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ENDOGENOUS TIMING IN A GAME WITH INCOMPLETE INFORMATION

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Endogenous Timing in a Game with Incomplete Information[1]

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1 Introduction

In many economic situations it seems perfectly reasonable that agents have some say not only over their choice of action, but also over the timing of that choice. It is, therefore, important to check the robustness of results obtained from models in which agents are restricted to a certain timing structure. In this paper is shown that letting the timing decision be endogenous in a two-player game of incomplete information has serious impact on what can be equilibrium behaviour. In particular, the strategies used in a game restricted to simultaneous moves will never be used in equilibrium in a version of the same game where sequential moves are possible. In other words, once sequential moves are allowed the players will never mimic the equilibrium behaviour of players in the simultaneous move game. In contrast, complete separation in time is shown always to be an equilibrium.

The model has a number of special features. There are two players and two periods. A player can take action in one of the two periods only. If she acts in period 1 she cannot act in period 2, and vice versa. There is no cost of waiting, that is, there is no discounting between the two periods. Payoffs are realized after period 2. However, the two periods need not be separated by any significant physical time. What is necessary is that a player acting in the first period makes some irreversible decision which the other player can observe before choosing her action in the second period. Another distinguishing feature of the model is that the players have incomplete information about the type of the other player. Player i's type influences only her own payoff, and not that of player j. However, the action of player i does influence the payoff of player j. The incomplete information gives an incentive for players to wait until the second period in order to observe the action of the other player. On the other hand, being in the first period can be advantageous in that it may entail a first mover advantage. Furthermore, some types of a player may prefer to hide their identity by delaying their action until the second period, while others will want to separate themselves from these "bad" types. The analysis of these conflicting motives of hiding and separating, and of reaping a first mover advantage versus reacting optimally to the rival's action, is the focus of the paper.

The main result is that simultaneous move configurations, where both players always move in the same period, regardless of type, can never be Perfect Bayesian Equilibria (PBEs) of this timing game. In contrast, sequential move configurations, where one player always moves in the first period, regardless of type, while the other always moves in the second period, regardless of type, can always be supported as PBEs. Furthermore, there may be equilibria where some types of both players are in period 1 and others in period 2. An example of such an equilibrium is presented in Section 4.

One natural application is to the well known Stackelberg leadership model. Consider for example two firms who know their own unit cost, but not that of their rival. The results from the general model show that leadership is a PBE of a model where the firms not only choose how much to produce, but also when to produce it. However, the (Bayesian) Cournot-Nash solution, in which the two firms simultaneously choose outputs, cannot be supported as an equilibrium of the more general timimg game. Recently, a number of studies have analysed endogenous timing in various versions of the Stackelberg model. For instance, Mailath (1988) lets a duopolist receive a private signal about a random demand parameter, that is, a parameter of common value to the two firms. This firm can then decide whether to play Nash or to be a Stackelberg leader. Mailath finds that the only equilbrium (after invoking an equilibrium refinement) has the informed firm moving first, no matter what the observed signal is. In Albæk (1990) I ask whether private cost information can lead to an endogenous explanation of the distribution of Stackelberg roles. However, in that paper the firms decide before they know their own cost whether they will play Stackelberg or Nash, and who shall be leader and follower. The answer is that in some cases the firms can indeed agree on such an endogenous distribution of roles.

Another strand of literature has analysed endogenous timing in Stackelberg models in full information environments. Hamilton and Slutsky (1990) extend the work of Dowrick (1986) to show that in a complete information model close to the model of this paper the two Stackelberg equilibria (that is, either firm can be the leader) are the only two pure strategy equilibria if attention is restricted to undominated strategies (Theorem VIII). Hence, their result confirms that the sequential move equilibrium tends to perform better than (simultaneous) Nash if games are extended to model the timing decision endogenously. A similar conclusion is reached by Robson (1990), who analyses a price-setting duopoly in which the firms can choose and commit to a price at any of a countable set of dates before the fixed market-clearing date. However, the cost of setting a price is increasing in the difference between the price-setting and the market-clearing dates. Robson's analysis shows that "the only subgame perfect equilibria are more reminiscent of Stackelberg than of Bertrand". Simon (1987) is the only paper modelling the timing decision in continuous time. The general conclusion carries over to this setting, since he finds that in a Stackelberg/Cournot model in continuous time the two firms will never choose output simultaneously.[1]

Saloner (1987) analyses a complete information Cournot model in which the firms can produce in both periods while the market clears after the second period. He shows that there is a large set of subgame perfect Nash equilibria, basically consisting of the points on the outer envelope of the reaction functions between the two[2] Stackelberg points. Banerjee and Cooper (1991) show that introducing a small fixed cost for producing in both periods in Saloner's model eliminates all equilibria except the Cournot equilibrium in the first period and the two Stackelberg equilibria. However, a simple form of asymmetric information about costs also eliminates the Cournot equilibrium.

In the next section the model is presented, while Section 3 contains the main results. In Section 4 I concentrate on the Stackelberg version of the model and give an example of an equilibrium where the firms sometimes are in period 1 and sometimes in period 2. In the final section I offer some concluding remarks.

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[1]In fact, Simon only uses the Stackelberg/Cournot model as an example of a more general theory of timing decisions in continuous time.

[2]Assuming for simplicity that each firm has only one Stackelberg point.

2 The Model

The players face two decisions: what action to take, and when to take it. If a player acts in period one, she cannot act in period 2, and vice versa. A player acting in period two can, before making her decision, observe the choice of a player acting in period one. However, if both players act in the same period, neither of them observes the other's action before choosing her own. Payoffs are determined after period two, and there is no discounting between the two periods. The presentation which follows at times relies heavily on the construction in Okuno-Fujiwara, Postlewaite and Suzumura (1990). The two players are denoted A and B. Each player has private information summarized by her type t_i, an element of $T_i = \{t_i^1, \ldots, t_i^{l_i}\}$, $|\ T_i\ | \geq 2$, i = A, B. To keep the analysis simple, T_i is assumed to be finite with elements ordered so that $t_i^1 < t_i^2 < \cdots < t_i^{l_i}$. Before period 1 each player learns her own type t_i. She does not know the other player's type; however, she does know the prior distribution p_j over T_j from which the other player's type was drawn. The distributions p_a and p_b are assumed independent and common knowledge.

If nobody acts in period 1 the players have to form beliefs about which type of the other player they are facing in period 2. Let Q_i be the set of all probability distributions on T_i. Then a period 2 belief about player i's type is an element $q_i \in Q_i$. Hence $q_i(t_i)$ is the probability which player j in the second period places on player i being of type t_i.

The set of possible actions of player i is denoted S_i. Player i therefore has to choose an element $s_i \in S_i$. For both players I assume that S_i is a closed interval $[0, \bar{s}_i]$ of the real line. Player i's payoff function is $\pi_i : S_i \times S_j \times T_i \rightarrow R$.

Note that only player j's action, but not her type, influences the payoff of player i.[3] Furthermore, the timing of actions is not per se important; in particular, there is no discounting between the two periods.

A strategy of player i is a quadruple of functions, $\sigma_i = (\theta_i, \sigma_i^1, \sigma_i^{2n}, \sigma_i^{2f})$ where $\theta_i : T_i \rightarrow [0,1]$ gives the probability that player i of a certain type t_i will act in the first period while $\sigma_i^1 : T_i \rightarrow S_i$ is the action as a function of type that she will take if she acts in the first period. If she instead decides to act in period 2, there are two possibilities: $\sigma_i^{2n} : T_i \rightarrow S_i$ is, again as a function of type, the action that she will take in period 2 if player j also acts in period 2 (n is for "Nash"); finally, $\sigma_i^{2f} : S_j \times T_i \rightarrow S_i$ gives, as a function of player j's (period 1) action and player i's type, the action that i will take in the second period when j has acted in the first period (f for "follower").

Given a strategy profile (σ_a, σ_b) the expected payoff to player A of type t_a is then

$$\begin{aligned}
P_a(\sigma_a, \sigma_b, t_a) &= \sum_{T_b} \theta_a(t_a) p_b(t_b) \theta_b(t_b) \pi_a(\sigma_a^1(t_a), \sigma_b^1(t_b), t_a) \\
&+ \sum_{T_b} \theta_a(t_a) p_b(t_b)[1 - \theta_b(t_b)] \pi_a(\sigma_a^1(t_a), \sigma_b^{2f}(\sigma_a^1(t_a), t_b), t_a) \\
&+ \sum_{T_b} [1 - \theta_a(t_a)] p_b(t_b) \theta_b(t_b) \pi_a(\sigma_a^{2f}(\sigma_b^1(t_b), t_a), \sigma_b^1(t_b), t_a) \\
&+ \sum_{T_b} [1 - \theta_a(t_a)] p_b(t_b)[1 - \theta_b(t_b)] \pi_a(\sigma_a^{2n}(t_a), \sigma_b^{2n}(t_b), t_a)
\end{aligned}$$

The second period "Nash" strategies σ_a^{2n} and σ_b^{2n} will depend on the second period beliefs q_a and q_b. It is convenient to consider in general simultaneous choice equilibria (σ_a^n, σ_b^n) depending on beliefs q_a and q_b. Hence,

[3] Letting player i's payoff depend directly on player j's type would change the set-up into a signalling game.

(σ_a^n, σ_b^n) constitute a simultaneous choice equilibrium if for all $t_i \in T_i$ and for all $s_i \in S_i$

$$\sum_{T_j} q_j(t_j)\pi_i(\sigma_i^n(t_i), \sigma_j^n(t_j), t_i) \geq \sum_{T_j} q_j(t_j)\pi_i(s_i, \sigma_j^n(t_j), t_i)$$

I shall assume that, given any beliefs q_a and q_b, the simultaneous choice equilibrium is unique, so that the simultaneous choice equilibrium strategy $\sigma_i^n(q_i, q_j, t_i)$, is uniquely defined.[4]

A period 2 belief $q_i \in Q_i$ is said to be consistent if

$$q_i(t_i) = \frac{[1-\theta_i(t_i)]p_i(t_i)}{\sum_{T_i}[1-\theta_i(t_i)]p_i(t_i)} \text{ if } \sum_{T_i}[1-\theta_i(t_i)] > 0$$

Acting in period 2 is a zero probability event if $\theta_i(t_i) = 1$ for all $t_i \in T_i$. In that case Bayesian updating puts no restrictions on beliefs, and any $q_i \in Q_i$ is consistent.

A Perfect Bayesian Equilibrium is a quadruple $(\sigma_a, \sigma_b, q_a, q_b)$ for which

(i) $P_i(\sigma_i, \sigma_j, t_i) \geq P_i(\sigma_i', \sigma_j, t_i)$ for all t_i and σ_i'

(ii) $\sigma_i^{2f}(s_j, t_i) \in \text{argmax}_{s_i \in S_i} \pi_i(s_i, s_j, t_i)$

(iii) q_i and q_j are consistent, and

$$\sigma_i^{2n}(t_i) = \sigma_i^n(q_i, q_j, t_i)$$

The first condition states that the strategy profile has to be a Nash equilibrium. Condition (ii) ensures that a follower will always act optimally in the second period; hence, incredible threats are eliminated. The third condition says that the strategies in a second period Nash-like situation can be rationalized by some beliefs q_i and q_j over which types of the other player would wait

[4]See Okuno-Fujiwara et al. (1990) for a discussion of this assumption.

and act in the second period. Of course, given a particular strategy profile, one or both of the conditions (ii) and (iii) may be implied by (i). However, for some strategy profiles certain events may happen with zero probability. In those situations conditions (ii) and (iii) guarantee that responses to out-of-equilibrium behaviour are rational. Note that no belief system about a leader's type is specified in condition (ii). A follower cares only about the action choice of the leader. The opponent's type matters only to a player in so far as it indicates something about the action that the opponent will take. When the leader has already chosen her action the follower simply maximizes payoffs taking the leader's action as given. In this situation the leader's type is of no interest to the follower.

The reader may well find the following assumptions about the payoff functions quite restrictive. However, the results are later shown to hold under a wide set of alternative assumptions. For the moment, the following must hold for all $(s_i, s_j) \in (S_i, S_j)$ and for all $t_i \in T_i$, i = A, B,

Assumption 1. π_i is strictly concave and twice continuously differentiable in s_i, and decreasing and continuously differentiable in s_j.

Assumption 2. $\frac{\partial}{\partial s_i}\pi_i(s_i, s_j, t_i)$ is decreasing and continuously differentiable in s_j.

Assumption 3. $\frac{\partial}{\partial s_i}\pi_i(s_i, s_j, t_i)$ is increasing in t_i.

Assumption 4. For all $q_i \in Q_i$, $q_j \in Q_j$ and $t_i \in T_i$, $\sigma_i^n(q_i, q_j, t_j) \in (0, \bar{s}_i)$

The first assumption is fairly self-explanatory, while the second asserts that the actions of the two players are strategic substitutes (Bulow, Geanakoplos and Klemperer, 1985). If player j increases s_j, player i will respond by lowering s_i in order to meet the first order condition for maximizing her payoff. In other words, the best response functions are downward sloping. Assumption 3 is by Okuno-Fujiwara et al. (1990) called "positive-monotonicity of best response functions". The higher a player's type, the more aggressive her behaviour will be, since the best response function shifts out. Hence, the lowest type is also the "weakest" type from the opponent's point of view. The final assumption restricts simultaneous choice equilibria to be interior.

3 Results

In this section the main results from the analysis are presented. As stated in the introduction the aim is to describe what can be Perfect Bayesian Equilibria of the timing game set up in the previous section. However, in the first two propositions I shall state what can not be equilibria.

Proposition 1 *Under Assumptions 1 - 4 there is no Perfect Bayesian Equilibrium in which* $\theta_a(t_a) = 1$ *for all* $t_a \in T_a$ *and* $\theta_b(t_b) = 1$ *for all* $t_b \in T_b$.

Proof: See Appendix. ||

The intuition behind this result is as follows. It is easy to see that, under Assumptions 1, 3, and 4, each type of a player must be choosing different actions. Then the other player, say B, will in general not be choosing her exact best response to A's action, but rather an average best response. By deviating to period 2 B will observe A's period 1 action, and, therefore, be able to respond optimally. Hence, both players always[5] acting in period 1 cannot be an equilibrium.

Remark. Often a stronger statement than Proposition 1 can be made, namely that there is no PBE in which $\theta_i(t_i) = 1$ for all $t_i \in T_i$ and $\theta_j(t_j) > 0$ for some $t_j \in T_j$, $i \neq j$. Imagine that one player (say A) always acts in period 1. When would a type of player B be willing also to act in period 1 with positive probability? The answer is: only if all types of A choose the same action. If two types of A choose different actions, B will only be choosing an average best response but would by moving in period 2 observe A's action and be able to play the best response to each of A's actions. That all types of A would choose the same actions cannot in general be ruled out; however, it seems rather unlikely. In the Appendix I discuss this possibility further and give a sufficient condition that it cannot happen.

The proposition says that equilibria in which both types always act in period 1 are not possible. The next proposition rules out such situations in period 2 as well.

Proposition 2 *Under Assumptions 1 - 4 there is no Perfect Bayesian Equilibrium in which $\theta_i(t_i) = 0$ for all $t_i \in T_i$ and $\theta_j(t_j) < 1$ for some $t_j \in T_j$, $i \neq j$.*

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[5]In this context "always" means "with probability one for all $t_i \in T_i$".

Proof: See Appendix. ||

Again the intuition is quite straightforward. Imagine now that player B always moves in period 2. It is easy to show that under Assumptions 1 - 4 the game exhibits a "first mover advantage" in the following sense. Imagine that only one type of player A waits until the second period. Then that type would prefer moving in the first period to the period 2 equilibrium. It would then choose a larger action which has no first order effects on its payoff (due to the envelope theorem) while it would lead the follower to be less aggressive. Hence, there can be no PBE in which only one type of player A moves in the second period. Now, if a subset (with more than one type) of T_a moves in period 2 with a positive probability, B will, using Bayes' rule, form a belief about who she is playing against. Denote by t_a^M the highest type of A playing in period 2. It can then be shown that t_a^M would prefer a period 2 equilibrium in which player B knew for sure that A was of the type t_a^M to the equilibrium when B only knows that t_a^M is the highest of several types. However, because of the first mover advantage, it is then clear that t_a^M will always deviate from the supposed equilibrium to the first period. This argument breaks any possible equilibrium with $\theta_a(t_a) < 1$ for some $t_a \in T_a$.

Two possible types of equilibrium remain. One can be thought of as a leader-follower situation where one player always moves in period 1 while the other always moves in period 2. The other possibility entails both players using strategies where they move in period 1 for some types and in period two for other types. The next proposition states that leader-follower situations can always be supported as PBEs.

Proposition 3 *Under Assumptions 1 - 4 there always exist Perfect Bayesian Equilibria in which $\theta_i(t_i) = 1$ for all $t_i \in T_i$ and $\theta_j(t_j) = 0$ for all $t_j \in T_j$, $i \neq j$.*

Proof. See Appendix. ||

Clearly the player who in equilibrium is supposed always to move in period 2 (say, player B) will never deviate, since the other player's (A's) action choice is not changed by this deviation; hence, deviating to period 1 for B simply means an unprofitable loss of information. I then concentrate on the belief used by B if she unexpectedly finds herself called upon to play a period 2 game instead of being a "follower". If I can find a belief which keeps all A types from deviating, I have proved the proposition. Now, for an A type considering a deviation the worst B can think is that A for sure is the lowest (which is also the "weakest") type t_a^1, since B then will behave aggressively and choose a high s_b. Because of the first mover advantage, type t_a^1 will not deviate if B holds this belief. Neither will any other type, since she will not only loose the first mover advantage, but also mistakenly be taken for a lower type in the period 2 game. Hence, I have found a belief which supports the sequential choice equilibrium path described in the appendix. Since I am free to choose B's period 2 belief, the proposition is indeed proved. Note that the proposition says nothing about which player will be in period 1; both "leader-follower" configurations can be sustained as equilibria. Furthermore, the proposition only describes the equilibrium path, not the equilibrium itself, since the associated beliefs are not specified. In fact, each of the two outcomes can be supported by any belief belonging to a connected set[6] in the space of possible beliefs, Q_a or Q_b, whichever is relevant.

Assumptions 1 - 4 are admittedly quite restrictive and rule out several well known industrial organization models. If, for instance, types are unit costs of production, and a higher type is a firm with a higher unit cost, neither standard Cournot nor Bertrand (with differentiated products) models meet all four assumptions. The Cournot model fails Assumption 3; the Bertrand model meets Assumption 3, but not Assumptions 1 and 2. I therefore consider a set of alternative assumptions and show that the propositions still hold.

Assumption 1'. π_i is strictly concave and twice continuously differentiable in s_i, and increasing and continously differentiable in s_j.

Assumption 2'. $\frac{\partial}{\partial s_i}\pi_i(s_i, s_j, t_i)$ is increasing and continuously differentiable in s_j.

Assumption 3'. $\frac{\partial}{\partial s_j}\pi_i(s_i, s_j, t_i)$ is decreasing in t_i.

According to Assumption 1' player i now sees player j as less aggressive if player j chooses a higher action, while Assumption 2' says that the actions of the two players are strategic complements. Finally, Assumption 3' is what Okuno-Fujiwara et al. (1990) call "negative-monotonicity of best re-

[6]See Kohlberg and Mertens (1986).

sponse functions". Note that, with incomplete information about the rival's unit cost, the standard Cournot duopoly model meets Assumptions 1, 2, 3' and 4, while the Bertrand duopoly model with differentiated products meets Assumptions 1', 2', 3 and 4. The following proposition can now be proved.

Proposition 4 *For any quadruple consisting of Assumptions 1 or 1', 2 or 2', 3 or 3', and 4, Propositions 1 - 3 will hold.*

To economize on space the proof of this proposition is omitted. However, the basic intuition is that changing one of the assumptions simply changes which type would for sure deviate in the proof of Proposition 2, and therefore also the specification of the out-of-equilibrium beliefs in Proposition 3. If I change only one of the assumptions, the lowest type A specified to stay in period 2 in the proof of Proposition 2 will always deviate to period 1; therefore the q_a in the proof of Proposition 3 should put all weight on the highest type. If I change yet another assumption, the incentives flip once more, and we are back to the highest type deviating.

As mentioned above, there may be more than the two sets of equilibria already found. Excluding the unlikely possibility discussed in the remark to Proposition 1, all additional equilibria would be characterized by some types of each player moving in the first period and others in the second, perhaps even with some types using mixed strategies to determine when to produce. In the next section I present an example of such an equilibrium.

4 A Simple Example

In this section I shall present a simple example based on an application to Stackelberg's leader-follower model. The derivations are quite elementary and therefore not be shown here; however, they can be found in Appendix 2 of Albæk (1991).

Consider a duopoly where the inverse demand function is linear in total output

$$p = d - (x_a + x_b)$$

where x_a and x_b are the outputs of the two firms A and B. The products of the two firms are assumed to be homogenous, and the slope has been normalized to unity. A firm's type is now its unit cost c_i, which can take on two values only. With probability 0.5, c_i = l, and with probability 0.5, c_i = h, i = A, B.

The analysis in the preceding section showed that there exist at least two equilibrium outcomes of this game. In one $\theta_a(l) = \theta_a(h) = 1$ while $\theta_b(l) = \theta_b(h) = 0$; in the other $\theta_a(l) = \theta_a(h) = 0$ and $\theta_b(l) = \theta_b(h) = 1$. The question is whether there are more equilibria.

Suppose both firms with probability 1 produce in period 1 if they have low marginal costs, and with probability 1 in period 2 if their marginal costs are high. Framed in the language of this paper, $\theta_i(l) = 1$ and $\theta_i(h) = 0$, i = A, B. I shall now show that this can be equilibrium behaviour for some parameter values, but not for others.

The expected profit to a low cost firm from this situation is

$$P(l) = \frac{3}{256}[3d + h - 4l]^2$$

while the expected profit to a high cost firm is

$$P(h) = \frac{1}{512}[5d - 9h + 4l]^2 + \frac{1}{18}[d - h]^2$$

By deviating to period 2, and making the optimal output choices, the low cost firm would alternatively have expected profits of

$$P'(l) = \frac{1}{72}[2d + h - 3l]^2 + \frac{1}{512}[5d - h - 4l]^2$$

Similarly, the maximal expected profits to a high cost firm from deviating to period 1 is

$$P'(h) = \frac{1}{768}[9d - 13h + 4l]^2$$

Suppose the parameters have the specific values d = 120, l = 10, and h = 20. Then P(l) = 1355, P(h) = 969, P'(l) = 1304, and P'(h) = 963. Since P(l) $\geq$ P'(l) and P(h) $\geq$ P'(h), the strategies form an equilibrium.[7] It is obvious that the low cost leader will not want to deviate. Since the cost difference is big, there is a large benefit to the high cost follower of knowing exactly which type it is playing against, and it will forego the first mover advantage to get this information. Hence, this example shows that there can be equilibria of other types than the ones discussed in the previous section. Furthermore,

[7] That is, the timing functions $\theta_i(c_i)$ given above, and the associated quantity functions $x_i^1(c_i)$, $x_i^{2n}(c_i)$ and $x_i^{2f}(c_i)$, which are not shown here, form an equilibrium.

the equilibrium is one in pure strategies, since for both firms $\theta_i(c_i)$ is either 0 or 1 for both types.

Now, change the value of h to 12. Then P(l) = 1292, P(h) = 1201, P'(l) = 1271, P'(h) = 1210. In this case the high cost firm will deviate to period 1, and the situation is not an equilibrium. Since the high and low cost firms are so similar, the value to the high cost firm of knowing which type it is playing against is small, while it will gain substantially if it ends up being a leader to a high cost follower. It is easy to show that with these cost values (l = 10 and h = 12) there are no other pure strategy equilibrium outcomes than the two Stackelberg situations. Hence, any other equilibrium would have to involve at least one type of one of the firms mixing over its timing decision.

5 Conclusion

This paper has analysed a game of imperfect information in which the players not only decide what to do, but also when to do it. Comparing the equilibria of this model to those of a game where the players are restricted to act simultaneously, one finds that the equilibrium strategies are never the same.

This result underlines the problems of concentrating on simultaneous-choice models in a world where economic agents often can choose when to act from a large set of possible times. Modelling this explicitly may prove very difficult. However, this paper has shown that using a simple two-period model can give drastically different results than the one-period simultaneous-choice model.

Appendix

In this appendix I make extensive use of the method used in the proof of Theorem 2 in Okuno-Fujiwara et al. (1990).

Before proving Proposition 1 it is convenient to introduce some extra notation. Consider a simultaneous choice situation with beliefs q_i and q_j. Let player j be using the strategy σ_j^n. Define player i's simultaneous choice best response by

$$\phi_i^n(\sigma_j^n, q_j, t_i) = \underset{s_i \in S_i}{\operatorname{argmax}} \sum_{T_j} q_j(t_j)\pi_i(s_i, \sigma_j^n(t_j), t_i)$$

Lemma 1 *Under Assumptions 1 and 3, i's simultaneous choice best response $\phi_i^n(\sigma_j^n, q_j, t_i)$ is increasing in t_i if its value lies in the interior of $S_i = [0, \bar{s}_i]$.*

Proof. If $\phi_i^n(\sigma_j^n, q_j, t_i)$ is interior, it is the s_i which secures that

$$\sum_{T_j} q_j(t_j)\frac{\partial}{\partial s_i}\pi_i(s_i, \sigma_j^n(t_j), t_i) = 0$$

By Assumptions 1 and 3 the lemma is obvious. $\|$

Proof of Proposition 1.

It is clear that if an equilibrium with $\theta_a(t_a) = 1$ for all $t_a \in T_a$ and $\theta_b(t_b) = 1$ for all $t_b \in T_b$ exists, we must have $\sigma_a^1(t_a) = \sigma_a^n(p_a, p_b, t_a)$ and $\sigma_b^1(t_b) = \sigma_b^n(p_b, p_a, t_b)$. From Lemma 1 and Assumption 4 we know that different types of a player always will choose different actions. Consider the timing choice of a type t_b. Acting in period 1 she chooses $\sigma_b^n(p_b, p_a, t_b) = \phi_b^n(\sigma_a^1, p_a, t_b) = \operatorname{argmax}_{s_b \in S_b} \sum_{T_a} p_a(t_a)\pi_b(s_b, \sigma_a^1(t_a), t_b)$. However, if t_b chooses to wait until the second period, she can react optimally to A's action, that is, choose $\phi_b^{2f}(s_a, t_b) = \text{argmax}_{s_b \in S_b} \pi_b(s_b, s_a, t_b)$. Since A chooses a different action for each t_a, and s_a has a (negative) impact on π_b, in general $\phi_b^{2f}(\sigma_a^1(t_a), t_b) \neq \phi_b^n(\sigma_a^1, p_a, t_b)$. Since the former is chosen optimally for each value of $\sigma_a^1(t_a)$, it must be true that $\sum_{T_a} p_a(t_a)\pi_b(\phi_b^{2f}(\sigma_a^1(t_a), t_b), \sigma_a^1(t_a), t_b) > \sum_{T_a} p_a(t_a)\pi_b(\phi_b^n(\sigma_a^1, p_a, t_b), \sigma_a^1(t_a), t_b)$. Hence, t_b will always deviate to period 2. ||

Remark to Proposition 1. In the remark I mention that a stronger result than Proposition 1 often can be shown to hold, namely that there is no PBE in which $\theta_i(t_i) = 1$ for all $t_i \in T_i$ and $\theta_j(t_j) > 0$ for some $t_j \in T_j$, $i \neq j$. To see when this is true suppose $\theta_a(t_a) = 1$ for all $t_a \in T_a$. Fix a player B strategy $\sigma_b = (\theta_b, \sigma_b^1, \sigma_b^{2n}, \sigma_b^{2f})$. A player A period 1 best response must then be

$$\begin{aligned}\phi_a^1(\sigma_b, t_a) \in \; & \underset{s_a \in S_a}{\text{argmax}} \sum_{T_b} p_b(t_b)\{\theta_b(t_b)\pi_a(s_a, \sigma_b^1(t_b), t_a) \\ & + [1 - \theta_b(t_b)]\pi_a(s_a, \sigma_b^{2f}(s_a, t_b), t_a)\}\end{aligned}$$

If $\phi_a^1(\sigma_b, t_a)$ is interior it is an s_a which secures that

$$\begin{aligned}\textstyle\sum_{T_b} p_b(t_b)\{\theta_b(t_b)\frac{\partial}{\partial s_a}\pi_a(s_a, \sigma_b^1(t_b), t_a) + [1 - \theta_b(t_b)]\frac{\partial}{\partial s_a}\pi_a(s_a, \sigma_b^{2f}(s_a, t_b), t_a) \\ + [1 - \theta_b(t_b)]\frac{\partial}{\partial s_a}\sigma_b^{2f}(s_a, t_b)\frac{\partial}{\partial s_b}\pi_a(s_a, \sigma_b^{2f}(s_a, t_b), t_a)\} = 0\end{aligned}$$

From the argument in the proof of Proposition 1 it is clear that a type t_b will only be willing to act in period 1 if A chooses the same action for all $t_a \in T_a$. If not, t_b would gain by deviating to period 2. Hence there has to exist an action $\tilde{s}_a$ which makes the first order condition above hold for all $t_a \in T_a$. While the present assumptions on the payoff functions do not rule this possibility out, it does seem rather unlikely. Note that the two first terms by Assumption 3 are increasing in t_a. Hence, only if the third term for all t_a exactly offsets the effect of the rise in the two first terms can a single $\tilde{s}_a$ be optimal for all $t_a \in T_a$. For this to be the case $\frac{\partial}{\partial s_b}\pi_a(s_a, \sigma_b^{2f}(s_a, t_b), t_a)$ must be increasing in t_a since $\frac{\partial}{\partial s_a}\sigma_b^{2f}(s_a, t_b)$ is negative (and independent of t_a). Therefore, a sufficient condition for the stronger statement to hold is that $\frac{\partial}{\partial s_j}\pi_i(s_i, \sigma_j^{2f}(s_i, t_j), t_i)$ is not (monotonically) increasing in t_i, and that not all t_i has a period 1 best response at the same endpoint of $[0, \bar{s}_i]$. It is easy to check that in the simple Cournot model with linear demand and incomplete information about the rival's unit cost, $\frac{\partial}{\partial s_j}\pi_i(s_i, \sigma_j^{2f}(s_i, t_j), t_i)$ is independent of t_i. Hence, the stronger statement is true for this model as long as $[0, \bar{s}_i]$ is sufficiently large.

Also in proving Proposition 2 some preliminaries are useful. Define first the degenerate belief $q_i^k \in Q_i$ associated with $t_i^k \in T_i$ as

$$q_i^k(t_i) = \begin{cases} 1 & \text{if } t_i = t_i^k \\ 0 & \text{otherwise} \end{cases}$$

Hence, the degenerate belief q_i^k indicates that player j with probability 1 believes that player i is of the type t_i^k. Now, suppose $\theta_b(t_b) = 0$ for all $t_b \in T_b$. Consider any candidate PBE in which $\theta_a(t_a) < 1$ for some $t_a \in T_a$. Player B's consistent period 2 belief q_a is then formed by Bayes' rule as described in Section 2. Denote by t_a^M the maximum t_a for which $\theta_a(t_a) < 1$, and by

q_a^M the degenerate belief associated with t_a^M. For a given player i period 2 strategy σ_i^{2n} and belief q_i, player j's period 2 best response $\phi_j^{2n}(\sigma_i^{2n}, q_i, t_j)$ is found as

$$\phi_j^{2n}(\sigma_i^{2n}, q_i, t_j) = \underset{s_j \in S_j}{\operatorname{argmax}} \sum_{T_i} q_i(t_i)\pi_j(s_j, \sigma_i^{2n}(t_i), t_j)$$

Note that by Lemma 1 we know that $\phi_j^{2n}(\sigma_i^{2n}, q_i, t_j)$ is increasing in t_j if its value lies in the interior of $S_j = [0, \bar{s}_j]$.

Lemma 2 *Under Assumptions 1 - 4, for any non-degenerate $q_a \in Q_a$, if $(\sigma_a^{2n}, \sigma_b^{2n})$ is the equilibrium of the period 2 simultaneous choice game with the beliefs (q_a, p_b) and q_a^M is the degenerate belief associated with the highest t_a in the support of q_a, then for any $t_b \in T_b$,*

$$\phi_b^{2n}(\sigma_a^{2n}, q_a^M, t_b) < \phi_b^{2n}(\sigma_a^{2n}, q_a, t_b)$$

Proof. By Lemma 1 σ_a^{2n} is increasing in t_a. Since $\partial\pi_b/\partial s_b$ is decreasing in s_a the lemma must be true. ||

Lemma 3 *Let q_a be non-degenerate and q_a^M the degenerate belief associated with t_a^M, the highest element in the support of q_a. If $(\sigma_a^{2n*}, \sigma_b^{2n*})$ and $(\sigma_a^{2nM}, \sigma_b^{2nM})$ are the period 2 equilibria associated with (q_a, p_b) and (q_a^M, p_b), respectively, then*

(a) $$\sigma_a^{2n*}(t_a^M) < \sigma_a^{2nM}(t_a^M)$$

(b) $\sum_{T_b} p_b(t_b)\pi_a(\sigma_a^{2n*}(t_a^M), \sigma_b^{2n*}(t_b), t_a^M) < \sum_{T_b} p_b(t_b)\pi_a(\sigma_a^{2nM}(t_a^M), \sigma_b^{2nM}(t_b), t_a^M)$

Proof. Proof of (a): Since q_a^M is degenerate, for any σ_a^{2n}, $\phi_b^{2n}(\sigma_a^{2n}, q_a^M, t_b) = \phi_b^{2f}(\sigma_a^{2n}(t_a^M), t_b)$. Hence, by the uniqueness of the period 2 equilibrium, $\sigma_a^{2nM}(t_a^M)$ is the unique fixed point of the composite mapping

$$\psi_a(s_a) = \phi_a^{2n}(\phi_b^{2f}(s_a, t_b), p_b, t_a^M)$$

By Lemma 2

$$\begin{aligned} \sigma_a^{2n*}(t_a^M) &= \phi_a^{2n}(\sigma_b^{2n*}, p_b, t_a^M) \\ &< \phi_a^{2n}(\phi_b^{2f}(\sigma_a^{2n*}(t_a^M), t_b), p_b, t_a^M) \\ &= \psi_a(\sigma_a^{2n*}(t_a^M)) \end{aligned}$$

By the uniqueness of the fixed point, the first part of the lemma must be true.

Proof of (b): From (a) and Assumption 3, for all $t_b \in T_b$,

$$\phi_b^{2n}(\sigma_a^{2n*}, q_a, t_b) > \phi_b^{2f}(\sigma_a^{2nM}(t_a^M), t_b)$$

By Assumption 1 the second part of the lemma must hold. ||

Lemma 4 *Let $q_a^k \in Q_a$ be the degenerate belief associated with $t_a^k \in T_a$, and let $(\sigma_a^{2nk}, \sigma_b^{2nk})$ be the period 2 equilibrium associated with (q_a^k, p_b). Then, under Assumptions 1 - 4, for all $t_a^k \in T_a$,*

$$\sum_{T_b} p_b(t_b)\pi_a(\sigma_a^{2nk}(t_a^k), \sigma_b^{2nk}(t_b), t_a^k) < \max_{s_a \in S_a} \sum_{T_b} p_b(t_b)\pi_a(s_a, \phi_b^{2f}(s_a, t_b), t_a^k)$$

Proof. Note first that the right hand side of the inequality is the best expected payoff to t_a^k if she deviates to the first period. Clearly, $\sigma_b^{2nk}(t_b) =$

$\phi_b^{2f}(\sigma_a^{2nk}(t_a^k), t_b) \equiv s_b^k(t_b)$. Hence, $\sigma_a^{2nk}(t_a^k)$ is implicitly defined by

$$\sum_{T_b} p_b(t_b) \frac{\partial}{\partial s_a} \pi_a(s_a, s_b^k(t_b), t_a^k) = 0$$

Moving in the first period t_a^k could ensure herself the same expected payoff as in the period 2 equilibrium by choosing the same action $\sigma_a^{2nk}(t_a^k)$. However, this is not optimal as

$$\begin{aligned} &\textstyle\sum_{T_b} p_b(t_b) \frac{\partial}{\partial s_a} \pi_a(\sigma_a^{2nk}(t_a^k), s_b^k(t_b), t_a^k) \\ &+ \textstyle\sum_{T_b} p_b(t_b) \frac{\partial}{\partial s_a} \phi_b^{2f}(\sigma_a^{2nk}(t_a^k), t_b) \frac{\partial}{\partial s_b} \pi_a(\sigma_a^{2nk}(t_a^k), s_b^k(t_b), t_a) > 0 \end{aligned}$$

since the first expression is zero and the second strictly positive under Assumptions 1 and 2. Hence, by moving to the first period and choosing a slightly larger action t_a^k could increase her payoff. The lemma, therefore, must be true. ||

Proof of Proposition 2.

Lemma 4 shows that there can never be an equilibrium with $\theta_b(t_b) = 0$ for all $t_b \in T_b$ and $\theta_a(t_a) < 1$ for a single $t_a \in T_a$ only. So suppose $\theta_a(t_a) < 1$ for more than one t_a. Then Lemmas 3 and 4 together show that the highest of these types would prefer deviating to the first period to staying in the second period. This proves the proposition. ||

Lemma 5 *Let $(\sigma_a^{2nh}, \sigma_b^{2nh})$ and $(\sigma_a^{2nm}, \sigma_b^{2nm})$ be the period 2 equilibria associated with (q_a^h, p_b) and (q_a^m, p_b), respectively, where $q_a^h \neq q_a^m$ are degenerate* *and $t_a^h < t_a^m$. Then, under Assumptions 1 - 4,*

$$\max_{s_a \in S_a} \sum_{T_b} p_b(t_b)\pi_a(s_a, \sigma_b^{2nh}(t_b), t_a^m) < \sum_{T_b} p_b(t_b)\pi_a(\sigma_a^{2nm}(t_a^m), \sigma_b^{2nm}(t_b), t_a^m)$$

Proof. By an argument similar to the proof of Lemma 3 (a), $\sigma_b^{2nh}(t_b) > \sigma_b^{2nm}(t_b)$ for all $t_b \in T_b$; hence, by Assumption 1, the lemma must be true.||

Proof of Proposition 3.

Let $\theta_a(t_a) = 1$ for all $t_a \in T_a$ and $\theta_b(t_b) = 0$ for all $t_b \in T_b$. Furthermore, let B's period 2 belief be the degenerate belief q_a^1, and let the strategies σ_a^1 and σ_b^{2n} be chosen optimally according to these probabilities. Clearly, no B type will ever deviate to period 1; this is simply the reverse of Proposition 1. By Lemma 4 the lowest A type, t_a^1, will not deviate to the second period. Neither will any other type, by combining Lemmas 4 and 5. ||

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