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## Size Monotonicity and Stability of the Core in Hedonic Games

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## Summary
We show that the core of each strongly size monotonic hedonic game is not empty and is externally stable. This is in sharp contrast to other sufficient conditions for core non-emptiness which do not even guarantee the existence of a stable set in such games.



**Keywords**: Core, Hedonic Games, Monotonicity, Stable Sets

**JEL Classification:** C71



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# Size monotonicity and stability of the core in hedonic games

Dinko Dimitrov* and Shao Chin Sung†

**Abstract**

We show that the core of each strongly size monotonic hedonic game is not empty and is externally stable. This is in sharp contrast to other sufficient conditions for core non-emptiness which do not even guarantee the existence of a stable set in such games.

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## 1 Introduction

A hedonic coalition formation game describes a situation in which every player's payoff depends only on the members of her coalition ([5]). Despite the simplicity of the model, it turned out that the question of the existence of a core partition, that is, a partition of the set of all players for which there is no group of individuals who can all be better off by forming a new deviating coalition, does not have an easy answer. A weak top coalition property introduced in [1] turned out to be a sufficient condition for the non-emptiness of the core of a hedonic game. This property was shown in [3] to be independent of the ordinal version

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of the well known Scarf-balancedness condition ([9]) guaranteeing the existence of a core partition as well.

Clearly, the set of all core partitions of a hedonic game is internally stable, i.e., any partition that is in the core cannot be dominated (in a sense to be defined) by another core partition. However, as we show in Section 3, neither the weak top coalition property nor the ordinal balancedness condition assure that the core enjoys external stability, i.e., it may happen that a non-member of the core is not dominated by any core partition. Moreover, there is no superset of the core of the games considered, which is both internally and externally stable; i.e., there is even no stable set ([13]) in these games. A stronger version of the weak top coalition property (the top coalition property) does not guarantee the external stability of the core, either.

In this paper we show that imposing size monotonicity on players' preferences over individually rational coalitions in hedonic games has two implications: (1) it guarantees the existence of a core partition, and (2) strengthening this condition to strong size monotonicity allows for a full characterization of the set of core partitions which turns out to be also externally stable and thus, the unique stable set (cf. Section 4). The domain of (strongly) size monotonic hedonic games includes the aversion to enemies type of preferences studied in [4], and it covers for instance situations in which a person joins a group as to increase her local status (cf. [14]).

Our work is also related to the study of core stability in two-sided matching problems and in non-transferable utility (NTU) games. Stable sets in one-to-one matching problems were studied in [6] and it was in particular shown that the (non-empty) core in such problems is the unique stable set if and only if it is a maximal set which is a lattice with the unmatched agents being identical for all matchings in the set. However, as shown in [6], this result do not extend to many-to-one matching problems. Hence, as many-to-one matching problems are special hedonic games, it is not surprising that we need a rather strong condition as to assure the external stability of the core. On the other hand, a hedonic game can be seen as an NTU game, where for each coalition the set of feasible payoff vectors is a cube (cf. [3], p. 209). Most of the literature on stable sets in NTU games is devoted to the study of the relationships between largeness (cf. [10]) and external stability of the core for the case of convex games (cf. [7, 11, 8]). For general NTU games it was shown in [2] that if the core is large, then it is a stable set. In order to establish this result, one needs however a no-level-segment condition imposed on the sets of feasible payoff vectors; this condition is clearly not satisfied when looking at a hedonic game as an NTU game.

## 2 Preliminaries

Consider a finite set of players $N = \{1, \ldots, n\}$. A *coalition* is a non-empty subset of $N$. For each player $i \in N$, by $\mathcal{N}_i = \{X \subseteq N \mid i \in X\}$ we denote the collection of all coalitions containing $i$. A collection $\mathcal{C}$ of coalitions is called a *coalition structure* if $\mathcal{C}$ is a partition of $N$, i.e., the coalitions in $\mathcal{C}$ are pairwise disjoint and $\cup_{C \in \mathcal{C}} C = N$. By $\mathbf{C}^N$ we denote the set of all coalition structures of $N$. For each coalition structure $\mathcal{C} \in \mathbf{C}^N$ and each player $i \in N$, by $\mathcal{C}(i)$ we denote the coalition in $\mathcal{C}$ which contains $i$, i.e., $\{\mathcal{C}(i)\} = \mathcal{C} \cap \mathcal{N}_i$.

We assume that each player $i \in N$ is endowed with a preference $\succeq_i$ over $\mathcal{N}_i$, i.e., a binary relation over $\mathcal{N}_i$ which is complete and transitive. We denote by $\succeq = (\succeq_1, \ldots, \succeq_n)$ a profile of preferences. Moreover, we assume that the preference of each player $i \in N$ over coalition structures is *purely hedonic*, i.e., it is completely characterized by $\succeq_i$ in such a way that, for each $\mathcal{C}, \mathcal{C}' \in \mathbf{C}^N$, player $i$ weakly prefers $\mathcal{C}$ to $\mathcal{C}'$ if and only if $\mathcal{C}(i) \succeq_i \mathcal{C}'(i)$. A *hedonic game* on a finite set $N$ of players with a preference profile $\succeq$ is denoted by the pair $(N, \succeq)$.

**Definition 1** *Let* $(N, \succeq)$ *be a hedonic game and* $\mathcal{C} \in \mathbf{C}^N$*. Then* $\mathcal{C}$ *is a* ***core partition*** *for* $(N, \succeq)$ *if there does not exist a coalition* $S$ *such that* $S \succ_i C(i)$ *for all* $i \in S$*.*

Let $(N, \succeq)$ be a hedonic game. Given two coalition structures $\mathcal{C}$ and $\mathcal{C}'$, and a coalition $S \in \mathcal{C}$, we say that $\mathcal{C}$ *dominates* $\mathcal{C}'$ *via* $S$, denoted by $\mathcal{C} \rhd_S \mathcal{C}'$, if $S = \mathcal{C}(i) \succ_i \mathcal{C}'(i)$ for all $i \in S$. Moreover, we simply say that $\mathcal{C}$ *dominates* $\mathcal{C}'$, denoted by $\mathcal{C} \rhd \mathcal{C}'$, if $\mathcal{C} \rhd_S \mathcal{C}'$ for some $S \in \mathcal{C}$.

**Definition 2** *Let* $(N, \succeq)$ *be a hedonic game and* $\mathbf{V} \subseteq \mathbf{C}^N$*. Then* $\mathbf{V}$ *is called a stable set of* $(N, \succeq)$ *if the following two conditions hold:*
*(1) (Internal stability) For all* $\mathcal{C}, \mathcal{C}' \in \mathbf{V}$*, we have* $\mathcal{C} \not\rhd \mathcal{C}'$*;*
*(2) (External stability) For all* $\mathcal{C}' \in \mathbf{C}^N \setminus \mathbf{V}$*, there is* $\mathcal{C} \in \mathbf{V}$ *such that* $\mathcal{C} \rhd \mathcal{C}'$*.*

A stable set of a hedonic game does not allow for inner contradictions, i.e., any partition that is stable can not be dominated by another partition that is also in the stable set. Moreover, every coalition structure excluded from the stable set is dominated by some partition in the stable set. Observe that the set of all core partitions is internally stable, and hence, it is a subset of each stable set, and if it is also externally stable, then it is the unique stable set of the corresponding game.

# 3 Top coalitions, ordinal balancedness, and stable sets

As a starting point, let us consider two well known sufficient conditions for non-emptiness of the core in hedonic games - the weak top coalition property and the ordinal balancedness condition introduced in [1] and [3], respectively. The first condition imposes a certain degree of commonality in players' preferences and it is mainly motivated by the multiplicity of economic applications as illustrated in [1]. The second condition is in fact an ordinal version of the Scarf-balancedness condition ([9]) which is often used to prove the non-emptiness of the core in NTU games.

**Definition 3** *Given a hedonic game $(N, \succeq)$ and a non-empty player set $X \subseteq N$, a coalition $S \subseteq X$ is*
*(1) a* ***top coalition*** *of $X$ if for any $i \in S$ and any $T \subseteq X$ with $i \in T$ we have $S \succeq_i T$, and*
*(2) a* ***weak top coalition*** *of $X$ if it has an ordered partition $\{S_1, \ldots, S_\ell\}$ such that (i) for any $i \in S_1$ and any $T \subseteq X$ with $i \in T$ we have $S \succeq_i T$, and (ii) for any $k > 1$, any $i \in S_k$ and any $T \subseteq X$ with $i \in T$ we have that $T \succ_i S$ implies $T \cap (\cup_{m<k} S_m) \neq \emptyset$.*
*A hedonic game satisfies the* ***(weak) top coalition property*** *if for each non-empty player set $X \subseteq N$, there exists a (weak) top coalition of $X$.*

As it turns out, the top coalition property does not guarantee the external stability of the core (Game 1), while its weaker version is not sufficient for the existence of stable sets in hedonic games (Game 2).

**Game 1** *Let $N = \{1, 2, 3\}$ and players' preferences be as follows:*

$$12 \succ_1 123 \sim_1 13 \sim_1 1,$$
$$123 \sim_2 23 \succ_2 12 \succ_2 2,$$
$$13 \sim_3 23 \succ_3 123 \sim_3 3.$$

**Claim** *Game 1 satisfies the top coalition property and its core is not externally stable.*

**Proof.** It is easy to check that each singleton and each doubleton is a top coalition of itself, and that 23 is the unique top coalition of 123, i.e., the game satisfies the top coalition property. The core partitions are $\{1, 23\}$ and $\{123\}$. Notice however that the partition $\{13, 2\}$ is blocked only by 12, and 12 does not belong to any core element, i.e., the core of the game is not externally stable. It is worth mentioning that the coalition 123 (which is the unique member of a core partition) is not a top coalition of itself. ■

**Game 2** *Let* $N = \{1, 2, 3\}$ *and players' preferences be as follows:*

$$123 \succ_1 12 \succ_1 13 \succ_1 1,$$
$$23 \succ_2 12 \succ_2 123 \succ_2 2,$$
$$13 \succ_3 123 \succ_3 23 \succ_3 3.$$

**Claim** *Game 2 satisfies the weak top coalition property and it has no stable set.*

**Proof.** The fact that the above game satisfies the weak top coalition property was shown in ([3], p. 212), i.e., we have only to show that it has no stable set.

Let $\mathcal{C}^1 = \{1, 2, 3\}$, $\mathcal{C}^2 = \{12, 3\}$, $\mathcal{C}^3 = \{13, 2\}$, $\mathcal{C}^4 = \{1, 23\}$, and $\mathcal{C}^5 = \{123\}$. The core of this game consists only of $\mathcal{C}^5$, and $\mathcal{C}^5$ can not dominate $\mathcal{C}^2$, i.e., $\{\mathcal{C}^5\}$ is not a stable set.

Suppose now that there is a stable set $\mathbf{V}$ for this game with $\mathcal{C}^5 \in \mathbf{V} \neq \{\mathcal{C}^5\}$. Notice that $\mathcal{C}^5 \triangleright_{123} \mathcal{C}^1$, i.e., $\mathcal{C}^1 \notin \mathbf{V}$. Moreover, by internal stability, the stable set $\mathbf{V}$ cannot contain the following pairs of coalition structures: $\mathcal{C}^2$ and $\mathcal{C}^3$ (because $\mathcal{C}^2 \triangleright_{12} \mathcal{C}^3$), $\mathcal{C}^2$ and $\mathcal{C}^4$ (because $\mathcal{C}^4 \triangleright_{23} \mathcal{C}^2$), and $\mathcal{C}^3$ and $\mathcal{C}^4$ (because $\mathcal{C}^3 \triangleright_{13} \mathcal{C}^4$). Notice that if $\mathbf{V} = \{\mathcal{C}^3, \mathcal{C}^5\}$, then $\mathcal{C}^2$ can not be dominated; if $\mathbf{V} = \{\mathcal{C}^4, \mathcal{C}^5\}$, then $\mathcal{C}^3$ can not be dominated, and if $\mathbf{V} = \{\mathcal{C}^2, \mathcal{C}^5\}$, then $\mathcal{C}^4$ can not be dominated. Thus, we conclude that there is no stable set in this game. ■

As we shall see next, the ordinal balancedness condition does not guarantee the existence of stable sets in hedonic games either.

**Definition 4** *A family* $\mathcal{B}$ *of coalitions is called* ***balanced*** *if there exists a vector of positive weights* $d_X$ *(with* $X \in \mathcal{B}$*) such that, for each player* $i \in N$, $\sum_{X \in \mathcal{B} \cap \mathcal{N}_i} d_X = 1$. *A hedonic game* $(N, \succeq)$ *is* ***ordinally balanced*** *if, for each balanced family* $\mathcal{B}$ *of coalitions, there exists a partition* $\mathcal{C}$ *of* $N$ *such that for each* $i \in N$ *there exists a coalition* $X \in \mathcal{B} \cap \mathcal{N}_i$ *satisfying* $\mathcal{C}(i) \succeq_i X$.

In other words, if we would like to check whether a game is ordinally balanced we have to find for each balanced family of coalitions a partition of $N$, in which every player is weakly better off in comparison to her worst situation in the corresponding balanced family.

**Game 3** *Let* $N = \{1, 2, 3\}$ *and players' preferences be as follows:*

$$12 \succ_1 123 \succ_1 13 \succ_1 1,$$
$$23 \succ_2 123 \succ_2 12 \succ_2 2,$$
$$13 \succ_3 123 \succ_3 23 \succ_3 3.$$

**Claim** *Game 3 is ordinally balanced and it has no stable set.*

**Proof.** The ordinal balancedness of the game was shown in ([3], p. 213), while the check that there are no stable sets follows exactly the proof of the corresponding claim for Game 2. ■

# 4 Size monotonicity and stability of the core

Let $(N, \succeq)$ be a hedonic game and $\mathcal{R}(N, \succeq)$ be the collection of all individually rational coalitions in $(N, \succeq)$. That is,

$$\mathcal{R}(N, \succeq) = \{X \in 2^N \setminus \{\emptyset\} \mid \forall i \in X, X \succeq_i \{i\}\}.$$

**Definition 5** *A hedonic game* $(N, \succeq)$ *is*
*(i)* ***size monotonic****, if for each* $i \in N$ *and* $X, Y \in \mathcal{R}(N, \succeq) \cap \mathcal{N}_i$, $|X| \geq |Y|$ *implies* $X \succeq_i Y$*;*
*(ii)* ***strongly size monotonic****, if it is size monotonic and for each* $i \in N$ *and* $X, Y \in \mathcal{R}(N, \succeq) \cap \mathcal{N}_i$, $|X| > |Y|$ *implies* $X \succ_i Y$*.*

As we first show, there are strongly size monotonic games which satisfy neither the weak top coalition property nor the ordinal balancedness condition.

**Game 4** *Let* $N = \{1, 2, 3, 4, 5\}$ *and players' preferences be as follows:*

$$1235 \succ_1 123 \sim_1 125 \sim_1 135 \succ_1 12 \sim_1 13 \sim_1 15 \succ_1 1 \succ_1 \ldots,$$
$$123 \succ_2 12 \sim_2 23 \succ_2 2 \succ_2 \ldots,$$
$$234 \succ_3 23 \sim_3 34 \succ_3 3 \succ_3 \ldots,$$
$$345 \succ_4 34 \sim_4 45 \succ_4 4 \succ_4 \ldots,$$
$$1345 \succ_5 135 \sim_5 145 \sim_5 345 \succ_5 15 \sim_5 35 \sim_5 45 \succ_5 5 \succ_5 \ldots.$$

**Claim** *Game 4 is strongly size monotonic and satisfies neither the weak top coalition property nor the ordinal balancedness condition.*

**Proof.** Consider first the weak top coalition property and take the set $X = \{1, 2, 3\}$. We show that there is no weak top coalition for $X$. Notice that no one of the singletons can be a weak top coalition for $X$ because of $12 \succ_1 1$, $12 \succ_2 2$, and $23 \succ_3 3$. The same reason rules out all partitions of candidates for a weak top coalition that have a singleton at the first place. Because two of the players in $X$ (1 and 2) prefer 123 to every doubleton consisting of players in $X$, all partitions of candidates for a weak top coalition that have a doubleton at the first place are ruled out as well. The entire set $X$ cannot be a weak top coalition of itself because, let's say, $3 \succ_3 123$. Hence, $X$ has no weak top coalition, i.e., the game does not satisfy the weak top coalition property.

As for the ordinal balancedness condition, let us take the following balanced family with balanced weight 1/2 for each coalition: $\mathcal{B} = \{12, 23, 34, 45, 15\}$. Notice that, given $\mathcal{B}$, all players do not like to remain single in a partition. Observe further that player 2 can be better off in a partition (in comparison to her worst situation in $\mathcal{B}$) if and only if that partition contains one of the coalitions 12, 23, 123. Hence, the possible candidates for such a partition are: $\{12, 345\}$, which is not liked by player 3; or $\{23, 145\}$, which is not liked by player 1; or $\{123, 45\}$, which is not liked again by player 3. Hence, for the balanced family of coalitions $\mathcal{B}$ there is no suitable partition of $N$, i.e., the game is not ordinally balanced. ■

For any hedonic game $(N, \succeq)$, any $P \subseteq N$ and $i \in P$, let $\succeq_{i|P}$ stand for the restriction of $\succeq_i$ over $2^P \cap \mathcal{N}_i$, and the corresponding restricted preference profile be denoted by $\succeq_{|P}$.

**Theorem 1** *If $(N, \succeq)$ is size monotonic, then it has a core partition.*

**Proof.** Let $(N, \succeq)$ be size monotonic and consider the following procedure.

- Set $P := N$ and $\mathcal{C} := \emptyset$.
- Repeat the following steps until $P$ becomes empty.
  - Select one of the largest members of $\mathcal{R}(P, \succeq_{|P})$, say $X$;
  - Set $P := P \setminus X$ and $\mathcal{C} := \mathcal{C} \cup \{X\}$.
- Return $\mathcal{C}$.

Obviously, the outcome $\mathcal{C}$ of this procedure is a coalition structure. We show that $\mathcal{C}$ is a core partition.

Let $K = |\mathcal{C}|$ and $X_1, \ldots, X_K$ be coalitions such that $\mathcal{C} = \{X_1, \ldots, X_K\}$ with $X_k$ $(1 \leq k \leq K)$ being the $k$-th coalition put into $\mathcal{C}$ by the above procedure. In addition, let $P_1 = N$ and $P_k = P_{k-1} \setminus X_{k-1}$ for each $2 \leq k \leq K$. We have then $|X_1| \geq \ldots \geq |X_K|$ and $X_K = P_K$.

Note first that $X_k \succeq_i \{i\} \succ_i Y$ holds for each $i \in X_k$ and each $Y \in \mathcal{N}_i \setminus \mathcal{R}(P_k, \succeq_{|P_k})$. Moreover, we have from the procedure that $|X_k| \geq |Y|$ for each $Y \in \mathcal{R}(P_k, \succeq_{|P_k})$, and by size monotonicity, $X_k \succeq_i Y$ holds for each $i \in X_k$ and each $Y \in \mathcal{N}_i \cap \mathcal{R}(P_k, \succeq_{|P_k})$. Hence, for each $1 \leq k \leq K$, there are no deviations from $\mathcal{C}$ which belong to $\{Y \in 2^{P_k} \mid X_k \cap Y \neq \emptyset\}$. Note additionally that

$$\{Y \in 2^{P_k} \mid X_k \cap Y \neq \emptyset\} = 2^{P_k} \setminus 2^{(P_k \setminus X_k)} = 2^{P_k} \setminus 2^{P_{k+1}}.$$

Finally, from $X_K = P_K$, we have $\{Y \in 2^{P_K} \mid X_K \cap Y \neq \emptyset\} = 2^{P_K} \setminus \{\emptyset\}$. Therefore, from $\cup_{k=1}^{K} \{Y \in 2^{P_k} \mid X_k \cap Y \neq \emptyset\} = 2^N \setminus \{\emptyset\}$, there are no deviations from $\mathcal{C}$ at all. ■

Let $(N, \succeq)$ be a hedonic game and $\Phi(N, \succeq)$ be the collection of all coalition structures produced by the procedure in Theorem 1.

**Theorem 2** *If* $(N, \succeq)$ *is strongly size monotonic, then* $\Phi(N, \succeq)$ *is exactly the set of core partitions in* $(N, \succeq)$*. Moreover,* $\Phi(N, \succeq)$ *is externally stable.*

**Proof.** Let $(N, \succeq)$ be strongly size monotonic and consider the following procedure with a coalition structure $\mathcal{C}$ as its input.

- Set $P := N$.
- Repeat the following steps.
  - Find the collection $\Gamma_P$ of all largest members of $\mathcal{R}(P, \succeq_{|P})$.
  - Test whether $\mathcal{C} \cap \Gamma_P = \emptyset$. If so, return $P$ and halt; otherwise set $P := P \setminus X$, where $X \in \mathcal{C} \cap \Gamma_P$.

Observe that this procedure always halts for any given coalition structure, and the set $P \subseteq N$ obtained by applying it to a coalition structure $\mathcal{C}$ is empty if and only if $\mathcal{C} \in \Phi(N, \succeq)$.

Suppose $\mathcal{C} \notin \Phi(N, \succeq)$ and let $P \subseteq N$ be obtained by the procedure applied to $\mathcal{C}$. Then, we have $P \neq \emptyset$ and let $X$ be one of the largest members of $\mathcal{R}\left(P, \succeq_{|P}\right)$. Notice then that each coalition in $\mathcal{C} \cap 2^P$ is either not in $\mathcal{R}\left(P, \succeq_{|P}\right)$ or is of size strictly smaller than that of $X$. For each $i \in X$, $\mathcal{C}(i) \notin \mathcal{R}(P, \succeq_{|P})$ implies $X \succeq_i \{i\} \succ_i \mathcal{C}(i)$, while by strong size monotonicity, $|\mathcal{C}(i)| < |X|$ implies $X \succ_i \mathcal{C}(i)$. Therefore, $X$ is a deviation from $\mathcal{C}$, and thus, $\mathcal{C}$ is not in the core of the game.

Finally, observe that there exists at least one member of $\Phi(N, \succeq)$ including $X$, and therefore for every $\mathcal{C} \notin \Phi(N, \succeq)$, there exists at least one $\mathcal{C}' \in \Phi(N, \succeq)$ including a coalition $X$ satisfying $X \succ_i \mathcal{C}(i)$ for each $i \in X$, i.e., $\Phi(N, \succeq)$ is externally stable. ■

As our last example shows, strong size monotonicity is crucial for the external stability of the core.

**Game 5** *Let* $N = \{1, 2, 3\}$ *and players' preferences be as follows:*

$$123 \succ_1 13 \sim_1 1 \succ_1 12,$$
$$123 \succ_2 23 \succ_2 2 \succ_2 12,$$
$$13 \sim_3 23 \succ_3 3 \succ_3 123.$$

**Claim** *Game 5 is size monotonic but not strongly size monotonic and its core is not externally stable.*

**Proof.** The game is not strongly size monotonic as $13 \sim_1 1$. The core partitions are $\{1, 23\}$ and $\{13, 2\}$ (and both of them can be found by applying the procedure in Theorem 1). Notice however that the partition $\{123\}$ is blocked only by player 3, and the singleton containing that player does not belong to any core element, i.e., the core of the game is not externally stable. ■

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