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Existence of equilibria in discontinuous Bayesian games ☆

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Abstract

We provide easily-verifiable sufficient conditions on the primitives of a Bayesian game to guarantee the existence of a behavioral-strategy Bayes–Nash equilibrium. We allow players' payoff functions to be discontinuous in actions, and illustrate the usefulness of our results via an example of an all-pay auction with general tie-breaking rules which cannot be handled by extant results.

JEL classification: C62; C72; D82

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1. Introduction

Bayesian games, where each player observes his own private information and then all players choose actions simultaneously, have been extensively studied and found wide applications in many fields of economics. The notion of Bayesian equilibrium is a fundamental game-theoretic concept for analyzing such games. In many applied works, Bayesian games with discontinuous payoffs arise naturally. For example, in auctions or price competitions, players' payoffs may not

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be continuous when a tie occurs. However, many previous works focus on the case of continuous payoffs,[1] while little is known about equilibrium existence results in Bayesian games with payoff discontinuities.

In a complete information environment, Reny (1999) showed that a better-reply secure game possesses a pure-strategy Nash equilibrium, and proposed the payoff security condition which is sufficient for a game to be better-reply secure together with some other conditions.[2] Recently, several authors have generalized the work of Reny (1999) to an incomplete information setting. Specifically, Carbonell-Nicolau and McLean (2015) extended the "uniform payoff security" condition of Monteiro and Page (2007) and the "uniform diagonal security" condition of Prokopovych and Yannelis (2014) to the setting of Bayesian games, and showed the existence of behavioral/distributional-strategy equilibria. He and Yannelis (2015a) proposed the "finite payoff security" condition and proved the existence of pure-strategy equilibria.

The purpose of this paper is to provide a new equilibrium existence result for Bayesian games with discontinuous payoffs. Our result is based on a Bayesian generalization of the clever condition called "disjoint payoff matching", which was introduced by Allison and Lepore (2014) for a normal form game. The advantage of this condition is that one only needs to check the payoff at each strategy profile itself. The standard payoff security-type condition forces one to check the payoffs in the neighborhood of each strategy profile, which is more demanding. Thus, our condition is relatively straightforward, and the equilibrium existence result can be easily verified for a large class of Bayesian games. Our result widens the applications in economics as we can cover situations that previous results in the literature are not readily applicable. As an illustrative example, we provide an application to an all-pay auction with general tie-breaking rules.

The rest of the paper is organized as follows. The model and our main results are presented in Section 2. Some preparatory results and the proof of the main theorem are collected in Section 3. An illustrative application to an all-pay auction with general tie-breaking rules is given in Section 4. Section 5 concludes the paper.

2. Model

2.1. Bayesian game and behavioral-strategy equilibrium

We consider a **Bayesian game** as follows:

$$G = \{u_i, X_i, (T_i, \mathcal{T}_i), \lambda\}_{i \in I}.$$

- There is **a finite set of players**, $I = \{1, 2, \ldots, n\}$.
- Player i's **action space** X_i is a nonempty compact metric space, which is endowed with the Borel σ-algebra $\mathcal{B}(X_i)$. Denote $X = \prod_{i \in I} X_i$ and $\mathcal{B}(X) = \otimes_{i \in I} \mathcal{B}(X_i)$; that is, $\mathcal{B}(X)$ is the product Borel σ-algebra.
- The measurable space $(T_i, \mathcal{T}_i)$ represents the **private information space** of player i. Let $T = \prod_{i \in I} T_i$ and $\mathcal{T} = \otimes_{i \in I} \mathcal{T}_i$.
- The **common prior** λ is a probability measure on the measurable space $(T, \mathcal{T})$.

[1] See, for example, Milgrom and Weber (1985) and Balder (1988).

[2] A number of recent papers have generalized the work of Reny (1999) in several directions; see Bagh and Jofre (2006), Carmona (2009), Bagh (2010), Carbonell-Nicolau and McLean (2013), Prokopovych (2013), Reny (2015), Carmona and Podczeck (2014, 2015), and He and Yannelis (2015b) among others.

- For every player $i \in I$, $u_i : X \times T \to \mathbb{R}_+$ is a $\mathcal{B}(X) \otimes \mathcal{T}$-measurable function representing the **payoff** of player i, which is bounded by some $\gamma > 0$.[3]

As usual, we write t_{-i} for an information profile of all players other than i, and T_{-i} as the space of all such information profiles. We adopt similar notation for action profiles, strategy profiles and payoff profiles.

For every player $i \in I$, a **pure strategy** is a $\mathcal{T}_i$-measurable function from T_i to X_i. Let $\mathcal{L}_i$ be **the set of all possible pure strategies** of player i, and $\mathcal{L} = \prod_{i\in I} \mathcal{L}_i$.

A **behavioral strategy** of player i is a $\mathcal{T}_i$-measurable function from T_i to $\triangle(X_i)$, where $\triangle(X_i)$ denotes the space of all Borel probability measures on X_i under the topology of weak convergence.[4] A pure strategy can be viewed as a special case of a behavioral strategy by considering it as a Dirac measure for every t_i. **The set of all behavioral strategies** of player i is denoted by $\mathcal{M}_i$, and $\mathcal{M} = \prod_{i\in I} \mathcal{M}_i$.

Given a behavioral strategy profile $f = (f_1, f_2, \dots, f_n) \in \mathcal{M}$, the **expected payoff** of player i is

$$U_i(f) = \int_T \int_{X_1} \dots \int_{X_n} u_i(x_1, \dots, x_n, t_1, \dots, t_n) f_n(\mathrm{d}x_n|t_n) \dots f_1(\mathrm{d}x_1|t_1)\lambda(\mathrm{d}t).$$

Definition 1. A **behavioral-strategy equilibrium** is a behavioral strategy profile $f^* = (f_1^*, f_2^*, \dots, f_n^*) \in \mathcal{M}$ such that f_i^* maximizes $U_i(f_i, f_{-i}^*)$ for any $f_i \in \mathcal{M}_i$ and each player $i \in I$.[5]

We impose the following assumption on the information structure. Let λ_i be the marginal probability of λ on $(T_i, \mathcal{T}_i)$ for each $i \in I$. Suppose that $(T, \mathcal{T}, \lambda)$ and $(T_i, \mathcal{T}_i, \lambda_i)$ are complete probability measure spaces.

Assumption *(Absolute Continuity (AC)).* The probability measure λ is absolutely continuous with respect to $\otimes_{i\in I}\lambda_i$ with the corresponding Radon–Nikodym derivative $\psi : T \to \mathbb{R}_+$.

This assumption is widely adopted in the setting of Bayesian games; see, for example, Milgrom and Weber (1985), Balder (1988), Jackson et al. (2002), Loeb and Sun (2006) and Carbonell-Nicolau and McLean (2015). Notice that the (AC) assumption is imposed in Milgrom and Weber (1985) and Balder (1988) even when the payoff function is continuous in the action variables. If players have independent priors in the sense that $\lambda = \otimes_{i\in I}\lambda_i$, then the (AC) assumption holds trivially.

3 Since u_i is bounded, we can assume that u_i takes values in $\mathbb{R}_+$ without loss of generality.

4 That is, a behavioral strategy f_i is a transition probability from $(T_i, \mathcal{T}_i)$ to $(X_i, \mathcal{B}(X_i))$ such that $f_i(\cdot|t_i)$ is a probability measure on $(X_i, \mathcal{B}(X_i))$ for all $t_i \in T_i$, and $f_i(B|\cdot)$ is a $\mathcal{T}_i$-measurable function for every $B \in \mathcal{B}(X_i)$. If λ_i is a probability measure on $(T_i, \mathcal{T}_i)$, then $\lambda_i \diamond f_i$ denotes a probability measure on $T_i \times X_i$ such that $\lambda_i \diamond f_i(A \times B) = \int_A f_i(B|t_i)\lambda_i(\mathrm{d}t_i)$ for any measurable subsets $A \subseteq T_i$ and $B \subseteq X_i$.

5 Milgrom and Weber (1985) considered distributional strategies and Balder (1988) extended their results to behavioral strategies. As remarked in Milgrom and Weber (1985), every behavioral strategy gives rise to a natural distributional strategy, and every distributional strategy corresponds to an equivalent class of behavioral strategies defined as the induced regular conditional probabilities. We consider behavioral strategies in this paper for simplicity, but all the results can be easily extended to distributional strategies.

2.2. Normal form game

Below, we convert a Bayesian game G to an (ex ante) normal form game G_0. If one can show the existence of a Nash equilibrium in the game G_0, then this equilibrium corresponds to a behavioral-strategy equilibrium in the original Bayesian game G.

A normal form game G_d is a collection $(X_i, u_i)_{i \in I}$, where X_i and u_i are the action space and payoff function of player i, respectively. We view a Bayesian game G as a normal norm game and denote it by $G_0 = (\mathcal{M}_i, U_i)_{i \in I}$, where $\mathcal{M}_i$ is the set of all possible behavioral strategies, and U_i is the expected payoff function of player i.

A **Nash equilibrium** in the game G_0 is a strategy profile $f^* = (f_1^*, f_2^*, \ldots, f_n^*) \in \mathcal{M}$ such that f_i^* maximizes $U_i(f_i, f_{-i}^*)$ for any $f_i \in \mathcal{M}_i$ and each player $i \in I$. Thus, if f^* is a Nash equilibrium in the game G_0, then it is also a behavioral-strategy equilibrium in the original Bayesian game G.

2.3. Main result

Reny (1999) proved that under some regularity conditions, a payoff secure game has a pure-strategy equilibrium.[6] To prove that the mixed extension of a normal form game is payoff secure, Allison and Lepore (2014) introduced the interesting notion of "disjoint payoff matching" in games with complete information. Below, we extend this notion to the setting of Bayesian games, and show that the ex ante game G_0 is payoff secure.

First, we describe the notion of "payoff security", which is due to Reny (1999).

Definition 2. In a normal form game G_d, player i can secure a payoff $\alpha \in \mathbb{R}$ at $(x_i, x_{-i}) \in X_i \times X_{-i}$ if there is some $\overline{x_i} \in X_i$ such that $u_i(\overline{x_i}, y_{-i}) \geq \alpha$ for all y_{-i} in some open neighborhood of x_{-i}.

The game G_d is called "payoff secure" if for every $i \in I$, $(x_i, x_{-i}) \in X_i \times X_{-i}$ and $\epsilon > 0$, player i can secure a payoff $u_i(x_i, x_{-i}) - \epsilon$ at (x_i, x_{-i}).

Consider the points at which a player's payoff function is discontinuous in other players' strategies. In particular, let $D_i \colon T_i \times X_i \to T_{-i} \times X_{-i}$ be defined by

$$D_i(t_i, x_i) = \{(t_{-i}, x_{-i}) \in T_{-i} \times X_{-i} : u_i(x_i, \cdot, t_i, t_{-i}) \text{ is discontinuous in } x_{-i}\}.$$

Suppose that D_i has a $\mathcal{B}(X) \otimes \mathcal{T}$-measurable graph for each $i \in I$. Given a pure strategy f_i of player i, denote $D_i^{f_i}(t_i) = D_i(t_i, f_i(t_i))$.

Remark 1. In many applications such as auctions and price competition, the discontinuity arises due to the action variables, and independently of the state variables. That is, the correspondence D_i does not depend on T in the sense that if $(t, x) \in \mathrm{Gr}(D_i)$, then $(t', x) \in \mathrm{Gr}(D_i)$ for any $t' \in T$. It is usually easy to check that D_i has a measurable graph in such cases.[7]

Definition 3. A Bayesian game G is said to satisfy the condition of "random disjoint payoff matching" if for any $f_i \in \mathcal{L}_i$, there exists a sequence of deviations $\{g_i^k\}_{k=1}^{\infty} \subseteq \mathcal{L}_i$ such that the following conditions hold:

[6] See Prokopovych (2011) for an alternative proof for metric games.
[7] If A is a correspondence from a space Y to Z, then $\mathrm{Gr}(A) \subseteq Y \times Z$ denotes the graph of A.

1. for λ-almost all $t = (t_i, t_{-i}) \in T$ and all $x_{-i} \in X_{-i}$,

$$\liminf_{k\to\infty} u_i(g_i^k(t_i), x_{-i}, t_i, t_{-i}) \geq u_i(f_i(t_i), x_{-i}, t_i, t_{-i});$$

2. $\limsup_{k\to\infty} D_i(t_i, g_i^k(t_i)) = \emptyset$ for any $i \in I$ and λ_i-almost all $t_i \in T_i$.[8]

When T_i is a singletons set for each player $i \in I$, the above definition reduces to be the notion of disjoint payoff matching introduced by Allison and Lepore (2014) in a complete information environment.

The following theorem is our main result, which shows that the random disjoint payoff matching condition of a Bayesian game G could guarantee the payoff security of the game G_0. Its proof is provided in Section 3.

Theorem 1. *Under Assumption (AC), if a Bayesian game G satisfies the random disjoint payoff matching condition, then the game G_0 is payoff secure.*

2.4. Existence of behavioral-strategy equilibria

Theorem 1 above shows that the random disjoint payoff matching condition of a Bayesian game G guarantees the payoff security of the ex ante game G_0. Reny (1999) showed that a payoff secure game has a pure-strategy Nash equilibrium provided that the game has compact action spaces, and each player's payoff function is quasiconcave in his own actions and satisfies some upper semicontinuity condition.

In the following theorem, we prove the existence of behavioral-strategy equilibria in Bayesian games based on Theorem 1.

Theorem 2. *Suppose that a Bayesian game G satisfies the random disjoint payoff matching condition and Assumption (AC). Furthermore, suppose that the mapping $\sum_{i\in I} u_i(\cdot, t)\colon X \to \mathbb{R}$ is upper semicontinuous for each $t \in T$. Then the game G_0 has a Nash equilibrium, which is a behavioral-strategy equilibrium for the Bayesian game G.*

Proof. By Theorem 1, the game G_0 is payoff secure. Then applying Lemma 3 in Carbonell-Nicolau and McLean (2015), the mapping

$$f \in \mathcal{M} \to \sum_{i\in I} U_i(f)$$

is upper semicontinuous. By Proposition 3.2 and Theorem 3.1 in Reny (1999), the game G_0 has a Nash equilibrium, which implies that G has a behavioral-strategy equilibrium. □

Remark 2. By extending the uniform payoff security condition of Monteiro and Page (2007) and adopting the (AC) assumption, Carbonell-Nicolau and McLean (2015) proved the existence of behavioral/distributional-strategy equilibria in Bayesian games with discontinuous payoffs. In particular, they showed that the ex ante game G_0 is payoff secure when the Bayesian game G satisfies their uniform payoff security condition. Our result does not cover the result of Carbonell-Nicolau and McLean (2015) and vice versa. Notice that our condition only needs

[8] For a sequence of sets $\{A_k\}$, $\limsup_{k\to\infty} A_k = \cap_{k=1}^{\infty} \cup_{j=k}^{\infty} A_j$ and $\liminf_{k\to\infty} A_k = \cup_{k=1}^{\infty} \cap_{j=k}^{\infty} A_j$.

to check the payoffs at each strategy profile itself, but not for those payoffs in the neighborhood of the strategy profile.

Remark 3. By adopting the "relative diffuseness" condition of He and Sun (2014) and the "uniform payoff security" condition of Carbonell-Nicolau and McLean (2015), He and Yannelis (2015a) presented a purification result for behavioral-strategy equilibrium in Bayesian games with discontinuous payoffs. It is straightforward to check that one can also obtain the existence of pure-strategy equilibria here via a similar purification result based on the "relative diffuseness" condition and Theorem 2.

3. Proof of Theorem 1

3.1. Preparatory results

The proof of Theorem 1 is based on a clever argument of Allison and Lepore (2014). However, our incomplete information framework introduces several subtle difficulties and necessitates new arguments that are far from trivial. Below, we present some technical results needed for the proof of Theorem 1.

We first consider the topology on the space $\mathcal{M}_i$ for each $i \in I$. Let $\mathcal{H}_i$ be the space of uniformly finite transition measures from $(T_i, \mathcal{T}_i, \lambda_i)$ to $(X_i, \mathcal{B}(X_i))$.

Definition 4. The weak topology on $\mathcal{H}_i$ is the weakest topology with respect to which the functional

$$\nu \to \int_{T_i} \int_{X_i} c(t_i, x_i)\nu(\mathrm{d}x_i|t_i)\lambda_i(\mathrm{d}t_i)$$

is continuous on $\mathcal{H}_i$ for every integrably bounded Carathéodory function c.[9]

The set $\mathcal{M}_i$ can be viewed as a subspace of $\mathcal{H}_i$ endowed with its relative topology. The Cartesian product $\mathcal{M} = \Pi_{i\in I}\mathcal{M}_i$ is endowed with the usual product topology.

The following lemma shows that each player i in the game G_0 has a nonempty, convex and weakly compact strategy space $\mathcal{M}_i$.

Lemma 1. *$\mathcal{M}_i$ is a nonempty, convex and weakly compact subset of the topological vector space $\mathcal{H}_i$.*

Proof. It is obvious that $\mathcal{M}_i$ is nonempty and convex. The weak compactness of $\mathcal{M}_i$ is from Theorem 2.3 of Balder (1988). □

Lemma 2. *If $\mathcal{M}_i$ is viewed as a subspace of $\mathcal{H}_i$ endowed with its relative topology, then the functional*

[9] The function c is said to be a Carathéodory function if $c(\cdot, x_i)$ is $\mathcal{T}_i$-measurable for each $x_i \in X_i$ and $c(t_i, \cdot)$ is continuous on X_i for each $t_i \in T_i$. In addition, c is called integrably bounded if there exists a λ_i-integrable function $\chi : T_i \to \mathbb{R}_+$ such that $|c(t_i, x_i)| \le \chi(t_i)$ for all $(t_i, x_i) \in T_i \times X_i$.

$$\nu \to \int_{T_i} \int_{X_i} c(t_i, x_i)\nu(\mathrm{d}x_i|t_i)\lambda_i(\mathrm{d}t_i)$$

is lower semicontinuous for every function $c\colon T_i \times X_i \to (-\infty, +\infty]$ *such that*

1. $c(t_i, \cdot)$ *is lower semicontinuous on* X_i *for every* $t_i \in T_i$*;*
2. c *is* $\mathcal{T}_i \otimes \mathcal{B}(X_i)$*-measurable;*
3. c *is integrably bounded from below in the sense that there exists some integrable function* $h\colon T_i \to \mathbb{R}$ *such that* $c(t_i, x_i) \geq h(t_i)$ *for all* $t_i \in T_i$ *and* $x_i \in X_i$*.*

Proof. Lemma 2 is from Theorem 2.2(a) in Balder (1988). □

For any nonempty subset $J \subseteq I$, let $\tilde{\mathcal{M}}_J$ be the space of transition probabilities from $(\prod_{j\in J} T_j, \otimes_{j\in J}\mathcal{T}_j, \otimes_{j\in J}\lambda_j)$ to $\prod_{j\in J} X_j$, and $\tilde{\mathcal{H}}_J$ the space of uniformly finite transition measures from $(\prod_{j\in J} T_j, \otimes_{j\in J}\mathcal{T}_j, \otimes_{j\in J}\lambda_j)$ to $\prod_{j\in J} X_j$. Suppose that $\tilde{\mathcal{H}}_J$ is endowed with the weak topology as defined in Definition 4, and $\tilde{\mathcal{M}}_J$ is viewed as a subset of $\tilde{\mathcal{H}}_J$ endowed with the relative topology.

Lemma 3. *The mapping* $(f_j)_{j\in J} \to \otimes_{j\in J} f_j$ *from* $\prod_{j\in J} \mathcal{M}_j$ *to* $\tilde{\mathcal{M}}_J$ *is continuous.*

Proof. Theorem 2.5 in Balder (1988) considers the case that J has two elements. It is obvious that his argument still holds for any finite set J. □

In the proof of our Theorem 1, we need to deal with some subtle measurability issues based on the projection theorem and Aumann's measurable selection theorem. These theorems are stated below for the convenience of the reader.

Projection Theorem: Let X be a Polish space and $(S, \mathcal{S}, \mu)$ a complete finite measure space. If a set E belongs to $\mathcal{S} \otimes \mathcal{B}(X)$, then the projection of E on S belongs to $\mathcal{S}$.

Aumann's measurable selection theorem: Let X be a Polish space and $(S, \mathcal{S}, \mu)$ a complete finite measure space. Suppose that F is a nonempty valued correspondence from S to X having an $\mathcal{S} \otimes \mathcal{B}(X)$-measurable graph. Then F admits a measurable selection; that is, there is a measurable function f from S to X such that $f(s) \in F(s)$ for μ-almost all $s \in S$.

3.2. Proof

We now proceed with the proof of Theorem 1.

Fix a behavioral strategy profile $(f_1, \dots, f_n) \in \mathcal{M}$, a player $i \in I$ and $\epsilon > 0$.

Let $S_i\colon T_i \to X_i$ be a correspondence defined by

$$S_i(t_i) = \{x_i \in X_i : \int_{T_{-i}} \int_{X_{-i}} u_i(x_i, x_{-i}, t_i, t_{-i})\psi(t_i, t_{-i}) f_{-i}(\mathrm{d}x_{-i}|t_{-i}) \otimes_{j\neq i} \lambda_i(\mathrm{d}t_{-i})$$
$$\geq \int_{T_{-i}} \int_{X} u_i(x_i, x_{-i}, t_i, t_{-i})\psi(t_i, t_{-i}) f(\mathrm{d}x|t_i, t_{-i}) \otimes_{j\neq i} \lambda_i(\mathrm{d}t_{-i})\}.$$

It is obvious that for each fixed t_i, $S_i(t_i)$ is nonempty. Since u_i is jointly measurable, and f and ψ are measurable, the correspondence S_i has a $\mathcal{B}(X_i) \otimes \mathcal{T}_i$-measurable graph. By the Aumann's measurable selection theorem, S_i has a $\mathcal{T}_i$-measurable selection f_i'. Therefore, we have that

$$\int_T \int_{X_{-i}} u_i(f_i'(t_i), x_{-i}, t_i, t_{-i}) f_{-i}(\mathrm{d}x_{-i}|t_{-i})\lambda(\mathrm{d}t) \geq \int_T \int_X u_i(x_i, x_{-i}, t_i, t_{-i}) f(\mathrm{d}x|t)\lambda(\mathrm{d}t).$$

By the random disjoint payoff matching condition, there exists a sequence of pure strategies $\{g_i^k\} \subseteq \mathcal{L}_i$ such that for λ-almost all $t = (t_i, t_{-i}) \in T$ and all $x_{-i} \in X_{-i}$,

$$\liminf_{k\to\infty} u_i(g_i^k(t_i), x_{-i}, t_i, t_{-i}) \geq u_i(f_i'(t_i), x_{-i}, t_i, t_{-i}),$$

and $\limsup_{k\to\infty} D_i(t_i, g_i^k(t_i)) = \emptyset$ for any $i \in I$ and λ_i-almost all $t_i \in T_i$.

Let

$$E_i^k(t_i) = \{(t_{-i}, x_{-i}) : u_i(g_i^k(t_i), x_{-i}, t_i, t_{-i}) > u_i(f_i'(t_i), x_{-i}, t_i, t_{-i}) - \epsilon\}.$$

Since the functions u_i, g_i^k and f_i' are all measurable, the correspondence E_i^k has a $\mathcal{B}(X_{-i}) \otimes \mathcal{T}$-measurable graph. For λ-almost all $t \in T$ and all $x_{-i} \in X_{-i}$, since

$$\liminf_{k\to\infty} u_i(g_i^k(t_i), x_{-i}, t_i, t_{-i}) \geq u_i(f_i'(t_i), x_{-i}, t_i, t_{-i}),$$

we have $(t, x_{-i}) \in \liminf_{k\to\infty} \mathrm{Gr}(E_i^k)$. As a result,

$$\lambda \diamond f_{-i}\left(\liminf_{k\to\infty} \mathrm{Gr}(E_i^k)\right) = 1,$$

which implies that

$$\liminf_{k\to\infty} \lambda \diamond f_{-i}\left(\mathrm{Gr}(E_i^k)\right) \geq \lambda \diamond f_{-i}\left(\liminf_{k\to\infty} \mathrm{Gr}(E_i^k)\right) = 1.$$

Thus, $\lim_{k\to\infty} \lambda \diamond f_{-i}\left(\mathrm{Gr}(E_i^k)\right) = 1$.

Notice that the t_i-section of the set $\limsup_{k\to\infty} \mathrm{Gr}(D_i^{g_i^k})$ is $\limsup_{k\to\infty} D_i(t_i, g_i^k(t_i))$, which is the empty set for λ_i-almost all $t_i \in T_i$. Thus, $\lambda \diamond f_{-i}\left(\limsup_{k\to\infty} \mathrm{Gr}(D_i^{g_i^k})\right) = 0$, and

$$\limsup_{k\to\infty} \lambda \diamond f_{-i}\left(\mathrm{Gr}(D_i^{g_i^k})\right) \leq \lambda \diamond f_{-i}\left(\limsup_{k\to\infty} \mathrm{Gr}(D_i^{g_i^k})\right) = 0.$$

As a result, $\lim_{k\to\infty} \lambda \diamond f_{-i}\left(\mathrm{Gr}(D_i^{g_i^k})\right) = 0$.

Therefore, $\lim_{k\to\infty} \lambda \diamond f_{-i}\left(\mathrm{Gr}(E_i^k) \setminus \mathrm{Gr}(D_i^{g_i^k})\right) = 1$. There exists some positive integer $K > 0$ such that for any $k \geq K$,

$$\lambda \diamond f_{-i}\left(\mathrm{Gr}(E_i^k) \setminus \mathrm{Gr}(D_i^{g_i^k})\right) > 1 - \epsilon.$$

Let $g_i = g_i^K$ and $F = \mathrm{Gr}(E_i^K) \setminus \mathrm{Gr}(D_i^{g_i^K})$. Then we have

$$\int_F u_i(g_i(t_i), x_{-i}, t_i, t_{-i})\lambda \diamond f_{-i}(\mathrm{d}(t_i, t_{-i}, x_{-i}))$$
$$\geq \int_F u_i(f_i'(t_i), x_{-i}, t_i, t_{-i})\lambda \diamond f_{-i}(\mathrm{d}(t_i, t_{-i}, x_{-i})) - \epsilon,$$

which implies that[10]

$$\begin{aligned}
&\int_{T \times X_{-i}} u_i(g_i(t_i), x_{-i}, t_i, t_{-i})\lambda \diamond f_{-i}(\mathrm{d}(t_i, t_{-i}, x_{-i})) \\
&= \int_F u_i(g_i(t_i), x_{-i}, t_i, t_{-i})\lambda \diamond f_{-i}(\mathrm{d}(t_i, t_{-i}, x_{-i})) \\
&+ \int_{F^c} u_i(g_i(t_i), x_{-i}, t_i, t_{-i})\lambda \diamond f_{-i}(\mathrm{d}(t_i, t_{-i}, x_{-i})) \\
&\geq \int_F u_i(f_i'(t_i), x_{-i}, t_i, t_{-i})\lambda \diamond f_{-i}(\mathrm{d}(t_i, t_{-i}, x_{-i})) - \epsilon \\
&+ \int_{F^c} u_i(f_i'(t_i), x_{-i}, t_i, t_{-i})\lambda \diamond f_{-i}(\mathrm{d}(t_i, t_{-i}, x_{-i})) - \gamma \cdot \epsilon \\
&= \int_{T \times X_{-i}} u_i(f_i'(t_i), x_{-i}, t_i, t_{-i})\lambda \diamond f_{-i}(\mathrm{d}(t_i, t_{-i}, x_{-i})) - (\gamma + 1)\epsilon.
\end{aligned}$$

Since X_{-i} is a compact metric space, it is second countable (see Royden and Fitzpatrick, 2010, Proposition 25, p. 204). Thus, we can find a countable base $\{V_m\}_{m \geq 1}$ for X_{-i}. Let

$$h_i^m(x_{-i}, t) = \begin{cases} \inf_{x'_{-i} \in V_m} u_i(g_i(t_i), x'_{-i}, t_i, t_{-i}), & \text{if } x_{-i} \in V_m, \\ -2\gamma, & \text{otherwise.} \end{cases}$$

It is easy to see that $h_i^m(\cdot, t)$ is lower semicontinuous on X_{-i} for each fixed $t \in T$ and $m \geq 1$. It can be easily checked that h_i^m is a jointly measurable function. Indeed, it suffices to show that for any $c \geq 0$, the set $\{(x_{-i}, t) \in X_{-i} \times T : h_i^m(x_{-i}, t) < c\}$ is $\mathcal{B}(X_{-i}) \otimes \mathcal{T}$-measurable. Since u_i is jointly measurable and g_i is $\mathcal{T}_i$-measurable, the set

$$\{(x_{-i}, t) \in V_m \times T : u_i(g_i(t_i), x_{-i}, t_i, t_{-i}) < c\}$$

is $\mathcal{B}(X_{-i}) \otimes \mathcal{T}$-measurable. By the Projection Theorem, the projection of the above set on T, denoted as T_m, is a $\mathcal{T}$-measurable subset. Notice that

$$\{(x_{-i}, t) \in X_{-i} \times T : h_i^m(x_{-i}, t) < c\} = (V_m \times T_m) \cup (V_m^c \times T),$$

which is $\mathcal{B}(X_{-i}) \otimes \mathcal{T}$-measurable. Thus, h_i^m is a jointly measurable function.

Let $\underline{u}_i(x_{-i}, t) = \sup_{m \geq 1} h_i^m(x_{-i}, t)$. For each fixed $t \in T$, as in the proof of Reny (1999, Theorem 3.1), $\underline{u}_i(\cdot, t)$ is the pointwise supremum of a sequence of lower semicontinuous function, which is also lower semicontinuous on X_{-i}. In addition, $\underline{u}_i$ is the supremum of a sequence of

10 For any subset E, E^c denotes the complement of the set E.

$\mathcal{B}(X_{-i}) \otimes \mathcal{T}$-measurable functions, which is also $\mathcal{B}(X_{-i}) \otimes \mathcal{T}$-measurable. Define a function $H_i^l\colon \prod_{j\neq i} \mathcal{M}_j \to \mathbb{R}$ as follows: for $g_{-i} = (g_1, \dots, g_{i-1}, g_{i+1}, \dots, g_n) \in \prod_{j\neq i} \mathcal{M}_j$,

$$H_i^l(g_{-i}) = \int_T \int_{X_{-i}} \underline{u}_i(x_{-i}, t)\psi(t) \otimes_{j\neq i} g_j(\mathrm{d}x_j|t_j) \otimes_{i\in I} \lambda_i(\mathrm{d}t).$$

Let $\phi(x_{-i}, t_{-i}) = \int_{T_i} \underline{u}_i(x_{-i}, t)\psi(t)\lambda_i(\mathrm{d}t_i)$. Since $\underline{u}_i(x_{-i}, t)\psi(t)$ is lower semicontinuous in x_{-i}, jointly measurable and integrably bounded, ϕ is also lower semicontinuous in x_{-i}, jointly measurable and integrably bounded. By Lemma 3, the functional $g_{-i} = (g_1, \dots, g_{i-1}, g_{i+1}, \dots, g_n) \to \otimes_{j\neq i} g_j$ from $\prod_j \mathcal{M}_{j\neq i}$ to $\tilde{\mathcal{M}}_{-i}$ is continuous. Then by Lemma 2, the functional

$$\nu \to \int_{T_{-i}} \int_{X_{-i}} \phi(x_{-i}, t_{-i})\nu(\mathrm{d}x_{-i}|t_{-i})\lambda_{-i}(\mathrm{d}t_{-i})$$

is lower semicontinuous on $\tilde{\mathcal{M}}_{-i}$. Since H_i^l is the composition of these two functionals, it is lower semicontinuous. As a result, there is an open neighborhood $\mathcal{N}_{-i}(f_{-i}) \subseteq \prod_{j\neq i} \mathcal{M}_j$ of f_{-i} such that for any $g_{-i} \in \mathcal{N}_{-i}(f_{-i})$,

$$\begin{aligned}&\int_T \int_{X_{-i}} \underline{u}_i(x_{-i}, t)\psi(t) g_{-i}(\mathrm{d}x_{-i}|t_{-i}) \otimes_{i\in I} \lambda_i(\mathrm{d}t)\\ &\geq \int_T \int_{X_{-i}} \underline{u}_i(x_{-i}, t)\psi(t) f_{-i}(\mathrm{d}x_{-i}|t_{-i}) \otimes_{i\in I} \lambda_i(\mathrm{d}t) - \epsilon.\end{aligned}$$

That is,

$$\begin{aligned}&\int_T \int_{X_{-i}} \underline{u}_i(x_{-i}, t) g_{-i}(\mathrm{d}x_{-i}|t_{-i})\lambda(\mathrm{d}t)\\ &\geq \int_T \int_{X_{-i}} \underline{u}_i(x_{-i}, t) f_{-i}(\mathrm{d}x_{-i}|t_{-i})\lambda(\mathrm{d}t) - \epsilon.\end{aligned}$$

Recall that $F = \mathrm{Gr}(E_i^K) \setminus \mathrm{Gr}(D_i^{g_i^K})$. Since $u_i(t, g_i(t_i), \cdot)$ is continuous on the t-section $\{x_{-i} \in X_{-i} \colon (x_{-i}, t) \in F\}$ of F, we have $\underline{u}_i(x_{-i}, t) = u_i(g_i(t_i), x_{-i}, t)$ for any $(x_{-i}, t) \in F$. As a result,

$$\begin{aligned}&\int_T \int_{X_{-i}} \underline{u}_i(x_{-i}, t) f_{-i}(\mathrm{d}x_{-i}|t_{-i})\lambda(\mathrm{d}t)\\ &= \int_F \underline{u}_i(x_{-i}, t)\lambda \diamond f_{-i}(\mathrm{d}(t, x_{-i})) + \int_{F^c} \underline{u}_i(x_{-i}, t)\lambda \diamond f_{-i}(\mathrm{d}(t, x_{-i}))\\ &\geq \int_F u_i(g_i(t_i), x_{-i}, t)\lambda \diamond f_{-i}(\mathrm{d}(t, x_{-i}))\\ &> \int_F u_i(g_i(t_i), x_{-i}, t)\lambda \diamond f_{-i}(\mathrm{d}(t, x_{-i})) + \int_{F^c} u_i(g_i(t_i), x_{-i}, t)\lambda \diamond f_{-i}(\mathrm{d}(t, x_{-i})) - \gamma \cdot \epsilon\end{aligned}$$

$$= \int_T \int_{X_{-i}} u_i(g_i(t_i), x_{-i}, t) f_{-i}(\mathrm{d}x_{-i}|t_{-i})\lambda(\mathrm{d}t) - \gamma \cdot \epsilon.$$

Therefore, for any $g_{-i} \in \mathcal{N}_{-i}(f_{-i})$, we have

$$\begin{aligned}
&\int_T \int_{X_{-i}} u_i(g_i(t_i), x_{-i}, t) g_{-i}(\mathrm{d}x_{-i}|t_{-i})\lambda(\mathrm{d}t) \\
&\geq \int_T \int_{X_{-i}} \underline{u}_i(x_{-i}, t) g_{-i}(\mathrm{d}x_{-i}|t_{-i})\lambda(\mathrm{d}t) \\
&\geq \int_T \int_{X_{-i}} \underline{u}_i(x_{-i}, t) f_{-i}(\mathrm{d}x_{-i}|t_{-i})\lambda(\mathrm{d}t) - \epsilon \\
&\geq \int_T \int_{X_{-i}} u_i(g_i(t_i), x_{-i}, t) f_{-i}(\mathrm{d}x_{-i}|t_{-i})\lambda(\mathrm{d}t) - (\gamma + 1) \cdot \epsilon \\
&\geq \int_T \int_{X_{-i}} u_i(f_i'(t_i), x_{-i}, t) f_{-i}(\mathrm{d}x_{-i}|t_{-i})\lambda(\mathrm{d}t) - 2(\gamma + 1) \cdot \epsilon \\
&\geq \int_T \int_X u_i(x_i, x_{-i}, t) f(\mathrm{d}x|t)\lambda(\mathrm{d}t) - 2(\gamma + 1) \cdot \epsilon,
\end{aligned}$$

and consequently, the game G_0 is payoff secure.

4. An application

Below, we provide an example of an all-pay auction with general tie-breaking rules to demonstrate the usefulness of our result.[11]

All-pay auction with general tie-breaking rules Suppose that N bidders compete for an object. Each bidder's valuation of the object is given by a measurable function $v \colon \Pi_{i \in I} T_i \to [0, 1]$, where T_i is the state space, $i = 1, \ldots, N$. The common prior is λ, and λ is absolutely continuous with respect to $\otimes_{i \in I} \lambda_i$. Bidder i observes his own state t_i and submits a bid $x_i \in X_i = [0, 1]$. The bidder who submits the highest bid wins the object and all bidders need to pay their bids. If multiple bidders submit the highest bid simultaneously, then the tie is broken as follows:

$$u_i(x_1, \ldots, x_N, t_1, \ldots, t_N) = \begin{cases} -x_i, & x_i < \max_{j \in I} x_j, \\ \frac{\xi_i(x_1, \ldots, x_N)}{\sum_{k \in I: x_k = \max_{j \in I} x_j} \xi_k(x_1, \ldots, x_N)} \cdot v(t_1, \ldots, t_N) - x_i, & x_i = \max_{j \in I} x_j; \end{cases}$$

[11] Jackson et al. (2002) showed the existence of a distributional-strategy equilibrium for discontinuous games with incomplete information by proposing a solution concept where the payoff is "endogenously defined" at the discontinuities. Araujo et al. (2008) first considered non-monotonic functions in auctions and showed that an all-pay auction tie-breaking rule is sufficient for the existence of pure-strategy equilibrium for a class of auctions. Carbonell-Nicolau and McLean (2015) considered an all-pay auction with the standard tie-breaking rule that the winning players share the object with equal probability. For other variations, see, for example, Klose and Kovenock (2015) for an all-pay auction with identity-dependent externalities. The results of this section are not covered by any of the above papers.

where $\xi = (\xi_1, \ldots, \xi_N)\colon [0,1]^N \to (0,1]^N$ is a continuous function which assesses the relative importance of each bidder's position when breaking the tie. In particular, if $\xi_i \equiv 1$ for any i, then the tie is broken via the equal probability rule. However, this is not necessary.

Proposition 1. *An all-pay auction with general tie-breaking rules satisfies the random disjoint payoff matching condition.*

Proof. Given any bidder i and $f_i \in \mathcal{L}_i$, let

$$g_i^k(t_i) = \begin{cases} \min\{f_i(t_i) + \frac{1}{k}, 1\}, & f_i(t_i) < 1, \\ \frac{1}{k}, & f_i(t_i) = 1. \end{cases}$$

It is obvious that $g_i^k \in \mathcal{L}_i$ for any $k \geq 1$.

Fix any $t \in T$ and $x_{-i} \in X_{-i}$. If $f_i(t_i) = 1$, then $u_i(f_i(t_i), x_{-i}, t_i, t_{-i}) \leq 0$ and $\liminf_{k\to\infty} u_i(g_i^k(t_i), x_{-i}, t_i, t_{-i}) \geq 0$. If $f_i(t_i) < 1$, we need to consider three possible cases.

1. If bidder i is the unique winner, then he is still the unique winner by adopting the strategy $g_i^k(t_i)$ since $g_i^k(t_i) > f_i(t_i)$. Since $g_i^k(t_i) \to f_i(t_i)$ and ξ is a continuous function, we have $\lim_{k\to\infty} u_i(g_i^k(t_i), x_{-i}, t_i, t_{-i}) = u_i(f_i(t_i), x_{-i}, t_i, t_{-i})$.
2. If bidder i is one of the multiple winners, then he becomes the unique winner by adopting the strategy $g_i^k(t_i)$. Then

$$\lim_{k\to\infty} u_i(g_i^k(t_i), x_{-i}, t_i, t_{-i}) = v_i(t_i, t_{-i}) - f_i(t_i) \geq u_i(f_i(t_i), x_{-i}, t_i, t_{-i}).$$

3. If bidder i does not get the object, then he still loses the game by adopting $g_i^k(t_i)$ for sufficiently large k. As a result, $\lim_{k\to\infty} u_i(g_i^k(t_i), x_{-i}, t_i, t_{-i}) = u_i(f_i(t_i), x_{-i}, t_i, t_{-i})$.

Thus, we have

$$\liminf_{k\to\infty} u_i(g_i^k(t_i), x_{-i}, t_i, t_{-i}) \geq u_i(f_i(t_i), x_{-i}, t_i, t_{-i}),$$

which implies that condition (1) of Definition 3 is satisfied. In addition, for all $t_i \in T_i$, $D_i(t_i, g_i^k(t_i)) = \left\{[0, g_i^k(t_i)]^{N-1} \setminus [0, g_i^k(t_i))^{N-1}\right\} \times T_{-i}$. Since $g_i^k(t_i) \neq g_i^{k'}(t_i)$ for sufficiently large k and k', we have

$$\limsup_{k\to\infty} D_i(t_i, g_i^k(t_i)) = \emptyset$$

for any $t_i \in T_i$. Thus, condition (2) of Definition 3 also holds.

Therefore, an all-pay auction with general tie-breaking rules satisfies the random disjoint payoff matching condition. □

Since $\sum_{i\in I} u_i(t,x) = v(t) - \sum_{i\in I} x_i$, $\sum_{i\in I} u_i(t,\cdot)$ is upper semicontinuous for every t. Thus, the existence of a behavioral-strategy equilibrium follows immediately by combining Theorem 2 and Proposition 1.

Corollary 1. *A behavioral-strategy equilibrium exists in an all-pay auction with general tie-breaking rules.*

Remark 4. Allison and Lepore (2014) presented a Bertrand–Edgeworth oligopoly model which has general specifications of costs, residual demand rationing, and tie-breaking rules. They showed that this price competition problem satisfies the disjoint payoff matching condition and a mixed-strategy equilibrium exists. One can easily extend their model to an incomplete information environment and formulate the problem as a Bayesian game. Then by referring to our Theorems 1 and 2, one can prove the existence of a behavioral-strategy equilibrium. For further applications on Bayesian games with discontinuous payoffs including the war of attrition, Cournot competition and rent seeking, see Carbonell-Nicolau and McLean (2015).

5. Concluding remarks

The purpose of this paper was to prove a new theorem on the existence of behavioral-strategy equilibria for Bayesian games with discontinuous payoffs. Our result is different from the recent ones in Carbonell-Nicolau and McLean (2015) and He and Yannelis (2015a). We applied our equilibrium existence theorem to an all-pay auction with general tie-breaking rules, and also indicated further applications to oligopoly theory. It remains an open question whether the existence result of this paper can be extended to a setting of a continuum of players. Such an extension will further widen the economic applications.

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