquiring information is a pure strategy equilibrium, there is also a mixed strategy equilibrium in which both firms randomize on buying and not buying information.

Lemma 1.1: Following the outcome (*NB*, *NB*) from the information acquisition stage, the extended game has the following pure strategy equilibrium:[11]

(i) Firms produce simultaneously in period T_1, if $\sigma^2 \leq \frac{7}{36}A^2$;

(ii) Firms produce simultaneously in period T_2, if $\sigma^2 \geq \frac{1}{8}A^2$.

When $\frac{1}{8}A^2 \leq \sigma^2 \leq \frac{7}{36}A^2$, the extended (timing) game becomes a coordination game with two equilibria: both firms act in period $T1$, and both firms act in period $T2$ (in either case the output game is then of course characterized by Cournot play). However, it is easy to see that the equilibrium with a simultaneous play in T_2 *payoff-dominates* the other equilibrium. Following Harsanyi and Selten (1988), this equilibrium can be selected as a Nash refinement.[12] Employing this criterion, I restrict attention to a unique equilibrium if both firms do not buy information. If $\sigma^2 < \frac{1}{8}A^2$, I have $E(\pi_i^1(NB, NB)) = \frac{1}{9}A^2$. Instead, if $\sigma^2 \geq \frac{1}{8}A^2$, then $E(\pi_i^2(NB, NB)) = \frac{1}{9}A^2 + \frac{1}{9}\sigma^2$ is the expected payoffs for both firms.

Combined with the payoffs I had in the extended games under asymmetric information, I am able to solve the game in the information acquisition stage. To simplify

[11] This is the same as the result shown in Spencer and Brander (1992), although they did not explicitly employ the model of extended games with observable delay.
[12] They argued that even without a preplay communication, if each player knows the other to be fully rational, they should trust each other and play the equilibrium strategies which yield higher payoffs for both. Also, a payoff-dominant equilibrium can be the focal point of the players. See e.g., Fudenberg and Tirole (1991) for more discussion.

notations, define $\Delta \equiv \frac{1}{9}(7A^2 - 4Ak - 20k^2)$, the right hand side of condition (1). The following proposition is obtained:

Proposition 1.4: The following outcomes are pure strategy equilibria in the information acquisition stage:

(i) Both firms buy information, (*B*, *B*), if $\sigma^2 \geq \max\{4Ak + 9f, -A^2 + \frac{68}{7}Ak + \frac{20}{7}k^2 + \frac{144}{7}f\}$.

(ii) One firm buys information and the other not, (*B*, *NB*) or (*NB*, *B*), if

(a) $\frac{16}{9}(Ak - k^2) + 4f \leq \sigma^2 < \min\left\{4Ak + 9f, \frac{1}{8}A^2\right\}$, or,

(b) $\max\left\{\frac{16}{5}(Ak - k^2) + \frac{36}{5}f, \frac{1}{8}A^2\right\} \leq \sigma^2 < \min\{4Ak + 9f, \Delta\}$.

(iii) Neither firm buys information, (*NB*, *NB*), otherwise.

Proposition 1.4 can be understood as follows. Both firms will buy information when the variance of demand is sufficiently high, and condition (i) comes from the comparison of profits in symmetric, informed Cournot play with those for an uninformed firm under asymmetric information which then chooses the maximum of the profit from being a Stackelberg follower or an uninformed Cournot competitor against an informed firm. If neither firm acquires information, then the equilibrium may be Cournot play in T_1 or in T_2. Each of these alternatives gives rise to different conditions for asymmetric information acquisition to occur, conditions (iia) and (iib). Depending on the parameters of the model, neither, either, or both of these conditions may be satisfied for some range of σ^2. In other words, there may be no range of demand variance for which asymmetric acquisition occurs, there may be one range, or there may be two (possibly discontinuous) ranges for which this occurs.

Whether symmetric, asymmetric, or no information acquisition occurs depends on the relative magnitudes of the variance of demand shock and the cost parameters (k, f) which enter into a firm's payoff function in a way contingent on the sequence of play in the basic game. The fact that if the variance of the demand shock is high enough, both firms buy information contrasts with the result of Daughety and Reinganum (1994) that both firms acquiring information is an equilibrium only if information is free. In their paper, extended games with action commitment are employed to study a signaling model with two types of demand, and the simultaneous play equilibria are deleted in undominated strategies.

It is worth emphasizing that, rather differently than previous work, I have modeled the value of information that is perishable and therefore does not generate a signaling dynamic. I find that early information has a strictly positive value, no matter whether the other firm acquires information or not. This is shown by comparing the expected payoffs with and without purchasing information. If information is free, $k = 0$ and $f = 0$, it is a strictly dominant strategy for one firm to choose B, regardless of the other firm's choice.

Note that the time value of information I study here is different from the concept of information value discussed in the previous section. Information value of choosing a quantity with knowledge of demand results from that a firm's profit function is convex on the demand intercept and choosing a quantity when knowing the realization of a demand shock is ex ante better off than acting according to the expected value, given the sequence of play in the competition. Here, the time value of information to a firm lies exactly in that the sequence of play may be affected, knowing the demand shock early or late. When the other firm does not buy information, earlier information grants one firm the opportunity of enjoying the information value alone (if the other firm produces in T_1) or taking the leadership (if the other firm produces in T_2). When the other firm buys information, also acquiring information avoids a firm's being at an information disadvantage (if producing in T_1 without information) or a strategic disadvantage (if producing in T_2).

Under the asymmetric information equilibrium, the purchase of information by one firm may generate a positive externality benefitting its competitor. If both firms acting in T_1 is the equilibrium of the extended game when neither firm buys information, then this positive externality will always be present. By acting in T_1, the uninformed firm does at least as well as before (and strictly better if $k > 0$). In addition, it can choose to delay production if that yields a higher payoff. If both firms producing in T_2 is the equilibrium of the extended game when neither firm buys information, it may still be the case that the uniformed firm benefits from its competitor buying information if the cost of information takes the form of incurring a higher production cost k.[13] It may in fact be the case that the uninformed firm earns a higher expected profit than the firm buying information.[14] That is, it may be that one firm's acquiring information benefits both and actually benefits its competitor more.

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[13] The uninformed firm is made better off when the other firm buys information under condition (iia) in Proposition 4, or, under condition (iib) and $\sigma^2 < 2Ak + k^2$.

[14] The uninformed firm earns a higher expected payoff than the informed firm if $\sigma^2 < \frac{8}{3}Ak - \frac{4}{3}k^2 + 4f$, which can be consistent with the conditions in (ii) of Proposition 4.

I now turn to the question of when asymmetric information occurs in equilibrium such that market leadership arises endogenously.

Proposition 1.5: When the cost of information represented by (k, f) is common to both firms, asymmetric information acquisition may occur in equilibrium, but only Cournot equilibrium could arise in the extended game.

This result occurs because the two conditions for an asymmetric information outcome, as listed in Proposition 1.4, both violate the condition for Stackelberg equilibrium in the timing game (condition (1)). The condition for Stackelberg equilibrium is that the variance of demand is sufficiently high, but when this is satisfied it must be the case that if the cost of information is sufficiently low and one firm obtains it then the other firm will obtain the information as well.

Asymmetric information acquisition and endogenous market leadership may arise when firms differ sufficiently in the cost of information. I will consider the case when the marginal cost component does not differ between firms, $k_1 = k_2 = k$, but the fixed cost component does. Assume now that firm *i*'s fixed cost of information is represented by f_i. Without loss of generality, let Firm 1 be the lower cost firm with $f_1 < f_2$. I can prove the following result:

Proposition 1.6: Given $f_1 < f_2$, Stackelberg equilibrium arises in the full game, if

$\max\{-A^2 + 36(Ak - k^2) + 72f_1, \Delta\} \leq \sigma^2 < -A^2 + \frac{68}{7}Ak + \frac{20}{7}k^2 + \frac{144}{7}f_2$.

For example, when $k = 0$, $f_2 > 0.09A^2$ and $f_2 > 3.5f_1$, there exists a range of values of σ^2 that give rise to asymmetric information acquisition and sequential timing of production. The firm with lower information cost acquires information and takes the leading role in the quantity competition.

1.4 Conclusion

In an oligopoly model of two production periods with all firms choosing to produce in either period, I have identified the circumstance under which a perishable information asymmetry regarding stochastic demand causes market leadership with Stackelberg competition emerging endogenously. Importantly, firms that know a competitor has a temporary information advantage may choose to act as followers in the market. In a general oligopoly model with $N > 2$ firms, a GSNC equilibrium with multiple leaders and followers occurs with the number of leaders and followers in equilibrium determined by the variance of demand and the number of firms who have early access to information.

The value of the perishable information advantage derives from confronting competitors with a choice between the strategic disadvantage of following in the market and the information disadvantage of being a simultaneous (Cournot) competitor and acting based only on expected demand. Given how the sequence of play and firm payoffs are affected under different information structures, symmetric or asymmetric, two natural questions are: is early information valuable and what cost will firms be willing to incur to obtain a perishable information advantage? In a duopoly information acquisition game I find that unlike the information advantage studied in signaling games, early information always has value. Both symmetric and asymmetric outcomes are possible when information is costly. However, Stackelberg equilibrium is supported only when firms have different costs of information.

An important direction for future work is the generalization of this model to allow for entry and thus identify a competitive equilibrium. In particular, if many potential firms can enter either as informed firms with a high fixed cost or uniformed firms with a low fixed cost, can it be shown that a zero expected profit equilibrium arises with both uniformed firms and informed firms entering? If so, will market leadership arise endogenously in some circumstances with uninformed firms choosing to follow? This is a very challenging problem because equilibrium entry is greatly complicated by the timing game that follows which depends on the number of each type of firm.

CHAPTER III

ESSAY 2: DEMAND UNCERTAINTY AND ENDOGENOUS PRICE LEADERSHIP

In this essay, I consider a duopoly in which firms supply a differentiated product and choose to set the price in one of two periods. Market demand is stochastic and the uncertainty resolves in the second period. In the first period, a firm learns only the expected demand unless it has chosen to acquire information. Different from the result under no uncertainty that only sequential play is pure strategy equilibrium, with both firms uninformed in the first period, simultaneous play in the second period emerges as the unique equilibrium when the variance of the demand shock is high. With firms asymmetrically informed, the sequential play with the information advantaged firm leading may be the unique equilibrium. Even when both sequential moves are equilibria, I show the equilibrium with the advantaged firm leading risk dominates the other. A firm's information advantage leads to a strategic disadvantage of leading in the price game. An information acquisition stage is then studied and I find both firms buying information is not an equilibrium even if information is free. The time value of information may well be negative, given the other firm's information choice.

2.1 Introduction

Market leadership, arising from for example a cost or information advantage, is an important issue in understanding strategic competitions. In quantity competition, the intuition that leadership confers an advantage and derives from an advantage is broadly confirmed. However, in price competition, this does not hold. Price competition differs from quantity competition in that following is usually preferred to leading since the follower can undercut the leader's price. In this context, does a cost or information advantage confer unwanted leadership?

Endogenous timing under asymmetric information has been studied in some earlier work (specifically in the context of quantity competitions), but a key assumption has been that the information known by an informed firm (e.g. the realization of an uncertain market demand) is never directly revealed to uninformed firms regardless of the timing of their actions. Consequently, a signaling game arises with uniformed firms possibly able to infer some information from the actions of the informed firm if they act as a follower in the market. I assume instead that any information advantage is perishable. That is, a firm may "get a jump" on competitors, becoming informed about realized demand earlier than others and thus have the possibility of acting in the market based on this information at a time when other firms can only act based only on expectations. However, if the other firm chooses to wait, it can act after also becoming fully informed.

I study the timing of firm actions in a duopoly in which firms supply a differentiated product and compete on price. Market demand is stochastic with a random intercept term. Uncertainty about the demand resolves in the second period, but in the first period firms learn only the expected value unless information acquisition activities have been undertaken. The determination of the sequence of price settings is studied under different information structures: symmetric, asymmetric or no information acquisitions. I find that simultaneous play may emerge as the unique equilibrium when neither firm acquires information. This contrasts with the result in the absence of demand uncertainty that only sequential play is a pure strategy equilibrium. There is an *information value* of acting with knowledge of demand: given the sequence of play, setting a price according to each realization of the demand shock is ex ante better than while without the information.

Under asymmetric information, I find that the firm with early access to demand information may have a first-mover advantage: it enjoys a higher payoff being a leader than being a follower. If the information disadvantaged firm leads, it sets a price according to expected demand, and this would adversely affect the profits of both firms when the realized value of the demand shock is positive. As a result, to avoid this possibility, the information advantaged firm may prefer to lead especially when the variance of the demand shock is high. The set of equilibria depends on the variance of the demand shock as well. When the variance is high, only the sequential move with the information advantaged firm leading is an equilibrium. Otherwise, both sequential moves are pure strategy equilibria. Following Harsanyi and Selten (1988), I apply the criterion of risk dominance and show that the equilibrium with the information advantaged firm being the price leader risk dominates the other. Asymmetric information gives rise to endogenous price leadership and a firm's information advantage leads to a strategic disadvantage of leading in the price game.

Considering how sequence of play resulting firm payoffs are affected by different information structures, is early information valuable and will firms be willing to pay to obtain it? I model an information acquisition stage and find that both firms acquiring information is never an equilibrium even if information is free. With the other firm buying information, ignorance of the state of demand in the first period secures a firm's role of being a follower in the price game (which is advantageous). Consequently, the *time value of information* to a firm is (weakly) negative when the other firm buys information. Furthermore, because a perishable information advantage makes a firm take the less preferred leading role in the price game, a firm that believes its competitor to be uninformed may choose to remain uninformed as well to avoid taking a leadership position.

It was first emphasized by von Stackelberg (1934) that timing of firm actions is an important aspect of competition in industrial economics when output is the strategic variable. A sequential play equilibrium (which is later referred to as Stackelberg equilibrium) differs from the simultaneous Cournot outcome. Gal-Or (1985) studied first- and second-mover advantages in general duopoly models. He showed that the relative magnitudes of equilibrium payoffs, being a leader or a follower, depend on the slope of the reaction curves. With downward sloping reaction curves, leading is preferred to being a follower and there is first-mover advantage. Usually a quantity game falls into this category and commitment is valuable. With upward sloping reaction curves, being a follower is preferred and there is second-mover advantage. Flexibility, instead, has a value.

While most duopoly models take the sequence of play as exogenously given, increasing interest has been to the endogenous determination of the timing in a game. Hamilton and Slutsky (1990) proposed two models to study endogenous timing, extended games with observable delay and extended games with action commitment. In the first model, firms announce at which time they will choose an action and are committed to it in the basic game of action choices. In the second model, firms can play early only by selecting an action to which it is then committed. Subsequent work has applied these models to study the timing of actions in some specific type of games, mostly in quantity competition.[15] Two papers have studied endogenous timing in a price game in which firms have different production costs. Van Damme and Hurkens (2004) employed the action commitment model to study a linear price setting duopoly game and found that while both sequential move sequences are equilibria in undominated strategies, the one with the lower cost firm leading risk dominates the other sequential move equilibrium. Amir and Stepanova (2006) instead used the observable delay model and obtained a similar result. The cost efficient firm becomes the price leader under the criterion of risk dominance. They also found that the lower cost firm may have a first-mover advantage when the difference in cost between the two firms is large. In these models, information is complete and there is no uncertainty. The effect of demand uncertainty on the sequence of play has not been modeled. This is the gap I fill here.

The remainder of this chapter is organized as follows. In section 2.2, I set up the stochastic duopoly model and study firms' timing choices under different information

[15] They include Mailath (1993), Daughety and Reinganum (1994), Normann (1997, 2002), Amir and Grilo (1999) and van Damme and Hurkens (1999).

structures. In section 2.3, I analyze an information acquisition stage in which firms can choose to acquire information or not. In section 2.4, I conclude this essay.

2.2 The Extended Games with Timing Choices

The full game to be studied in this section and the following consists of the following stages in a sequence: the information acquisition stage in which firms choose whether to buy information and thus obtain an early signal of market demand in the pricing stage, the timing choice stage in which firms choose to act in either of two price-setting periods, and the two-period pricing stage in which firms set the price of their products in the period they have chosen. In this section, I will take the information status of the firms, which are known to each firm, as given and study endogenous timing under each information structure.

Consider two risk-neutral firms, 1 and 2, in a market. They supply a differentiated product and compete on price. The products of the firms are imperfect substitutes and demand for firm i's product is:

$$q_i(P_i, P_j) = a - P_i + \theta P_j$$

where $a = a_0 + \varepsilon$ is the stochastic demand intercept with mean a_0 and variance σ^2, $0 < \theta < 1$ is the coefficient of cross-price effect, P_i is the price charged by firm i, $i = 1, 2$, and P_j is the price charged by firm j, $i \neq j$.[16] They produce the products at the

[16] This linear form of demand function is widely used in the endogenous timing literature and other duopoly models. It can be derived from the utility maximization problem of a representative consumer whose utility function takes a quadratic form. For more discussion, see, for example, Vives (1984). The stochastic component is added when the coefficient on the linear part of the utility function is stochastic.

same constant marginal cost c. Letting $A \equiv a_0 - (1-\theta)c$, I can write the demand functions as:

$$q_i(p_i, p_j) = A + \varepsilon - p_i + \theta p_j$$

where prices in lower case are net of costs. The random component of the intercept term ε follows distribution $F(\cdot)$ with $E(\varepsilon) = 0$ and $var(\varepsilon) = \sigma^2$. Also, I assume the support of ε is such that every firm sets a positive price and supplies a positive quantity throughout my considerations. That is, I assume the lower support of F is greater than $-A$.

To study endogenous timing of firm actions in the price game, I employ the model of extended games with observable delay developed by Hamilton and Slutsky (1990). The basic price game is played in two periods, T_1, T_2. At a prestage of timing choices, each firm chooses one of the two periods to set the price of its product. Once chosen, they are committed to it and the timing choices become common knowledge. If one firm chooses to set a price in period T_1 and the other in T_2, a sequential play equilibrium arises in the basic game. If both firms choose to set prices in the same period, T_1 or T_2, I identify a simultaneous play equilibrium. As is common in the endogenous timing literature, I only consider pure strategy equilibria.[17]

Uncertainty about demand resolves in period T_2. So both firms observe the realized state of demand at that time. But in T_1, firms only know the mean of the random shock (ε) to be zero and the variance of the shock (σ^2) unless information acquisition activities have been undertaken. In this section, I take the information structure of the

[17] This was the practice by, e.g., Daughety and Reinganum (1994), Damme and Hurkens (2004), Amir and Stepanova (2006). Inclusion of mixed strategy equilibria slightly complicates the analyses but does not change the qualitative conclusions.

firms as given. There are four possible outcomes from the information acquisition stage. They are denoted as the following: (*B*, *B*) means that both firms choose to buy information in the information acquisition stage and as a result will be informed in period T_1 in the price game; (*NB*, *NB*) means neither firm buys information and they will not be informed until in period T_2; (*B*, *NB*) and (*NB*, *B*) represents asymmetric information acquisitions and so there are an information advantaged firm and an information disadvantaged firm. It is worth noting that my assumption of asymmetric information is different from that in the signaling games studied in quantity competition in the literature. In those models, there is one informed firm who learns the type of demand from the very beginning and one uninformed firm who remains uninformed unless the informed firm reveals the type through its quantity choices (signaling). Here, information acquisition only grants the firm an earlier knowledge about the realization of the demand intercept, in period T_1 rather than T_2 in the price game.[18] As a result, this information advantage is perishable.

Restricting to subgame perfect equilibrium (SPE), I can use backward induction to solve the extended games. I first find the equilibria in the basic price games following each possible timing choices and then use the equilibrium payoffs of each price game as the payoffs of the reduced game in the prestage of timing choices. The SPE of an extended game is in one-to-one correspondence with equilibrium in the reduced game. There are four extended games following the outcomes from the information acquisition

[18] To my knowledge, Spencer and Brander (1992) is the only other paper in the endogenous timing literature that employs a similar timing structure of information. However, they consider a quantity game and do not allow for information acquisition. So both firms learn the demand intercept only after the uncertainty resolves and only Cournot Nash equilibrium could possibly arise in the two-period quantity competition.

stage. By analyzing the extended games under asymmetric information, (*B*, *NB*) and (*NB*, *B)*, together, there are three cases to be analyzed.

□ **Case 1: Both firms are informed in T_1.**

If (*B*, *B*) is chosen in the information acquisition stage, both firms will learn the realized value of the demand shock in period T_1. This is analogous to the case when there is no uncertainty about market demand. The result can serve as a baseline for comparisons with the other two cases when demand uncertainty plays a role.

Let S_k denote a simultaneous play in period T_k, $k = 1, 2$, and let L and D denote leading and following respectively in a sequential play. Let $p_i(p_j)$ be the best response function of firm i, $i = 1, 2$, $i \neq j$. Then firm i's objective function is:

$$\max_{p_i} \left(A + \varepsilon_0 - p_i + \theta p_j^{'}\right) p_i,$$

where ε_0 is the realized value of ε, and $p_j^{'} = \begin{cases} p_j(p_i), & \text{if firm } j \text{ moves after firm } i \\ p_j, & \text{otherwise} \end{cases}$.

By solving the maximization problem, we can see the best response function is positively sloped: $p_i(p_j) = \frac{A+\varepsilon_0+\theta p_j}{2}$. The simultaneous play equilibrium payoffs are: $\pi_i^{S_k}(B, B) = x(A + \varepsilon_0)^2$, where $x = \frac{1}{(2-\theta)^2}$. The sequential play equilibrium payoffs with firm i being the leader and firm *j* being the follower are: $\pi_i^L(B, B) = y(A + \varepsilon_0)^2$, and $\pi_j^F(B, B) = z(A + \varepsilon_0)^2$, where $y = \frac{(2+\theta)^2}{8(2-\theta^2)}$, and $z = \frac{(4+2\theta-\theta^2)^2}{16(2-\theta^2)^2}$.

It is easy to verify that with $0 < \theta < 1$, $z > y > x > \frac{1}{4}$, which means payoffs in a sequential play Pareto dominate those in a simultaneous play and there is second-mover advantage: being a follower is preferred to being a leader. As in a quantity competition, being a leader is preferred to being a simultaneous player because a firm can choose any point on the other firm's reaction curve including the simultaneous moving point. What is different in a price game, with positively sloped reaction curves, is that being a follower is better than being a leader since a follower can undercut the other firm's set price: flexibility in the price setting game is valuable.

I can then solve the reduced game of timing choices in the prestage by using the expected payoffs from the price subgames under each possible sequence of play. The following lemma is obtained. (All proofs are in the Appendix.)

Lemma 2.1: When both firms are informed about the uncertain demand in period T_1, sequential plays with either firm being the price leader and the other firm being the follower are the only pure strategy equilibria in the extended game.[19]

In the equilibrium, the follower's payoff is higher than the leader's: $E(\pi_i^F(B,B)) > E(\pi_i^L(B,B))$. Positively sloped reaction curves lead to second-mover advantage, consistent with Gal-Or (1985). When both firms are informed from the first period, the extended game is a coordination game: although both firms want to be the follower, one firm would choose to lead if it knows the other firm chooses to set a price in T_2. The next two cases will have at least one firm being uninformed in period T_1. Demand uncertainty then plays a role in that information about the realization of the

[19] Apparently, there is also a mixed strategy equilibrium where both firms randomize on choosing T_1 or T_2.

demand shock is valuable and must be considered by the firm that faces uncertainty in the first period. The results turn out to be quite different.

□ **Case 2: Neither firm is informed in T_1.**

Following the choices (*NB*, *NB*) from the information acquisition stage, both firms do not know the realization of the random shock until in period T_2. For each firm, its objective function is the same as in the previous case if it chooses to set a price in T_2. However, in period T_1, without learning the true value of the demand intercept, its price choice is then based on the distribution of the random component ε:

$$\max_{p_i} \int \left(A + \varepsilon - p_i + \theta p_j^{'}\right) p_i \, dF(\varepsilon),$$

$$\text{where } p_j^{'} = \begin{cases} p_j(p_i), & \text{if firm } j \text{ moves in } T_2 \\ p_j \,, & \text{otherwise} \end{cases}.$$

With risk-neutral firms, only the expectation of the random shock matters: a firm sets a price as a function of the mean of the demand intercept. Note that a firm's profit function is convex in the demand intercept. For any given sequence of play, setting a price while knowing the realized value of the demand intercept is *ex ante* superior to setting the price when only the expected value is known. I will generally refer to this as the information value of acting with full knowledge of demand.

When firms set their prices simultaneously in period T_1, both prices are based on the expected value of the demand intercept. Their expected payoffs are $E(\pi_i^{S_1}(NB, NB)) = xA^2$, the same as when there is no uncertainty and demand is at its mean. In contrast, with simultaneous play in period T_2, both firms are informed about the realized value of demand and their payoffs are the same as in Case 1. The expected payoffs at the prestage can be written as: $E(\pi_i^{S_2}(NB,NB)) = x(A^2 + \sigma^2)$. A comparison of these payoffs tells us the information value under a simultaneous play. With full knowledge of market demand, each firm ex ante enjoys a higher profit than when they are uninformed. The magnitude, $x\sigma^2$, is increasing with the variance of the demand shock.

In sequential play with firm i being the leader, firm j observes not only firm i's chosen price but also the realized state of demand. However, firm i must choose a price according to its expectation of the demand intercept. Their expected payoffs are respectively $E(\pi_i^L(NB,NB)) = yA^2$, and $E(\pi_j^F(NB,NB)) = zA^2 + \sigma^2/4$. Compare the expected profits of the leader and the follower, we can notice that being a follower, a firm not only has a strategic timing advantage (represented by a bigger coefficient before A^2) but also can set his price according to each realization of the demand shock (and thus enjoy an information value of $\sigma^2/4$).

By solving the reduced game in the prestage of timing choices, and defining $\beta \equiv \frac{\theta^4}{16-8\theta^2}$, I have the following result:

Proposition 2.1: When both firms are uninformed about the uncertain demand in period T_1, the following are the only pure strategy equilibria in the extended game:

(i) Simultaneous play in the second period, if $\sigma^2 \geq \beta A^2$;

(ii) Sequential play with either firm being the price leader and the other firm being the follower, if $\sigma^2 < \beta A^2$.

In this case with both firms being uninformed in the first period, the equilibrium result differs from that in Case 1 analyzed earlier. It depends on the variance of the demand shock. Simultaneous price setting emerges endogenously in the price subgame when the variance of the demand shock is large. Relating to my earlier discussion about information value, both firms choose to delay their choice of prices and play a simultaneous game even though being a price leader is strategically preferred to playing simultaneously. When demand is highly uncertain, the incentive to wait for the uncertainty to resolve outweighs the strategic considerations and leads to a simultaneous play equilibrium. When the variance of the demand shock is low, the strategic timing considerations dominate and sequential play again results with either firm acting as the price leader. Under sequential play equilibria, it is easy to verify that there is second-mover advantage as well: firms prefer to be the follower.

□ **Case 3: One firm is informed in T_1 and the other not.**

Following the choices (B, NB) or (B, NB) from the information acquisition stage, one firm learns the realization of the demand intercept in T_1, but the other does not until in T_2. Without loss of generality, I assume firm i is the information advantaged firm and firm j is the information disadvantaged firm. As I have discussed, this advantage in information is perishable: it will vanish if firm i chooses not to execute it in time, that is, set the price of its product in T_1. Firm i's objective function is the same as in Case 1 since it is informed in both periods. For firm j, its choice of price in period T_1 would be based on the expectation of the demand shock, while in T_2 it also learns the true state of the demand. Its maximization problem is the same as in Case 2.

By solving backward, I obtain the expected payoffs from each price subgame which give the following payoff matrix for the reduced game of timing choice:

Table 2.1 The Reduced Game of Timing Choice under Asymmetric Information

		Firm j: T_1	Firm j: T_2
Firm i	T_1	$xA^2 + \frac{1}{4}\sigma^2, xA^2$	$y(A^2 + \sigma^2), z(A^2 + \sigma^2)$
	T_2	$zA^2 + \frac{1}{4}\sigma^2, yA^2$	$x(A^2 + \sigma^2), x(A^2 + \sigma^2)$

Simultaneous price setting in either period is not an equilibrium, similar to Case 1 when both firms learn the demand shock from T_1. With one firm being informed in both periods, it always wants to avoid playing simultaneously with the other firm due to strategic timing considerations. Again, only a sequential play equilibrium is possible. Before I fully characterize the equilibrium outcomes, it is interesting to note that the information advantaged firm, firm i, may actually prefer a leading role to a following role. This is different from the previous two cases.

Proposition 2.2: Under asymmetric information, if $\sigma^2 \geq \frac{\theta^2}{4-2\theta^2} A^2$, the information advantaged firm has a first-mover advantage. Otherwise, it has a second-mover advantage. The information disadvantaged firm always has a second-mover advantage.

That the information advantaged firm may prefer being a price leader to being a price follower stems from the fact that prices are strategic complements and the profit function is convex on the demand intercept. When the realized value of the demand is high, both firms should charge a high price and enjoy a high profit. However, if firm j takes the leading role and sets the price of its product in period T_1, its choice is made according to the mean of the demand. This price is lower than that it would set if firm j had known the demand information, and makes the follower, firm i, unable to charge a price sufficiently high. Although this is to some extent offset when demand is low and firm j charges a higher price than it would have charged if it had known demand is low, on average, there is some loss in profit to the information advantaged firm because of the leader's ignorance of the true level of demand. This loss is increasing in the variance of the random shock. As a result, when the variance of demand shock is very high, as is stated in Proposition 2.2, firm i would rather take the leadership role just to prevent the other firm setting a low price that is costly to both. First-mover advantage arises in the price game under this condition, quite at odds from when firms have symmetric information (Case 1 and Case 2).

When $\sigma^2 \geq \frac{\theta^2}{4-2\theta^2}A^2$ and firm i has a first-mover advantage, its leading is actually the unique equilibrium in the extended game under asymmetric information. Generally, equilibria in the extended game are characterized as follows:

Proposition 2.3: Under asymmetric information, the following are the only pure strategy equilibria in the extended game:

(i) Sequential play with the information advantaged firm being the price leader and the disadvantaged firm being the follower, if $\sigma^2 \geq \beta A^2$.

(ii) Sequential plays with either firm being the price leader and the other firm being the follower, if $\sigma^2 < \beta A^2$.

The condition for a unique equilibrium to arise (with the information advantaged firm leading) is the same as the condition in Proposition 2.1 for a simultaneous playing equilibrium when both firms are uninformed in the first period. This is not surprising. When $\sigma^2 \geq \beta A^2$, the information disadvantaged firm has a dominant strategy to play second. This pushes the information advantaged firm into a leadership position, since it will avoid a simultaneous play. Of course, Proposition 2.2 tells us that it may actually prefer to be the leader. However, with $0 < \theta < 1$, I have $\frac{\theta^2}{4-2\theta^2} > \beta$. This means, if $\sigma^2 \in [\beta A^2, \frac{\theta^2}{4-2\theta^2})$, the information advantaged firm prefers being a follower but reluctantly takes the leading role in the unique equilibrium.

When the variance of the demand shock is relatively small, both sequential plays are pure strategy equilibria. Harsanyi and Selten (1988) proposed two criteria that can be used to make an equilibrium selection: payoff dominance and risk dominance. However, payoff dominance does not help in my setting. One equilibrium payoff dominates the other if the payoff in this equilibrium is strictly higher than that in the other equilibrium for each player. But this is not the case when both sequential moves are equilibria under $\sigma^2 < \beta A^2$.

Lemma 2.2: Under asymmetric information, if $\sigma^2 < \beta A^2$ such that both sequential moves are equilibria to the extended game, no equilibrium payoff dominates the other.

In this type of coordination games with two equilibria existing and the outcome relying on players choosing corresponding strategies, there is fundamental risk to each player when choosing to play one way or the other. As a result, risk considerations are inevitable by rational players and can be used to make equilibrium selections. Following Harsanyi and Selten (1988), a risk dominant equilibrium can be interpreted as "dominant in the players' expectation after due consideration of the risks involved in the initial state of uncertainty". The original definition of risk dominance is comprised of two concepts, the bicentric priors and the linear tracing procedure. Under the initial uncertainty about player j's strategy, player i has a subjective probability z_i about player j's strategy profile. As was argued by Harsanyi and Selten, z_i has a uniform distribution on [0, 1]. For each z_i, player i has a best response. Integrating the best responses with respect to z_i, a probability profile for player i's best strategies, p_i, is obtained, which forms the bicentric prior of player j about player i's strategy. The linear tracing procedure assesses each equilibrium by adjusting the relative weights players put on one's bicentric prior and the strategy profile of other players in the equilibrium. If some equilibrium point is selected in the single feasible path, then this equilibrium risk dominates the other.

Although this procedure is fairly complicated and very difficult to apply to some games, Harsanyi and Selten have shown that it is easy to characterize a risk dominant equilibrium in a 2×2 game with two Nash equilibria: one equilibrium risk dominates the other if the product of deviation losses is larger for the former. With attention being restricted to SPE, I can apply risk dominance to the reduced game of timing choices.[20] The following result is obtained:

Proposition 2.4: Under asymmetric information, if $\sigma^2 < \beta A^2$ such that both sequential moves are equilibria to the extended game, the equilibrium with the information advantaged firm leading risk dominates the other equilibrium with the information disadvantaged firm leading.

As a result, risk dominance selects the equilibrium with firm i being the price leader when $\sigma^2 < \beta A^2$. This is also the more efficient outcome for the industry, since the joint profits are higher in this equilibrium than the other one with firm j leading. When attention is restricted to the risk-dominant equilibrium in this case, then there is always a unique equilibrium under asymmetric information. Regardless of the magnitude of the demand volatility, the information advantaged firm acts as the price leader in the extended game.

Note that the information disadvantaged firm gains the most under this information structure. Its ignorance of demand information in the first period guarantees him a more favorable role in the price competition: following. Being a follower and setting the price in T_2, it enjoys a strategic timing advantage without losing the information value because uncertainty eventually resolves in T_2. To the information advantaged firm, however, being pushed into a leadership role in the equilibrium may

[20] This is also the method used by Amir and Stepanova (2006). Van Damme and Hurkens (2004) have to apply the original definition of risk dominance to assess the whole game since there is no proper reduced game with the action commitment model.

well be detrimental. As I have shown, when the variance of the demand shock is low, it has a second-mover advantage. Earlier knowledge about the true state of demand grants him an information value (which he does not necessarily lose even without this superior information), but at the cost of becoming the leader in the price game.

From the above analyses, we see that the timing of firm actions in equilibrium depends on the information structure. When demand volatility is high and both firms do not know the realized value of the market demand until in the second period, the information value of acting with knowledge of market demand causes both firms to delay price setting. This gives rise to the unique equilibrium of simultaneous play in the extended game, which differs from the result that only sequential plays could possibly arise in pure strategy equilibrium without uncertainty. The convexity of profit functions with respect to the stochastic demand intercept plays an important role in firms' timing choices. However, if one of the firms has a perishable information advantage over its competitor, only sequential price setting is possible. When the variance of the demand shock is high, the information disadvantaged firm has a dominant strategy to act in T_2 and the information advantaged firm takes the leading role to avoid a simultaneous play. Even when the variance is low such that both sequential moves are equilibria, the one with the information advantaged firm leading risk dominates the other and this equilibrium is selected. As a result, one's information advantage leads to a strategic disadvantage in the price game. This raises the interesting question of whether earlier information is valuable.

2.3 Information Acquisition

The literature on endogenous timing focuses almost entirely on how some type of exogenous asymmetry, e.g. in information or cost, leads to endogenous timing of firm actions in the basic game.[21] Less attention has been paid to how this asymmetry arises and whether it will arise. Considering that the strategic role of firms would be different under different information or cost structures, how will firms choose their information status or production technology in the first place? This is an interesting and important question. I have shown how different information structures lead to different sequence of play in the price competition and different firm payoffs. Then is early information valuable and will firms acquire information if they have the option to do so? Will the different information structures I studied, symmetric, asymmetric and no information, result endogenously at the equilibrium?

Before the extended games in the previous section are played, now I add another stage of information acquisition. By saying information acquisition, I mean the general costly activities that lead to earlier knowledge about the realized state of demand, at period T_1 instead of period T_2 (uncertainty automatically resolves in T_2). This includes, but not limited to, building a forecasting team on one's own or signing a contract with some third party agency that is able to offer demand information in the first period of the price game. I assume the cost of information is $f \geq 0$.

[21] To my knowledge, the only exception is Daughety and Reinganum (1994) who analyze firms' information acquisition choices. They study a signaling quantity game and use the action commitment model. With Cournot equilibrium being eliminated in undominated strategies, they conclude that only one firm acquires information when cost of information is low and both firms acquire information only when information is free.

Focusing on SPE, the full game can be solved backward. There are possibly four different outcomes from this information stage: (*B*, *B*), (*B*, *NB*), (*NB*, *B*) and (*NB*, *NB*). Each outcome leads to an extended game I studied before. As I have characterized, if both firms buy information, (*B*, *B*), both sequential moves are pure strategy equilibria. If only one firm acquires information, (*B*, *NB*) or (*NB*, *B*), the acquiring firm would become the leader in the price game. If none of them buy information, (*NB*, *NB*), as I have in Proposition 2.1, the set of equilibria depends on whether the condition $\sigma^2 \geq \beta A^2$ holds or not. If this condition holds, simultaneous play in period T_2 is the unique equilibrium. Otherwise, if $\sigma^2 < \beta A^2$, then both sequential moves could arise in pure strategies.

The reduced game in the information acquisition stage can be obtained by plugging in the equilibrium payoffs from the corresponding subgames, here, the extended price games with timing choices. Solving each possible equilibrium outcomes, I have the following result:

Proposition 2.5: In the information acquisition stage, the following are the only equilibrium outcomes in pure strategies:

(i) Neither firm acquires information, if and only if:

(a) $\sigma^2 < \min\{\beta A^2, \frac{f}{y}\}$, or,

(b) $\beta A^2 \leq \sigma^2 < \frac{f}{y-x} - A^2$;

(ii) One firm acquires information and the other not, if and only if:

(a) $\frac{f}{y} \leq \sigma^2 < \beta A^2$, or,

(b) $\sigma^2 \geq \max\{\beta A^2, \frac{f}{y-x} - A^2\}$.

That both firms acquire information is not an equilibrium outcome.

Even if information is free, that both firms buy information cannot arise as an equilibrium outcome. When both firms learn the realized state of market demand in T_1, one firm takes the leadership role and the other becomes the follower. By deviating and letting the other firm have a perishable information advantage, the leading firm could instead take the preferred following role without losing the information value: it chooses a price observing both the price chosen by the other firm and the realized value of the demand shock in T_2. The following firm also has an incentive to deviate if information is costly. Both of these follow from the result that an information disadvantage leads to a strategic advantage of following.

Thus I find a scenario in which early information has a negative value. If the other firm buys information, one would not buy and can then take the following role in the price game. Moreover, even when the other firm does not buy information, it is likely that early information (now a perishable information advantage) is a “bad” to one of the firms. The time value of information in this model of price competition can be summarized as follows:

Proposition 2.6: Early information has a strictly negative value to one of the firms and zero value to the other if its competitor acquires information. Early information has a strictly negative value to one of the firms if its competitor does not acquire information and $\sigma^2 < \beta A^2$.

This interesting result contradicts our usual understanding that better information (here earlier information) must be valuable. A perishable information advantage over one's competitor may be strategically harmful, and information as early as one's competitor is definitely harmful in this endogenous timing model of price competition. This is different from my conclusion in the first essay when firms compete on quantity. In a price game with uncertain market demand in the first period, delaying price setting can grant a firm both a strategic timing advantage and an information value of acting while informed. If the other firm acquires information, ignorance of the true state of demand makes the firm take a following role in the equilibrium. If the other firm does not buy information and $\sigma^2 < \beta A^2$, whether earlier information is valuable depends on the role of the firm in the price game when both sequential plays are possible. The bottom line is, one of them (the firm taking the following role) would find learning the demand information earlier than its competitor to make it strictly worse off. If $\sigma^2 > \beta A^2$, the firms would play simultaneously and both of them will want to avoid this outcome by acquiring information (given that information cost is not too high) although only one buys it in equilibrium.

With that said, very likely only one firm will obtain early information and the other not especially when the cost of information is low. This is seen by comparing the equilibrium conditions in Proposition 2.5. When f decreases, the intervals in (ii) expand and will include all positive values when $f = 0$. Following this asymmetric information structure, market leadership is endogenously determined with the information advantaged firm becoming the price leader. The information disadvantaged firm may have a dominant strategy to wait and in this case the advantaged firm leading is the unique equilibrium. Even when sequential play with either firm leading is a pure strategy equilibrium, risk considerations pushes the information advantaged firm into the leading role. When σ^2 does fall into the range such that neither firm buys information, the equilibrium in the extended game can be either a sequential move or a simultaneous move. If $\sigma^2 < \min\{\beta A^2, \frac{f}{y}\}$, both sequential plays with either firm being the price leader are equilibria. If $\beta A^2 \leq \sigma^2 < \frac{f}{y-x} - A^2$ (subject to existence of such an interval), information value of choosing a price with knowledge of market demand dominates their strategic timing considerations and simultaneous play equilibrium emerges.

2.4 Conclusion

In a duopoly model with two price-setting periods and both firms choose to set a price in either period, information about the stochastic demand plays an important role. When both firms learn the realized demand only until uncertainty resolves in the second period, simultaneous play in the second period may emerge as the unique equilibrium. This contrasts with the result in the absence of demand uncertainty that only sequential play is a pure strategy equilibrium. Under asymmetric information, I find an interesting result that the information advantaged firm may have a first-mover advantage. This is due to the strategic complementarity of price competition. Letting an uninformed firm to set a price first would adversely affect the informed follower as well. Generally, the set of equilibria depends on the magnitude of the variance of the demand shock. If the variance is high such that the information disadvantaged firm has a dominant strategy to play second, the unique equilibrium has a sequential play with the information advantaged firm leading. If the variance is low and both sequential plays are equilibria, risk dominance selects the equilibrium with the information advantaged firm leading.

Considering that the sequence of play in the price game and correspondingly firm payoffs would be different under different information structures, two important questions follow: is early information valuable, and will firms buy information? An information acquisition stage is then studied and I find that both asymmetric information acquisition and no information acquisition could possibly arise. However, that both firms buy information is never an equilibrium even if information is free. The time value of information may well be negative. This contrasts with the result in my first essay that early information has strictly positive value in the quantity game.

My analyses of endogenous timing in the price game are conducted under the assumptions that firms face symmetric demand functions and the mean and variance of the demand shock are public information. However, this variance of demand intercept may just be firms' subjective perception of market volatility and, if so, may not be the same for both firms. Also, asymmetry can arise from different parameters in the demand functions or different production costs of the firms. The algebra would become very tedious with any of these asymmetries added to the model. Nonetheless, most of the results should still hold in a similar way given that a firm's payoff function is continuous in these parameters.

CHAPTER IV

ESSAY 3: TIMING OF INVESTMENTS AND THIRD DEGREE PRICE DISCRIMINATION IN INTERMEDIATE GOOD MARKETS

I study third degree price discrimination in intermediate good markets, in which costs of production for the downstream firms are determined by their investment choices. I focus on the effect of the sequence of firm actions and analyze two models with different timing of investments. When investments are chosen before the upstream monopolist sets the input prices, under a fairly general condition, the result does not differ from previous finding that a less efficient downstream firm receives a discount instead of the more efficient one. However, when investments are determined after the prices are set, an indirect effect of input prices on the quantity demanded from downstream firms must be taken into account, due to the change of investment incentives. This causes the upstream firm to possibly charge the more efficient downstream firm a lower price. These results are illustrated using linear demand and quadratic investment costs. Interestingly, not only the downstream firms but also the upstream monopolist prefers the sequence of play in the latter model, i.e. it benefits from committing to prices before investments are undertaken. Considering that consumer surplus is also improved due to higher output, a change of sequence of play from the first model to the second constitutes a strict Pareto improvement.

3.1 Introduction

Price discrimination in intermediate good markets is prevalent especially in countries where such practices are not prohibited or in international markets where national antitrust laws do not apply. Perhaps counter-intuitively, models of third degree price discrimination have generally shown that a less efficient firm receives a discount from the monopolistic upstream firm relative to a more efficient firm. In these models, however, the importance of the timing of firm actions has been largely neglected. Different sequences of play affect the strategic interactions between firms and can lead to different market outcomes. In this essay, I consider that downstream firms make complementary investments that lower production cost and then explore the consequence of timing of these investments in relation to price setting by upstream monopolist.

I study two models of vertical structure with different timing of investments made by the downstream firms. By saying investments, I mean the general costly activities that can be used to lower a firm's production cost. They may include, but are not limited to, R&D expenditures, managerial effort, and the purchase of fixed capital, etc. I show that if investment levels are chosen after the monopolist sets the prices of the intermediate good, a more efficient firm may end up paying a lower price than a less efficient firm. The timing of investments plays an important role: an indirect effect of input price on quantity demanded, through the change of downstream firms' investment incentives, must also be taken into account when the monopolist sets the prices before the downstream firms invest. Also, I show that a change of sequence from one model (the upstream firm commits to input prices first) to the other (the upstream firm sets input prices after investments are made) benefits all parties including the upstream monopolist, the downstream firms and the consumers. This suggests firms have a strong incentive to structure a vertical relationship to achieve this, and makes the latter model an appealing choice for future research.

While the Anti-Price Discrimination Act of 1936 (often referred to as Robinson-Patman Act) in the United States concerned primarily intermediate goods markets, most economic studies have been on price discrimination in the final goods markets. One of the main findings in this literature is that the monopolist should charge more in markets with lower elasticity of demand, an optimal pricing rule under third degree discrimination.[22] In a seminal paper, DeGraba (1990) employed a model with a monopoly supplier and two downstream producers who engage in Cournot competition in the final market. He showed that the supplier charges the lower cost producer a higher price than the higher-cost firm under price discrimination, partially offsetting the cost advantage. This was confirmed in Yoshida (2000) in an extension to n downstream firms with different *α-β-efficiency* (to produce one unit of the final good, one firm needs more of the input and also incurs a higher marginal cost). These theoretical findings are actually consistent with the results in final good markets that elasticity is the determinant of price charged. Demand for inputs from the lower cost firm is less elastic and thus it should be charged a higher price by the upstream firm to maximize profit. What is different in a vertical structure, as compared with price discrimination in final good markets, the *derived* demand for the upstream firm's good is based on a downstream firm's choice of output to supply in the final good market.

[22] See, e.g., Tirole (1988), for more discussion.

Though theoretically intuitive, it contradicts many people's expectation that, being a larger buyer, a more efficient firm should be able to get a better deal. Katz (1987) first argued that a large downstream firm has higher ability to vertically integrate backward and consequently should be charged a lower price by the input provider. Following a similar spirit, Inderst and Valletti (2009) showed that if there is threat of demand-side substitution the more efficient buyer receives a discount. Because the transaction cost for finding another supplier of the same inputs can be spread over a larger volume, this lower cost buyer is more likely to switch. The additional participation constraint leads to a lower price charged to it. Allowing the use of two-part tariff contracts, Inderst and Shaffer (2009) also showed that a more efficient firm obtains a lower wholesale price than their rivals since in this case the monopolist's interest is in line with the downstream firms. In this essay, I study price discrimination under linear pricing, without altering the upstream firm's monopolistic status.

Different from the extant literature which exogenously assumes downstream firms' marginal production costs, with one firm's cost being higher than another, I make costs of production endogenous by allowing firms to choose the level of complementary investment. One firm is more efficient than another if a lower cost of investment is incurred to reduce marginal cost to a same level. I distinguish two types of vertical structures which differ in the timing of downstream firms' investment choice. In a supplier-manufacturer type of vertical relationship, as I name it primarily for convenience, the marginal cost of a downstream firm is determined by its production technology which usually entails large scale investment and long time horizon, and thus is assumed to be done before the upstream supplier sets input prices. For a wholesaler-retailer type of vertical relationship, a downstream firm's marginal cost in selling products in the final market may be highly variable due to choice of complementary inputs such as managerial effort, shelf space, etc. In this case, the downstream firms' choices of investment are more likely made after the input price is set and the profitability of this product is fully understood. It is worth noting that both DeGraba (1990) and Inderst and Valletti (2009) have studied downstream firms' technology choices under price discrimination. The timing in their models would be analogous to my first model.[23] My second model is new to the literature.

I focus on the case of downstream firms that operate in separate markets. This can be due to geographical or technological barriers. For instance, in many countries, one mobile service provider is the exclusive contractor with Apple Inc. to provide mobile services bundling iPhone products. Because of differences in language and telecommunication standards, cross-border shopping is rare and each service provider can be seen as a monopolist in its own country.[24] The assumption of separate markets can also be appropriate when the downstream firms pursue monopolistic competition in the final good market. A unique branding, distinctive packaging or different after-sale services can all grant a firm substantial market power in the short run. Independence among final markets greatly reduces the analytical challenges in these three stage models. Also, it enables me to do a clear-cut interpretation of the results and compare them with

[23] They derive the upstream firm's pricing rules by directly assuming the downstream firms have different production costs and then study their technological choices under such rules assuming they have identical investment costs. Difference in production costs actually does not arise. Here, I directly assume different investment costs at the very beginning and use an "integrated" three stage model.
[24] Inderst and Valletti (2009) argue that geographic market segmentation is particularly relevant for Europe.

the existing literature on price discriminations in the intermediate good markets and in the final markets as well.

The rest of this chapter is organized as follows. In section 3.2, I introduce the two three-stage models with different timing of the downstream firms' investment choices to study the upstream firm's pricing strategy and obtain general results. In section 3.3, I assume a linear demand function and a quadratic cost function to illustrate the results and compare market outcomes under different timing. The last section discusses these two models and concludes the essay.

3.2 The Models

Consider a monopolistic upstream firm which sells an intermediate good to n downstream firms. To produce each unit of the final good, each downstream firm uses one unit of the intermediate good as input. Also, downstream firm i, $i = 1, 2, \dots, n$, incurs a constant marginal cost to transform the intermediate good into the final good. The initial level of marginal cost is c_0, which can be lowered to $(c_0 - x_i)$ by investing into the complementary production technology, $i = 1, 2, \dots, n$.[25] I will call $(x_1, x_2, \dots, x_n)$ the firms' cost reduction levels, which is in one-to-one correspondence with their chosen investments with the following assumptions. The cost of investments is $R(x_i, \theta_i)$, with $\frac{\partial R(\cdot)}{\partial x_i} > 0$, $\frac{\partial^2 R(\cdot)}{\partial {x_i}^2} > 0$, $\frac{\partial R(\cdot)}{\partial \theta_i} > 0$ and $\frac{\partial^2 R(\cdot)}{\partial x_i \partial \theta_i} > 0$. Downstream firm i's cost efficiency is measured by θ_i. Note that a lower value of θ represents higher efficiency: if $\theta_i < \theta_j$, lowering marginal production cost to any same level would cost firm j more than firm i,

[25] It is a common assumption in industrial economics that investment spending lowers a firm's marginal production cost. Specifically, my framing follows Shleifer (1985) and D'Aspremont and Jacquemin (1988).

so firm i is more efficient. The last inequality, $\frac{\partial^2 R(\cdot)}{\partial x_i \partial \theta_i} > 0$, is referred to as the single-crossing condition in the contract theory literature. Here, it simply says that the marginal cost of investment rises with θ. I do not consider the trivial case that only fixed cost of investment is different for these firms, since in that case their incentives for investment will be the same as long as cost reduction is profitable. The upstream firm's cost of supplying the intermediate good is normalized to zero.

As has been discussed in the introduction, I focus on the circumstance when downstream firms operate in n separate markets and each serve as a monopolist in its own market. In market i, consumer demand for the final good is represented by $p_i = P_i(q_i)$, with $P_i{}'(q_i) < 0$. Also, I assume the demand function and investment cost function are well behaved such that the optimization problems have their second order conditions satisfied and a unique interior solution exists.

Two models with different sequence of firm actions are analyzed. In the first model, the downstream firms choose investment before the upstream monopolist sets the price of intermediate goods. This may best characterize a supplier-manufacturers type of vertical structure where downstream firms' production technology usually involves large investment and a long time horizon and thus must be done before this vertical relationship is built. In the second model, downstream firms' investment decisions are made after the price of intermediate goods is set. This may better represent a wholesaler-retailers type of vertical structure where costs involved in the selling procedure are easily variable in the short run. I call the first model the supplier-manufacturers model (S-M) and the second model the wholesaler-retailer model (W-R). These names are mainly for convenience and the timing of the game is what is essential.

3.2.1 The Supplier-Manufacturers model

Consider a vertical structure in which a monopolistic upstream firm sells an input to n downstream firms. As I have noted, in this model, investment levels are chosen before the upstream firm sets the input prices. The timing of the game is then: at stage 1, downstream firms choose an investment level that lowers their marginal cost of production; at stage 2, observing the downstream firms' costs of production, the upstream firm sets input prices, $w = (w_1, w_2, \dots, w_n)$, where w_i is the unit price charged to firm i; at stage 3, downstream firms purchase the intermediate goods, produce the final goods and sell them in the final markets.

Using backward induction, I start with the downstream firms' choice of quantities, which also determines their demands for inputs in the intermediate good market. In stage 3, given w_i, the input price charged by the upstream monopolist, and $c_0 - x_i$, the cost of production it has chosen in stage 1, downstream firm i's optimal production level (and equivalently the demand for inputs) is given by:

$$P_i'(q_i)q_i + P_i(q_i) - c_0 - (w_i - x_i) = 0. \tag{6}$$

And the second order condition ensuring a unique interior sollution is:

$$P_i''(q_i)q_i + 2P_i'(q_i) < 0. \tag{7}$$

Write $q_i = q_i(w_i - x_i)$, I have $q_i'(\cdot) = \frac{1}{P_i''q_i + 2P_i'} < 0$, which means a downstream firm's demand for input decreases in the price charged by the upstream firm and increases in the cost reduction level it has chosen in the first stage.

Then in stage 2, given the cost reduction levels of the downstream firms, x_i, the upstream monopolist then sets input prices w to solve:

$$\max_{w} \sum_{i=1}^{n} q_i(w_i - x_i)w_i$$

The first order condition determines the input prices charged to each downstream firm:

$$q_i(w_i - x_i) + q_i{}'(w_i - x_i)w_i = 0. \qquad (8)$$

The second order condition ensuring a unique interior solution is: $2q_i{}'(\cdot) + w_i q_i{}''(\cdot) < 0$. Plugging in $q_i{}'(\cdot)$ and $q_i{}''(\cdot)$, it can be written as:

$$4P_i{}'(\cdot) + 5P_i{}''(\cdot)q_i(\cdot) + P'''(\cdot)q_i{}^2(\cdot) < 0. \qquad (9)$$

Write $w_i = w_i(x_i)$, I have the following result. (All proofs are in the Appendix.)

Lemma 3.1: $0 < \frac{\partial w_i(\cdot)}{\partial x_i} < 1$, if and only if:

$$2P'(\cdot) + 4P''(\cdot)q(\cdot) + P'''(\cdot)q^2(\cdot) < 0. \qquad (10)$$

Condition (10) is stronger than the second order condition (9). Together with (7), it implies (9). It is valid for a number of demand functions including linear demand which I will use to derive a closed form solution. Other functions satisfying this condition include $p = a - bq^c$ for $c > 0$, $p = a + \frac{b}{q^c}$ for $c > 1$ and $p = a - be^q$. Under this condition, the benefits from cost reductions taken by the downstream firms will be partially appropriated by the upstream firm. Intuitively, investment lowers the downstream firm's cost and raises its profit margin for each unit of production. As a result, the value of the input is increased and a higher price can be charged.

When condition (10) is satisfied, the downstream firm which has a lower marginal cost (determined by its chosen investment level in the first stage) will be charged a higher input price by the upstream firm. However, since the appropriation is only partial, with identical demand in these final good markets, there is still incentive for the more efficient firm to select a lower cost technology, and consequently receive a higher price for each unit of the intermediate good.

Proposition 3.1: In the supplier-manufacturers model, the upstream monopolist charges a higher price of the intermediate good to the more efficient downstream firm than to a less efficient firm if consumer demand is identical in the markets and condition (10) is satisfied.

By adding an investment stage before the monopolist setting input prices in which the production costs of the downstream firms are endogenized, the result is consistent with previous findings that a less efficient firm receives a discount under price discrimination. Cost reductions by the downstream firms are only partially appropriated by the upstream monopolist, and as a result, there is still incentive for the more efficient firm to choose a lower cost technology given its lower cost of investment. The upstream firm, after observing their chosen costs, charges the downstream firm with lower elasticity of derived demand (the lower production cost firm) a higher input price.

3.2.2 The Wholesaler-Retailers Model

I now turn to another model which differs in the timing of firm actions from the one discussed earlier. It may better characterize a wholesaler-retailers type of vertical structure in which the monopolistic upstream firm is a manufacturer of a consumer product under its unique brand name or an exclusive distributor of this manufacturer. Final goods sold to consumers may be very close, in a physical sense,[26] to intermediate goods provided by the upstream firm. The downstream firms are mainly in charge of selling them to consumers in the final good market. Few, if any, further production process is needed. However, the selling procedure may entail some costs which are easily variable and heavily impacted by managerial effort. For example, costs involved in organizing products on shelves, managing inventory, providing follow-up services, etc. How much investment to spend on these procedures is more likely determined after prices of the intermediate goods have been set by the upstream firm so that a full cost-benefit analysis can be conducted. As a result, I make a different assumption on the timing of the game that investments to lower production cost are chosen after the upstream firm sets the input prices.

The game is played in the following sequence: in stage 1, the upstream firm sets input prices, w, charged to the downstream firms; in stage 2, downstream firms choose an investment level that lowers marginal cost of production; and in stage 3, downstream firms produce final goods and sell them in the final markets.

The third stage is the same as before. The optimal quantity is defined by (6) and I have the same first and second derivatives for $q_i = q_i(w_i - x_i)$. In stage 2, given the

[26] Before consumers make a purchase from a retailer, extra packaging may be needed at the sales stage. Also, after-sale services might be bundled with the physical part of the product.

input price, w_i, which was set by the upstream monopolist in the first stage, downstream firm *i*'s objective function is then:[27]

$$\max_{x_i} \ (P_i(q_i(w_i - x_i)) - c_0 + x_i - w_i)q_i(w_i - x_i) - R(x_i, \theta_i)$$

By plugging the optimal condition for quantity choice in the last stage (6) into the first order condition, I have the optimal choice of cost reduction level as defined by:

$$q_i(w_i - x_i) - \frac{\partial R(\cdot)}{\partial x_i} = 0. \tag{11}$$

Write $x_i = x_i(w_i, \theta_i)$. With the second order condition being satisfied, I can prove the following comparative statics:

Lemma 3.2: $\frac{\partial x_i(\cdot)}{\partial \theta_i} < 0$, and $\frac{\partial x_i(\cdot)}{\partial w_i} < 0$.

The first comparative static in Lemma 3.2 says that with higher cost of investments, a downstream firm chooses a lower cost reduction level (or equivalently, lower investments), holding everything else constant. The second comparative static says that being charged a higher input price, the downstream firm chooses a lower cost reduction level. This is a very important result since it tells us that the upstream firm's pricing strategy in the first stage would affect a downstream firm's investment incentives, which in turn affect the quantity of inputs demanded from this downstream firm. In determining an input price charged to a downstream firm, the upstream monopolist need consider both a direct effect and an indirect effect of this price on the derived quantities

[27] Since the choices of q_i and x_i are made by the same firm, they are effectively simultaneous here. Of course, the analytical results are not changed whether I solve them simultaneously or sequentially.

demanded as defined by (6). As I have had in the third stage, $q_i = q_i(w_i - x_i)$, w_i affects q_i directly, but also indirectly through its effect on x_i, another determinant of q_i. Suppose that the monopolist increase the price charged on downstream firm *i*, w_i, the direct effect will cause the downstream firm to decrease its demand of inputs since $q'(\cdot) < 0$. But also, this will cause the downstream firm to decrease its investment in the cost reduction technology, which again causes q_i to decrease. This additional effect, as compared with that in the supplier-manufacturers model, will indeed affect the upstream firm's optimal pricing strategy.

In the first stage, the upstream firm's problem is to solve:

$$\max_{w} \sum_{i=1}^{n} q_i(w_i - x(w_i, \theta_i))w_i.$$

The first order condition is then:

$$q_i'(\cdot)\left(1 - \frac{\partial x(\cdot)}{\partial w_i}\right)w_i + q_i(w_i - x(w_i, \theta_i)) = 0. \tag{12}$$

Again, assume the second order conditions are satisfied in all ranges I consider ($\widehat{S.O.C.} < 0$). Then, by differentiating (11) with respect to θ_i, I find how the optimal input prices vary with respect to the downstream firms' cost parameters:

$$\frac{\partial w_i}{\partial \theta_i} = -\frac{\Sigma}{\widehat{S.O.C.}}, \text{ where } \Sigma = -\left(q_i'(\cdot) - \frac{q_i''(\cdot)q_i}{q_i'(\cdot)}\right)\frac{\partial x(\cdot)}{\partial \theta_i} - q_i'(\cdot)w_i\frac{\partial^2 x(\cdot)}{\partial w_i \partial \theta_i}. \tag{13}$$

With the denominator being negative, the sign of the partial derivative of the input price charged to firm *i* with respect to its efficiency coefficient is the same as the sign of Σ, which is in general ambiguous. Thus I prove the following result:

***Proposition 3.2*: In the wholesaler-retailers model with identical demand in the final good markets, the upstream monopolist charges a lower price of the intermediate good to the more efficient downstream firm than to a less efficient firm if $\Sigma > 0$, a higher price if $\Sigma < 0$, and an equal price if $\Sigma = 0$.

Thus by alternating the sequence of the upstream firm setting input prices and downstream firms making investments, I have obtained a result different from that in the previous model. The monopolist may charge a lower price to the more efficient firm. The first term in Σ (when divided by $\widehat{S.O.C.}$) accounts for the direct effect of the input price on the downstream firm 's derived demand. Under condition (10), $q_i'(\cdot) - \frac{q_i''(\cdot)q_i}{q_i'(\cdot)} = \frac{2P_i' + 4P_i''q_i + P_i'''q_i^2}{(P_i''q_i + 2P_i')^2} < 0$. As a result, this term is negative since $\frac{\partial x_i(\cdot)}{\partial \theta_i} < 0$. That means, considering this effect only, the monopolist should charge a more efficient downstream firm a higher input price. This is quite intuitive and consistent with the result in the supplier-manufacturers model and the literature that the monopolist should charge more in markets with lower elasticity of demand under third degree price discrimination. Since a more efficient firm will choose a lower cost technology and thus become less flexible with respect to its derived demand for the intermediate good, a higher input price can be charged.

However, there is a second term which (when divided by $\widehat{S.O.C.}$) accounts for the indirect effect of the input price on the downstream firm's derived demand. With $q_i'(\cdot) < 0$, the sign of it depends on the sign of the cross partial derivative, $\frac{\partial^2 x_i(\cdot)}{\partial w_i \partial \theta_i}$, which measures how a downstream firm's investment responsiveness with respect to the input prices varies for different cost parameters. Since $\frac{\partial x_i(\cdot)}{\partial \theta_i} < 0$, if this cross partial derivative is positive, that means a less efficient firm (with higher θ) is less responsive to an input price change. Then this indirect effect alone leads the monopolist to charge a higher price to this firm and a lower price to the more efficient firm. Again, lower elasticity is penalized under third degree price discrimination. Together with my earlier discussion, the sign of $\frac{\partial w_i}{\partial \theta_i}$ would depend on which effect has a larger magnitude. If $\frac{\partial^2 x_i(\cdot)}{\partial w_i \partial \theta_i} \leq 0$, then I have $\frac{\partial w_i}{\partial \theta_i} < 0$ and the upstream monopolist should again charge the more efficient downstream firm a higher price for the intermediate good.

Unfortunately, the sign of this cross partial derivative is generally ambiguous without additional restrictions placed on the demand function and the cost functions. However, under some common assumptions in the literature, when the final good market has linear demand and the cost of investment can be expressed as the form $R(\cdot) = \theta_i f(\cdot) + g(\cdot)$, I do have $\frac{\partial^2 x_i(\cdot)}{\partial w_i \partial \theta_i} > 0$ and a positive second term in Δ.[28] Having obtained these general intuitions, in the next section I will assume a specific functional form for the market demand and costs of investment to conduct further analyses in these three-stage models.

[28] This can be seen by differentiating (6) first by w_i and then by θ_i.

3.3 Timing of Investments

From the previous section, I find that timing of investments taken by the downstream firms play an important role. The strategic interaction between firms is affected by the sequence of play and the monopolist's pricing strategy changes. In the wholesaler-retailers model, the monopolist may charge a more efficient downstream firm a lower price, which contrasts with some established results from the literature. To further the analysis of the timing issue, I assume specific functional forms for the demand in the final good market and downstream firms' costs of investment.

Linear demand and quadratic investment costs have been widely used in the literature of price discrimination and R&D (e.g., D'Aspremont and Jacquemin 1988, DeGraba 1990). In the following, I assume the inverse demand function in market *i* is:

$$p_i = a - bq_i. \tag{14}$$

I normalize b equal to one by the appropriate adjustment of output units and define $A \equiv a - c_0$ to simplify notation.

Also, assume the costs of investment for downstream firm *i* is given by:

$$R_i(x_i) = \gamma_i x_i^2 + \beta_i x_i + \alpha_i. \tag{15}$$

Firm *i* is more efficient than firm *j* if $\gamma_i \leq \gamma_j$, $\beta_i \leq \beta_j$ and $\alpha_i \leq \alpha_j$ with at least one of the first two inequalities being strict.[29] To ensure that the firms' objective functions are well defined and a unique interior solution exists, I assume the following restrictions on the parameters are satisfied:

(A1) $\gamma_i > 1/4$;

[29] As discussed earlier, the case that only the fixed cost differs would not affect the firms' incentives of investment as long as zero investment is ruled out.

(A2) $\beta_i < A/8$.

The coefficient on the linear term (β_i) can be positive or negative. But if β_i is negative, I only consider the range where $R_i(x_i)$ rises. That is, $x_i \in [-\frac{\beta_i}{2\gamma_i}, \infty)$ if $\beta_i < 0$. Also, I assume the constant term α_i is sufficiently small such that a zero investment solution is avoided. Using backward induction same as in the previous section, I can solve the equilibrium prices and cost reduction levels.

In the supplier-manufacturers model, the downstream firms choose:

$$x_i^{S-M} = \frac{A-8\beta_i}{16\gamma_i-1}. \quad (16)$$

And the upstream monopolist sets the input prices as:

$$w_i^{S-M} = \frac{A}{2} + \frac{A-8\beta_i}{32\gamma_i-2}, \quad (17)$$

which decreses both in γ_i and in β_i. As a result, consistent the conclusion in Proposition 3.1, a less efficient firm is charged a lower price by the upstream monopolist.

In the wholesaler-retailers model, the downstream firms choose:

$$x_i^{W-R} = \frac{A-w_i-2\beta_i}{4\gamma_i-1} = \frac{\frac{A}{2}+\frac{\beta}{4\gamma_i}-2\beta_i}{4\gamma_i-1}, \quad (18)$$

and the upstream firm sets the following input prices:

$$w_i^{W-R} = \frac{A}{2} - \frac{\beta_i}{4\gamma_i}. \quad (19)$$

Since $\gamma_i > 0$, which downstream firm receives a lower input price simply depends on the magnitude of $\frac{\beta_i}{\gamma_i}$. This yields the following result:

***Proposition 3.3*:** With linear final good market demand and quadratic investment costs, in the supplier-manufacturers model, the upstream firm's optimal pricing rule is: ${w_i}^{S-M} = \frac{A}{2} + \frac{A-8\beta_i}{32\gamma_i - 2}$. The more efficient downstream firm is charged a higher input price than the less efficient firm. In the wholesaler-retailers model, the upstream firm's optimal pricing rule is ${w_i}^{W-R} = \frac{A}{2} - \frac{\beta_i}{2\gamma_i}$. The more efficient downstream firm (firm *i*) is charged a lower input price than the less efficient firm (firm *j*) if $\frac{\beta_i}{\gamma_i} > \frac{\beta_j}{\gamma_j}$, a higher input price if $\frac{\beta_i}{\gamma_i} < \frac{\beta_j}{\gamma_j}$, and an equal input price if $\frac{\beta_i}{\gamma_i} = \frac{\beta_j}{\gamma_j}$.

These results illustrate the general conclusion found in the previous section. Since a linear demand function satisfies condition (10), the more efficient downstream firm is charged a higher input price than the less efficient firm in the supplier-manufacturers model. Also, the result is generally ambiguous in the wholesaler-retailers model. Under the assumed functional forms, whether the upstream firm charges a higher or lower price to the more efficient firm depends on the ratio of the coefficients on the quadratic term and the linear term.

Thus I find a circumstance under which a more efficient firm receives a discount, unlike what has been established in the literature. The timing of investments taken by the downstream firms play a critical role: when the upstream firm sets the input prices before they choose the investment levels, an indirect effect of the prices on the downstream firms' quantity demanded, through the change of their cost reduction incentives, must be taken into consideration in additional to the direct effect. With final good market demand being linear and the costs of investment being quadratic, this indirect effect is in opposite direction and may dominate the direct effect, causing the upstream firm to charge a lower price to the more efficient firm and a higher price to the less efficient firm.

An important question that follows is, if a downstream firm can choose the timing of its investment, then should it commit to a production technology before the monopolist sets the price for the intermediate good or to retain flexibility and choose the investment level until the upstream firm has sets the price? This may have rich implications in real world situations.

Proposition 3.4**:** With linear final good market demand and quadratic investment costs, ${x_i}^{W-R} > {x_i}^{S-M}$, ${w_i}^{W-R} < {w_i}^{S-M}$, and ${\pi_i}^{W-R} > {\pi_i}^{S-M}$. That is, by remaining flexible and choosing its investment level after the price of the intermediate good is set, a downstream firm is charged a lower price, chooses a lower cost production technology and earns a higher profit than by committing an investment level before the price of the intermediate good is set.

This is not surprising. From Lemma 3.2, we learned that a higher input price would lower the investment level taken by the downstream firms and consequently the quantity demanded, in addition to the direct effect. This is, apparently, in the favor of the downstream firm. Thus by remaining flexible and not committing to a production technology at that time, a downstream firm is better off by making the monopolist consider both effects when setting the input price.

What is more interesting, the upstream monopolist also prefers this sequence of play, that is, letting the downstream firms choose a production technology after it has set the input prices.

Proposition 3.5**:** With linear final good market demand and quadratic investment costs, the monopolist earns a higher profit when downstream firms choose investment after the price of the intermediate good is set. Therefore, the upstream firm benefits from commitment to a price prior to investment.

Considering that the upstream monopolist charges higher prices in the supplier-manufacturers model than in the wholesaler-retailers model, this is quite striking result. Proposition 3.5 tells that its gain from selling a larger amount of the intermediate good outweighs the higher prices it charges for each unit it sells to the downstream firms. Since both parties are better off under this sequence of play, the wholesaler-retailers model is probably more reasonable to be choosen especially when at least one of the two parties is flexible in the timing of its strategies. Of course, commitment in the wholesaler-retailer model is problematic: the upstream firm has an incentive to renege on its set price and charge a higher price after observing the downstream firm's investment level. In real world settings, signing a contract can easily solve the problem.

The welfare implication of these comparisons is straightforward. Since all the firms gain under the wholesaler-retailers model, and a higher quantity is sold by the upstream firm which implies higher final outputs and higher consumer surplus, social welfare is improved in the wholesaler-retailers model when compared to that in the supplier-manufacturers model.

***Proposition 3.6*:** With linear final good market demand and quadratic investment costs, changing the sequence of play in the supplier-manufacturers model into that in the wholesaler-retailers model is a strict Pareto improvement.

Under the supplier-manufacturers model, choosing the lower cost technology by investments are partially penalized by a higher input prices set by the upstream firm. This causes lower investment levels, lower output level and lower social welfare. This is partly corrected when the investment choices are made after the input prices are set in the wholesaler-retailers model. An indirect effect will be taken into consideration and the monopolistic power of the upstream firm is refrained from harming social welfare, at least to some extent.

3.4 Conclusion

In this essay, I study two models of third degree price discrimination in intermediate good markets. Downstream firms' complementary production technologies are endogenously determined by their investments but the timing of investments can be either before or after the input prices are set by the upstream monopolist. When investments are chosen before the upstream monopolist sets the prices, under a fairly general condition, my result does not differ from previous findings that a less efficient downstream firm receives a discount instead of the more efficient one. However, when investments are determined after the prices are set, the upstream monopolist may charge the more efficient firm a lower price than the less efficient firm. An indirect effect of input prices on the quantity demanded from the downstream firms must be taken into account, through the change of investment incentives. I illustrate these general results using linear demand and quadratic investment costs. Interestingly, both parties in the vertical structure prefer the sequence of play in the wholesaler-retailers model. Considering that consumer surplus also increases as output is higher, a change of timing from the supplier-manufacturers model to the wholesaler-retailers model constitutes a strict Pareto improvement.

The applicability of these models depends on the likely timing of investments, before or after prices of intermediate goods are set, and the ability of upstream monopolist to commit to a price. In naming the two models, I argued that for a supplier-manufacturer type of vertical relationship, production cost is mainly determined by technological innovations which must be done in a long horizon and thus may be before input prices are set. While in a wholesaler-retailer relationship, cost involved in the selling process is easily controllable by the downstream firms' managerial effort and may be done after input prices are set. However, this is only for conceptual convenience and does not apply to every setting. As was discussed later on, since both parties are better off under the sequence of play in the wholesaler-retailers model, it is probably more reasonable to choose this model especially when at least one of the two parties is flexible in its timing.

Admittedly, it is also very likely that some portion of the downstream firm's cost is determined before this vertical relationship builds, and the remaining portion is still variable after prices of the intermediate goods are set by the upstream firm. While the general ideas within this paper should still apply, the optimal pricing rule will be much more complicated as the number of stages expands to four. Also, the welfare effects of antitrust regulations (bans of price discriminations in some countries) in these three stage models are open for future researches.

CHAPTER V

GENERAL CONCLUSION

In this dissertation, I study the determinants and implications of the timing of firm actions in a variety of scenarios in industrial economics. The timing of firm actions is an important aspect of market competition. It is key to strategic advantage in oligopoly models whether firms compete on quantity or on price. In other types of industrial relations such as interactions between input suppliers and final-good manufacturers, the sequence of play also affects the strategic interaction between the firms. A firm which chooses a strategy first will take into account the response by those firms moving second. Different sequence of play leads to different market outcomes.

My first two essays examine how market leadership may arise endogenously in oligopoly models and focus on the effect of information about uncertain market demand. My first essay studies a quantity game in which firms choose the output levels in one of two periods. My second essay studies a price duopoly in which a firm's action space is the price of its product. Due to the different strategic nature of quantity competitions and price competitions, quite different results are obtained. In my third essay, I consider that downstream firms make complementary investments that lower production cost and then explore the consequence of timing of these investments in relation to price setting by upstream monopolist.

In my first essay, by studying a duopoly model of two production periods and each firm choosing either period to produce, I find a circumstance under which

Stackelberg competition emerges endogenously. Two values are considered in making a timing choice: a strategic value of timing and an information value of choosing a quantity with knowledge of realized demand. While the firm with early access to information about the demand shock captures both of them by producing in the first period, the firm with late access may choose to wait until it is informed about the market demand. If the variance of the demand shock is high, the information value outweighs the strategic value and the information disadvantaged firm becomes the Stackelberg follower. In a general oligopoly model with $N > 2$ firms, a GSNC equilibrium with multiple leaders and followers emerges endogenously. The number of leaders and followers in equilibrium is uniquely determined by the magnitude of demand volatility.

The value of a perishable information advantage derives from confronting competitors with a choice between the strategic disadvantage of following in the market and the information disadvantage of being a simultaneous (Cournot) competitor and acting based only on expected demand. Considering that the sequence of play and firm payoffs would be changed under different information structures, symmetric, asymmetric or no information, two natural questions are: is early information valuable in this setting and will firms buy information? An information acquisition stage is then studied. I find that both symmetric and asymmetric outcomes are possible when information is costly. However, Stackelberg equilibrium is supported only when firms have different costs of information. With the same information cost, firms play simultaneously even when asymmetric information arises from the information acquisition stage. Generally, the time value of information is strictly positive: earlier information than its competitor enables one firm to either enjoy the information value alone or take a leadership role; information as timely as its competitor prevents one firm from being in a disadvantage, informationally or strategically.

The results in this essay rely only on firms knowing the mean and variance of the demand shock. Moreover, this variance may just be firms' subjective perception of market volatility and, if so, does not have to be the same for both firms. The modeling of a perishable information asymmetry enables me to assume a general stochastic shock and extend the result from a duopoly to the general *N*-firm case which has not been done before. Correspondingly, I study the time value of information, and is the first in the endogenous timing literature.

Following a similar modeling of demand uncertainty and firm information, my second essay studies a price competition. In a duopoly model with two price-setting periods and both firms choosing to set a price in either period, information about the stochastic demand affects a firm's timing choice. When both firms learn the realized state of demand in the first period, sequential play with either firm being the leader is the pure strategy equilibrium. This is analogous to the deterministic model studied in the literature. However, when both firms learn the realized demand only when uncertainty resolves in the second period, simultaneous play equilibrium with both firms choosing to delay price setting emerges as the unique equilibrium when the variance of the demand intercept is high. As in the first essay, there is an information value of acting with knowledge of realized demand given that a firm's profit is convex on the demand intercept. When the variance of the demand shock is low, strategic timing considerations dominate and sequential play equilibrium emerges again.

Under asymmetric information with one firm learning the state of demand earlier than the other, I find an interesting result that the information advantaged firm may have a first-mover advantage. When the variance of demand intercept is high, letting the uninformed firm to set a price according to expected demand in the first period lowers both firms' expected profits. Generally, the set of equilibria depends on the magnitude of the variance. If the variance is higher than some threshold such that the information disadvantaged firm has a dominant strategy to play second, the unique equilibrium has a sequential play with the information advantaged firm leading. Instead, if the variance is low, then both sequential plays are pure strategy equilibria. However, risk dominance selects the equilibrium with the information advantaged firm leading. A perishable information advantage leads to a strategic disadvantage of leading in the price game. This is actually the more efficient outcome for the industry since the joint profit is higher in this equilibrium.

Considering that the sequence of play in the price game and correspondingly firm payoffs would be affected under different information structures, I then study an information acquisition stage and two important questions are answered: is earlier information valuable, and will firms buy information? I find that both asymmetric information acquisitions and no information acquisition could possibly arise. However, that both firms buy information is never an equilibrium even when information is free. When the other firm acquires information, ignorance of information makes one firm take the preferred following role in the equilibrium. As a result, one firm would rather not buy information and the time value of information is negative in this circumstance. Even when the other firm does not acquire information, to the firm that plays the following role in the equilibrium when neither firm learns the demand shock in the first period, the time value of information is negative because with earlier information this firm then becomes the price leader. The typical information outcome would have one firm acquiring information and the other not, especially when the cost of information is low. And such a perishable information asymmetry leads to the endogenous price leadership: the information advantaged firm becomes the price leader and the information disadvantaged firm follows.

These results of endogenous timing and the time value of information contrast with those in the first essay of quality competition. In a quantity duopoly, sequential play equilibrium emerges only when firms have asymmetric information and the variance of the demand shock is high. The usual outcome would be a simultaneous Cournot equilibrium. In the price duopoly, sequential play is the usual equilibrium and simultaneous play only occurs when both firms have no information in the first period and the variance of the demand shock is high. Also, since following is preferred to leading, the time value of information in the price game may be negative, while in the quantity game it is always strictly positive. These comparisons advance our understanding about the two forms of market competition in industrial organization.

In the third essay, I endogenize downstream firms' complementary production technologies and study third degree price discrimination in intermediate good markets. Marginal costs incurred in the production process that transform the intermediate good into the final good are reduced when the firms invest in R&D or exert managerial effort. One firm is more efficient than another if a smaller investment cost is incurred to lower marginal cost to a same level. Two models with different sequence of play are studied. In these three stage models, the timing of investment by downstream firms can be either before or after the input prices are set by the upstream monopolist. I focus on the case of downstream firms that operate in separate markets.

When investments are chosen before the upstream monopolist sets the prices, under a fairly general condition, the result does not differ from the literature that a less efficient downstream firm receives a discount instead of the more efficient one. Higher input price leads to lower demand from the downstream firms but the demand from a more efficient firm is less elastic. The optimal pricing strategy suggests charging this inelastic firm a higher price. However, when investments are determined after the prices are set, an indirect effect of input prices on the quantity demanded from the downstream firms must be taken into account, through the change of investment incentives. This may be in the opposite direction to the direct effect that higher input price causes lower demand but a more efficient firm is less flexible. As a result, the upstream monopolist may charge the more efficient firm a higher or lower price than the less efficient firm depending on the magnitudes of these effects.

With linear demand and quadratic investment costs, I show that the more efficient firm indeed ends up receiving a lower input price when the ratio of the cost parameters, β/γ, is higher than that of the less efficient firm. Interestingly, both parties in the vertical structure prefer the sequence of play in the latter model. That is, the upstream firm commits to the prices of the intermediate good first, and the downstream firms chooses a production technology second. While the prices of the intermediate good charged by the upstream firm is lower, investment level chosen by a downstream firm and its output are both larger in this model. This higher quantity dominates the effect of lower input price and makes the upstream monopolist also enjoy a higher profit. Considering that consumer surplus increases with output, a change of timing from the former model to the latter constitutes a strict Pareto improvement.

Looking forward, there are many topics related to my work here that are open for future endeavors. For example, an important extension to the model studied in my first essay is to allow for entry and thus identify a competitive equilibrium. A signaling dynamic under incomplete information about market demand has only been studied for quantity games previously and seems also interesting for a price competition setting. On price discrimination in intermediate good markets, if downstream firms pursue Bertrand competition in the final good market, interesting result about the upstream monopolist's optimal pricing strategy may be obtained. All these can further advance the literature on timing of firm actions and I look forward to working on them in the future.

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Appendix

Proof of Proposition 1.1:

First, Firm 1 has a strictly dominant strategy to act in T_1: $\frac{(A-2k)^2}{9}+\frac{\sigma^2}{4}>\frac{(A-3k)^2}{16}+\frac{\sigma^2}{4}$, if Firm 2 chooses to produce in T_1; and $\frac{(A-2k)^2}{8}+\frac{\sigma^2}{8}>\frac{(A-2k)^2}{9}+\frac{\sigma^2}{9}$, if Firm 2 chooses to produce in T_2.

Given that Firm 1 chooses to produce in T_1, Firm 2's expected payoff is then $\frac{(A+k)^2}{9}$ if it chooses T_1, and $\frac{(A+2k)^2}{16}+\frac{\sigma^2}{16}$ if it chooses T_2. The condition for Firm 2 to choose T_2 is then $\frac{(A+2k)^2}{16}+\frac{\sigma^2}{16}\geq\frac{(A+k)^2}{9}$, which can be solved as condition (1). Otherwise, it chooses to produce in T_1. ■

Proof of Proposition 1.2:

If condition (1) holds, the equilibrium outputs are given by (2), and $q_1^{1S}\leq q_2^{2S}$ if $\varepsilon_0\leq 6k-A$. If condition (1) does not hold, the equilibrium outputs are given by (3), and $q_1^{1C}\leq q_2^{1C}$ if $\varepsilon_0\leq 2k$. Also notice that with the price of the product being the same, Firm 2 has a (weakly) higher markup per unit than Firm 1. ■

Proof of Proposition 1.3:

First, no $I1$ firm wants to delay production: regardless of the number of other firms producing in each period, nothing is gained but the strategic value is lost for an $I1$ firm when producing in T_2. I can show it mathematically in a more general case. For an $I1$ firm *k*, suppose the number of all other firms choosing to produce in T_1 is $z\geq 0$ and within them $0\leq z_1\leq z$ are $I1$ firms; the rest $y\geq 0$ firms choose to produce in T_2 and

$0 \leq y_1 \leq y$ out of them are $I1$ firms. Firm k's expected profit by choosing T_1 is $\frac{A^2}{(z+2)^2(y+1)} + \frac{\sigma^2}{(z_1+2)^2(y+1)}$, which is greater than $\frac{A^2}{(z+1)^2(y+2)^2} + \frac{\sigma^2}{(z_1+1)^2(y+2)^2}$, the expected profit by choosing T_2. And this is independent of the values of z, z_1, y, y_1.

Then conditioning on that all $I1$ firms produce in period one, I solve the output and expected profit for each $I2$ firm. Denote $q_i^j(n_1 + x, n_2 - x)$ and $\pi_i^j(n_1 + x, n_2 - x)$ as the output level and profit of an Ii firm, which produces in period T_j, if x of the $I2$ firms produce in period one and the other $n_2 - x$ firms produce in period two, where x is an integer subject to $0 \leq x \leq n_2$. By solving backwards, I have the following equilibrium output levels in the quantity subgame:

$$q_1^1(n_1 + x, n_2 - x) = \frac{A}{n_1+x+1} + \frac{\varepsilon_0}{n_1+1},$$

$$q_2^1(n_1 + x, n_2 - x) = \frac{A}{n_1+x+1},$$

$$q_2^2(n_1 + x, n_2 - x) = \frac{A}{(n_1+x+1)(n_2-x+1)} + \frac{\varepsilon_0}{(n_1+1)(n_2-x+1)};$$

and expected payoffs are:

$$E[\pi_1^1(n_1 + x, n_2 - x)] = \frac{A^2}{(n_1+x+1)^2(n_2-x+1)} + \frac{\sigma^2}{(n_1+1)^2(n_2-x+1)},$$

$$E[\pi_2^1(n_1 + x, n_2 - x)] = \frac{A^2}{(n_1+x+1)^2(n_2-x+1)},$$

$$E[\pi_2^2(n_1 + x, n_2 - x)] = \frac{A^2}{(n_1+x+1)^2(n_2-x+1)^2} + \frac{\sigma^2}{(n_1+1)^2(n_2-x+1)^2}.$$

Three cases need to be considered. First, if at least one but not all $I2$ firms produce in period T_1 ($0 < x < n_2$), no $I2$ firm deviates if and only if (a) $E[\pi_2^1(n_1 + x, n_2 - x)] > E[\pi_2^2(n_1 + x - 1, n_2 - x + 1)]$, that is, no $I2$ firm who produces in period one wants to delay production, and (b) $E[\pi_2^2(n_1 + x, n_2 - x)] \geq E[\pi_2^1(n_1 + x + 1, n_2 -$

$x-1)]$, that is, no $I2$ firm who produces in period two has an incentive to advance production. Solving (b) I have the first inequality of the condition in (ii), and solving (a) I have the second inequality. Second, if all $I2$ firms produce in period $T2$ $(x=0)$, then no $I2$ firm deviates if and only if (b) is satisfied. The condition in (i) is just the first inequality of the condition in (ii) evaluated at $x=0$. Third, if all firms produce in period T_1 $(x=n_2)$, then no $I2$ firm deviates if and only if (a) is satisfied. And the condition in (iii) is just the second inequality of the condition in (ii) evaluated at $x=n_2$.

To see that the number of leading (and following) firms is uniquely determined, I only need to show that $\theta(N,n_1,x)$ is strictly decreasing in x for $x\in[0,n_2-1]$. Then for any $\sigma^2>0$, it falls into one and only one interval as specified in (i), (ii) and (iii). To show that, take a derivative of $\theta(\cdot)$ with respective to x:

$$\begin{aligned}\frac{d\theta(N,n_1,x)}{dx} &= (n_1+1)^2[-2(N-n_1-x+1)(n_1+x+2)^{-2}(N-n_1-x)^{-1} \\ &\quad + (N-n_1-x+1)^2(n_1+x+2)^{-2}(N-n_1-x)^{-2} \\ &\quad - 2(N-n_1-x+1)^2(n_1+x+2)^{-3}(N-n_1-x)^{-1} \\ &\quad + 2(n_1+x+1)^{-3}] < 0.\end{aligned}$$

The sum of the first two terms in the brackets is weakly negative when $x\le n_2-1$, since $\frac{2(N-n_1-x+1)(n_1+x+2)^{-2}(N-n_1-x)^{-1}}{(N-n_1-x+1)^2(n_1+x+2)^{-2}(N-n_1-x)^{-2}}=\frac{2(N-n_1-x)}{(N-n_1-x+1)}\ge 1$.

The sum of the last two terms is strictly negative since $\frac{2(N-n_1-x+1)^2(n_1+x+2)^{-3}(N-n_1-x)^{-1}}{2(n_1+x+1)^{-3}}=\frac{(N-n_1-x+1)^2(n_1+x+1)^3}{(N-n_1-x)(n_1+x+2)^3}\ge 4\times\frac{8}{27}>1$. This is because $\frac{(N-n_1-x+1)^2}{(N-n_1-x)}\ge 4$ when $x\le n_2-1$, and $\frac{(n_1+x+1)^3}{(n_1+x+2)^3}\ge\frac{8}{27}$ when $n_1\ge 1$. ■

Proof of Lemma 1.1:

The following reduced game at the prestage is obtained when (*NB*, *NB*) is the outcome from the information acquisition stage:

Table 1.2 The Reduced Game of Timing Choice under (*NB, NB*)

		Firm 2	
		$T1$	$T2$
Firm 1	$T1$	$\frac{A^2}{9}, \frac{A^2}{9}$	$\frac{A^2}{8}, \frac{A^2}{16} + \frac{\sigma^2}{4}$
	$T2$	$\frac{A^2}{16} + \frac{\sigma^2}{4}, \frac{A^2}{8}$	$\frac{A^2}{9} + \frac{\sigma^2}{9}, \frac{A^2}{9} + \frac{\sigma^2}{9}$

Solving this game gives the result. ■

Proof of Proposition 1.4:

The game in the information acquisition stage has four possible cases, subject to existence, based on possible equilibria in the extended games when neither firm buys information and when only one firm buys information.

Case 1: $\sigma^2 < \frac{1}{8}A^2$ and $\sigma^2 < \Delta$. Firms produce simultaneously in T_1 under (*NB*, *NB*), (*B*, *NB*) or (*NB*, *B*). The following payoffs matrix is obtained for the information acquisition stage:

Table 1.3 The Reduced Game of Information Acquisition - 1

		Firm 2: B	Firm 2: NB
Firm 1	B	$\frac{(A-k)^2}{9}+\frac{\sigma^2}{9}-f, \frac{(A-k)^2}{9}+\frac{\sigma^2}{9}-f$	$\frac{(A-2k)^2}{9}+\frac{\sigma^2}{4}-f, \frac{(A+k)^2}{9}$
	NB	$\frac{(A+k)^2}{9}, \frac{(A-2k)^2}{9}+\frac{\sigma^2}{4}-f$	$\frac{A^2}{9}, \frac{A^2}{9}$

Case 2: $\sigma^2 < \frac{1}{8}A^2$ and $\sigma^2 \geq \Delta$. Firms produce simultaneously in T_1 under (*NB*, *NB*), and sequentially under (*B*, *NB*) or (*NB*, *B*) with the firm buying information leading. However, with $k < \frac{A}{3}$, $\Delta > \frac{1}{8}A^2$, a contradiction.

Case 3: $\sigma^2 \geq \frac{1}{8}A^2$ and $\sigma^2 < \Delta$. Firms produce simultaneously in T_2 under (*NB*, *NB*) and simultaneously in T_1 under (*B*, *NB*) or (*NB*, *B*). The game in the information acquisition stage is:

Table 1.4 The Reduced Game of Information Acquisition - 2

		Firm 2: B	Firm 2: NB
Firm 1	B	$\frac{(A-k)^2}{9}+\frac{\sigma^2}{9}-f, \frac{(A-k)^2}{9}+\frac{\sigma^2}{9}-f$	$\frac{(A-2k)^2}{9}+\frac{\sigma^2}{4}-f, \frac{(A+k)^2}{9}$
	NB	$\frac{(A+k)^2}{9}, \frac{(A-2k)^2}{9}+\frac{\sigma^2}{4}-f$	$\frac{A^2}{9}+\frac{\sigma^2}{9}, \frac{A^2}{9}+\frac{\sigma^2}{9}$

Case 4: $\sigma^2 \geq \frac{1}{8}A^2$ and $\sigma^2 \geq \Delta$. Firms produce simultaneously in T_2 under (*NB*, *NB*), and sequentially under (*B*, *NB*) or (*NB*, *B*) with the firm buying information leading. The game in the information acquisition stage is then:

Table 1.5 The Reduced Game of Information Acquisition - 3

		Firm 2	
		B	NB
Firm 1	B	$\frac{(A-k)^2}{9}+\frac{\sigma^2}{9}-f, \frac{(A-k)^2}{9}+\frac{\sigma^2}{9}-f$	$\frac{(A-2k)^2}{8}+\frac{\sigma^2}{8}-f, \frac{(A+2k)^2}{16}+\frac{\sigma^2}{16}$
	NB	$\frac{(A+2k)^2}{16}+\frac{\sigma^2}{16}, \frac{(A-2k)^2}{8}+\frac{\sigma^2}{8}-f$	$\frac{A^2}{9}+\frac{\sigma^2}{9}, \frac{A^2}{9}+\frac{\sigma^2}{9}$

Solving these games, and noting that $0 \leq k < \frac{A}{3}$, I prove the result. ■

Proof of Proposition 1.5:

Stackelberg equilibrium arises only when firms have asymmetric information and condition (1) is satisfied. When $k < \frac{A}{3}$, I have $\frac{1}{8}A^2 < \Delta$. As a result, both conditions (iia) and (iib) in Proposition 1.4 violate condition (1). ■

Proof of Proposition 1.6:

Similar to the proof of Proposition 1.3, if $\sigma^2 \geq \Delta$, I have firms produce simultaneously in T_2 under (*NB*, *NB*), and sequentially under (*B*, *NB*) or (*NB*, *B*). The game in the information acquisition stage is then:

Table 1.6 The Reduced Game of Information Acquisition - 4

		Firm 2	
		B	NB
Firm 1	B	$\frac{(A-k)^2}{9}+\frac{\sigma^2}{9}-f_1, \frac{(A-k)^2}{9}+\frac{\sigma^2}{9}-f_2$	$\frac{(A-2k)^2}{8}+\frac{\sigma^2}{8}-f_1, \frac{(A+2k)^2}{16}+\frac{\sigma^2}{16}$
	NB	$\frac{(A+2k)^2}{16}+\frac{\sigma^2}{16}, \frac{(A-2k)^2}{8}+\frac{\sigma^2}{8}-f_2$	$\frac{A^2}{9}+\frac{\sigma^2}{9}, \frac{A^2}{9}+\frac{\sigma^2}{9}$

Under the condition specified in the proposition, (*B, NB*) is the unique equilibrium and Stackelberg competition with Firm 1 leading emerges in the extended game under (*B*, *NB*). ■

Proof of Lemma 2.1:

The payoffs of the reduced game in the prestage of timing choice are obtained by taking an expectation of the *ex post* payoffs in the price games corresponding to each outcomes of firms' timing choices. The reduced game is:

Table 2.2 The Reduced Game of Timing Choice under (*B, B*)

		Firm 2	
		$T1$	$T2$
Firm 1	$T1$	$x(A^2+\sigma^2), x(A^2+\sigma^2)$	$y(A^2+\sigma^2), z(A^2+\sigma^2)$
	$T2$	$z(A^2+\sigma^2), y(A^2+\sigma^2)$	$x(A^2+\sigma^2), x(A^2+\sigma^2)$

With $x < y < z$, (T_1, T_2) and (T_2, T_1) are the only pure strategy equilibria. ■

Proof of Proposition 2.1:

Using the expected payoffs in the basic games corresponding to each sequence of play, the following reduced game in the prestage is obtained:

Table 2.3 The Reduced Game of Timing Choice under (*NB*, *NB*)

		Firm 2	
		$T1$	$T2$
Firm 1	$T1$	xA^2, xA^2	$yA^2, zA^2 + \sigma^2/4$
	$T2$	$zA^2 + \sigma^2/4, yA^2$	$x(A^2 + \sigma^2), x(A^2 + \sigma^2)$

Apparently, (T_1, T_1) is not an equilibrium. For (T_2, T_2) to be an equilibrium, I need $x(A^2 + \sigma^2) \geq yA^2$, which can be solved as $\sigma^2 \geq \beta A^2$, where $\beta = \frac{\theta^4}{16-8\theta^2}$. Otherwise, one firm would deviate by playing the leadership role and both sequential moves are equilibria. ■

Proof of Proposition 2.2:

From the payoff matrix, I have $E(\pi_i^L(B, NB)) \geq E(\pi_i^F(B, NB))$ if and only if $\sigma^2 \geq \frac{\theta^2}{4-2\theta^2} A^2$. For firm j, I always have $E(\pi_j^L(B, NB)) < E(\pi_j^F(B, NB))$. ■

Proof of Proposition 2.3:

Solving the reduced game in Table 2.1 directly gives the results. ■

Proof of Lemma 2.2:

From Proposition 2.2, and note that $\beta < \frac{\theta^2}{4-2\theta^2}$, I have that both firms prefer being the follower if $\sigma^2 < \beta A^2$. ■

Proof of Proposition 2.4:

Compare the products of deviation losses of the two equilibria in Table 2.1 when $\sigma^2 < \beta A^2$. With $z > y > x$, $(y - x)(A^2 + \sigma^2)\big((z - x)A^2 + z\sigma^2\big) > (z - x)A^2\big((y - xA2-x\sigma 2$. So, the equilibrium with firm i leading risk dominates the other. ■

Proof of Proposition 2.5:

The equilibrium in the extended game under (*NB*, *NB*) depends on whether the condition $\sigma^2 \geq \beta A^2$ is satisfied. If it is satisfied, equilibrium in each of the extended games under (*NB*, *NB*), (*B*, *NB*), (*NB*, *B*) is unique. But the extended games under (*B*, *B*) will have two sequential play equilibria. As a result, two cases need to be discussed in the information acquisition stage. If $\sigma^2 < \beta A^2$, the extended games under both (*B*, *B*) and (*NB*, *NB*) will have multiple equilibria. Then there are four cases to be discussed in the information acquisition stage.

When $\sigma^2 < \beta A^2$:

Case 1: If (T_1, T_2) under (NB, NB) and (T_1, T_2) under (B, B), the reduced game in the information acquisition stage can be written as:

Table 2.4 The Reduced Game of Information Acquisition - 1

		Firm 2	
		B	*NB*
Firm 1	*B*	$y(A^2 + \sigma^2) - f, z(A^2 + \sigma^2) - f$	$y(A^2 + \sigma^2) - f, z(A^2 + \sigma^2)$
	NB	$z(A^2 + \sigma^2), y(A^2 + \sigma^2) - f$	$yA^2, z(A^2 + \sigma^2)$

In this case, (B, NB) is the unique equilibrium if and only if $f \leq y\sigma^2$, and (NB, NB) is the unique equilibrium if and only if $f > y\sigma^2$.

Case 2: If (T_1, T_2) under (NB, NB) and (T_2, T_1) under (B, B), the reduced game of information acquisition can be written as:

Table 2.5 The Reduced Game of Information Acquisition - 2

		Firm 2	
		B	*NB*
Firm 1	*B*	$z(A^2+\sigma^2)-f, y(A^2+\sigma^2)-f$	$y(A^2+\sigma^2)-f, z(A^2+\sigma^2)$
	NB	$z(A^2+\sigma^2), y(A^2+\sigma^2)-f$	$yA^2, z(A^2+\sigma^2)$

In this case, (B, NB) is the unique equilibrium if and only if $f \leq y\sigma^2$, and (NB, NB) is the unique equilibrium if and only if $f > y\sigma^2$.

Case 3: If (T_2, T_1) under (NB, NB) and (T_1, T_2) under (B, B), the reduced game of information acquisition can be written as:

Table 2.6 The Reduced Game of Information Acquisition - 3

		Firm 2	
		B	*NB*
Firm 1	*B*	$y(A^2+\sigma^2)-f, z(A^2+\sigma^2)-f$	$y(A^2+\sigma^2)-f, z(A^2+\sigma^2)$
	NB	$z(A^2+\sigma^2), y(A^2+\sigma^2)-f$	$z(A^2+\sigma^2), yA^2$

In this case, (NB, B) is the unique equilibrium if and only if $f \leq y\sigma^2$, and (NB, NB) is the unique equilibrium if and only if $f > y\sigma^2$.

Case 4: If (T_2, T_1) under (NB, NB) and (T_2, T_1) under (B, B), the reduced game of information acquisition can be written as:

Table 2.7 The Reduced Game of Information Acquisition - 4

		Firm 2: B	Firm 2: NB
Firm 1	B	$z(A^2 + \sigma^2) - f, y(A^2 + \sigma^2) - f$	$y(A^2 + \sigma^2) - f, z(A^2 + \sigma^2)$
	NB	$z(A^2 + \sigma^2), y(A^2 + \sigma^2) - f$	$z(A^2 + \sigma^2), yA^2$

In this case, (NB, B) is the unique equilibrium if and only if $f \leq y\sigma^2$, and (NB, NB) is the unique equilibrium if and only if $f > y\sigma^2$.

Due to symmetry of the firms, all four cases yield the same conditions for both symmetric and asymmetric outcomes to arise in the information stage. Thus when $\sigma^2 < \beta A^2$, equilibrium outcomes can be summarized as: one firm buys information and the other not if and only if $f \leq y\sigma^2$; neither firm buys information if and only if $f > y\sigma^2$.

When $\sigma^2 \geq \beta A^2$:

Case 1: If (T_1, T_2) under (B, B), the reduced game of information acquisition can be written as:

Table 2.8 The Reduced Game of Information Acquisition - 5

		Firm 2 *B*	Firm 2 *NB*
Firm 1	*B*	$y(A^2+\sigma^2)-f, z(A^2+\sigma^2)-f$	$y(A^2+\sigma^2)-f, z(A^2+\sigma^2)$
	NB	$z(A^2+\sigma^2), y(A^2+\sigma^2)-f$	$x(A^2+\sigma^2), x(A^2+\sigma^2)$

In this case, (NB, B) and (B, NB) are equilibria if and only if $f \leq y\sigma^2$, and (NB, NB) is the unique equilibrium if and only if $f > y\sigma^2$.

Case 2: If (T_2, T_1) under (B, B), the reduced game of information acquisition can be written as:

Table 2.9 The Reduced Game of Information Acquisition - 6

		Firm 2 *B*	Firm 2 *NB*
Firm 1	*B*	$z(A^2+\sigma^2)-f, y(A^2+\sigma^2)-f$	$y(A^2+\sigma^2)-f, z(A^2+\sigma^2)$
	NB	$z(A^2+\sigma^2), y(A^2+\sigma^2)-f$	$x(A^2+\sigma^2), x(A^2+\sigma^2)$

In this case, (NB, B) and (B, NB) are equilibria if and only if $f \leq y\sigma^2$, and (NB, NB) is the unique equilibrium if and only if $f > y\sigma^2$.

Both cases yield the same result since the payoffs under (B, B) do not matter: (B, B) is never an equilibrium outcome. Thus when $\sigma^2 \geq \beta A^2$, equilibrium outcomes can be summarized as: one firm buys information and the other not if and only if $f \leq (y - x)(A^2 + \sigma^2)$; neither firm buys information if and only if $f > (y - x)(A^2 + \sigma^2)$.

Different from when $\sigma^2 < \beta A^2$, here both asymmetric information acquisitions are equilibria if cost of information is low.

Combining the preceding results and representing the conditions as an expression of the variance of demand intercept, I prove the proposition. ■

Proof of Proposition 2.6:

This is proved by direct comparisons of payoffs in each case in the proof of Proposition 2.5. Setting $f = 0$, if one firm strictly prefers not to obtain information given the other firm's choice of information, then early information has a strictly negative value. If one firm is indifferent between acquiring and not acquiring information, then early information has zero value. The first statement follows from the fact that (B, B) is never an equilibrium outcome with one firm strictly preferring to deviate and the other being indifferent. The second statement follows from the fact that when $\sigma^2 < \beta A^2$, only one of the firms chooses to buy information and is the unique asymmetric equilibrium when information is free. ■

Proof of Lemma 3.1:

From (8), $\frac{\partial w_i(\cdot)}{\partial x_i} = -\frac{-q'-w_i q''}{2q'+w_i q''} = 1 - \frac{q'}{2q'+w_i q''} < 1$. Also, $\frac{\partial w_i(\cdot)}{\partial x_i} = \frac{q'+w_i q''}{2q'+w_i q''} = \frac{1}{2q'+w_i q''}\left(q' - \frac{qq''}{q'}\right) = \frac{1}{2q'+w_i q''}\left(\frac{1}{P''q+2P'} + \frac{3P''q+P'''q^2}{(P''q+2P')^2}\right)$ which is greater than zero if and only if (10) is satisfied. ■

Proof of Proposition 3.1:

In the first stage, downstream firm i's choice of investment (equivalently, choice of cost reduction x_i) is determined by solving the following problem:

$$\max_{x_i} \left(P\left(q(w(x_i) - x_i)\right) - c_0 + x_i - w(x_i)\right)q(w(x_i) - x_i) - R(x_i, \gamma_i)$$

The first order condition implicitly defines the optimal level of effort:

$$(P(q_i) - c_0 + x_i - w(x_i))q'(\cdot)\left(\frac{\partial w(\cdot)}{\partial x_i} - 1\right)$$
$$+ \left(P'(\cdot)q'(\cdot)\left(\frac{\partial w(\cdot)}{\partial x_i} - 1\right) - \frac{\partial w_i}{\partial x_i} + 1\right)q(w_i - x_i) - \frac{\partial R(\cdot)}{\partial x_i} = 0.$$

With the second order condition being satisfied and $\frac{\partial^2 R(\cdot)}{\partial x_i \partial \theta_i} > 0$, differentiate the above with respect to θ_i and I obtain $\frac{\partial x_i}{\partial \theta_i} < 0$, which means a more efficient downstream firm chooses a lower cost technology. Together with Lemma 3.1, I prove the proposition. ■

Proof of Lemma 3.2:

From (11), I have $\frac{\partial x_i(\cdot)}{\partial \theta_i} = \frac{\frac{\partial^2 R(\cdot)}{\partial x_i \partial \theta_i}}{-q' - \frac{\partial^2 R(\cdot)}{\partial x_i^2}} < 0$, given that the denominator is negative (the second order condition). Also, $\frac{\partial x_i(\cdot)}{\partial w_i} = -\frac{q'}{-q' - \frac{\partial^2 R(\cdot)}{\partial x_i^2}} < 0$. ■

Proof of Proposition 3.4:

Comparing (16) to (18), and (17) to (19), I have ${x_i}^{W-R} > {x_i}^{S-M}$ and ${w_i}^{W-R} < {w_i}^{S-M}$. In the wholesaler-retailer model, if firm *i* were to choose $x_i = {x_i}^{S-M}$, its profit is

$\pi_i(x_i{}^{S-M}) = \left(\frac{A-w_i{}^{W-R}+x_i{}^{S-M}}{2}\right)^2 - R_i(x_i{}^{S-M})$ which is greater than $\pi_i{}^{S-M} =$

$\left(\frac{A-w_i{}^{S-M}+x_i{}^{S-M}}{2}\right)^2 - R_i(x_i{}^{S-M})$ since $w_i{}^{W-R} < w_i{}^{S-M}$. And $\pi_i{}^{W-R} > \pi_i(x_i{}^{S-M})$. ■

Proof of Proposition 3.5:

In the supplier-manufacturers model, the upstream monopolist's profit from market *i* is

$$\pi_{mi}{}^{S-M} = \frac{1}{2}(A - w_i{}^{S-M} + x_i{}^{S-M})w_i{}^{S-M} = 8\left(\frac{2A\gamma_i - \beta_i}{16\gamma_i - 1}\right)^2,$$

while in the wholesaler-retailers model, its profit is

$$\pi_{mi}{}^{W-R} = \frac{1}{2}(A - w_i{}^{W-R} + x_i{}^{W-R})w_i{}^{W-R} = \frac{(2A\gamma_i - \beta_i)^2}{8\gamma_i(4\gamma_i - 1)}.$$

It can be easily verified that $\pi_{mi}{}^{S-M} < \pi_{mi}{}^{W-R}$ when $\gamma_i > 0$. ■

Proof of Proposition 3.6:

Proposition 3.4 and Proposition 3.5 indicate that all firms earn a higher profit under the wholesaler-retailers model. Also by Proposition 4, final output in market *i* is $q_i{}^{W-R} = \frac{1}{2}(A - w_i{}^{W-R} + x_i{}^{W-R})$ in the wholesaler-retailers model, greater than the final output in the supplier-manufacturers model $q_i{}^{S-M} = \frac{1}{2}(A - w_i{}^{S-M} + x_i{}^{S-M})$. As a result, consumer surplus is also greater. ■

Vita

Youping Li was born in Hunan, China. He received a bachelor's degree in finance from Fudan University in July 2003 and worked for PetroChina before coming to study in the United States in August 2006. At the University of Tennessee, he received a Master of Arts degree in May 2008 and a Doctor of Philosophy degree in August 2011, both in economics. Among the job offers he received from Chinese universities, Youping has accepted the position of Assistant Professor in School of Business at East China University of Science and Technology. Although his current research focuses primarily on firm strategies in imperfect markets, he is also interested in topics in public economics and environmental economics.