Cooperative Games

Lecture 5: The nucleolus

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Today

- We consider one way to compare two imputations.
- We define the Nucleolus and look at some properties.
- We prove important properties of the nucleolus, which requires some elements of analysis.

Excess of a coalition

Definition (Excess of a coalition)

Let (N,v) be a TU game, $\mathcal{C} \subseteq N$ be a coalition, and x be a payoff distribution over N. The **excess** $e(\mathcal{C},x)$ of coalition $\mathcal{C}$ at x is the quantity $e(\mathcal{C},x) = v(\mathcal{C}) - x(\mathcal{C})$.

An example: let $N = \{1,2,3\}$, $\mathcal{C} = \{1,2\}$, $v(\{1,2\}) = 8$, $x = \langle 3,2,5\rangle$, $e(\mathcal{C},x) = v(\{1,2\}) - (x_1+x_2) = 8-(3+2) = 3$.

We can interpret a positive excess ($e(\mathcal{C},x) \geqslant 0$) as the amount of **dissatisfaction** or **complaint** of the members of $\mathcal{C}$ from the allocation x.

We can use the excess to define the core:
$Core(N,v) = \{x \in \mathbb{R}^n \mid x \text{ is an imputation and } \forall \mathcal{C} \subseteq N, e(\mathcal{C},x) \leqslant 0\}$

This definition shows that no coalition has any complaint: each coalition's demand can be granted.

$N = \{1,2,3\}$, $v(\{i\}) = 0$ for $i \in \{1,2,3\}$
$v(\{1,2\}) = 5$, $v(\{1,3\}) = 6$, $v(\{2,3\}) = 6$
$v(N) = 8$

Let us consider two payoff vectors $x = \langle 3,3,2\rangle$ and $y = \langle 2,3,3\rangle$.
Let $e(x)$ denote the sequence of **excesses** of all coalitions at x.

$x = \langle 3,3,2\rangle$

coalition $\mathcal{C}$	$e(\mathcal{C},x)$
{1}	-3
{2}	-3
{3}	-2
{1,2}	-1
{1,3}	1
{2,3}	1
{1,2,3}	0

$y = \langle 2,3,3\rangle$

coalition $\mathcal{C}$	$e(\mathcal{C},y)$
{1}	-2
{2}	-3
{3}	-3
{1,2}	0
{1,3}	1
{2,3}	0
{1,2,3}	0

Which payoff should we prefer? x or y? Let us write the excess in the decreasing order (from the greatest excess to the smallest)

$\langle 1,1,0,-1,-2,-3,-3\rangle$ $\langle 1,0,0,0,-2,-3,-3\rangle$

Definition (lexicographical order of $\mathbb{R}^m$ $\geqslant_{lex}$)

Let $\geqslant_{lex}$ denote the **lexicographical** ordering of $\mathbb{R}^m$, i.e., $\forall (x,y) \in \mathbb{R}^m$, $x \geqslant_{lex} y$ iff

$$\begin{cases} x=y \text{ or} \\ \exists t \text{ s. t. } 1 \leqslant t \leqslant m \text{ and } \forall i \text{ s. t. } 1 \leqslant i < t \; x_i = y_i \text{ and } x_t > y_t \end{cases}$$

example: $\langle 1,1,0,-1,-2,-3,-3\rangle \geqslant_{lex} \langle 1,0,0,0,-2,-3,-3\rangle$
Let l be a sequence of m reals. We denote by $l^{\blacktriangleright}$ the **reordering** of l in **decreasing** order.

In the example, $e(x) = \langle -3,-3,-2,-1,1,1,0\rangle$ and then $e(x)^{\blacktriangleright} = \langle 1,1,0,-1,-2,-3,-3\rangle$.

Hence, we can say that y is better than x by writing

$$e(x)^{\blacktriangleright} \geqslant_{lex} e(y)^{\blacktriangleright}.$$

Some properties of $\leqslant_{lex}$ and its strict version

- $\forall x \in \mathbb{R}^m$ $x \leqslant_{lex} x^{\blacktriangleright}$
- $\forall x \in \mathbb{R}^m$ and any permutation σ of $\{1,\dots,m\}$, $\sigma(x) \leqslant_{lex} x^{\blacktriangleright}$
- $\forall x,y,u,v \in \mathbb{R}^m$ and $\alpha > 0$
  - $x \leqslant_{lex} y \Rightarrow \alpha x \leqslant_{lex} \alpha y$
  - $x <_{lex} y \Rightarrow \alpha x <_{lex} \alpha y$
  - $(x \leqslant_{lex} y \wedge u \leqslant_{lex} v) \Rightarrow x+u \leqslant_{lex} y+v$
  - $(x <_{lex} y \wedge u \leqslant_{lex} v) \Rightarrow x+u <_{lex} y+v$
  - $x \leqslant_{lex} y$ we **cannot** conclude anything for the comparison between $-\alpha x$ and $-\alpha y$.

Definition (Nucleolus)

Let (N,v) be a TU game.
Let $\mathcal{I}mp$ be the set of all imputations.
The **nucleolus** $Nu(N,v)$ is the set
$Nu(N,v) = \left\{x \in \mathcal{I}mp \mid \forall y \in \mathcal{I}mp \;\; e(y)^{\blacktriangleright} \geqslant_{lex} e(x)^{\blacktriangleright}\right\}$

An alternative definition in terms of objections and counter-objections

Let (N,v) be a TU game. **Objections** are made by **coalitions** instead of individual agents. Let $P \subseteq N$ be a coalition that expresses an objection.

A pair (P,y), in which $P \subseteq N$ and y is an imputation, is an **objection** to x iff $e(P,x) > e(P,y)$.

Our excess for coalition P is too large at x, payoff y reduces it.

A coalition (Q,y) is a **counter-objection** to the objection (P,y) when $e(Q,y) > e(Q,x)$ and $e(Q,y) \geqslant e(P,x)$.

Our excess under y is larger than it was under x for coalition Q! Furthermore, our excess at y is larger than what your excess was at x!

An imputation fails to be stable if the excess of some coalition P can be reduced without increasing the excess of some other coalition to a level at least as large as that of the original excess of P.

Definition (Nucleolus)

Let (N,v) be a TU game. The **nucleolus** is the set of imputations x such that for every objection (P,y), there exists a counter-objection (Q,y).

M.J. Osborne and A. Rubinstein. **A course in game theory**, *MIT Press*, 1994, Section 14.3.3.

a detour: ϵ-core and least-core

Definition (ϵ-core)

A payoff distribution is in the ϵ-core of the superadditive game (N,v) for some $\in \mathbb{R}$ if $x(C) \geqslant v(\mathcal{C}) - \epsilon$.

Definition (least-core)

Let $\epsilon^\star(G) = inf\{\epsilon \in \mathbb{R} | \epsilon\text{-core of G is non-empty }\}$

The **least-core** of G is the $\epsilon^\star(G)$-core.

$$(LP)\left\{\begin{array}{l}\text{minimize } \epsilon \\ \text{subject to } \left\{\begin{array}{l} x_i \geqslant 0 \text{ for each } i \in N \\ \sum_{j\in N} x_j = v(N) \\ \sum_{j\in \mathcal{C}} x_j \geqslant v(\mathcal{C}) - \epsilon \text{ for each } \mathcal{C} \subseteq N \end{array}\right.\end{array}\right.$$

Definition (Nucleolus)

A payoff vector x is in the nucleolus of the game (N,v) if it is the solution of optimization programs $O_1,\ldots,O_{|N|}$ where these programs are defined recursively as follows:

$$(O_1)\left\{\begin{array}{l}\text{minimize } \epsilon \\ \text{subject to } \sum_{i\in S} x_i \geqslant v(S) - \epsilon \;\; \forall S \subset N\end{array}\right.$$

$$(O_i)\left\{\begin{array}{l}\text{minimize } \epsilon \\ \text{subject to } \left\{\begin{array}{l} \sum_{j\in S} x_j \geqslant v(S) - \epsilon_0 \;\; \forall S \in S_1 \\ \vdots \\ \sum_{j\in S} x_j \geqslant v(S) - \epsilon_{i-1} \;\; \forall S \in S_{i-1} \setminus S_{i-2} \\ \sum_{j\in S} x_j \geqslant v(S) - \epsilon \;\; \forall S \in 2^N \setminus S_{i-1} \end{array}\right.\end{array}\right.$$

where ϵ_{i-1} is the optimal objective value to program O_{i-1} and S_{i-1} is the set of coalitions for which the constraints are realized as equalities in the optimal solution to O_{i-1}.

Theorem

Let (N,v) be a TU game with a non-empty core. Then $Nu(N,v) \subseteq Core(N,v)$

Proof

This will be part of homework 2 □

Theorem

Let (N,v) be a superadditive game and $\mathcal{I}mp$ be its set of imputations. Then, $\mathcal{I}mp \neq \emptyset$.

Proof

Let (N,v) be a superadditive game.
Let x be a payoff distribution defined as follows:
$x_i = v(\{i\}) + \frac{1}{|N|}\left(v(N) - \sum_{j\in N} v(\{j\})\right)$.

- $v(N) - \sum_{j\in N} v(\{j\}) > 0$ since (N,v) is superadditive.
- It is clear x is individually rational ✔
- It is clear x is efficient ✔

Hence, $x \in \mathcal{I}mp$. □

Theorem (Non-emptyness of the nucleolus)

Let (N,v) be a TU game, if $\mathcal{I}mp \neq \emptyset$,
then the nucleolus $Nu(N,v)$ is **non-empty**.

Element of Analysis

Let $E = \mathbb{R}^m$ and $X \subseteq E$. $||.||$ denote a distance in E, e.g., the euclidean distance.
We consider functions of the form $u : \mathbb{N} \to \mathbb{R}^m$. Another viewpoint on u is an infinite **sequence** of elements indexed by natural numbers $(u_0, u_1, \ldots, u_k, \ldots)$ where $u_i \in X$.

- **convergent sequence:** A sequence (u_t) converges to $l \in \mathbb{R}^m$ iff for all $\epsilon > 0$, $\exists T \in \mathbb{N}$ s.t. $\forall t \geqslant T$, $||u_t - l|| \leqslant \epsilon$.
- **extracted sequence:** Let (u_t) be an infinite sequence and $f : \mathbb{N} \to \mathbb{N}$ be a monotonically increasing function. The sequence v is extracted from u iff $v = u \circ f$, i.e., $v_t = u_{f(t)}$.
- **closed set:** a set X is closed if and only if it contains all of its limit points.
i.e. for all converging sequences $(x_0, x_1 \ldots)$ of elements in X, the limit of the sequence has to be in X as well.
An example: if $X = (0,1]$, $(1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \ldots, \frac{1}{n}, \ldots)$ is a converging sequence. However, 0 is not in X, and hence, X is not closed.
"A closed set contains its borders".

Element of Analysis

- **bounded set:** A subset $X \subseteq \mathbb{R}^m$ is **bounded** if it is contained in a ball of finite radius, i.e. $\exists c \in \mathbb{R}^m$ and $\exists r \in \mathbb{R}^+$ s.t. $\forall x \in X$ $||x - c|| \leqslant r$.
- **compact set:** A subset $X \subseteq \mathbb{R}^m$ is a **compact** set iff from all sequences in X, we can extract a convergent sequence in X.
- A set is **compact** set of $\mathbb{R}^m$ iff it is **closed** and **bounded**.
- **convex set:** A set X is convex iff $\forall (x,y) \in X^2$, $\forall \alpha \in [0,1]$, $\alpha x + (1-\alpha)y \in X$ (i.e. all points in a line from x to y is contained in X).
- **continuous function:** Let $X \subseteq \mathbb{R}^n$, $f : \mathbb{R}^n \to \mathbb{R}^m$.
f is **continuous at $x_0 \in X$** iff $\forall \epsilon \in \mathbb{R}$, $\epsilon > 0$, $\exists \delta \in \mathbb{R}$, $\delta > 0$ s.t. $\forall x \in X$ s.t. $||x - x_0|| < \delta$, we have $||f(x) - f(x_o)|| < \epsilon$, i.e. $\forall \epsilon > 0$ $\exists \delta > 0$ $\forall x \in X$ $\;||x - x_0|| < \delta \Rightarrow ||f(x) - f(x_0)|| < \epsilon$.

Element of Analysis

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

Thm A_1 If $f : \mathbb{R}^n \to \mathbb{R}^m$ is continuous and $X \subseteq E$ is a non-empty compact subset of $\mathbb{R}^n$, then $f(X)$ is a non-empty compact subset of $\mathbb{R}^m$.

Thm A_2 Extreme value theorem: Let X be a non-empty compact subset of $\mathbb{R}^n$, $f : X \to \mathbb{R}$ a **continuous** function. Then f is bounded and it reaches its supremum.

Thm A_3 Let X be a non-empty compact subset of $\mathbb{R}^n$. $f : X \to \mathbb{R}$ is continuous iff for every closed subset $B \subseteq \mathbb{R}$, the set $f^{-1}(B)$ is compact.

Proof of non-emptyness of the nucleolus

Assume we have the following theorems 1 and 2 (we will prove them in the next slide).

Theorem (1)

Let A be a non-empty compact subset of $\mathbb{R}^m$.
$\{x \in A \mid \forall y \in A \; x \leqslant_{lex} y\}$ is non-empty.

Theorem (2)

Assume we have a TU game (N,v), and consider its set $\mathcal{I}mp$.
If $\mathcal{I}mp \neq \emptyset$, then set $B = \{e(x)^{\blacktriangleright} \mid x \in \mathcal{I}mp\}$ is a non-empty compact subset of $\mathbb{R}^{2^{|N|}}$

Let us take a TU game (N,v) and let us assume $\mathcal{I}mp \neq \emptyset$. Then B in theorem 2 is a non-empty compact subset of $\mathbb{R}^{2^{|N|}}$. Now let A in theorem 1 be B in theorem 2. So $\{e(x)^{\blacktriangleright} \mid (x \in \mathcal{I}mp) \wedge (\forall y \in \mathcal{I}mp \; e(x)^{\blacktriangleright} \leqslant_{lex} e(y)^{\blacktriangleright})\}$ is non-empty. From this, it follows that:
$Nu(N,v) = \{x \in \mathcal{I}mp \mid \forall y \in \mathcal{I}mp \; e(y)^{\blacktriangleright} \geqslant_{lex} e(x)^{\blacktriangleright}\} \neq \emptyset$. ✔

Proof of theorem 2

Let (N,v) be a TU game and consider its set $\mathcal{I}mp$. Let us assume that $\mathcal{I}mp \neq \emptyset$ to prove that $B = \{e(x)^{\blacktriangleright} \mid x \in \mathcal{I}mp\}$ is a non-empty compact subset of $\mathbb{R}^{2^{|N|}}$.

First, let us prove that $\mathcal{I}mp$ is a non-empty compact subset of $\mathbb{R}^{|N|}$.

- $\mathcal{I}mp$ non-empty by assumption.
- To see that $\mathcal{I}mp$ is bounded, we need to show that for all i, x_i is bounded by some constant (independent of x). We have $v(\{i\}) \leqslant x_i$ (ind. rational) and $x(N) = v(N)$ (efficient). Then $x_i + \sum_{j=1, j\neq i}^{n} v(\{j\}) \leqslant v(N)$, hence $x_i \leqslant v(N) - \sum_{j=1, j \neq i}^{n} v(\{j\})$.
- $\mathcal{I}mp$ is closed (the boundaries of $\mathcal{I}mp$ are members of $\mathcal{I}mp$).

This proves that $\mathcal{I}mp$ is a non-empty compact subset of $\mathbb{R}^{|N|}$.

Thm A$_1$ If $f: E \to \mathbb{R}^m$ is continuous, $X \subseteq E$ is a non-empty compact subset of $\mathbb{R}^n$, then $f(X)$ is a non-empty compact subset of $\mathbb{R}^m$.

$e()^{\blacktriangleright}$ is a continuous function and $\mathcal{I}mp$ is a non-empty and compact subset of $\mathbb{R}^{2^{|N|}}$. Using thm A$_1$, $e(\mathcal{I}mp)^{\blacktriangleright} = \{e(x)^{\blacktriangleright} | x \in \mathcal{I}mp\}$ is a non-empty compact subset of $\mathbb{R}^{2^{|N|}}$.

Proof of theorem 1

For a non-empty compact subset A of $\mathbb{R}^m$, we need to prove that the set $\{x \in A \mid \forall y \in A \;\; x \leqslant_{lex} y\}$ is non-empty.

First, let $\pi_i: \mathbb{R}^m \to \mathbb{R}$ the projection function s.t. $\pi_i(x_1, \ldots, x_m) = x_i$.

Then, let us define the following sets:

$$\begin{cases} A_0 = A \\ A_{i+1} = \operatorname{argmin}_{x \in A_i} \pi_{i+1}(x) \\ i \in \{0, 1, \ldots, m-1\} \end{cases}$$

- $A_0 = A$
- $A_1 = \operatorname{argmin}_{x \in A} \pi_1(x)$ is the set of elements in A with the smallest first entry in the sequence.
- $A_2 = \operatorname{argmin}_{x \in A_1} \pi_2(x)$ composed of the elements that have the smallest second entry among the elements with the smallest first entry
- …
- $A_m = \{x \in A \mid \forall y \in A \;\; x \leqslant_{lex} y\}$

We want to prove by induction that each A_i is non-empty compact subset of $\mathbb{R}^m$ for $i \in \{1, \ldots, m\}$ to prove that A_m is non-empty.

Proof of theorem 1

- $A_0 = A$ is non-empty compact of $\mathbb{R}^m$ by hypothesis ✔.
- Let us assume that A_i is a non-empty compact subset of $\mathbb{R}^m$ and let us prove that A_{i+1} is a non-empty compact subset of $\mathbb{R}^m$. π_{i+1} is a continuous function and A_i is a non-empty compact subset of $\mathbb{R}^m$.

  Thm A$_2$: Extreme value theorem: Let X be a non-empty compact subset of $\mathbb{R}^m$, $f: X \to \mathbb{R}$ a **continuous** function.

  Using the extreme value theorem, $\min_{x \in A_i} \pi_{i+1}(x)$ exists and it is reached in A_i, hence $\operatorname{argmin}_{x \in A_i} \pi_{i+1}(x)$ is non-empty.
  Now, we need to show it is compact.
  We note by $\pi_i^{-1}: \mathbb{R} \to \mathbb{R}^m$ the inverse of π_i. Let $\alpha \in \mathbb{R}$, $\pi_i^{-1}(\alpha)$ is the set of all vectors $\langle x_1, \ldots, x_{i-1}, \alpha, x_{i+1}, \ldots, x_m\rangle$ s.t. $x_j \in \mathbb{R}$, $j \in \{1, \ldots, m\}$, $j \neq i$. We can rewrite A_{i+1} as:
  $$A_{i+1} = \pi_{i+1}^{-1}\left(\min_{x \in A_i} \pi_{i+1}(x)\right) \bigcap A_i$$

Proof of theorem 1

Thm A$_3$: Let X be a non-empty compact subset of $\mathbb{R}^n$.
$f: X \to \mathbb{R}$ is continuous iff for every closed subset $B \subseteq \mathbb{R}$, the set $f^{-1}(B)$ is compact.

$$A_{i+1} = \underbrace{\underbrace{\pi_{i+1}^{-1}\left(\left(\underbrace{\left\{\min_{x \in A_i} \pi_{i+1}(x)\right\}}_{\text{closed}}\right)\right)}_{\text{According to Thm A}_3\text{, it is a compact subset of }\mathbb{R}^m} \bigcap A_i}_{}$$

is a compact subset of $\mathbb{R}^m$ since
the intersection of two closed sets is closed and in $\mathbb{R}^m$,
and a closed subset of a compact subset of $\mathbb{R}^m$
is a compact subset of $\mathbb{R}^m$ ✔

Hence A_{i+1} is a non-empty compact subset of $\mathbb{R}^m$ and the proof is complete. □

For a TU game (N,v) the nucleolus $Nu(N,v)$ is non-empty when $\mathcal{I}mp \neq \emptyset$, which is a great property as agents will always find an agreement. But there is more!

Theorem

The nucleolus has **at most one** element

In other words, there is **one** agreement which is stable according to the nucleolus.

For a TU game (N,v), the $Nu(N,v) \neq \emptyset$ when $\mathcal{I}mp \neq \emptyset$, which is a great property as agents will always find an agreement.

Theorem

The nucleolus has **at most one** element

In other words, there is **one** agreement which is stable according to the nucleolus.

To prove this, we need theorems 3 and 4.

Theorem (3)

Let A be a non-empty convex subset of $\mathbb{R}^m$
Then the set $\{x \in A \mid \forall y \in A \;\; x^{\blacktriangleright} \leqslant_{lex} y^{\blacktriangleright}\}$ has at most one element.

Theorem (4)

Let (N,v) be a TU game such that $\mathcal{I}mp \neq \emptyset$.
(i) $\mathcal{I}mp$ is a non-empty and convex subset of $\mathbb{R}^{|N|}$
(ii) $\{e(x) \mid x \in \mathcal{I}mp\}$ is a non-empty convex subset of $\mathbb{R}^{2^{|N|}}$

Proof of Theorem 3

Let A be a non-empty convex subset of $\mathbb{R}^m$, and $M^{in} = \{x \in A \mid \forall y \in A \;\; x^{\blacktriangleright} \leqslant_{lex} y^{\blacktriangleright}\}$. We now prove that $|M^{in}| \leqslant 1$.

Towards a contradiction, let us assume M^{in} has at least two elements x and y, $x \neq y$. By definition of M^{in}, we must have $x^{\blacktriangleright} = y^{\blacktriangleright}$.

Let $\alpha \in (0,1)$ and σ be a permutation of $\{1, \ldots, m\}$ such that $(\alpha x + (1-\alpha) y)^{\blacktriangleright} = \sigma(\alpha x + (1-\alpha)y) = \alpha\sigma(x) + (1-\alpha)\sigma(y)$.
Let us show by contradiction that $\sigma(x) = x^{\blacktriangleright}$ and $\sigma(y) = y^{\blacktriangleright}$.

Let us assume that either $\sigma(x) <_{lex} x^{\blacktriangleright}$ or $\sigma(y) <_{lex} y^{\blacktriangleright}$, it follows that $\alpha\sigma(x) + (1-\alpha)\sigma(y) <_{lex} \alpha x^{\blacktriangleright} + (1-\alpha) y^{\blacktriangleright} = x^{\blacktriangleright}$.
Since A is convex, $\alpha x + (1-\alpha) y \in A$. But this is a contradiction because by definition of M^{in}, $\alpha x + (1-\alpha)y \in A$ cannot be strictly smaller than $x^{\blacktriangleright}$, $y^{\blacktriangleright}$ in A. This proves $\sigma(x) = x^{\blacktriangleright}$ and $\sigma(y) = y^{\blacktriangleright}$.

Since $x^{\blacktriangleright} = y^{\blacktriangleright}$, we have $\sigma(x) = \sigma(y)$, hence $x = y$. This contradicts the fact that $x \neq y$. Hence, M^{in} cannot have at least two elements, and $|M^{in}| \leqslant 1$.

Proof Theorem 4 (i)

Let (N,v) be a TU game s.t. $\mathcal{I}mp \neq \emptyset$ (in case $\mathcal{I}mp = \emptyset$, $\mathcal{I}mp$ is trivially convex). Let $(x,y) \in \mathcal{I}mp^2$, $\alpha \in [0,1]$. Let us prove $\mathcal{I}mp$ is convex by showing that $u = \alpha x + (1-\alpha)y \in \mathcal{I}mp$, i.e., individually rational and efficient.

Individual rationality: Since x and y are individually rational, for all agents i,
$u_i = \alpha x_i + (1-\alpha)y_i \geqslant \alpha v(\{i\}) + (1-\alpha)v(\{i\}) = v(\{i\})$. Hence u is individually rational.

Efficiency: Since x and y are efficient, we have
$\sum_{i\in N} u_i = \sum_{i\in N} \alpha x_i + (1-\alpha)y_i \geqslant \alpha \sum_{i\in N} x_i + (1-\alpha)\sum_{i\in N} y_i$
$\sum_{i\in N} u_i \geqslant \alpha v(N) + (1-\alpha)v(N) = v(N)$, hence u is efficient.

Thus, $u \in \mathcal{I}mp$.

Proof Theorem 4 (ii)

Let (N,v) be a TU game and $\mathcal{I}mp$ its set of imputations. We need to show $\{e(z) \mid z \in \mathcal{I}mp\}$ is a non-empty convex subset of $\mathbb{R}^m$.
Let $(x,y) \in \mathcal{I}mp^2$, $\alpha \in [0,1]$, and $\mathcal{C} \subseteq N$ and we consider the sequence $\alpha e(x) + (1-\alpha)e(y)$, and we look at the entry corresponding to coalition $\mathcal{C}$.

$$\begin{aligned}(\alpha e(x) + (1-\alpha)e(y))_{\mathcal{C}} &= \alpha e(\mathcal{C},x) + (1-\alpha)e(\mathcal{C},y)\\ &= \alpha(v(\mathcal{C}) - x(\mathcal{C})) + (1-\alpha)(v(\mathcal{C}) - y(\mathcal{C}))\\ &= v(\mathcal{C}) - (\alpha x(\mathcal{C}) + (1-\alpha)y(\mathcal{C}))\\ &= v(\mathcal{C}) - ([\alpha x + (1-\alpha)y](\mathcal{C}))\\ &= e(\alpha x + (1-\alpha)y, \mathcal{C})\end{aligned}$$

Since the previous equality is valid for all $\mathcal{C} \subseteq N$, both sequences are equal: $\alpha e(x) + (1-\alpha)e(y) = e(\alpha x + (1-\alpha)y)$.

Since $\mathcal{I}mp$ is convex, $\alpha x + (1-\alpha)y \in \mathcal{I}mp$, it follows that $e(\alpha x + (1-\alpha)y) \in \{e(z) \mid z \in \mathcal{I}mp\}$. Hence, $\{e(z) \mid z \in \mathcal{I}mp\}$ is convex.

Proof that the nucleolus has at most one element

Let (N,v) be a TU game, and $\mathcal{I}mp$ its set of imputations.
Theorem 4(ii): $\{e(x) \mid x \in \mathcal{I}mp\}$ is a non-empty convex subset of $\mathbb{R}^{2^{|N|}}$.
Theorem 3: If A is a non-empty convex subset of $\mathbb{R}^m$, then the set $\{x \in A \mid \forall y \in A\ x^{\blacktriangleright} \leqslant_{lex} y^{\blacktriangleright}\}$ has at most one element.

Applying theorem 3 with $A = \{e(x) \mid x \in \mathcal{I}mp\}$ we obtain $B = \{e(x) \mid x \in \mathcal{I}mp \wedge \forall y \in \mathcal{I}mp\ \ e(x)^{\blacktriangleright} \leqslant_{lex} e(y)^{\blacktriangleright}\}$ has at most one element.
B is the image of the nucleolus under the function e. We need to make sure that an $e(x)$ corresponds to at most one element in $\mathcal{I}mp$. This is true since for $(x,y) \in \mathcal{I}mp^2$, we have $x \neq y \Rightarrow e(x) \neq e(y)$.

Hence $Nu(N,v) = \{x \mid x \in \mathcal{I}mp \wedge \forall y \in \mathcal{I}mp\ \ e(x)^{\blacktriangleright} \leqslant_{lex} e(y)^{\blacktriangleright}\}$ has at most one element!

Summary

- We defined the excess of a coalition at a payoff distribution, which can model the complaints of the members in a coalition.
- We used the ordered sequence of excesses over all coalitions and the lexicographic ordering to compare any two imputations.
- We defined the nucleolus for a TU game.

pros:
- If the set of imputations is non-empty, the nucleolus is non-empty.
- The nucleolus contains at most one element.
- When the core is non-empty, the nucleolus is contained in the core.

cons: Difficult to compute.

Coming next

- The **kernel**, also a member of the bargaining set family, also based on the excess.