Theory of Game Theory

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*These notes are intended to summarize the main concepts, definitions and results covered in the first year of micro sequence for the Economics PhD of the University of Minnesota. The material is not my own. Please let me know of any errors that persist in the document. E-mail: pawel042@umn.edu .

1 Normal Form Games

1.1 Games on Consequences

Definition 1 (Games on Consequences). *consists of:*

- $I = \{1, \dots, n\}$ *is the finite set of players.*
- A^i *is the (finite) set of actions for player* i.
- $A \equiv X_{i \in I} A^i$ *is the (finite) set of action profiles*
- C *is finite the set of consequences,* $C = \{c^1, \dots, c^m\}$.
- $\succeq_i$ *preference relation of Mr* i *over* C
- $g : A \to C$ *mapping of actions to consequences*

This will be compactly denoted as a $\left\langle I, \left(A^i\right)_{i \in I}, \left(\succeq^i\right)_{i \in I}, C, g \right\rangle$.

Example 1.

Mr 2

		L	R
Mr 1	T	c^1	c^2
	B	c^3	c^4

Table above induces g

$A^1 = \{T, B\}$, $A^2 = \{L, R\}$

$c^1 = (10, 5)$, $c^1 = (1, 2)$, $c^1 = (3, 2)$, $c^1 = (4, 3)$

Mr 1 : $c^1 \succeq_1 c^3$ and $\succeq_1 c^2 \succeq_1 c^4$

Mr 2 : $c^2 \succeq_2 c^1$ and $\succeq_2 c^4 \succeq_2 c^3$

1.2 Preferences on lotteries

Definition 2 (Simplex).

$$\Delta(C) \equiv \left\{ p = \left(p^1, \dots, p^m\right) \mid \forall i \quad p^i \geq 0 \quad \sum_{i=1}^{m} p^i = 1 \right\}$$

Definition 3 (Lottery). $L \in \Delta(C)$ *is a simple lottery, where*

$$L = \begin{pmatrix} p^1 & \cdots & p^i & \cdots & p^m \\ c^1 & \cdots & c^i & \cdots & c^m \end{pmatrix}$$

Example 2 (Degenerated lottery). $\delta_{c^i} \in \mathcal{L}$

$$\delta_{c^i} = \begin{pmatrix} 0 & \cdots & 1 & \cdots & 0 \\ c^1 & \cdots & c^i & \cdots & c^m \end{pmatrix}$$

Definition 4. *$\mathcal{L} \equiv \Delta(C)$ is the set of (simple) lotteries.*

Definition 5. *$G = \left(q^1 L^1, \ldots, q^K L^K\right) \in \Delta(\mathcal{L})$ is a compound lottery, where*

$$G = \begin{pmatrix} q^1 & \cdots & q^k \\ L^1 & \cdots & L^k \end{pmatrix}$$

$L^k \in \mathcal{L} \quad \forall k = 1, \ldots, K, q^k \geq 0$ *and* $\sum_{k=1}^{K} q^k = 1$

Definition 6. *$\mathcal{G} \equiv \Delta(\mathcal{L})$ is the set of compound lotteries.*

Note that all simple lotteries can be viewed as compound lotteries with degenerate distributions. For example, the simple lottery $L = \left(p^1, \ldots p^m\right)$ can be viewed as a compound lottery $L = \left(p^1 \delta_{c^1}, \ldots, p^m \delta_{c^m}\right)$, where δ_{c^i} is a degenerate lottery giving fully probability to consequence c^i

Definition 7 (Reduction of a lottery)**.** . *For every $G \in \mathcal{G}, R(G) \in \mathcal{L}$ is the reduction of* G, *and gives probability $\sum_{k=1}^{K} q^k p^i_k$ to consequence c^i*

Definition 8 (Convex combination)**.** *For any F, G and $\alpha \in [0, 1]$, denote the convex combination as $F\alpha G \equiv \alpha F + (1 - \alpha)G$*

1.3 Assumptions on $\succeq$

We are interested in the binary preference relation $\succeq_i$ on $\mathcal{L}$.

Definition 9 (Complete (C))**.** *$\forall F, G \in \mathcal{G}$ either $F \succeq G$ or $G \succeq F$*

Definition 10 (Reflexive (R))**.** *$\forall F \in \mathcal{G}$ $F \succeq F$*

Definition 11 (Transitive (T))**.** *$\forall F, G, H \in \mathcal{G}$ such that $F \succeq G$, $G \succeq H$ then $F \succeq H$*

Definition 12 (Weak Order (WO)-A1)**.** *$\succeq$ is compete , reflexive, and transitive.*

Definition 13 (Independence (I)-A2)**.** *$\forall F, G, H \in \mathcal{G}$ and $\alpha \in (0, 1)$: such that*

$$F \succ G \Rightarrow F\alpha H \succ G\alpha H$$

Definition 14 (Continuity (Cty)-A3)**.** *$\forall F, G, H \in \mathcal{G}$ such that $F \succeq G \succeq H, \forall \alpha \in [0, 1]$ such that $\{\alpha | F\alpha H \geq G\}$ and $\{\beta | F\beta H \leq G\}$ are closed sets.*

Alternative definition of Cty

Definition 15 (Continuity (Cty2))**.** *$\forall F, G, H \in \mathcal{G}$ such that $F \succeq G \succeq H, \exists \alpha \in [0, 1]$ such that $F\alpha H \sim G$*

Lemma 1. *If $[C, T, Cty]$ holds then $Cty2$ holds too.*

Proof. Suppose $F \succeq G$. Define A=$\{\alpha | F\alpha H \geq G\}$ and B=$\{\beta | F\beta H \leq G\}$. Observe that:

- $A, B \subset [0, 1]$
- $1 \in A$, $0 \in B$

- A, B are closed (by Cty)
- $A \cup B = [0, 1]$
- $[0, 1]$ is a connected set

(1)-(5) implies that $A \cap B \neq \varnothing$. So $\exists \alpha \in A \cap B$ s.t. $F\alpha G \succeq H \succeq F\alpha G$. Thus $F\alpha G \sim H$. □

Lemma 2. *Suppose* [WO, I] *hold then:*

$$\forall_{F \in \mathcal{L}} \quad \delta_{c^1} \succeq F \succeq \delta_{c^m}$$

Proof. Since C is finite then $\exists$ best and worst outcome δ_{c^b} and δ_{c^w}. WTS $\forall L \quad \delta_{c^b} \succeq L \succeq \delta_{c^w}$. I will use (easy to prove) corollary

Corollary 1. *Let $L_0, \ldots L_K$ be (1+K) lotteries $\alpha_k \geq 0 : \sum_k \alpha_k = 1$:*

$$\begin{aligned} &\textit{If} \quad \forall k \quad L_k \succeq L_0 \quad \Rightarrow \quad \sum_k \alpha_k L_k \succeq L_0 \\ &\textit{If} \quad \forall k \quad L_0 \succeq L_k \quad \Rightarrow \quad L_0 \succeq \sum_k \alpha_k L_k \end{aligned}$$

Now let lottery L^k yields outcome k with probability 1. Then $\delta_{c^b} \succeq L \succeq \delta_{c^w}$ and any L can be represented as $L = \sum_k p_k L^k$ so by corollary $\delta_{c^b} \succeq L \succeq \delta_{c^w}$ □

Definition 16 (Monotonicity (M))**.** *$\forall F, G \in \mathcal{G}$ such that $F \succ G$, then for $\alpha, \beta \in (0, 1)$:*

$$\alpha > \beta \Leftrightarrow F\alpha G \succ F\beta G$$

Lemma 3. *If I holds and $F \succ G$ $\forall \alpha \in (0, 1) \quad \Rightarrow F \succ F\alpha G \succ G$*

Proof.

$$F = \alpha F + (1-\alpha)F \succ^I \alpha F + (1-\alpha)G = F\alpha G = \alpha F + (1-\alpha)G \succ^I \alpha G + (1-\alpha)G = M$$

□

Lemma 4. *Prove that WO, Cty, I imply M.*

Proof. $\Rightarrow$ Suppose $\alpha > \beta$. Observe that

$$F = \alpha F + (1-\alpha)G = \gamma F + (1-\gamma)[\beta F + (1-\beta)G]$$

after rearrangement $\gamma = \frac{\alpha-\beta}{1-\beta} \in (0, 1)$ By lemma 3 $F \succ G$: $F \succ F\beta G$

$$F\alpha G = F\gamma(F\beta G) \succ^I (F\beta G)\gamma(F\beta G) = F\beta G$$

Now $\Leftarrow$ part. Suppose $F \succ G$ and $F\alpha G \succ F\beta G$. WTS: $\alpha > \beta$.
Suppose not. So either $\alpha = \beta$ or $\alpha < \beta$. If $\alpha = \beta$ then we have contradiction with $F\alpha G \succ F\beta G$.
If $\alpha < \beta$ by $\Rightarrow$ part $F\beta G \succ F\alpha G$ contradiction. □

Definition 17 (Reduction (R)). $\forall G \in \mathcal{G}, R(G) \sim G$

Definition 18 (Substitution (S):). $\forall G \in \mathcal{G}$, *if* $G = \begin{pmatrix} q^1 & \dots & q^j & \dots & q^K \\ L^1 & \dots & L^j & \dots & L^K \end{pmatrix}$ *is modified by substituting* L^j *for* M^j, *where* $M^j \sim L^j$, *then* $G \sim H$, *where* $H = \begin{pmatrix} q^1 & \dots & q^j & \dots & q^K \\ L^1 & \dots & M^j & \dots & L^K \end{pmatrix}$

1.4 Utility representation

Definition 19 (Utility representation). *The function* $u : \mathcal{G} \to \mathbb{R}$ *is a representation of* $\succeq$ *if and only if:*

$$F \succeq G \Leftrightarrow u(F) \geq u(G)$$

Recall:

$$F \succ G \Leftrightarrow F \succeq G \text{ and not } G \succeq F$$
$$F \sim G \Leftrightarrow F \succeq G \text{ and } G \succeq F$$

Lemma 5. *If* u *represents* $\succeq$ *and* $T : \mathbb{R} \to \mathbb{R}$ *is strictly increasing, then* $T(u(\cdot)) : \mathcal{G} \to \mathbb{R}$ *is a representation of* $\succeq$

Lemma 6 (Recap from MINI 1). *If* $\succeq$ *satisfies WO and C, then* $\succeq$ *has some (continuous) utility representation.*

Definition 20 (Linear utility). *If* u *is linear then* $u(F\alpha G) = u(F)\alpha u(G)$, *where* $\alpha \in [0, 1]]$

Alternative definition of linearity:

Definition 21 (Linear utility). u *is linear if and only if* $u(L) = \sum_{i=1}^{m} p^i u\left(c^i\right)$, *where* $L = \left(p^1, \dots, p^m\right)$

Example 3. *If* u *represents* $\succeq$ *and is linear, then if* $A > 0$ *and* $B \in \mathbb{R}, Au(\cdot) + B$ *also represents* $\succeq$ *and is linear.*

Example 4. $\succeq$ *satisfies* $\mathrm{WO}, \mathrm{Cty}$, *and* M *if and only if* $\forall F \in \mathcal{G} \quad \exists u(F) \in [0, 1]$ *such that* $F \sim \delta_{c^1} u(F) \delta_{c^m}$ *and* $u(F)$ *is unique. In particular,* $\forall c^i \in C \quad \exists u\left(c^i\right) \in [0, 1]$ *such that* $c^i \sim c^1 u\left(c^i\right) c^m$.

Theorem 1 (von Neumann-Morgenstern (I)). ***1. (existence)*** $\succeq$ ***on*** $\mathcal{L}$ ***satisfies*** $\mathrm{WO}, \mathrm{Cty}, \mathrm{I}$ ***if and only if there exists a linear*** $u : \mathcal{G} \to \mathbb{R}$ ***that represents*** $\succeq$

2. (uniqueness) If u, v ***are linear representations of*** $\succeq$***, then*** $\exists A > 0, B \in \mathbb{R}$ ***such that*** $u(\cdot) = Av(\cdot) + B$

Proof. We will proceed in three steps: 1) (existence): $\Rightarrow$; 2)(existence): $\Leftarrow$; 3)(uniqueness)

- (existence): $\Rightarrow$

By lemma 2: $\exists \delta_{c^1}, \delta_{c^m} : \forall F : \delta_{c^1} \succeq F \succeq \delta_{c^m}$ and $\delta_{c^1} \succ \delta_{c^m}$.
Define $u(F) : \delta_{c^1} u(F) \delta_{c^m} \sim F$. By lemma 1 we know that such $u(F)$ is well defined. Our goal is to show for $\alpha = u(F)$ that this is representation, it is unique and linear. We do it with two lemmas. We want to avoid $\alpha \neq \beta$ $\delta_{c^1}\alpha\delta_{c^m} \sim \delta_{c^1}\beta\delta_{c^m}$, we want $\delta_{c^1}\alpha\delta_{c^m} \succ \delta_{c^1}\beta\delta_{c^m} \iff \alpha > \beta$.

Lemma 7. *$u(F) : \delta_{c^1} u(F) \delta_{c^m} \sim F$ is unique*

Proof. Let $\bar{u}(F)$ and $u(F)$ be two different values and WLOG $\bar{u}(F) > u(F)$.

$$\delta_{c^1} u(F) \delta_{c^m} \sim F \sim \delta_{c^1} \bar{u}(F) \delta_{c^m}$$

by applying lemma 4 ($\delta_{c^1} \succ \delta_{c^m}$), $\bar{u}(F) > u(F)$):

$$\delta_{c^1} u(F) \delta_{c^m} \succ \delta_{c^1} \bar{u}(F) \delta_{c^m}$$

contradiction.

$\square$

By last lemma $F \succeq G \iff \delta_{c^1} u(F) \delta_{c^m} \succeq \delta_{c^1} u(G) \delta_{c^m}$ by lemma 4 $\iff u(F) \geq u(G)$. So $u : \mathcal{L} \to \mathbb{R}$ represents $\succeq$.

Lemma 8. *$u(\cdot)$ is linear*

Proof. By definition of u

$$F \sim \delta_{c^1} u(F) \delta_{c^m}$$

$$G \sim \delta_{c^1} u(G) \delta_{c^m}$$

by I (and rearrangement) :

$$F\alpha G \sim (\delta_{c^1} u(F) \delta_{c^m})\alpha G \sim (\delta_{c^1} u(F) \delta_{c^m})\alpha(\delta_{c^1} u(G) \delta_{c^m}) \sim \delta_{c^1}(u(F)\alpha u(G))\delta_{c^m}$$

Thus $u(F\alpha G) = u(F)\alpha u(G)$ $\square$

- (existence):$\Leftarrow$

Let's show that $\succeq$ satisfy weak order (WO). Let's start with completeness.

$$\forall F, G \in \mathcal{L} \quad u(F) \geq u(G) \quad \text{or} \quad u(F) \leq u(G) \quad \iff \quad F \succeq G \quad \text{or} \quad G \succeq F$$

since it is order on real line.
Transitivity. WLOG $F \succeq G$ and $G \succeq H$. Observe that since u represents preferences:

$$u(F) \geq u(G) \iff F \succeq G$$

$$u(G) \geq u(H) \iff G \succeq H$$

$$u(F) \geq u(H) \iff F \succeq H$$

we have $u(F) \geq u(G)$,$u(G) \geq u(H) \Rightarrow u(F) \geq u(H)$ comes from linear order on real line. So $F \succeq H$.

Now we show continuity. Consider any sequence $\{\alpha_i\}_{i=1}^{\infty} \to \alpha$, (where $\forall i, \alpha_i \in [0,1]$) and $\alpha_i F + (1-\alpha_i) G \succsim H, \forall i$ Then,

$$U(\alpha_i F + (1-\alpha_i) G) \geq U(H), \forall i$$

and using the linearity of U

$$\alpha_i U(F) + (1-\alpha_i) U(G) \geq U(H), \forall i$$

which implies (taking limit as $i \to \infty$)

$$\alpha U(F) + (1-\alpha) U(G) \geq U(H)$$

so that $\alpha F + (1-\alpha) G \succsim H$.

Next, we show independence. Consider $F, G, H \in \mathcal{L}$ and $\alpha \in (0,1)$ Need to show: $F \succsim G \Longleftrightarrow \alpha F + (1-\alpha) H \succsim \alpha G + (1-\alpha) H$ Suppose $F \succsim G$ Then, $U(F) \geq U(G)$ so that

$$\alpha U(F) + (1-\alpha) U(H) \geq \alpha U(G) + (1-\alpha) U(H)$$

which implies

$$\alpha F + (1-\alpha) H \succsim \alpha G + (1-\alpha) H$$

Suppose that $\alpha F + (1-\alpha) H \succsim \alpha G + (1-\alpha) H$ Then,

$$U(\alpha F + (1-\alpha) H) \geq U(\alpha G + (1-\alpha) H)$$

and using linearity of U,

$$\alpha U(F) + (1-\alpha) U(H) \geq \alpha U(G) + (1-\alpha) U(H)$$

which implies that $U(F) \geq U(G)$

- (uniqueness):

Let u, v be linear representations of $\succeq$ and take F such that $F \sim c^1 \alpha c^m$ for some $\alpha \in [0,1]$. Then, by linearity:

$$u(F) = u\left(c^1 \alpha c^m\right) = \alpha u\left(c^1\right) + (1-\alpha) u\left(c^m\right)$$

$$\text{and} \quad v(F) = v\left(c^1 \alpha c^m\right) = \alpha v\left(c^1\right) + (1-\alpha) v\left(c^m\right)$$

$$\alpha = \frac{u(F) - u\left(c^m\right)}{u\left(c^1\right) - u\left(c^m\right)} = \frac{v(F) - v\left(c^m\right)}{v\left(c^1\right) - v\left(c^m\right)} \Longrightarrow u(F) = \frac{u\left(c^1\right) - u\left(c^m\right)}{v\left(c^1\right) - v\left(c^m\right)} v(F) - \frac{u\left(c^1\right) - u\left(c^m\right)}{v\left(c^1\right) - v\left(c^m\right)} v\left(c^m\right) + u\left(c^m\right)$$

$$u(F) = A v(F) + B$$

where $A \equiv \frac{u\left(c^1\right) - u\left(c^m\right)}{v\left(c^1\right) - v\left(c^m\right)}$ and $B \equiv u\left(c^m\right) - \frac{u\left(c^1\right) - u\left(c^m\right)}{v\left(c^1\right) - v\left(c^m\right)} v\left(c^m\right)$

$\square$

Theorem is true under alternative set of axioms. We present proof of it for pedagogical reasons.

Theorem 2 (von Neumann-Morgenstern (M,S,R)). *1. (existence)* $\succeq$ *on* $\mathcal{L}$ *satisfies* WO, Cty, M, S, R *if and only if there exists a linear* $u : \mathcal{G} \to \mathbb{R}$ *that represents* $\succeq$

2. (uniqueness) If u, v *are linear representations of* $\succeq$*, then* $\exists A > 0, B \in \mathbb{R}$ *such that* $u(\cdot) = Av(\cdot) + B$

Proof. Below we prove theorem when $\succeq$ on $\mathcal{G}$ satisfies $\mathrm{WO}, \mathrm{Cty}, \mathrm{M}, \mathrm{R} and \mathrm{S}$. We show only (existence)$\Rightarrow$ part. Uniqueness remains the same and $\Leftarrow$ of existence is easy exercise left for a reader.

(existence): $\Rightarrow$

By WO, Cty, and M, we know there exists $u : C \to \mathbb{R}$ and thus $c^i \sim c^1 u\left(c^i\right) c^m$ implies $\bar{u}(L) \equiv \sum_{i=1}^m p^i u\left(c^i\right)$, where $L = \left(p^1, \ldots, p^m\right)$ and $L \sim c^1 u(L) c^m$

Lemma 9. $\bar{u}(L) = u(L)$

Proof: Recall $c^2 \sim c^1 u\left(c^2\right) c^m$ and construct

$$L' = \begin{pmatrix} p^1 & p^2 & \ldots & p^m \\ c^1 & c^1 u\left(c^2\right) c^m & \ldots & c^m \end{pmatrix}$$

where $L' \sim L$ by substitution. Repeat this substitution process for all but c^1 and c^m. Now take the reduction

$$R\left(L'\right) = \begin{pmatrix} p^1 + p^2 u\left(c^2\right) + p^3 u\left(c^3\right) \ldots & 0 & \ldots & 1 - \left(p^1 + \ldots\right) \\ c^1 & c^2 & \ldots & c^m \end{pmatrix}$$

and note $R\left(L'\right) \sim L$ by reduction. Then $u(L) = \sum_{i=1}^m p^i u\left(c^i\right) = \bar{u}(L)$. □

Definition 22 (Sure Thing Principle)**.** *For lotteries* $L, M, N, R \in \mathcal{L}$ *and* $\alpha \in (0, 1]$

$$L\alpha M \succ N\alpha M \Leftrightarrow L\alpha R \succ N\alpha R$$

Lemma 10. *If* $\succeq$ *satisfies the vNM axioms, then* $\succeq$ *satisfies the Sure Thing Principle.*

Proof. Since $\succeq$ satisfies the vNM axioms, there exists a linear utility representation $u(\cdot)$. Thus, $\forall \alpha \in (0, 1]$:

$$\begin{aligned} L\alpha M \succ N\alpha M &\Leftrightarrow u(L\alpha M) > u(N\alpha M) \\ &\Leftrightarrow \alpha u(L) + (1-\alpha)u(M) > \alpha u(N) + (1-\alpha)u(M) \\ &\Leftrightarrow u(L) > u(N) \\ &\Leftrightarrow \alpha u(L) + (1-\alpha)u(R) > \alpha u(N) + (1-\alpha)u(R) \\ &\Leftrightarrow u(L\alpha R) > u(N\alpha R) \\ &\Leftrightarrow L\alpha R \succ N\alpha R \end{aligned}$$

□

From a game on consequences, we elicit $\succeq_i$ for each player.

We then use the von Neumann-Morgenstern Theorem to construct utility functions $u^i : C \to \mathbb{R}$

Then we construct utility functions $\hat{u}^i : A \to \mathbb{R}$ defined by $\hat{u}^i = u^i(g(a))$.

Thus we transform a game on consequences into a **normal form game**

Definition 23 (Normal Form Game (NFG))**.** *is a tuple* $\left(I, \left(A^i\right)_{i\in I}, \left(u^i\right)_{i\in I}\right)$

1.5 Strategies of Normal Form Games

Definition 24. *A mixed strategy for player i is $s^i \in \Delta\left(A^i\right)$; we denote the mixed strategies of all players $j \neq i$ as $s^{-i} \in \Delta\left(A^{-i}\right)$*

Definition 25. *The set of mixed strategy profiles for player i is $S^i \equiv \Delta\left(A^i\right)$; we denote the set for all players $j \neq i$ as $S^{-i} \equiv \Delta\left(A^{-i}\right)$. Equivalently,*

$$S^i = \left\{ \left\{s^i\left(a^i\right)\right\}_{a^i\in A^i} \mid \sum_{a^i\in A^i} s^i\left(a^i\right) = 1; \forall a^i \in A^i, s^i\left(a^i\right) \geq 0 \right\}$$

[Note: $S^i = \text{co}\left(A^i\right)$, and so S^i is convex. If A^i is finite, then $S^i = \overline{co}\left(A^i\right)$

Definition 26. *A mixed strategy for all players is $s \in S$, where $S \equiv X_{i\in I} S^i$ is the set of all mixed strategy profiles.*

Definition 27. *Fully mixed strategy A mixed strategy $s^i \in \Delta\left(A^i\right)$ is a fully mixed strategy if* $\forall a^i \in A^i, s^i\left(a^i\right) > 0$

1.6 Nash Equilibrium

Definition 28. *A normal form game* (NFG) *is a tuple* $\left(I, \left(A^i, u^i\right)_{i\in I}\right)$, *where* $\forall i u^i : A \to \mathbb{R}$

Definition 29 (Mixed extension of NFG)**.** *For a NFG* $\left(I, \left(A^i, u^i\right)_{i\in I}\right)$, *the mixed extension is* $\left(I, \left(S^i, u^i\right)_{i\in I}\right)$, *where* $\forall i s^i \in S^i$ *and* $u^i : S \to \mathbb{R}$

We define agent i 's expected utility over mixed strategy profiles as $u^i : S \to \mathbb{R}$, where:

$$\begin{aligned}
u^i(s) &= \sum_{a\in A} \Pr_s(a) u^i(a) \\
&= \sum_{a^i\in A^i} s^i\left(a^i\right) \sum_{a^{-i}\in A^{-i}} \Pr_{s^{-i}}\left(a^{-i}\right) u^i\left(a^i, a^{-i}\right) \\
&= \sum_{a^i\in A^i} s^i\left(a^i\right) u^i\left(a^i, s^{-i}\right) \\
&= u^i\left(s^i, s^{-i}\right)
\end{aligned}$$

We will use this representation extensively.

Definition 30 (Pure action best response correspondence)**.** *The action best response correspon-*

dence of player $i, BR^i_{A^i} : S \rightrightarrows A^i$*, is:*

$$\begin{aligned} BR^i_{A^i}(s) &\equiv \left\{a^i \in A^i \mid \forall b^i \in A^i u^i\left(a^i, s^{-i}\right) \geq u^i\left(b^i, s^{-i}\right)\right\} \\ &= \arg\max_{a^i \in A^i} u^i\left(a^i, s^{-i}\right) \end{aligned}$$

Definition 31 (Best response correspondence)**.** *The best response correspondence of player* $i, BR^i : S \rightrightarrows S^i$*, is:*

$$\begin{aligned} BR^i\left(s^{-i}\right) = BR^i(s) &\equiv \left\{r^i \in S^i \mid \forall t^i \in S^i u^i\left(r^i, s^{-i}\right) \geq u^i\left(t^i, s^{-i}\right)\right\} \\ &= \left\{r^i \in S^i \mid u^i\left(r^i, s^{-i}\right) = \max_{t^i \in S^i} u^i\left(t^i, s^{-i}\right)\right\} \\ &= \arg\max_{s^i \in S^i} u^i\left(s^i, s^{-i}\right) \end{aligned}$$

The only difference between those two Best responses is on domain of correspondences.

Definition 32 (Best reply correspondence)**.** *The best reply correspondence* $BR : S \rightrightarrows S$ *is defined by:*

$$BR(s) = \prod_{i \in I} BR^i(s)$$

Definition 33 (Nash equilibrium)**.** *If* $\left(I, \left(S^i, u^i\right)_{i \in I}\right)$ *is the mixed extension of a NFG, then* $\hat{s} \in S$ *is a Nash equilibrium if and only if* $\forall i \hat{s}^i \in BR^i(\hat{s})$*.*

Example 5.

1/2	L	R
T	3,1	0,0
B	0,0	1,3

- Define: pure actions, mixed actions, best correspondences
- Find all Nash Equilibria

pure strategies: $A^1 = \{T, B\}$, $A^2 = \{L, R\}$,$A = A^1 A^2$
mixed strategies:

$$S = S^1 \times S^2 = \Delta(A^1) \times \Delta(A^2) = \{((p, 1-p), (q, 1-q)) \,|\, p, q \in [0, 1]\}$$

We can solve for the best responses as follows: Mr 1 best response:

$$BR^1\left((q, 1-q)\right) : \left\{ \begin{array}{cc} T & B \\ 3\left(q\right) + 0\left(1-q\right) & 0\left(q\right) + 1\left(1-q\right) \end{array} \right\}$$

Equality only holds when $q = \frac{1}{4}$. $T > B \iff p > \frac{1}{4}$. $T < B \iff p < \frac{1}{4}$ Therefore, player 1 sets $p = 1$ if $q > frac14$ and sets $p = 0$. She picks $p \in [0, 1]$ where is indifferent between T and B.

otherwise.

$$BR^1\left((q,1-q)\right)=\begin{cases}0 & \text{if } p<\frac{1}{4}\\ [0,1] & \text{if } p=\frac{1}{4}\\ 1 & \text{if } p>\frac{1}{4}\end{cases}$$

Mr 2 best response:

$$BR^2\left((p,1-p)\right):\left\{\begin{array}{cc} L & R \\ p+0\left(1-p\right) & 0\left(p\right)+3\left(1-p\right)\end{array}\right\}$$

Equality only holds when $p=\frac{3}{4}$. $L>R \iff p>\frac{3}{4}$,$L<R \iff p<\frac{3}{4}$ Similarly, player 2 sets $q=1$ if $p>\frac{3}{4}$ and sets $q=0$ otherwise.

$$BR^2\left((p,1-p)\right)=\begin{cases}0 & \text{if } p<\frac{3}{4}\\ [0,1] & \text{if } p=\frac{3}{4}\\ 1 & \text{if } p>\frac{3}{4}\end{cases}$$

These best responses can be graphed :

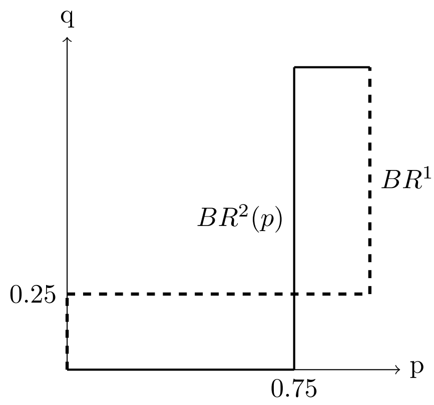

Figure 1: Best Responses

The points of interesection

$$\left(\frac{3}{4},\frac{1}{4}\right),(1,1),(0,0)$$

yield the set of Nash equilibria

$$\text{NE}=\Big\{\big((1,0),(1,0)\big),\big((0,1),(0,1)\big),((\frac{3}{4},\frac{1}{4}),(\frac{1}{4},\frac{3}{4}))\Big\}.$$

Corollary 2. *A NE exists if and only if the best response correspondence $BR:S\rightrightarrows S$ has a fixed point (i.e. $s\in BR(s)$)*

Lemma 11. *Show that* $\mathrm{BR}_i(s)=\mathrm{co}\left(\left\{\delta_{b^i}:b^i\in\mathrm{BR}^i_{A^i}(s)\right\}\right)$

Proof. • $\mathrm{BR}_i(s) \subset \mathrm{co}\left(\left\{\delta_{b^i} : b^i \in \mathrm{BR}^i_{A^i}(s)\right\}\right)$

We present here small but important result: if strategy is not best response in pure best response, corresponding probability in best response in mixed strategies is zero.
Let $s^i \in \mathrm{BR}^i(s)$.

Lemma 12.

$$\forall b^i \notin BR_{A^i}(s), b^i \in A^i \Rightarrow s^i(b^i) = 0$$

Proof. Suppose not. if the strategy $s^i \in \mathrm{BR}^i(s)$ uses some pure action $b^i \in A^i$ which $\notin \mathrm{BR}_{A^i}(s)$, i.e. $s^i(b^i) > 0$ then

$$\forall c^i \in \mathrm{BR}_{A^i}(s): \quad u^i(c^i, s^{-i}) > u^i(b^i, s^{-i})$$

Consider another mixed strategy r^i, defined as follows:

$$\begin{cases} r^i(a^i) = s^i(a^i) & \forall a^i \in A^i/\{b^i, c^i\} \\ r^i(b^i) = 0 \\ r^i(c^i) = s^i(b^i) + s^i(c^i) \end{cases}$$

then

$$u^i(r^i, s) = \sum_{a^i \in A^i} r^i(a^i)u(a^i, s^{-i}) + r^i(b^i)u^i(b^i, s^{-i}) + r^i(c^i)u^i(c^i, s^{-i}) =$$

$$= \sum_{a^i \in A^i} s^i(a^i)u^i(a^i, s) + [s^i(b^i) + s^i(c^i)]u^i(c^i, s^{-i}) >$$

$$\sum_{a^i \in A^i} s^i(a^i)u^i(a^i, s^{-i}) + s^i(b^i)u^i(b^i, s^{-i}) + s^i(c^i)u^i(c^i, ^{-i}s) = u^i(s^i, s^{-i})$$

contradiction with $s^i \in \mathrm{BR}^i(s)$. □

$\mathrm{BR}_i(s) \subset \mathrm{co}\left(\left\{\delta_{b^i} : b^i \in \mathrm{BR}^i_{A^i}(s)\right\}\right)$ comes straight from lemma (our mixed best response has zeros when it is not in pure best response).

• $\mathrm{BR}_i(s) \supset \mathrm{co}\left(\left\{\delta_{b^i} : b^i \in \mathrm{BR}^i_{A^i}(s)\right\}\right)$

BR is convex valued. We need to show that $\left(\left\{\delta_{b^i} : b^i \in \mathrm{BR}^i_{A^i}(s)\right\}\right) \subset \mathrm{BR}^i(s)$
Suppose not Let $b^i \in \mathrm{BR}^i(s)$ and suppose $\delta_{b^i} \notin \mathrm{BR}^i(s)$ then

$$\exists s^i \in \Delta(A^i) \quad u^i(s^i, s^{-i}) > u^i(b^i, s^{-i})$$

$$\sum_{a^i \in A^i} s^i(a)u^i(a^i, s^{-i}) > u^i(b^i, s^{-i}) = \sum_{a^i \in A^i} s^i(a^i)u^i(b^i, s^{-i})$$

for at least one a^i $u^i(a^i, s^{-i}) > u^i(b^i, s^{-i})$ contradicts $b^i \in \mathrm{BR}^i_{A^i}(s)$ □

Lemma 13. $\forall i \quad \forall s^{-i} \quad u^i\left(\cdot, s^{-i}\right) : s^i \to u^i\left(s^i, s^{-i}\right)$ *is linear, and thus it is continuous.*

Lemma 14. $\forall i \quad u^i : S \to \mathbb{R}$ *is continuous and linear in each argument, fixing other arguments.*

Lemma 15. *If A^i is finite then S^i is closed.*

Proof. Let A^i be finite. Take any $\{s_n^i\}_{n\in\mathbb{N}} \in S^{i^{\mathbb{N}}}$ such that $s_n^i \to s^i$. Then $\forall n \sum_{a^i\in A^i} s_n^i\left(a^i\right) = 1$. Taking limits:

$$\begin{aligned}
\lim_{n\to\infty} \sum_{a^i\in A^i} s_n^i\left(a^i\right) &= \lim_{n\to\infty} 1 \\
\implies \sum_{a^i\in A^i} \lim_{n\to\infty} s_n^i\left(a^i\right) &= 1 \\
\implies \sum_{a^i\in A^i} s^i\left(a^i\right) &= 1
\end{aligned}$$

Also $\forall n \forall a^i \in A^i s_n^i\left(a^i\right) \geq 0$. Taking limits again, clearly $s^i\left(a^i\right) \geq 0$. Thus S^i is closed. □

1.7 Correspondences

Let $\Theta \subseteq \mathbb{R}^n, X \subseteq \mathbb{R}^n$.

Definition 34. *A correspondence* $\Gamma : \Theta \rightrightarrows X$ *is a map s.t.* $\Gamma(\Theta) \subseteq X$. $\left(\Gamma : \Theta \to 2^X\right)$

Definition 35. ***(Graph of correspondence)****.* $Gr(\Gamma) = \{(\theta, x) : \theta \in \Theta, x \in \Gamma(\theta)\}$

Definition 36. ***(Properties of correspondences)****.*

1. ***not empty valued*** *if* $\Gamma(\theta) \neq \emptyset \quad \forall\theta$
2. ***single valued*** *if* $|\Gamma(\theta)| = 1 \quad \forall\theta$
3. ***closed valued*** *if* $\Gamma(\theta)$ *is closed set* $\forall\theta$
4. ***compact valued*** *if* $\Gamma(\theta)$ *is compact set* $\forall\theta$
5. ***convex valued*** *if* $\Gamma(\theta)$ *is convex set* $\forall\theta$
6. ***closed (graph)*** *if* $\mathrm{Gr}(\Gamma)$ *is closed subset of* $\mathbb{E} \times X$
7. ***convex (graph)*** *if* $Gr(\Gamma)$ *is convex on* $\Theta \times X$

Lemma 16. $Gr(\Gamma)$ *is closed graph* $\iff \forall_{\theta:\theta_n\to\theta} \forall_{x_n\to x} : x_n \in \Gamma\left(\theta_n\right) \Rightarrow \quad x \in \Gamma\left(\theta\right)$

Lemma 17. $\mathrm{Gr}(\Gamma)$ *is convex graph* $\iff \forall_\theta, \theta', x \in \Gamma(\theta), x' \in \Gamma\left(\theta'\right)$ *it holds that* $\lambda x + (1-\lambda)x' \in \Gamma\left(\theta\lambda + (1-\lambda)\theta'\right) \forall_{x\in[0,1]}$

Lemma 18. $\Gamma : \Theta \rightrightarrows X$ *has closed* graph $\Rightarrow$ *it is closed valued. If* X *is compact, than* Γ *is also compact valued.*

Definition 37. ***(Upper Hemi-Continuity)*** *Let* $\Gamma : \Theta \rightrightarrows X$ *be a correspondence.*

- Γ *is said to be* ***upper hemi-continuous (uhc)*** *at a point* $\theta \in \Theta$ *if and only if for all open sets* $V \subseteq X$ *such that* $\Gamma(\theta) \subseteq V$*, there exists an open set* $U \subseteq \Theta$ *such that* $\theta \in U$ *and for all* $\theta' \in U$ *it holds that* $\Gamma\left(\theta'\right) \subseteq V$

- *A compact valued correspondence* $\Gamma : \Theta \rightrightarrows X$ *is u.h.c. at* $\theta \in \Theta$ *if and only if for every* $\{\theta_n\} \subset \Theta$ *such that* $\theta_n \to \theta$ *and every sequence* $\{x_n\} \subset X$ *such that* $x_n \in \Gamma(\theta_n)$ *there exits a convergent subsequence* $\{x_{n_k}\}$ *such that* $x_{n_k} \to x \in \Gamma(\theta)$

$$\forall_{\theta_n \to \theta} \forall_{x_n \in \Gamma(\theta_n)} \exists_{\{x_{n_k}\}} x_{n_k} \to x \in \Gamma(\theta)$$

Definition 38. ***(Lower Hemi-Continuity)****. Let* $\Gamma : \Theta \rightrightarrows X$ *be a correspondence.*

- Γ *is said to be* ***lower hemi-continuous (lhc)*** *at a point* $\theta \in \Theta$ *if and only if for all open sets* $V \subseteq X$ *such that* $\Gamma(\theta) \cap V \neq \emptyset$*, there exists an open set* $U \subseteq \Theta$ *such that* $\theta \in U$ *and for all* $\theta' \in U$ *it holds that* $\Gamma(\theta') \cap V \neq \emptyset$

- *A correspondence* $\Gamma : \Theta \rightrightarrows X$ *is l.h.c. at* $\theta \in \Theta$ *if for all* $x \in \Gamma(\theta)$ *and all sequences* $\{\theta_n\} \subset \theta$ *such that* $\theta_n \to \theta$ *there exits a sequence* $\{x_n\} \subset X$ *such that* $x_n \in \Gamma(\theta_n)$ *and* $x_n \to x$

$$\forall_{\theta_n \to \theta} \forall_{x \in \Gamma(\theta)} \exists_{x_n \in \Gamma(\theta_n)} x_n \to x$$

Definition 39. ***(Continuity)*** Γ *is said to be continuous at a point* $\theta \in \Theta$ *if it is both UHC an LHC.*

Lemma 19. ***(u.h.c and Closed graph)*** *Let* $\Gamma : \Theta \rightrightarrows X$*. If* Γ *is u.h.c, then* Γ *is closed (has a closed graph).*

Lemma 20. ***(Closed graph and u.h.c.)*** *Let* $\Gamma : \Theta \rightrightarrows X$*. If* X *is compact and* Γ *is closed (has a closed graph), then* Γ *is u.h.c.*

Theorem 3. ***(Berge (1961) of Maximum) Let*** $\Theta \subseteq \mathbb{R}^m$ ***and*** $X \subseteq \mathbb{R}^n$***, let*** $f : \Theta \times X \to \mathbb{R}$ ***be a continuous function and*** $\Gamma : \Theta \rightrightarrows X$ ***a nonempty, compact valued, continuous correspondence. Define:***

$$v(\theta) = \max_{x \in \Gamma(\theta)} f(x, \theta) \quad G(\theta) = \{x \in \Gamma(\theta) \mid f(x, \theta) = v(\theta)\}$$

Then

- $v : \Theta \to X$ ***is continuous***

- $G : \Theta \rightrightarrows X$ ***is nonempty and compact valued, and UHC***

Proof. The proof is divided in three parts. First it is proven that G is nonempty and compact valued, then that it is u.h.c. and finally that v is continuous.

1. G is nonempty valued and compact valued.

    - Let $\theta \in \Theta$, by hypothesis $\Gamma(\theta)$ is compact and nonempty. since $f(\cdot, \theta)$ is continuous a maximum is attained on $\Gamma(\theta)$ by the extreme value theorem (Weierstrass). This proves that $G(\theta)$ is nonempty for arbitrary θ.

- Let $\theta \in \Theta$, by hypothesis $\Gamma(\theta)$ is compact and nonempty. since $G(\theta) \subseteq \Gamma(\theta)$ it follows that $G(\theta)$ is bounded, it is left to show closedness to establish compactness. Let $x_n \rightarrow x$ and $x_n \in G(\theta)$ for all n. Clearly $x_n \in \Gamma(\theta)$ for all n, since Γ is closed valued it follows that $x \in \Gamma(\theta)$, so its feasible. By definition of G we have $v(\theta)=f\left(x_n, \theta\right)$ for all n, since f is continuous we get $v(\theta)=\lim f\left(x_n, \theta\right)=f(x, \theta)$, then by definition $x \in G(\theta)$, which proves closedness.

2. G is u.h.c. Consider $\theta \in \Theta$, a sequence in Θ such that $\theta_n \rightarrow \theta$ and a sequence in X such that $x_n \in G\left(\theta_n\right)$ for all n. Note that $x_n \in \Gamma\left(\theta_n\right)$. since Γ is u.h.c. there exists a subsequence $x_{n_k} \rightarrow x \in \Gamma(\theta)$ Now consider $z \in \Gamma(\theta)$. since Γ is l.h.c. there exists a sequence in X such that $z_n \in \Gamma\left(\theta_n\right)$ and $z_n \rightarrow z$. In particular the subsequence $\left\{z_{n_k}\right\}$ also converges to z since $x_n \in G\left(\theta_n\right)$ and $z_n \in \Gamma\left(\theta_n\right)$ it follows that $f\left(x_n, \theta_n\right) \geq f\left(z_n, \theta_n\right)$. since f is continuous in both arguments we get by taking limits: $f(x, \theta) \geq f(z, \theta)$. since the inequality holds for arbitrary $z \in \Gamma(\theta)$ we get the result: $x \in G(\theta)$. This proves u.h.c.

3. v is continuous. Let $\theta \in \Theta$ and $\theta_n \rightarrow \theta$ an arbitrary sequence converging to θ. Consider an arbitrary sequence in X such that $x_n \in G\left(\theta_n\right)$ for all n. Let $\bar{v}=\limsup v\left(\theta_n\right)$. By proposition 2.9 there is a subsequence $\left\{\theta_{n_k}\right\}$ such that $v\left(\theta_{n_k}\right) \rightarrow \bar{v}$. since G is u.h.c. there exists a subsequence of $\left\{x_{n_k}\right\}$ (call it $\left\{x_{n_{kl}}\right\}$) converging to a point $x \in G(\theta)$. Then

$$\bar{v}=\lim v\left(\theta_{k_l}\right)=\lim f\left(x_{k_l}, \theta_{k_l}\right)=f(x, \theta)=v(\theta)$$

where the second equality follows from $x_{k_l} \in G\left(\theta_{k_l}\right)$, the third one from f being continuous and the final one from $x \in G(\theta)$. Let $\underline{v}=\liminf v\left(\theta_n\right)$ and by a similar argument we get $v(\theta)=\underline{v}$ since $v(\theta)=\liminf v\left(\theta_n\right)=\limsup v\left(\theta_n\right)$ we get $v(\theta)=\lim v\left(\theta_n\right)$ for arbitrary $\left\{\theta_n\right\}$ converging to θ. This proves continuity.

□

Theorem 4. ***(ToM under convexity) Let $\Theta \subseteq \mathbb{R}^m$ and $X \subseteq \mathbb{R}^n$, let $f: \Theta \times X \rightarrow \mathbb{R}$ be a continuous function and $\Gamma: \Theta \rightrightarrows X$ a nonempty, compact valued, continuous correspondence. Define:***

$$v(\theta)=\max_{x \in \Gamma(\theta)} f(x, \theta) \quad G(\theta)=\{x \in \Gamma(\theta) \mid f(x, \theta)=v(\theta)\}$$

a If $f(\cdot, \theta)$ is concave in x for all θ and Γ is convex valued then G is convex valued.

b If $f(\cdot, \theta)$ is strictly concave in x for all θ and Γ is convex valued then G is single valued, hence a continuous function.

c If f is concave on $\Theta \times X$ and Γ has a convex graph then v is concave and G is convex valued.

d If f is strictly concave on $\Theta \times X$ and Γ has a convex graph then v is strictly concave and G is single valued, hence a continuous function.

Theorem 5. ***Kakutani's Fixed Point Theorem – u.h.c. correspondence***

Let $S \subset \mathbb{R}^n$ be nonempty, compact, and convex, and $\Gamma : S \rightrightarrows S$ be a nonempty, convex-valued, and u.h.c. correspondence.
Then Γ has a fixed point in S, i.e. $\exists x^* \in S : x^* \in \Gamma(x^*)$

Since S is compact, u.h.c. is equivalent to Γ having a closed graph.

Example 6. *Under standard assumptions, prove the following properties of $\mathrm{BR}^i_{A^i}(s)$:*
i) non-empty valued,
ii) compact valued,
iii) upper hemi continuous.
iv) Is it convex-valued?

Example 7. *Under standard assumptions, prove the following properties of $\mathrm{BR}_i(s)$:*
i) non-empty valued,
ii) compact valued,
iii) upper hemi continuous.
iv) Is it convex-valued?

Proof. (i)Take any $s \in S$. Then $BR^i(s) = \arg\max_{r^i \in S^i} u^i\left(r^i, s^{-i}\right)$. Since $u^i\left(\cdot, s^{-i}\right)$ is continuous and $S^i = \Delta\left(A^i\right)$ is compact, by the Weierstrass Theorem u^i achieves a maximum on S^i. Hence, $BR^i(s)$ is nonempty. Since s has been arbitrary, $BR^i(\cdot)$ is nonempty-valued.

(ii) Fix $s \in S$ arbitrarily and take any sequence $\left(r^i_m\right) \in BR^i(s)^\infty$ that converges in S^i, i.e. $r^i_m \rightarrow r^i \in S^i$. By definition we have $u^i\left(r^i_m, s^{-i}\right) \geq u^i\left(t^i, s^{-i}\right) \forall t^i \in S^i, m \in \mathbb{N}$. Then since $u^i\left(\cdot, s^{-i}\right)$ is continuous,

$$u^i\left(r^i, s^{-i}\right) = u^i\left(\lim_{m\to\infty} r^i_m, s^{-i}\right) = \lim_{m\to\infty} u^i\left(r^i_m, s^{-i}\right) \geq u^i\left(t^i, s^{-i}\right) \quad \forall t^i \in S^i$$

Hence, $r^i \in BR^i(s)$. Since s has been arbitrary, $BR^i(\cdot)$ is closed-valued.

(iii) Since S^i (the range of $BR^i(\cdot)$) is compact, it is sufficient to establish that $BR^i(\cdot)$ has a closed graph. Fix $s \in S$ arbitrarily and take any sequences $(s_m) \in S^\infty$ and $\left(r^i_m\right) \in S^{i\infty}$ with $s_m \rightarrow s \in S, r^i_m \rightarrow r^i \in S^i$ and $r^i_m \in BR^i\left(s_m\right) \forall m \in \mathbb{N}$. Then $u^i\left(r^i_m, s^{-i}_m\right) \geq u^i\left(t^i, s^{-i}_m\right), \forall t^i \in S^i$. Since $u^i(\cdot,\cdot)$ is continuous it follows that $\forall t^i \in S^i$

$$\begin{aligned} u^i\left(r^i, s^{-i}\right) = u^i\left(\lim_{m\to\infty} r^i_m, \lim_{m\to\infty} s^{-i}_m\right) &= \lim_{m\to\infty} u^i\left(r^i_m, s^{-i}_m\right) \\ &\geq \lim_{m\to\infty} u^i\left(t^i, s^{-i}_m\right) \\ &= u^i\left(t^i, \lim_{m\to\infty} s^{-i}_m\right) \\ &= u^i\left(t^i, s^{-i}\right) \end{aligned}$$

Hence, $r^i \in BR^i(s)$ and $BR^i(\cdot)$ is closed at s. Since s has been arbitrary, $BR^i(\cdot)$ has a closed graph.

(iv) Fix $s \in S$ arbitrarily and take any $r_a^i, r_b^i \in BR^i(s)$ and $\lambda \in (0,1)$. Then it must be that $u^i\left(r_a^i, s^{-i}\right) = u^i\left(r_b^i, s^{-i}\right) \geq u^i\left(r^i, s^{-i}\right) \forall r^i \in S^i$. Or, equivalently,

$$\sum_{a^i \in A^i} r_a^i\left(a^i\right) u^i\left(a^i, s^{-i}\right) = \sum_{a^i \in A^i} r_b^i\left(a^i\right) u^i\left(a^i, s^{-i}\right) \geq \sum_{a^i \in A^i} r^i\left(a^i\right) u^i\left(a^i, s^{-i}\right) \quad \forall r^i \in S^i$$

Now consider the mixed strategy $\lambda r_a^i + (1-\lambda) r_b^i$. The utility of this strategy profile is

$$\begin{aligned} u^i\left[\lambda r_a^i + (1-\lambda) r_b^i, s^{-i}\right] &= \sum_{a^i \in A^i} \left[\lambda r_a^i\left(a^i\right) + (1-\lambda) r_b^i\left(a^i\right)\right] u^i\left(a^i, s^{-i}\right) \\ &= \lambda \sum_{a^i \in A^i} r_a^i\left(a^i\right) u^i\left(a^i, s^{-i}\right) + (1-\lambda) \sum_{a^i \in A^i} r_b^i\left(a^i\right) u^i\left(a^i, s^{-i}\right) \\ &= \sum_{a^i \in A^i} r_a^i\left(a^i\right) u^i\left(a^i, s^{-i}\right) \\ &\geq u^i\left(r^i, s^{-i}\right) \quad \forall r^i \in S^i, \end{aligned}$$

where the third line follows from (2) and the inequality holds since $r_a^i \in BR^i(s)$. Hence, $\lambda r_a^i + (1-\lambda) r_b^i \in BR^i(s)$ and, since s has been arbitrary, $BR^i(\cdot)$ is convex-valued. □

Lemma 21 (Properties of Best Response Correspondence)**.** *$BR^i : S \rightrightarrows S^i$ is nonempty-valued, compact-valued, convex-valued, and upper hemicontinuous.*

Proof. Assume A^i is nonempty and finite. Then recall BR^i is the argmax of the problem (for a given s^{-i})

$$\max_{s^i \in S^i} u^i\left(s^i, s^{-i}\right)$$

then by Berge theorem we have that $BR^i : S \rightrightarrows S^i$ is nonempty-valued, compact-valued, convex-valued, and upper hemicontinuous. □

Theorem 6 (Existence of Nash Equilibrium 1950)**.** ***The correspondence $BR : S \rightrightarrows S$ defined by $BR(s) = X_{i \in I} BR^i(s)$ is***

(1) nonempty-valued

(2) closed-valued

(3) convex-valued

(4) upper hemicontinous.

Proof. Fix $s = \left(s^1, s^2, \ldots, s^n\right) \in S$ arbitrarily.
(1) BR maps s into the set $BR^1(s) \times BR^2(s) \times \cdots \times BR^n(s)$. Since each $BR^i(s), i \in I$, is nonempty and I is finite, we can choose an element $r^i \in BR^i(s)$ for each $i \in I$. Then $\left(r^1, r^2, \ldots, r^n\right) \in BR^1(s) \times \cdots \times BR^n(s) = BR(s)$. Then, since s has been arbitrary, $BR(s)$ is nonempty for all $s \in S$. Hence, BR is nonempty-valued.

(2) Take any $r_a, r_b \in BR(s)$ and $\lambda \in (0,1)$. Then

$$\lambda r_a + (1-\lambda) r_b = \left(\lambda r_a^1 + (1-\lambda) r_b^1, \ldots, \lambda r_a^n + (1-\lambda) r_b^n\right)$$

Since for each $i \in I$ the set $BR^i(s)$ is convex, $\lambda r_a^i + (1-\lambda) r_b^i \in BR^i(s) \forall i \in I$. Then $\lambda r_a + (1-\lambda) r_b \in BR(s)$ and, hence, $BR(s)$ is a convex set for all $s \in S$, i.e., BR is convex- valued.

(3) Take any point $v = (v^1, \ldots, v^n) \notin BR(s)$. Then for some $i \in I, v^i \notin BR^i(s)$. Since $BR^i(S)$ is closed in S^i, v^i is not a limit point of $BR^i(s)$. That is, there exists an open set ${}^1U^i \subset S^i$ containing v^i that contains no more than a finite number of points of $BR^i(s)$. Now, $\forall j \neq i$, choose any $U^j \subset S^j$. Then the neighborhood $U = X_{i \in I} U^i$ of v contains no more than a finite number of points of $BR(s)$, i.e. v is not a limit point of $BR(s)$. Since v has been arbitrary, for all $v \notin BR(s) v$ is not a limit point of $BR(s)$, which implies that $BR(s)$ contains all of its limit points and is, hence, closed in S.

Since $S^i \subset \mathbb{R}_+^{m_i}, \forall i \in I$, where m_i is the cardinality of A^i, I consider each S^i as a metric subspace of $\mathbb{R}^{m_i}$ with the Euclidean metric. Then $S = \mathrm{X}_{i \in I} S^i$ is considered as a metric subspace with the usual product metric.

(4) Take any sequences $(s_m), (r_m) \in S^\infty$ such that $s_m \to s$ and $r_m \in BR(s_m) \forall m$.[2] Then for all $i \in I, (s_m^i), (r_m^i) \in S^{i\infty}, s_m^i \to s^i$, and $r_m^i \in BR^i(s_m) \forall m$. Since BR^i is u.h.c., this implies that there exists a subsequence $r_{m_k}^i \to r^i \in BR^i(s)$. Then the sequence $r_{m_k} = (r_{m_k}^1, \ldots, r_{m_k}^n)$ of r_m converges to $r = (r^1, \ldots, r^n) \in BR^1(s) \times \cdots \times BR^n(s)$. Hence, BR is upper hemicontinuous

□

1.8 Zero sum games

Definition 40. *A two players finite action normal form game is zero sum if the sum of the utilities of the two players is equal to 0 for any action profile, so* $u^1 = -u^2$*.*

Theorem 7 (Minimax- von Neumann 1928)**.** ***For any 2-player zero-sum game,***

$$\min_{\alpha^2 \in \Delta(A^2)} \max_{\alpha^1 \in \Delta(A^1)} u(\alpha^1, \alpha^2) = \max_{\alpha^1 \in \Delta(A^1)} \min_{\alpha^2 \in \Delta(A^2)} u(\alpha^1, \alpha^2) \equiv v$$

Proof. We will do it in two steps: First we will prove that $\geq$ holds. Secondly that $\leq$ holds.

$\geq$. Note that for any $\bar{s}^1 \in \Delta(A^1)$ and $\bar{s}^2 \in \Delta(A^2)$ it holds that:

$$u(\bar{s}^1, \bar{s}^2) \geq \min_{s^2 \in \Delta(A^2)} u(\bar{s}^1, s^2)$$

Then by taking maximum at both sides with respect to s^1 :

$$\max_{s^1 \in \Delta(A^1)} u(s^1, \bar{s}^2) \geq \max_{s^1 \in \Delta(A^1) s^2 \in \Delta(A^2)} \min_x u(s^1, s^2)$$

Note that the RHS is now constant, and a lower bound to the LHS across s^2, then:

$$\min_{s^2 \in \Delta(A^2)} \max_{s^1 \in \Delta(A^1)} u(s^1, s^2) \geq \max_{s^1 \in \Delta(A^1)} \min_{s^2 \in \Delta(A^2)} u(s^1, s^2) \tag{1}$$

$\leq$. Note that for any $\bar{s}^1 \in \Delta\left(A^1\right)$ it holds that:

$$\max_{s^1\in\Delta(A^1)} \min_{s^2\in\Delta(A^2)} u\left(s^1, s^2\right) \geq \min_{s^2\in\Delta(A^2)} u\left(\bar{s}^1, s^2\right)$$

In particular for $\hat{s}^1$ a NE of the game the inequality must hold. We assume that such NE exists in mixed strategies. Note that if $\left(\hat{s}^1, \hat{s}^2\right)$ it is defined as an strategy profile such that:

$$u\left(\hat{s}^1, \hat{s}^2\right) = \max_{s^1\in\Delta(A^1)} u\left(s^1, \hat{s}^2\right) \quad -u\left(\hat{s}^1, \hat{s}^2\right) = \max_{s^2\in\Delta(A^2)} -u\left(\hat{s}^1, s^2\right)$$

The second condition implies:

$$u\left(\hat{s}^1, \hat{s}^2\right) = \min_{s^2\in\Delta(A^2)} u\left(\hat{s}^1, s^2\right) = \max_{s^1\in\Delta(A^1)} u\left(s^1, \hat{s}^2\right)$$

thus

$$\begin{aligned}
\min_{s^2\in\Delta(A^2)} u^1\left(\hat{s}^1, s^2\right) &= u^1\left(\hat{s}^1, \operatorname*{argmin}_{s^2\in\Delta(A^2)} u^1\left(\hat{s}^1, s^2\right)\right) \\
&= u^1\left(\hat{s}^1, \operatorname*{argmax}_{s^2\in\Delta(A^2)} u^2\left(\hat{s}^1, s^2\right)\right) \\
&= u^1\left(\hat{s}^1, \hat{s}^2\right) \\
&= \max_{s^1\in\Delta(A^1)} u^1\left(s^1, \hat{s}^2\right) \\
&\geq \min_{s^2\in\Delta(A^2)} \max_{s^1\Delta(A^1)} u^1\left(s^1, s^2\right)
\end{aligned}$$

Then by taking max over $\Delta\left(A^1\right)$:

$$\max_{s^1\in\Delta(A^1)} \min_{s^2\in\Delta(A^2)} u\left(s^1, s^2\right) \geq \min_{s^1\in\Delta(A^1)} u\left(s^1, \hat{s}^2\right) \geq \min_{s^2\in\Delta(A^2)} \max_{s^1\in\Delta(A^1)} u\left(s^1, s^2\right) \tag{2}$$

Inequalities (1) and (2) gives us thesis of minimax theorem. □

Definition 41. *For a zero sum game of two players define the value of the game as $V : \mathbb{R}^{nm} \to \mathbb{R}$ (where $n = \#A^1$ and $m = \#A^2$) :*

$$V(u) = \max_{s^1\in\Delta(A^1)} \min_{s^2\in\Delta(A^2)} U\left(s^1, s^2 \mid u\right)$$

where for a given strategy profile $s^1 = (p_1, \ldots, p_n)$, $s^2 = (q_1, \ldots, q_n)$ and payoffs $u \in \mathbb{R}^{nm}$ we define

$$U\left(s^1, s^2 \mid u\right) = \sum_{i=1}^{n} \sum_{j=1}^{m} p_i q_j u_{ij}$$

Lemma 22. *Show that **The value of a game** is*

a) continuous

b) non-decreasing

c) homogenous of degree one in payoffs.

- Consider the problem:

$$v\left(s^1, u\right) = \min_{s^2\in\Delta(A^2)} U\left(s^1, s^2 \mid u\right)$$

note that U is continuous in s_1, s_2 and u and that the minimum is being taken over s^2 in a compact set that does not vary with s^1 or u. By the theorem of the maximum the value of this problem, as a function of s^1 and u is a continuous function. Now consider:

$$V(u) = \max_{s^1 \in \Delta(A^1)} \min_{s^2 \in \Delta(A^2)} U\left(s^1, s^2 \mid u\right) = \max_{s^1 \in \Delta(A^1)} v\left(s^1, u\right)$$

again since v is continuous and s^1 varies in a compact set independent of u by the theorem of the maximum V is a continuous function of u.

- Let $u_1 \leq u_2$. Clearly for all s^1, s^2:

$$U\left(s^1, s^2 \mid u_1\right) = \sum_{i=1}^{n} \sum_{j=1}^{m} p_i q_j u_{ij}^1 \leq U\left(s^1, s^2 \mid u_1\right) = \sum_{i=1}^{n} \sum_{j=1}^{m} p_i q_j u_{ij}^2$$

so $U\left(s^1, s^2 \mid u_1\right) \leq U\left(s^1, s^2 \mid u_2\right)$. Then:

$$\min_{s^2 \in \Delta(A^2)} U\left(s^1, s^2 \mid u_1\right) \leq \min_{s^2 \in \Delta(A^2)} U\left(s^1, s^2 \mid u_2\right)$$
$$V\left(u_1\right) = \max_{s^1 \in \Delta(A^1)} \min_{s^2 \in \Delta(A^2)} U\left(s^1, s^2 \mid u_1\right) \leq \max_{s^1 \in \Delta(A^1)} \min_{s^2 \in \Delta(A^2)} U\left(s^1, s^2 \mid u_2\right) = V\left(u_2\right)$$

- Let $\lambda \in \mathbb{R}$, note that $U\left(s^1, s^2 \mid \lambda u\right) = \sum_{i=1}^{n} \sum_{j=1}^{m} p_i q_j \lambda u_{ij} = \lambda U\left(s^1, s^2 \mid u\right)$ and $\max_x \lambda f(x) = \lambda \max_x f(x)$. Thus $V(\lambda u) = \lambda V(u)$