Cooperative Games

Lecture 6: The Kernel

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One last stability concept from the bargaining set family:

The kernel.

M. Davis. and M. Maschler, **The kernel of a cooperative game**. *Naval Research Logistics Quarterly*, 1965.

Excess

Definition (Excess)

For a TU game (N, v), the excess of coalition $\mathcal{C}$ for a payoff distribution x is defined as $e(\mathcal{C}, x) = v(\mathcal{C}) - x(\mathcal{C})$.

We saw that a positive excess can be interpreted as an amount of complaint for a coalition.
We can also interpret the excess as a potential to generate more utility.

Let (N,v) be a TU game, $\mathcal{S} \in \mathscr{S}_N$ a coalition structure and x a payoff distribution. Objections and counter-objections are exchanged between **members of the same coalition** in $\mathcal{S}$. Objections and counter-objections take the form of **coalitions**, i.e., they do not propose another payoff distribution.

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Let $\mathcal{C} \in \mathcal{S}$, $k \in \mathcal{C}$, $l \in \mathcal{C}$.

Objection: A coalition $P \subseteq N$ is an objection of k against l to x iff $k \in P$, $l \notin P$ and $x_l > v(\{l\})$.

> *"P is a coalition that contains k, excludes l and which sacrifices too much (or gains too little)."*

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Counter-objection: A coalition $Q \subseteq N$ is a counter-objection to the objection P of k against l at x iff $l \in Q$, $k \notin Q$ and $e(Q, x) \geqslant e(P, x)$.

> *"k's demand is not justified: Q is a coalition that contains l and excludes k and that sacrifices even more (or gains even less)."*

A first definition

Remember that the set of feasible payoff vectors for $(N, v, \mathcal{S})$ is $X_{(N,v,\mathcal{S})} = \{x \in \mathbb{R}^n \mid \text{for every } \mathcal{C} \in \mathcal{S} : x(\mathcal{C}) \leqslant v(\mathcal{C})\}$.

Definition (Kernel)

Let $(N, v, \mathcal{S})$ be a TU game in coalition structure. The **kernel** is the set of imputations $x \in X_{(N,v,\mathcal{S})}$ s.t. for any coalition $\mathcal{C} \in \mathcal{S}$, for each objection P of an agent $k \in \mathcal{C}$ over any other member $l \in \mathcal{C}$ to x, there is a counter-objection of l to P.

Another definition

Definition (Maximum surplus)

For a TU game (N,v), the **maximum surplus** $s_{k,l}(x)$ of **agent** k **over agent** l with respect to a payoff distribution x is the **maximum excess** from a coalition that **includes** k but does **exclude** l, i.e.,

$$s_{k,l}(x) = \max_{\mathcal{C}\subseteq N \,|\, k\in\mathcal{C},\, l\notin\mathcal{C}} e(\mathcal{C},x).$$

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Definition (Kernel)

Let $(N, v, \mathcal{S})$ be a TU game with coalition structure. The **kernel** is the set of imputations $x \in X_{(N,v,\mathcal{S})}$ such that for every coalition $\mathcal{C} \in \mathcal{S}$, if $(k, l) \in \mathcal{C}^2$, $k \neq l$, then we have either $s_{kl}(x) \geqslant s_{lk}(x)$ or $x_k = v(\{k\})$.

$s_{kl}(x) < s_{lk}(x)$ calls for a transfer of utility from k to l unless it is prevented by individual rationality, i.e., by the fact that $x_k = v(\{k\})$.

Properties

Theorem

Let $(N, v, \mathcal{S})$ a game with coalition structure, and let $\mathcal{I}mp \neq \emptyset$. Then we have:

- (i) $Nu(N, v, \mathcal{S}) \subseteq K(N, v, \mathcal{S})$
- (ii) $K(N, v, \mathcal{S}) \subseteq BS(N, v, \mathcal{S})$

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Theorem

Let $(N, v, \mathcal{S})$ a game with coalition structure, and let $\mathcal{I}mp \neq \emptyset$. The kernel $K(N, v, \mathcal{S})$ and the bargaining set $BS(N, v, \mathcal{S})$ of the game are non-empty.

Proof

Since the Nucleolus is non-empty when $\mathcal{I}mp \neq \emptyset$, the proof is immediate using the theorem above. □

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$x \notin K(N,v,\mathcal{S})$, hence, there exists $\mathcal{C} \in CS$ and $(k,l) \in \mathcal{C}^2$ such that $s_{lk}(x) > s_{kl}(x)$ and $x_k > v(\{k\})$.

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Let y be a payoff distribution corresponding to a transfer of utility $\epsilon > 0$ from k to l: $y_i = \begin{cases} x_i \text{ if } i \neq k \text{ and } i \neq l \\ x_k - \epsilon \text{ if } i = k \\ x_l + \epsilon \text{ if } i = l \end{cases}$

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Since $x_k > v(\{k\})$ and $s_{lk}(x) > s_{kl}(x)$, we can choose $\epsilon > 0$ small enough s.t.

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Note that for any coalition $S \subseteq N$ s.t. $e(S,x) \neq e(S,y)$ we have either

- $k \in S$ and $l \notin S$ ($e(S,x) > e(S,y)$ since $e(S,y) = e(S,x) + \epsilon > e(S,x)$)
- $k \notin S$ and $l \in S$ ($e(S,x) < e(S,y)$ since $e(S,y) = e(S,x) - \epsilon < e(S,x)$)

Proof of (i)

Let $\{B_1(x),\dots,B_M(x)\}$ a partition of the set of all coalitions s.t.

- $(S,T) \in B_i(x)$ iff $e(S,x) = e(T,x)$. We denote by $e_i(x)$ the common value of the excess in $B_i(x)$, i.e. $e_i(x) = e(S,x)$ for all $S \in B_i(x)$.
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In other words, $e(x)^{\blacktriangleright} = \langle \underbrace{e_1(x), \dots, e_1(x)}_{|B_1(x)| times}, \dots, \underbrace{e_M(x), \dots, e_M(x)}_{|B_M(x)| times} \rangle$.

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Let i^* be the minimal value of $i \in \{1,\dots,M\}$ such that there is $\mathcal{C} \in B_{i^*}(x)$ with $e(\mathcal{C},x) \neq e(\mathcal{C},y)$.

For all $i < i^*$, we have $B_i(x) = B_i(y)$ and $e_i(x) = e_i(y)$.

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Since $s_{lk}(x) > s_{kl}(x)$ B_{i^*} contains

- at least one coalition S that contains l but not k, for such coalition, we must have $e(S,x) > e(S,y)$
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If B_{i^*} contains either

- coalitions that contain both k and l
- or coalitions that do not contain both k and l

Then, for any such coalitions S, we have $e(S,x) = e(S,y)$, and it follows that $B_{i^*}(y) \subset B_{i^*}(x)$.

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In both cases, we have $e(y)$ is lexicographically less than $e(x)$, and hence y is not in the nucleolus of the game $(N, v, \mathcal{S})$.

Proof of (ii)

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- $P \subseteq N$ is a coalition such that $i \in P$ and $j \notin P$.
- $y \in \mathbb{R}^p$ where p is the size of P
- $y(P) \leqslant v(P)$ (y is a feasible payoff for members of P)
- $\forall k \in P$, $y_k \geqslant x_k$ and $y_i > x_i$

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An **counter-objection to** (P,y) is a pair (Q,z) where

- $Q \subseteq N$ is a coalition such that $j \in Q$ and $i \notin Q$.
- $z \in \mathbb{R}^q$ where q is the size of Q
- $z(Q) \leqslant v(Q)$ (z is a feasible payoff for members of Q)
- $\forall k \in Q$, $z_k \geqslant x_k$
- $\forall k \in Q \cap P$ $z_k \geqslant y_k$

Proof of (ii)

Let (P,y) be an objection of player i against player j to x. $i \in P$, $j \notin P$, $y(P) \leqslant v(P)$ and $y(P) > x(P)$.

- $x_j = v(\{j\})$: Then $(\{j\}, v(\{j\}))$ is a counter objection to (P,y). ✔
- $x_j > v(\{j\})$: Since $x \in K(N,v,\mathcal{S})$ we have $s_{ji}(x) \geqslant s_{ij}(x) \geqslant v(P) - x(P) \geqslant y(P) - x(P)$ since $i \in P$, $j \notin P$.

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  Let $Q \subseteq N$ such that $j \in Q$, $i \notin Q$ and $s_{ji}(x) = v(Q) - x(Q)$.
  We have $v(Q) - x(Q) \geqslant y(P) - x(P)$.

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$$v(Q) \geqslant y(P) + x(Q) - x(P)$$

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$$\begin{aligned} v(Q) &\geqslant y(P) + x(Q) - x(P) \\ &\geqslant y(P \cap Q) + y(P \setminus Q) + x(Q \setminus P) - x(P \setminus Q) \end{aligned}$$

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v(Q) &\geqslant y(P) + x(Q) - x(P) \\
&\geqslant y(P \cap Q) + y(P \setminus Q) + x(Q \setminus P) - x(P \setminus Q) \\
&> y(P \cap Q) + x(Q \setminus P) \text{ since } i \in P \setminus Q,\ y(P \setminus Q) > x(P \setminus Q)
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$$\begin{aligned} v(Q) &\geqslant y(P) + x(Q) - x(P) \\ &\geqslant y(P \cap Q) + y(P \setminus Q) + x(Q \setminus P) - x(P \setminus Q) \\ &> y(P \cap Q) + x(Q \setminus P) \text{ since } i \in P \setminus Q,\ y(P \setminus Q) > x(P \setminus Q) \end{aligned}$$

Let us define z as follows $\begin{cases} x_k \text{ if } k \in Q \setminus P \\ y_k \text{ if } k \in Q \cap P \end{cases}$

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- $x_j = v(\{j\})$: Then $(\{j\}, v(\{j\}))$ is a counter objection to (P,y). ✔
- $x_j > v(\{j\})$: Since $x \in K(N,v,\mathcal{S})$ we have
  $s_{ji}(x) \geqslant s_{ij}(x) \geqslant v(P) - x(P) \geqslant y(P) - x(P)$ since $i \in P$, $j \notin P$.
  Let $Q \subseteq N$ such that $j \in Q$, $i \notin Q$ and $s_{ji}(x) = v(Q) - x(Q)$.
  We have $v(Q) - x(Q) \geqslant y(P) - x(P)$. Then, we have

$$\begin{aligned} v(Q) &\geqslant y(P) + x(Q) - x(P) \\ &\geqslant y(P \cap Q) + y(P \setminus Q) + x(Q \setminus P) - x(P \setminus Q) \\ &> y(P \cap Q) + x(Q \setminus P) \text{ since } i \in P \setminus Q,\ y(P \setminus Q) > x(P \setminus Q) \end{aligned}$$

Let us define z as follows $\begin{cases} x_k \text{ if } k \in Q \setminus P \\ y_k \text{ if } k \in Q \cap P \end{cases}$

(Q,z) is a counter-objection to (P,y). ✔

Proof of (ii)

Let (P, y) be an objection of player i against player j to x. $i \in P$, $j \notin P$, $y(P) \leqslant v(P)$ and $y(P) > x(P)$. We choose $y(P) = v(P)$.

- $x_j = v(\{j\})$: Then $(\{j\}, v(\{j\}))$ is a counter objection to (P, y). ✔
- $x_j > v(\{j\})$: Since $x \in K(N, v, \mathcal{S})$ we have $s_{ji}(x) \geqslant s_{ij}(x) \geqslant v(P) - x(P) \geqslant y(P) - x(P)$ since $i \in P$, $j \notin P$.
  Let $Q \subseteq N$ such that $j \in Q$, $i \notin Q$ and $s_{ji}(x) = v(Q) - x(Q)$.
  We have $v(Q) - x(Q) \geqslant y(P) - x(P)$. Then, we have

$$\begin{aligned} v(Q) &\geqslant y(P) + x(Q) - x(P) \\ &\geqslant y(P \cap Q) + y(P \setminus Q) + x(Q \setminus P) - x(P \setminus Q) \\ &> y(P \cap Q) + x(Q \setminus P) \text{ since } i \in P \setminus Q,\ y(P \setminus Q) > x(P \setminus Q) \end{aligned}$$

  Let us define z as follows $\begin{cases} x_k \text{ if } k \in Q \setminus P \\ y_k \text{ if } k \in Q \cap P \end{cases}$

  (Q, z) is a counter-objection to (P, y). ✔

Finally $x \in BS(N, v, \mathcal{S})$.

Computing a kernel-stable payoff distribution

- There is a transfer scheme converging to an element in the kernel.
- It may require an infinite number of small steps.
- We can consider the ϵ-kernel where the inequality are defined up to an arbitrary small constant ϵ.

R. E. Stearns. **Convergent transfer schemes for n-person games**. *Transactions of the American Mathematical Society*, 1968.

Computing a kernel-stable payoff distribution

Algorithm 1: Transfer scheme converging to a ϵ-Kernel-stable payoff distribution for the CS $\mathcal{S}$

```
compute-ϵ-Kernel-Stable(N, v, S, ϵ)
repeat
    for each coalition C ∈ S do
        for each member (i,j) ∈ C, i ≠ j do      // compute the maximum surplus
            // for two members of a coalition in S
            s_ij ← max_{R⊆N|(i∈R, j∉R)} v(R) − x(R)
    δ ← max_{(i,j)∈C², C∈S} s_ij − s_ji;
    (i*, j*) ← argmax_{(i,j)∈N²} (s_ij − s_ji);
    if (x_{j*} − v({j})) < δ/2 then              // payment should be individually rational
        d ← x_{j*} − v({j*});
    else
        d ← δ/2;
    x_{i*} ← x_{i*} + d;
    x_{j*} ← x_{j*} − d;
until δ/v(S) ⩽ ϵ;
```

- The complexity for one side-payment is $O(n \cdot 2^n)$.
- Upper bound for the number of iterations for converging to an element of the ϵ-kernel: $n \cdot log_2(\frac{\delta_0}{\epsilon \cdot v(S)})$, where δ_0 is the maximum surplus difference in the initial payoff distribution.
- To derive a polynomial algorithm, the number of coalitions must be bounded. For example, only consider coalitions which size is bounded in $[K_1, K_2]$. The complexity of the truncated algorithm is $O(n^2 \cdot n_{coalitions})$ where $n_{coalitions}$ is the number of coalitions with size in$[K_1, K_2]$, which is a polynomial of order K_2.

• M. Klusch and O. Shehory. **A polynomial kernel-oriented coalition algorithm for rational information agents**. In *Proceedings of the Second International Conference on Multi-Agent Systems*, 1996.

• O. Shehory and S. Kraus. **Feasible formation of coalitions among autonomous agents in non-superadditve environments**. *Computational Intelligence*, 1999.

Summary

- We saw another way to use the excess to make objections and counter-objections.
- We defined the kernel.
- We proved that both the kernel and the bargaining set are non-empty if the set of imputations is non-empty.

pros:
- If the set of imputations is non-empty, the nucleolus, kernel, bargaining set are non-empty.
- There is an algorithm to compute a payoff in the kernel.

cons: The algorithm is not polynomial

Coming next

- The **Shapley value**.
  It is not a stability concept, but it tries to guarantee fairness. We will see it can be defined axiomatically or using the concept of marginal contributions.