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ABSTRACT

Asymptotic Efficiency in Stackelberg Markets with Incomplete Information

by Jianbo Zhang and Zhentang Zhang*

This paper examines the asymptotic (in)efficiency of Stackelberg markets with incomplete information. Firms who are early in the queue make their quantity choices based on limited information and their output choices are likely to deviate from those optimal under complete information. Due to the presence of both *payoff externality* and *information externality*, the output deviations of early firms have a lasting effect on all subsequent output decisions. Consequently, the total market output diverges from the competitive equilibrium output even as the number of firms goes to infinity. That is, Stackelberg markets with incomplete information are asymptotically inefficient with probability one.

ZUSAMMENFASSUNG

Asymptotische Effizienz in Stackelberg-Märkten mit unvollständiger Information

In diesem Beitrag wird die asymptotische (In-)Effizienz von Stackelberg-Märkten mit unvollständiger Information untersucht. Unternehmen, die frühzeitig auf den Markt kommen, bestimmen ihre Ausbringungsmengen unter unvollständiger Information. Aus diesem Grunde sind ihre Mengenentscheidungen im allgemeinen verschieden von den optimalen Ausbringungsmengen unter vollständiger Information. Auszahlungswirksame Externalitäten und Informationsexternalitäten bewirken, daß die Mengenentscheidungen der frühzeitig auf den Markt treffenden Unternehmen zu pfadabhängigen Mengenentscheidungen nachfolgender Unternehmen führen. Im Ergebnis ist dann die gesamte Ausbringungsmenge aller Unternehmen verschieden von dem Konkurrenzgleichgewicht - selbst dann, wenn die Anzahl der Unternehmen gegen unendlich strebt. Das heißt, Stackelberg-Märkte mit unvollständiger Information sind asymptotisch ineffizient mit der Wahrscheinlichkeit eins.

* We would like to thank Larry Samuelsen for his insightful discussions on the topic of this paper.

1. Introduction

It is well known that markets may fail because of limited competition or the existence of incomplete information[1]. The inefficiency due to these two sources, however, can be respectively eliminated in a large market as the number of firms tends to infinity. Wilson (1977) demonstrates that in a sealed bid tender auction where each bidder has private information, the winning bid will converge in probability to the true value of the object as the number of bidders grows large. This result is extended and generalized by Milgrom (1979), who obtains necessary and sufficient conditions for convergence.[2] Regarding the inefficiency from market power, Novshek (1980) and Robson (1990) investigate Cournot and Stackelberg markets respectively and show that under general demand and U-shaped average cost curves, the inefficiency arising from market power will disappear asymptotically as the minimum efficient scale tends to zero. That is, both Cournot and Stackeberg equilibria under complete information converge to the competitive equilibrium as the number of firms tends to infinity.

A natural question to raise is whether inefficiency in markets with both market power and incomplete information is also eliminated as the number of firms tends to infinity? The asymptotic property of the Cournot model with incomplete information has been investigated in the literature. Palfey (1985) shows that, under certain assumptions on the information structure, a Cournot market with unknown demand becomes efficient as the number of firms grows large. Li (1985) obtains the same result by endogenizing firms' decision to share information.[3] Vives (1988) demonstrates that Palfey and Li's result depends on the production technology exhibiting constant returns to scale. However, so far in the literature, no studies have looked at whether the inefficiency in Stackelberg markets with incomplete information could be eliminated as the number of firms tends to infinity? That is, whether large Stackelberg markets aggregate information efficiently? This paper attempts to fill this gap.

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1 See, for example, Akerlof (1980) for classical discussion of the problem.

2 Swinkels (1996) shows that discriminatory private value auctions for multiple objects are asymptotically efficient as the number of players grows large.

3 The incentives for Cournot oligopolists to share information have been studies extensively in the literature, for example, by Li (1985), Shapiro (1986) and Vives (1984). They conclude that when the uncertainty is about a firm-specific parameter, perfect revelation is the unique equilibrium. On the other hand, when the uncertainty is about a common parameter, no information sharing is the unique equilibrium.

The information structure arising in Stackelberg competition is similar to the one in information cascade literature introduced by Banerjee(1992), and Bikchandani, Hirshleifer and Welch (1992). Under such an information structure, agents take actions sequentially after observing the action history and a private signal. An *information externality* occurs since each agent's private information is revealed, perfectly or imperfectly, through its action to the following agents and may thereby alter their believes about the underlying uncertainty. This information externality may give rise to information cascades[4]. Although the literature on information cascade illuminates how inefficiencies can be generated in a sequential action model through information externality, it is not well suited to analyze the information aggregation problem in large Stackelberg markets. The reason for this is that information cascade models assume that there is no strategic value for a player early in the queue to manipulate its action in order to influence the actions of the following players. That is, they assume that there are no strategic interactions between players and thereby *no payoff externality*. By assuming away the strategic interactions, the information cascade literature captures the inefficiencies resulting only from information externalities but not from payoff externalities.[5] In Stackelberg markets with incomplete information, the effects of every firm's action on the payoffs of its successive firms are two-folded: First, the strategic interactions between leaders and followers create payoff externality. Second, every firm's action conveys its private information and thereby affects its following firms' belief about the unknown state, which creates information externality. It is this payoff externality entwined with the information externality, as shown below, that drives the efficiency loss even as the number of firms goes to infinity.

The main result of the paper can be illustrated by considering the following scenario: a number of firms engage in Stackelberg competition making their production choices sequentially. The nature of demand is unknown to the firms. In addition to receiving a private signal, each firm observes all the actions of the preceding firms and tries to infer their private information through these actions. Based on the private signal and the inferred public information, every firm makes its quantity choice. In general, this game is an extended signaling game with many players where the quantity choice of each

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4 An information cascade is defined, as by Lee (1993), as the convergence of the sequence of actions. A fully revealing information cascade is said to occur if the limit is optimal under the true state. Otherwise, a non-fully revealing information cascade occurs.

5 Similarly, Vives (1993) studies the speed of convergence to the rational expectations equilibrium in a simple dynamic model of rational learning between agents. However, he assumes that the action of one player does not affect the profits of other periods. That is, he assumes that there are no strategic interactions between players across periods.

leader is a signal about its private information to all its followers.[6] Recall that dynamic games with incomplete information tend to have multiple equilibria and there is no exception in this game.[7] The refinement of Perfect Bayesian equilibrium adopted in this paper is called the extended intuitive criterion, which is an extended version of the intuitive criterion of Cho and Kreps (1987). More precisely, the intuitive criterion is applied to every continuation game of the extended signaling game. Since every continuation game satisfies the single crossing property, the extended intuitive criterion leaves us with a unique separating equilibrium. This implies that every firm's quantity choice fully reveals its private information to all its followers. Therefore, according to the strong law of large numbers, the true state of demand is eventually revealed to the firms who are sufficiently late in the queue. The basic point is as follows: in the information cascade models with *no payoff externality*, the revelation of the truth necessarily forces the later players to take actions which are optimal under complete information. This cannot happen in the current model precisely due to the payoff externality that is present. Intuitively, the first firm can get either a high or a low signal with a positive probability regardless of what the true state of demand is. As a consequence, its quantity choice may be different from the quantity choice under complete information. The quantity choice of the first firm will then affect the quantity choices of all the firms later in the queue, due to the payoff externality. As a result, output deviations of early firms have a lasting effect on all subsequent output decisions and the total market output does not converges to the competitive equilibrium. This is true despite the fact that firms sufficiently back in the queue have almost complete information about demand.[8]

The rest of the paper is organized as follows. In Section 2 we sets up the model. In Section 3 we investigates the asymptotic (in)efficiency of the Stackelberg market. In Section 4 comments and concludes are given.

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6 In this extended signalling game, every player has private information while in the standard signalling games, only the first player has private information.

7 To obtain a unique equilibrium a refinement is necessary.

8 In our set-up, we do not assume that there is a designed mechanism which solicit information before implementing the transactions as in Gul and Postlewaite (1992). Neither do we assume there is a market auctioneer who pools information and sets market clearing price as in Rutichini, Satterthwaite and Williams (1994). Instead, the private information is revealed through the quantity choices of the firms.

2. Model

Consider a Stackelberg market with N firms making production choices sequentially. Firms are assumed to have constant marginal cost; i.e., $c(q_n) = cq_n$, $n = 1,2,...N$. There are no fixed costs. Following Novshek and Sonnenschein (1982) and Vives (1988), firms' private information is about the demand intercept: $p = a + S - bQ$; where Q is total market output and it is assumed that $a > c$ and $b > 0$. State S is a random variable which is distributed over a finite state space $\Omega \subset R^1$. The unknown state could be interpreted as a parameter affecting consumers' taste, so that a higher state would result in a higher market demand and vice versa. Firms do not know the realization s of S, but have common initial prior distribution $\mu_0(s) = Prob(S = s)$, which is assumed to be non-degenerate.

The information structure of the game is as follows: at the beginning of the game, a state s is drawn randomly from the finite state space Ω and remains fixed throughout. Each firm makes output choice based on its private signal and the public information in order to maximize its profits. Following Lee (1993), the private signal of firm n, x_n, is drawn randomly from a Bernoulli distribution $x_n \in \{0,1\}$. The draw of a signal is conditionally i.i.d. given the state.

Firm n, chooses q_n from its action set A_N, where $A_N = \lfloor 0,\overline{Q} \rfloor$[9]. The fact that A_N is compact and convex guarantees the existence of an equilibrium. Given the state of nature s, the information set of firm n is given by $\Omega_n = \{h_n, x_n\}$, where $h_n = (q_1, q_2, \ldots, q_{n-1})$ ($h_1 = \phi$) is the history of actions and x_n is the private signal of firm n. The behavior strategy of firm n, $\sigma_n(q_n|(h_n, x_n))$ is a mapping from the information set to the action set. Each firm, before making its output choice, has an identical initial prior belief $\mu_0(s)$ over the states. After observing the output choices of its preceding firms as well as receiving a private signal, the firm updates its prior belief according to Bayes' rule. The output choice is optimal with respect to the posterior belief. Let $\mu_n = prob(s|(h_n, x_n))$ denote the posterior belief of firm n. Firm n's expected profit function is given by $E_{\mu_n}\pi_n = E\{(a + S - c - bQ)q_n|\Omega_n\}$, where Q is the total market output. We solve for Perfect Bayesian equilibria.

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9 The upper bound of firm n's output is given by $\overline{Q} = \frac{1}{b}\left[a - c + \frac{1}{N}\sum_{n=1}^{N}\left[E(S|\Omega_n)\right]\right]$. This is because any choice of quantity greater than $\overline{Q}$ results in a strict expected loss, regardless of other firms' choices.

Given the number of firms N and the realized signal vector $\vec{x}=(x_1,x_2,\ldots,x_N)$, a perfect Bayesian equilibrium (hereafter, PBE) is defined as follows:

Definition: A PBE is a set of strategies $(\sigma_1^*,\ldots,\sigma_N^*)$ *and posterior beliefs* $(\mu_1,\ldots,\mu_N)$ *such that for any* μ_0, h_n *and n=1,2,...,N,*

$$(P_1)\ \sigma_n^*(q_n|(h_n,x_n)) \in \arg\max_{q_n} E_{\mu_n}\pi_n(h_n,q_n,q_{n+1}^*(q_n),\ldots,q_N^*(q_n));$$

$$(P_2)\ \sigma_{n+i}^*(q_n) \in \arg\max_{q_{n+i}} E_{\mu_{n+i}}\pi_{n+i}(h_{n+i},q_{n+i},q_{n+i+1}^*(q_{n+i}),\ldots,q_N^*(q_{n+i})),\ \textit{for any}$$

i=1, 2,...,N-n;

(B) $\mu_n(s|(h_n,x_n))$ *is derived from the prior* $\mu_0(s)$, $\sigma_{n-1}^*(q_{n-1}|(h_{n-1},x_{n-1}))$ *and* $\sigma_{n-1+i}^*(q_{n-1})$ *according to Bayes' rule, when applicable.*[10]

That is, a PBE of an extended signaling game with N players requires that the strategies yield a PBE for every continuation game.

To simplify the analysis, we make the following assumptions.

Assumption 1: The signals are unbiased estimators of the state. That is, $E(x_n|s)=s$.

From Assumption 1, we have that $s = prob(x_n = 1|s)$ and $1-s = prob(x_n = 0|s)$. That is, it is more likely to get a good signal ($x_n = 1$) when the state of nature is good.

Assumption 2: The conditional probability of signal, $x_n = 1$, *is strictly between 0 and 1. That is,* $0 < prob(x_n = 1|s) < 1$.

Assumption 2 implies that for any given state, there is a positive probability that each firm gets either signal $x_n = 1$ or signal $x_n = 0$. Assumption 2 rules out degenerate cases.

To extend the spirit of subgame perfection to this game, we would like to require that the strategies yield PBE for every continuation game starting from every possible

[10] Note that if q_{n-1} is not part of firm (n-1)'s optimal strategy for some private signal, observing q_{n-1} is a probability 0 event, and Bayes' rule does not pin down posterior beliefs. Any posterior beliefs are then admissible.

history h_n. We make the following assumptions on players' beliefs at the start of each continuation game.

Assumption 3: For any history h_n, player n+1 to player N have the same beliefs about the state of nature given h_n.

Recall that dynamic games with incomplete information tend to have multiple equilibria because Bayes' rule has no bite in out-of-equilibrium events and any posterior beliefs are admissible at out-of-equilibrium information sets. Consequently, the game above will potentially have multiple equilibria, unless we make use of a refinement. Using the intuitive criterion introduced by Cho and Kreps (1987), we propose an "extended intuitive criterion" which means that we apply the intuitive criterion of Cho and Kreps (1987) to every continuation game. In other word, we extend the intuitive criterion to our extended signaling game with many players.

3. Stackelberg Competition with incomplete Information

We can now investigate whether Stackelberg markets with incomplete information are asymptotically efficient in the presence of both information and payoff externalities. There are *N* firms making their output choice sequentially in a hierarchical Stackelberg framework. Without loss of generality, the order of firms' actions is assumed to be exogenously given by *1,2,..., N.*[11]

Let us examine pooling equilibria first. At a pooling equilibrium, firm n produces the same output no matter what signal he gets (0 or 1). The followers of firm n, firm n+1 to firm N, therefore update their posterior believes only based on their private signals. This implies that for any n, the information set of firm n is simply $\Omega_n = \{x_n\}$. Hence, firm n's expected payoff function can be simplified to

$$E_{\mu_n}\pi_n = E\{(a + S - c - bQ)q_n | x_n\}.$$

11 It is an interesting problem to endogenize the order of firms' actions. Mailath (1993) studies endogenous sequencing of firm decisions in a duopoly setup with asymmetric information between firms. Chamley and Gale (1994) and Zhang (1997) endogenize the sequential choice of agents in an information cascade context.

The existence and refinement of the pooling equilibria are given in the following proposition:

Proposition 1: Given the number of firms N and the realized signal vector $\vec{x} = (x_1, x_2, \ldots, x_N)$*, there exists a continuum of pooling PBE. Furthermore, the extended intuitive criterion eliminates all the pooling equilibria.*

Proof: See Appendix.

Next, we study separating equilibria. For a separating equilibrium, every firm's quantity choice perfectly reveals its private information. Therefore, firm n's information set Ω_n can be reduced to $\Omega_n = \{x_1, x_2, \ldots, x_{n-1}, x_n\}$. Consequently, the expected payoff function of firm n is given by

$$E_{\mu_n}\pi_n = E\{(a + S - c - bQ)q_n | (x_1, \ldots, x_n)\}.$$

The existence and the refinement of the separating equilibria are given by the following proposition:

Proposition 2: Given the number of firms N and the realized signal vector $\vec{x} = (x_1, x_2, \ldots, x_N)$*, there exists a continuum of separating PBE. Furthermore, the extensive intuitive criterion eliminates all but one separating equilibrium which is given as follows:*

$$Q(N, \vec{x}) = (1 - \frac{1}{2^N})\frac{a - c}{b} + \frac{1}{b}\sum_{n=1}^{N}\frac{E(S|\Omega_n)}{2^n}, \qquad (1)$$

$$p(N, \vec{x}) = a - bQ(N, \vec{x}) + S. \qquad (2)$$

Proof: See Appendix.

Proposition 1 and 2 imply that the extended intuitive criterion equilibrium refinement leaves us with a unique PBE. Before proceeding to investigate the asymptotic (in)efficiency of Stackelberg markets in the presence of both information and payoff externalities, we present the following useful lemmas.

Lemma 1: Along the unique PBE path, the best responses of firm n's followers, firm n+1 to firm N, satisfy respectively

$$\frac{dq_{n+1}}{dq_n} = -\frac{1}{2}, \quad \frac{dq_{n+2}}{dq_n} = -\frac{1}{4}, \quad \ldots, \quad \frac{dq_N}{dq_n} = -\frac{1}{2^{N-n}}; \quad \text{where } n = 1,2,\ldots N-1, \text{ and}$$

$\Omega_n = \{x_1, x_2, \ldots, x_{n-1}, x_n\}$.

Proof: See Appendix.

From Lemma 1, it is trivial to show that $\frac{dQ}{dq_n} = (\frac{1}{2})^{N-n}$. This is an important result as it implies that the impact of a firm's output choice on total output is smaller the later back in the game the firm is. Conversely, the output choices of early firms have a lasting effect on all subsequent output decisions.

In order to have a base for comparison, we use the perfect competitive equilibrium outcome with complete information as a benchmark.[12] The following lemma is trivial to obtain.

Lemma 2: Let $(Q^0(s), p^0(s))$ *be the competitive equilibrium outcome with complete information. Then* $Q^0(s) = \frac{a-c+s}{b}$ *and* $p^0(s) = c$.

We are now ready to state our main result regarding the asymptotic (in)efficiency of Stackelberg markets with incomplete information.

Theorem: For any realization s *of* S, *Let* $(Q(N|s), p(N|s))$ *be the vector of random variables which represents the unique (stochastic) PBE given by (1) and (2). Then* $(Q(N|s), p(N|s))$ *converges to some* $(Q^*(s), p^*(s))$ *as N goes to infinity. For almost all realizations* s, $(Q^*(s), p^*(s)) \neq (Q^0(s), p^0(s))$.[13]

[12] Our main results would not change if we use the competitive equilibrium outcome under incomplete information as the benchmark since the stochastic competitive equilibrium outcome converges in probability to a degenerate distribution, as the number of firms goes to infinity (see Vives (1988)).

Proof: From Proposition 2, for any N and $\vec{x}$, there exists a unique PBE given by equation (1) and (2). For any realization s of S, it is trivial that

$$Q(N|s) = (1 - \frac{1}{2^N})\frac{a-c}{b} + \frac{1}{b}\sum_{n=1}^{N}\frac{\left[E(S|\Omega_n)|s\right]}{2^n}, \text{ and}$$

$$p(N|s) = a - bQ(N|s) + s\text{ ; where } \Omega_n = \{x_1, x_2, \ldots, x_{n-1}, x_n\}.$$

As $N \to \infty$, according to the strong law of large numbers,

$$Q(N|s) \to \frac{a-c}{b} + \frac{1}{b}\sum_{n=1}^{\infty}\frac{E\left[E(S|\Omega_n)|s\right]}{2^n} \equiv Q^*(s), \text{ and}$$

$$p(N|s) \to c + s - \sum_{n=1}^{\infty}\frac{E\left[E(S|\Omega_n)|s\right]}{2^n} \equiv p^*(s).$$

Let s^* be the unique solution to the following equation:

$$s = \sum_{n=1}^{\infty}\frac{E\left[E(S|\Omega_n)|s\right]}{2^n}.$$

It is then trivial that $\left(Q^*(s), p^*(s)\right) \neq \left(Q^0(s), p^0(s)\right)$ unless $s = s^*$. Q.E.D.

The Theorem shows that the Stackelberg output is insufficiently low ($Q^*(s) < Q^0(s)$) when the true state of demand is good ($s > s^*$), while it is insufficiently high ($Q^*(s) > Q^0(s)$) when the true state of demand is bad ($s < s^*$). In sum, the Stackelberg output is asymptotically inefficient with probability one.[14]

The intuition behind the above result is as follows. Firms make their production decisions sequentially based on their private information as well as the inferred public information of the preceding firms. Since every continuation game of the Stackelberg

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13 We are grateful to an anonymous referee for the way this theorem is now stated.

14 The fact that the stochastic Stackelberg equilibrium outcome does not converge to the competitive equilibrium outcome is equivalent to stating that there is no convergence to a degenerate distribution since the degenerate Stackelberg equilibrium outcome converges to the competitive equilibrium outcome (See Robson (1990)).

game satisfies the single crossing property, the extended intuitive criterion selects a separating equilibrium, which implies that the leaders' quantity choices fully reveal their private information. Consequently, the firms who are sufficiently back in the queue have almost complete information, according to the strong law of large numbers. However, the firms who are early in the queue have very limited information about the unknown demand and their quantity choices tend to be different from the choices under complete information. In addition, these early firms' production choices affect the output choices of the later firms due to the payoff externality existing in the game. Therefore, the deviations of the early firms' output choice have a lasting effect on all subsequent output decisions and causes the total market output to be diverging from the competitive equilibrium output even as the number of firms goes to infinity.

The above theorem can be further illustrated in the following example.

Example: Suppose the initial prior distribution $\mu_o(s)$ is the uniform distribution over (0,1). The expected value of posterior distribution in the unique separating PBE can be simplified as:

$$E(S|\Omega_n) = \frac{1}{n+2}\left[1 + \sum_{n=1}^{N} x_n\right], \text{ where } \Omega_n = \{x_1, x_2, \ldots, x_{n-1}, x_n\}.^{15}$$

$$\text{Therefore, } \sum_{n=1}^{\infty} \frac{E\left[E(S|\Omega_n)|s\right]}{2^n} = \sum_{n=1}^{\infty} \frac{ns+1}{2^n(n+2)} \text{ by Assumption 1.}$$

Hence, $Q(N|s) \to \frac{a-c}{b} + \frac{1}{b}\sum_{n=1}^{\infty}\frac{ns+1}{2^n(n+2)}$; $p(N|s) \to c + s - \sum_{n=1}^{\infty}\frac{ns+1}{2^n(n+2)}$.

From Taylor expansion $ln(1-r) = -(r + \frac{r^2}{2} + \ldots + \frac{r^n}{n} + \ldots)$ for $-1 < r < 1$, we have that

$$\sum_{n=1}^{\infty} \frac{1}{2^n}\frac{ns+1}{n+2} = (6 - 8\ln 2)s + (4\ln 2 - 2.5) \approx 0.46s + 0.27 .$$

Therefore, $Q(N|s) \to \frac{a-c}{b} + \frac{1}{b}(0.46s + 0.27) \equiv Q^*(s)$, and

$$p(N|s) \to c + (0.54s - 0.27) \equiv p^*(s) .$$

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15 See Welch (1992).

It is trivial that $Q^*(s) < Q^0(s)$ if $s > \frac{1}{2}$, $Q^*(s) > Q^0(s)$ if $s < \frac{1}{2}$, and otherwise $Q^*(s) = Q^0(s)$.

4. Concluding Remarks

In this paper, we have demonstrated that large Stackelberg markets do not aggregate information efficiently, even if the technology exhibits constant return to scale. That is, in the presence of incomplete information, Stackelberg markets are asymptotically inefficient with probability one. This is because the early firms make their production choices based on the very limited information and consequently tend to over- or under-produce. In addition, the payoff externality ensures that the quantity choices of the early firms have a lasting effect on the output decisions of all subsequent firms. As a result, the over- or under-production of the early firms gets carried over and drives the efficiency loss.

The extended intuitive criterion selects a unique separating equilibrium, which ensures that each firm's private information is fully revealed to the successive firms and accordingly the underling uncertainty is gradually resolved along the queue as the number of firms becomes large. Therefore, firms who are sufficiently far back in the queue have almost complete information about the demand. In this sense, there is no efficiency loss from the information externality per se, and there is no possibility for a non-fully revealing information cascade to occur. It would be interesting to investigate a class of games where agents' actions do not fully reveal their private information.[16] In this case, a non-fully revealing information cascade may arise as discussed in Banerjee(1992), Bikchandani, Hirshleifer and Welch (1992), and Zhang and Zhang (1995). The efficiency loss in these games is therefore expected to be larger due to the additional inefficiency from information externalities.

[16] One example of this class of games is a Stackelberg game where each firm can only observe some but not all its preceding firms' actions.

Appendix

Proof of Proposition 1: At a pooling equilibrium, each firm updates its posterior belief only based on its own private signal, i.e. $\Omega_n = \{x_n\}$ for n = 1, .., N. For any given N and history h_n, a pooling equilibrium is said to survive the extended intuitive criterion if it survives intuitive criterion of Cho and Kreps (1987) in every continuation game. We solve this game backward.

1. Continuation game N

For any given h_{N-1}, this continuation game consists of only the Nth firm whose equilibrium output is given by,

$$q_N^* \in \arg\max_{q_N} E\left[q_N(a-c+S-bQ)\middle|x_N\right] \tag{A1}$$

2. Continuation game N-1

For any given h_{N-2}, this continuation game consists of firm (N-1) and firm N. Let q_{N-1} denote a pooling equilibrium for firm N-1. Firm (N-1)'s expected payoff is

$E\left[q_{N-1}(a-c+S-bQ_{N-1}-bq_N^*)\middle|x_{N-1}\right]$, where $Q_{N-1}=\sum_{i=1}^{N-1}q_i$ and $q_N^*(q_{N-1})$ is given by (A1).

Thus the best way to sustain q_{N-1} as a pooling equilibrium is to assume that firm N believes that firm N-1 gets signal $x_{N-1}=1$ when it observes $q'_{N-1}\neq q_{N-1}$. So q_{N-1} will indeed be a pooling equilibrium if and only if the following conditions are satisfied.

$$(M1):\ E\left[\pi(q_{N-1},q_N^*)\middle|x_{N-1}=1\right]\geq \max_{q'_{N-1}} E\left[\pi(q'_{N-1},q_N'^*)\middle|x_{N-1}=1\right],$$

$$(M2):\ E\left[\pi(q_{N-1},q_N^*)\middle|x_{N-1}=0\right]\geq \max_{q'_{N-1}} E\left[\pi(q'_{N-1},q_N'^*)\middle|x_{N-1}=0\right],$$

where $q_N^*(q_{N-1})$ is given by (A1) and $q_N'^*(q'_{N-1})$ is given as follows:

$$q_N'^* \in \arg\max_{q'_N} E\left[q'_N(a-c+S-bQ)\middle|(x_{N-1}=1,x_N)\right].$$

Therefore, there exists a continuum pooling equilibria $q_{N-1}\in\left[\underline{q}_{N-1},\overline{q}_{N-1}\right]$, where $\underline{q}_{N-1}$ and $\overline{q}_{N-1}$ are the lower and upper bound of q_{N-1} which satisfies (M1) and (M2).

In order to eliminate this continuum pooling equilibria, we use intuitive criterion of Cho and Kreps (1987) to this continuation game. Define $q'_{N-1} < q_{N-1}$ by the smallest root of

$$E\left[\pi(q'_{N-1}, r_N^*)\middle|x_{N-1} = 1\right] = E\left[\pi(q_{N-1}, q_N^*)\middle|x_{N-1} = 1\right], \textit{ where}$$

$$r_N^* \in \arg\max_{r_N} E\left[r_N(a - c + S - bQ_{N-2} - bq'_{N-1} - br_N)\middle|(x_{N-1} = 0, x_N)\right].$$

Now, playing $q'_{N-1} - \varepsilon$ (for $\varepsilon > 0$) is equilibrium dominated for firm N-1 with signal $x_{N-1} = 1$ but not for firm N-1 with signal $x_{N-1} = 0$ since

$$E\left[\pi(q'_{N-1}, q_N^*)\middle|x_{N-1} = 0\right] - E\left[\pi(q_{N-1}, q_N^*)\middle|x_{N-1} = 0\right]$$

$$= \frac{E(S|(x_{N-1} = 1, x_N)) - E(S|(x_{N-1} = 0, x_N))}{2b} > 0.$$

Therefore, firm N's posterior belief should put all the weight on $x_{N-1} = 0$ following output $q'_{N-1} - \varepsilon$. However, firm N-1 who gets $x_{N-1} = 0$ prefers to playing $q'_{N-1} - \varepsilon$ to q_{N-1}. Thus, q_{N-1} is not pooling output anymore.

3. Continuation game N-2

For any given h_{n-3}, this game consists of firm N-2, firm N-1 and firm N. From assumption 3, firm N-1 and firm N have the same believes after observing q_{N-2}. Applying the similar argument and technique used in last continuation game to this continuation game, we can eliminate pooling equilibria in this continuation game.

Continuing this process for every continuation game, we will then eliminate all the pooling equilibria. Q.E.D.

Proof of Proposition 2: For a separating equilibrium, every firm's quantity choice perfectly reveals its private information. Hence, the information set of firm n can be simplified to $\Omega_n = \{x_1, x_2, \ldots, x_{n-1}, x_n\}$. In addition, a separating equilibrium is said to survive the extended intuitive criterion if it survives intuitive criterion of Cho and Kreps (1987) in every continuation game. We solve this game backward.

1. Continuation game N

For any given h_{N-1}, this game consists of only firm N whose equilibrium output is given by

$$q_N^* \in \arg\max_{q_N} E\left[q_N(a-c+S-bQ)\middle|\Omega_N\right], \text{ where } \Omega_N = \left\{x_1, x_2, .., x_N\right\}. \qquad \text{(A2)}$$

2. Continuation game N-1

For any given h_{N-2}, this game consists of firm N-1 and firm N. At a separating equilibrium, the private information of firm N-1 is fully revealed to firm N through its quantity choice. Therefore, for firm N-1 with signal $x_{N-1} = 1$, it chooses the following optimal quantity:

$$q_{N-1}^{*H} \in \arg\max_{q_{N-1}} E\left[q_{N-1}(a-c+S-bQ_{N-1}-bq_N^{*H}(q_{N-1}))\middle|(\Omega_{N-2}, x_{N-1}=1)\right], \qquad \text{(A3)}$$

where $Q_{N-1} = \sum_{i=1}^{N-1} q_i$ and $q_N^{*H}(q_{N-1})$ is given by (A2) with $x_{N-1} = 1$. That is,

$$q_N^{*H}(q_{N-1}) \in \arg\max_{q_N} E\left[q_N(a-c+S-bQ)\middle|(\Omega_{N-2}, x_{N-1}=1, x_N)\right]. \qquad \text{(A4)}$$

On the other hand, for firm N-1 with signal $x_{N-1} = 0$, a separating equilibrium q_{N-1} is such that the following conditions are satisfied jointly:

$$(S1):\ \max_{q_{N-1}} E\left[\pi(q_{N-1}, q_N^{*H})\middle|(\Omega_{N-2}, x_{N-1}=1)\right] \geq E\left[\pi(q_{N-1}, r_N^*)\middle|(\Omega_{N-2}, x_{N-1}=1)\right],$$

$$(S2):\ E\left[\pi(q_{N-1}, r_N^*)\middle|(\Omega_{N-2}, x_{N-1}=0)\right] \geq \max_{q_{N-1}} E\left[\pi(q_{N-1}, q_N^{*H})\middle|(\Omega_{N-2}, x_{N-1}=0)\right],$$

where q_N^{*H} is given by (A4) & $r_N^* \in \arg\max_{q_N} E\left[q_N(a-c+S-bQ)\middle|(\Omega_{N-2}, x_{N-1}=0, x_N)\right]$.

(S1) says that when firm N-1 gets signal $x_{N-1} = 1$, it does not want to produce the output which corresponds to signal $x_{N-1} = 0$. *(S2)* says that when firm N-1 gets signal $x_{N-1} = 0$, it does not want to produce output which conveys signal $x_{N-1} = 1$. Therefore, there exists a continuum separating equilibria $q_{N-1}^L \in \left[\underline{q}_{N-1}^L, \overline{q}_{N-1}^L\right]$, where $\underline{q}_{N-1}^L$ and $\overline{q}_{N-1}^L$ are the lower and upper bound of q_{N-1}^L which satisfies (S1) and (S2).

Therefore, there exists a continuum separating equilibria. The firm with signal $x_{N-1} = 1$ prefers playing q_{N-1}^{*H} while the firm with signal $x_{N-1} = 0$ prefers playing $q_{N-1}^L \in \left[\underline{q}_{N-1}^L, \overline{q}_{N-1}^L\right]$. From (S1), it is clear that playing q_{N-1}^L is equilibrium dominated for the firm with signal $x_{N-1} = 1$, but not for the firm with signal $x_{N-1} = 0$. So firm N's posterior belief should put all the weight on signal $x_{N-1} = 0$ following q_{N-1}^L. Let q_{N-1}^{*L} denote

$$q^{*L}_{N-1} \in \arg\max_{q_{N-1}} E\left[\pi(q_{N-1}, r^*_N) \| (\Omega_{N-2}, x_{N-1} = 0)\right]$$

Then q^{*L}_{N-1} is the unique separating equilibrium surviving the elimination of weakly dominated strategies for firm with signal $x_{N-1} = 0$.

Hence, for any h_{N-2}, the equilibrium refinement of this continuation game leaves us with a set of unique PBE strategy (q^*_{N-1}, q^*_N), where q^*_N is given by (A2) and q^*_{N-1} is given by the following (A5):

$$q^*_{N-1} \in \arg\max_{q_{N-1}} E\left[q_{N-1}(a - c + S - bQ_{N-1} - bq^*_N) \middle| \Omega_{N-1}\right]. \tag{A5}$$

3. Continuation game N-2

For any given h_{n-3}, this game consists of firm N-2, firm N-1 and firm N. From assumption 3, firm N-1 and firm N have the same beliefs after observing q_{N-2}. By the similar reasoning as in last continuation game, the elimination of weakly dominated strategies of this continuation game leave us with a set of unique separating PBE profile $(q^*_{N-2}, q^*_{N-1}, q^*_N)$, where q^*_N is given by (A2), q^*_{N-1} is given by (A5) and q^*_{N-2} is given by the following (A6)

$$q^*_{N-2} \in \arg\max_{q_{N-2}} E\left[q_{N-2}(a - c + S - bQ_{N-2} - bq^*_{N-1} - bq^*_N) \middle| \Omega_{N-2}\right]. \tag{A6}$$

Continuing this process for every continuation game, the extended intuitive criterion leaves us with a unique separating PBE satisfying

$$q^*_n \in \arg\max_{q_n} E\left[q_n(a - c + S - bQ) \middle| \Omega_n\right], \text{ for n= 1, 2, …,N.}$$

Therefore, along the unique separating PBE path, we have

$$a - c - bq_n - bQ_N - bq_n \sum_{i=n+1}^{N} \frac{dq_i}{dq_n} + E(S|\Omega_n) = 0;$$

where $Q_N = \sum_{j=1}^{N} q_j$ and n=1, 2, …, N.[17]

Applying Lemma 1 (which is proved below) and rearranging the above equation, we have

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[17] We have implicitly assumed that firms have rational expectations, i.e., $E(q_i(\Omega_i)|\Omega_n) = q_i ; i > n$.

$$q_n^* = 2^{N-n}\left(\frac{a - c + E(S|\Omega_n)}{b} - Q_N\right);\ \text{n=1,2,...,N.}^{18}$$

Summing over $n = 1,2,...,N$, we have that for every N and the realized signal vector $\vec{x} = (x_1,\ldots,x_N)$, the unique stochastic PBE which survives the extended intuitive criterion is given as follows:

$$Q(N,\vec{x}) = (1 - \frac{1}{2^N})\frac{a-c}{b} + \frac{1}{b}\sum_{n=1}^{N}\frac{E(S|\Omega_n)}{2^n}.$$

Thus, $p(N,X) = a - bQ(N,X) + S$. Q.E.D.

Proof of Lemma 1: We prove this lemma by mathematical induction.

Along the unique separating PBE path, we have that

$$a - c - 2bq_N - bQ_{N-1} + E(s|\Omega_N) = 0;\ \text{where } Q_{N-1} = \sum_{j=1}^{N-1} q_j.$$

Thus, the best response of firm N to firm (N-1)'s output is satisfies that

$$\frac{dq_N}{dq_{N-1}} = -\frac{1}{2}.$$

Now suppose that the lemma holds for firm n+1. That is, along the unique separating PBE path, the best responses of firm (n+1)'s followers, firm n+2 to firm N, satisfy that

$$\frac{dq_{n+2}}{dq_{n+1}} = -\frac{1}{2},\ \frac{dq_{n+3}}{dq_{n+1}} = -\frac{1}{4},\quad \frac{dq_N}{dq_{n+1}} = -\frac{1}{2^{N-(n+1)}} \tag{L1}$$

From the above, it is trivial that $\frac{\partial q_j}{\partial q_{n+1}} = -\frac{1}{2}$ for any $j \geq n+2$. (L2)

Now we want to show the lemma also holds true for firm n.

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18 We therefore assume that $a - c > 2^N\left[min(E(S|\Omega_1),\ldots,E(S|\Omega_N)) - \sum_{n=1}^{N}\frac{E(S|\Omega_n)}{2^n}\right]$ in order to guarantee that $q_n^* > 0$.

From the proof of Proposition 2, firm (n+1)'s best response along the unique separating PBE path can be derived as follows:,

$$a-c-2bq_{n+1}-bQ_n-b\sum_{j=n+2}^{N}q_j-bq_{n+1}\sum_{j=n+2}^{N}\frac{dq_j}{dq_{n+1}}+E(S|\Omega_{n+1})=0\text{; where } Q_n=\sum_{j=1}^{n}q_j\,.$$

Rearrange it and applying (L1), we have

$$\left[1+(\frac{1}{2})^{N-n-1}\right]bq_{n+1}+b\sum_{j=n+2}^{N}q_j=a-c-bQ_n+E(S|\Omega_{n+1})$$

Taking derivative with respect to q_n, we have

$$\left[1+(\frac{1}{2})^{N-n-1}\right]b\frac{dq_{n+1}}{dq_n}+b\sum_{j=n+2}^{N}\frac{dq_j}{dq_n}=-b\,; \qquad \text{(L3)}$$

where $\frac{dq_{n+2}}{dq_n}=-\frac{1}{2}\frac{dq_{n+1}}{dq_n}-\frac{1}{2}$ from (L2).

Similarly,

$$\frac{dq_{n+3}}{dq_n}=-\frac{1}{2}\frac{dq_{n+2}}{dq_n}-\frac{1}{2}\frac{dq_{n+1}}{dq_n}-\frac{1}{2}=-\frac{1}{4}\frac{dq_{n+1}}{dq_n}-\frac{1}{4},\ldots, \text{ and}$$

$$\frac{dq_N}{dq_n}=-\frac{1}{2^{N-n-1}}\frac{dq_{n+1}}{dq_n}-\frac{1}{2^{N-n-1}}\,.$$

Therefore, $\sum_{j=n+2}^{N}\frac{dq_j}{dq_n}=-\left[1-(\frac{1}{2})^{N-n-1}\right](1+\frac{dq_{n+1}}{dq_n})$.

Substituting the above back into (L3) and rearrange it, we have that

$$\frac{dq_{n+1}}{dq_n}=-\frac{1}{2}\,.$$

Hence, $\frac{dq_{n+2}}{dq_n} = -\frac{1}{2}\frac{dq_{n+1}}{dq_n} - \frac{1}{2} = -\frac{1}{4}$,

$$\frac{dq_{n+3}}{dq_n} = -\frac{1}{4} - \frac{1}{4}\frac{dq_{n+1}}{dq_n} = -\frac{1}{8}$$,..., and

$$\frac{dq_N}{dq_n} = -\frac{1}{2^{N-n-1}} - \frac{1}{2^{N-n-1}}\frac{dq_{n+1}}{dq_n} = -\frac{1}{2^{N-n}} .$$ Q.E.D.

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