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On strategy-proofness and semilattice single-peakedness¹

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Abstract

We study social choice rules defined on the domain of semilattice single-peaked preferences. Semilattice single-peakedness has been identified as the condition that a set of preferences must satisfy so that the set can be the domain of a strategy-proof, tops-only, anonymous and unanimous rule. We characterize the class of all such rules on that domain and show that they are deeply related to the supremum of the underlying semilattice structure.

Keywords: Strategy-proofness; Unanimity; Anonymity; Tops-onlyness; Single-peakedness.

JEL Classification Numbers: D71.

1 Introduction

We characterize the class of all strategy-proof and simple rules defined on the domain of semilattice single-peaked preferences. A rule is a systematic procedure to select an alternative as a function of the declared

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profile of agents' preferences. A rule is strategy-proof if for each agent truthful declaration is optimal regardless of the other agents' declared preferences. A rule is simple if it is tops-only (the selected alternative depends only on the profile of top alternatives), unanimous (whenever all agents agree that an alternative is the most preferred one, the rule selects it), and anonymous (agents' identities do not play any role).

The notion of semilattice single-peakedness constitutes a weakening of the classical notion of single-peakedness, identified by Black (1948) as a natural and meaningful restriction on preferences whenever the set of alternatives is linearly ordered.⁴ A preference is single-peaked if there is a unique most preferred alternative (the top), and alternatives further away from the top, in each of the two possible directions of the linear order, are less preferred than alternatives closer to the top. Moulin (1980) characterizes the family of all strategy-proof and tops-only rules on the domain of single-peaked preferences.

Semilattice single-peakedness requires that the underlying order structure on the set of alternatives is a (join-)semilattice and that the preference is decreasing further away from the top, *only* in the increasing direction of the semilattice.⁵

There are at least three reasons to study the domain of semilattice single-peaked preferences.

First, semilattice single-peakedness may represent a substantial weakening of the single-peaked condition, meaningful whenever agents' preferences are restricted (by the underlying partial order structure on the set of alternatives) only along a particular direction of the partial order,

⁴A set is linearly ordered if there is a complete, antisymmetric and transitive binary relation over it.

⁵A partial order over a set is a reflexive, antisymmetric and transitive binary relation. A partial order is a (join-)semilattice if every pair of elements in the set has a least upper bound, named the supremum of the pair.

and not in others. Since a strategy-proof and simple rule on a domain of preferences remains strategy-proof and simple in any of its subdomains, characterizations of strategy-proof and simple rules on larger domains are useful because they identify rules that will remain strategy-proof and simple even if the rule would have to operate only on any of its subdomains.

Second, many of the domain restrictions identified in the literature as domains admitting strategy-proof rules satisfy weak versions of single-peakedness.⁶ Thus, one may read these results as identifying single-peakedness as a sufficient condition to be satisfied by a domain in order to guarantee that the domain admits the possibility of designing on it strategy-proof rules. However, all those domains are subsets of semilattice single-peaked preferences.

Third, semilattice single-peakedness is a condition that a rich domain has to satisfy in order to admit a strategy-proof and simple rule.⁷ Some recent papers have tried to identify the key property of a domain of preferences admitting strategy-proof and simple rules. Chatterji, Sanver and Sen (2013) identifies a structure on the set of alternatives for which the domain of preferences over this set has to be semi single-peaked, an extended weak version of single-peakedness for finite sets of alternatives with a tree structure induced by a connectedness property

⁶Among others, Demange (1982), Border and Jordan (1983), Barberà, Sonnenschein and Zhou (1991), Barberà, Gül and Stacchetti (1993), Danilov (1994), Barberà, Massó and Neme (1997), Peremans, Peters, van der Stel and Storcken (1997), Barberà, Massó and Serizawa (1998), Schummer and Vohra (2002), Barberà, Massó and Neme (2005) and Weymark (2008) study the family of strategy-proof rules (or some of its subfamilies) in settings where the set of alternatives has a more complex structure than just a linear order. In each of these generalizations, single-peakedness still appears as a natural and meaningful domain restriction.

⁷Observe that if the domain of preferences is not rich (*i.e.* too small in a precise sense), strategy-proofness loses all of its bite, and then arbitrary (and not rich) domains may trivially appear as being essential for the possibility of admitting strategy-proof and simple rules.

of the domain. That is, if a domain is rich and connected then semilattice single-peakedness is a necessary condition that any set of preferences has to satisfy in order to admit a strategy-proof and simple rule, whenever the number of agents is even. Chatterji and Massó (2018) takes a similar approach to the one taken by Chatterji, Sanver and Sen (2013) but without assuming any *a priori* structure on the set of alternatives nor a connectedness property of the domain. They show that when the number of agents is even, if a rich domain admits a strategy-proof and simple rule then the domain has to be a subset of the set of semilattice single-peaked preferences, where the semilattice from which semilattice single-peakedness is defined is obtained from the rule. They also show that given any set of alternatives, partially ordered by a semilattice (denoted by \succeq), the rule that selects at each preference profile the supremum (according to \succeq) of the set of tops is strategy-proof and simple on the domain of semilattice single-peaked preferences, regardless of whether the number of agents is even or odd. We refer to this rule as the *supremum* rule and denote it by sup_{\succeq} .

Our aim in this paper is to identify the class of *all* strategy-proof and simple rules defined on a semilattice single-peaked domain. Specifically, assume that the set of alternatives A is partially ordered by a semilattice \succeq . Consider the set of all semilattice single-peaked preferences relative to the semilattice (A, \succeq) . Theorem 1 characterizes the family of all strategy-proof and simple rules on this domain.⁸ One of the main consequences of Theorem 1 is the following. Assume that the set of alternatives A does not have a supremum according to the semilattice \succeq .⁹ Then, the supremum rule is the unique strategy-proof

⁸We already know that this family is non-empty because the sup_{\succeq} rule is one of them.

⁹The fact that (A, \succeq) is a semilattice guarantees that any pair of alternatives has supremum (the least upper bound of the pair of alternatives), but if A is not finite it may or it may not have, as a

and simple rule on the domain of semilattice single-peaked preferences on (A, \succeq) . To understand this result remember that in Chatterji and Massó (2018) the property of semilattice single-peakedness is defined relative to the partial order induced by the rule itself. Hence, in this case the domain is so tailor-made to the rule that it only admits the supremum rule. And the supremum rule is strategy-proof and simple even when the set of alternatives has a supremum, denoted by α (*i.e.*; $\alpha \succ x$ for all x in A different from α). However, in this case other rules may also be strategy-proof and simple, and we identify all of them by the following procedure. Consider the set of alternatives $A^*(\succeq)$ with the property that each alternative in the set is (strictly) related by the semilattice only to α . If the set $A^*(\succeq)$ is empty, then the \sup_{\succeq} is again the unique strategy-proof and simple rule on the domain of semilattice single-peaked preferences over A (note that $\alpha \notin A^*(\succeq)$). If this set is non-empty, for each alternative x belonging to $A^*(\succeq)$ and each integer $1 \leq q^x < n$, where n is the number of agents, define a rule f on the domain of semilattice single-peaked preferences on (A, \succeq) as follows. Consider any profile of semilattice single-peaked preferences R . If the number of agents with top on x is larger or equal to q^x , set $f(R) = x$; otherwise, $f(R)$ is equal to the supremum (according to \succeq) of the set of top alternatives in the profile R . A rule f that can be described in this way is named a *quota-supremum* rule.

Our main result says that the class composed by the supremum of the original semilattice \succeq , the \sup_{\succeq} rule, and the family of all quota-supremum rules, one for each pair composed by $x \in A^*(\succeq)$ and $1 \leq q^x < n$, coincides with the class of all strategy-proof and simple rules on the domain of semilattice single-peaked preferences on (A, \succeq) . We also

set, a supremum (a least upper bound of A).

obtain additional results related to the quota-supremum rules and show that the domain of semilattice single-peaked preferences on (A, \succeq) is maximal for the sup_{\succeq} rule; namely, the sup_{\succeq} rule is not strategy-proof on any domain of preferences strictly containing the set of semilattice single-peaked preferences on (A, \succeq) .

The paper is organized as follows. Section 2 contains basic notation and definitions, the definition of semilattice single-peakedness, and preliminary results. Section 3 contains the main result of the paper. In Section 4 we illustrate our result by applying it to the setting of two well-known restricted domains of preferences: the domain of single-peaked preferences over a subset of real numbers and the domain of separable preferences over the family of all subsets of a given set of objects. Section 5 contains the definition of rich domain, the statement that any semilattice single-peaked domain is rich, and some additional results. Section 6 concludes with four final remarks. The Appendix at the end of the paper contains the statements and proofs of some remarks and lemmata that will be used in the proof of the main result, and collects the proofs that are omitted in the text.

2 Preliminaries

2.1 Basic notation and definitions

Let $N = \{1, \dots, n\}$ be the finite set of agents, with $n \geq 2$, and A be any set of alternatives. The set A can be finite or infinite. We assume throughout the paper that $|A| > 2$.¹⁰ Each agent $i \in N$ has a preference (relation) $R_i \in \mathcal{D}$ over A , where \mathcal{D} is an arbitrary and given subset of

¹⁰The cardinality of any given set X is denoted by $|X|$. The case $|A| = 2$ is very especial and discussed in the Final Remarks section at the end of the paper.

complete and transitive binary relations over A .¹¹ The set \mathcal{D} is referred to as the domain of preferences. For any $x, y \in A$, xR_iy means that agent i considers alternative x to be at least as good as alternative y . Let P_i and I_i denote the strict and indifference relations induced by R_i over A , respectively.¹² We assume that for each $R_i \in \mathcal{D}$ there exists $t(R_i) \in A$, the top of R_i , such that $t(R_i)P_iy$ for all $y \in A \setminus \{t(R_i)\}$. For $x \in A$, we denote by R_i^x an arbitrary preference in \mathcal{D} with $t(R_i^x) = x$. Let \mathcal{R} denote the universal domain of preferences over A with a unique top. We also assume that for each $x \in A$ the domain \mathcal{D} contains at least one preference R_i^x . A profile $R = (R_1, \dots, R_n) \in \mathcal{D}^n$ is an n -tuple of preferences, one for each agent. To emphasize the role of agent i or subset of agents S we will often write the profile R as (R_i, R_{-i}) or as (R_S, R_{-S}) .

A (*social choice*) *rule* is a mapping $f : \mathcal{D}^n \rightarrow A$ that assigns to every profile $R \in \mathcal{D}^n$ an alternative $f(R) \in A$.¹³

A rule $f : \mathcal{D}^n \rightarrow A$ is *tops-only* if for all $R, R' \in \mathcal{D}^n$ such that $t(R_i) = t(R'_i)$ for all $i \in N$, $f(R) = f(R')$. Tops-onlyness constitutes a basic simplicity requirement. Hence, a tops-only rule $f : \mathcal{D}^n \rightarrow A$ can be written as $f : A^n \rightarrow A$. Accordingly, whenever f be tops-only we will use the notation $f(t(R_1), \dots, t(R_n))$ interchangeably with $f(R_1, \dots, R_n)$.

A rule $f : \mathcal{D}^n \rightarrow A$ is *unanimous* if for all $R \in \mathcal{D}^n$ and $x \in A$ such that $t(R_i) = x$ for all $i \in N$, $f(R) = x$. Unanimity is a natural and

¹¹A binary relation \succeq over A is *complete* if for all $x, y \in A$ either $x \succeq y$ or $y \succeq x$ and it is *transitive* if for all $x, y, z \in A$, $x \succeq y$ and $y \succeq z$ imply $x \succeq z$.

¹²Namely, for any $x, y \in A$, xP_iy if and only if xR_iy and yR_ix does not hold, and xI_iy if and only if xR_iy and yR_ix .

¹³We are assuming that alternatives do not have private components. Accordingly, the domain of a rule is a Cartesian product of the same set n times. While this is standard in the public-good literature, it excludes meaningful private-good applications where agents only care about their own component of social alternatives and preferences ought to be idiosyncratic.

weak form of efficiency: if all agents consider an alternative as being the most-preferred one, the rule should select it.

Anonymity imposes that the rule treats all agents equally: the social outcome is selected without paying attention to the identities of the agents. To formally describe an anonymous rule on \mathcal{D}^n define, for every profile $R \in \mathcal{D}^n$ and every one-to-one mapping $\sigma : N \rightarrow N$, the profile $R^\sigma = (R_{\sigma(1)}, \dots, R_{\sigma(n)})$ as the σ -permutation of R , where for all $i \in N$, $R_{\sigma(i)}$ is the preference that agent $\sigma(i)$ had in the profile R . Observe that the domain \mathcal{D}^n is closed under permutations, since it is the Cartesian product of the same set \mathcal{D} . A rule $f : \mathcal{D}^n \rightarrow A$ is *anonymous* if for all one-to-one mappings $\sigma : N \rightarrow N$ and all $R \in \mathcal{D}^n$, $f(R^\sigma) = f(R)$.

We will refer to a tops-only, anonymous and unanimous rule as a *simple* rule.

Preferences are idiosyncratic and agents' private information, and they have to be elicited by means of a rule. A rule is strategy-proof if for every agent at every preference profile truth-telling is a weakly dominant strategy in the direct revelation game induced by the rule at the preference profile. Formally, a rule $f : \mathcal{D}^n \rightarrow A$ is *strategy-proof* if for all $R \in \mathcal{D}^n$, all $i \in N$ and all $R'_i \in \mathcal{D}$,

$$f(R) R_i f(R'_i, R_{-i}).$$

We say that agent i can manipulate f at R if there exists $R'_i \in \mathcal{D}$ such that $f(R'_i, R_{-i}) \succ_i f(R)$.

We are interested in strategy-proof and simple rules. To study them, we will assume that the set A is partially ordered by a binary relation \succeq that is a semilattice over A ; namely, for all $x, y, z \in A$, (i) $x \succeq x$ (reflexivity), (ii) $x \succeq y$ and $y \succeq x$ imply $x = y$ (antisymmetry), and (iii) $x \succeq y$ and $y \succeq z$ imply $x \succeq z$ (transitivity). The partial order \succeq

is a (*join-*)*semilattice* over A if for each pair $x, y \in A$ the least upper bound of $\{x, y\}$ exists; in this case it is named the *supremum* of x and y , and it is denoted by $\sup_{\succeq}\{x, y\}$.¹⁴ A semilattice \succeq over A will often be denoted by (A, \succeq) . Given a semilattice (A, \succeq) and $x, y \in A$, we write $x \succ y$ if $x \succeq y$ and $x \neq y$.

Fix a binary relation \succeq over A . Given two alternatives $x, y \in A$ with $y \succeq x$, define the set $[x, y]$ as

$$[x, y] = \{z \in A \mid y \succeq z \text{ and } z \succeq x\}.$$

If x and y are two distinct alternatives and related by \succeq as $y \succeq x$, then the set $[x, y]$ is obtained by adding to the set $\{x, y\}$ all alternatives in A that “lie between” x and y according to \succeq . For $y \not\succeq x$ define $[x, y] = \emptyset$.

2.2 Semilattice single-peakedness

Chatterji and Massó (2018) shows that if a rich domain of preferences admits a strategy-proof and simple rule $f : \mathcal{D}^n \rightarrow A$, for n even, then all preferences in the domain \mathcal{D} have to be semilattice single-peaked, where the semilattice from which semilattice single-peakedness is defined is identified from the rule. As we have already said in the Introduction, this notion constitutes a weakening of single-peakedness and contains as particular cases many of the domains identified in the restricted domain literature; for instance, those studied in Moulin (1980), Demange (1982), Border and Jordan (1983), Barberà, Sonnenschein and Zhou (1991), Barberà, Gül and Stacchetti (1993), Danilov (1994), Peremans, Peters, van der Stel and Storcken (1997), Barberà, Massó and Serizawa (1998), Schummer and Vohra (2001), Weymark (2008) and Chatterji,

¹⁴Given $x, y \in A$, an element $z \in A$ is an *upper bound* of $\{x, y\}$ if $z \succeq x$ and $z \succeq y$. An element $t \in A$ is the *supremum* of $\{x, y\}$ if and only if (i) t is an upper bound of $\{x, y\}$ and (ii) $w \succeq t$ for all upper bound w of $\{x, y\}$ (*i.e.*, t is the least upper bound of $\{x, y\}$).

Sanver and Sen (2013).¹⁵ Following Chatterji and Massó, we now define semilattice single-peaked preferences on a semilattice (A, \succeq) .

Definition 1 *Let \succeq be a semilattice over A and let $x \in A$. The preference $R_i^x \in \mathcal{D}$ is **semilattice single-peaked** on (A, \succeq) if, for all $y, z \in A$, $\sup_{\succeq}\{x, y\} R_i^x \sup_{\succeq}\{z, y\}$.*

Example 1 at the end of this section illustrates this definition. Given a semilattice \succeq over A , denote by $\mathcal{SSP}(\succeq)$ the domain of semilattice single-peaked preferences on (A, \succeq) .

2.3 Preliminary results and example

Chatterji and Massó (2018) characterizes semilattice single-peakedness by means of two properties, the first one more directly related to the notion of single-peakedness. Remark 1 states this result, which will be very useful in the sequel.

Remark 1 *Let \succeq be a semilattice over A and let $x \in A$. The preference $R_i^x \in \mathcal{D}$ is semilattice single-peaked on (A, \succeq) if and only if the following two properties hold:*

- (i) *for all $y, z \in A$ such that $x \preceq y \preceq z$, $y R_i^x z$;*
- (ii) *for all $w \in A$ such that $x \not\preceq w$, $\sup_{\succeq}\{x, w\} R_i^x w$.*

The well-known notion of single-peakedness on a linearly ordered set can be naturally extended to a set that is partially ordered by a semilattice.

Definition 2 *Let \succeq be a semilattice over A and let $x \in A$. The preference $R_i^x \in \mathcal{D}$ is **single-peaked** on (A, \succeq) if the following two properties hold:*

¹⁵Chatterji and Massó (2018) carefully describes some of these inclusions.

- (i) for all $y, z \in A$ such that $x \preceq y \prec z$ or $z \prec y \preceq x$, $yP_i^x z$;
- (ii) for all $w \in A$ such that $x \not\preceq w$, $\sup_{\succeq}\{x, w\}P_i^x w$.

Given a semilattice \succeq over A , denote by $\mathcal{SP}(\succeq)$ the domain of single-peaked preferences on (A, \succeq) .

Remark 2 For every semilattice \succeq over A , $\mathcal{SP}(\succeq) \subset \mathcal{SSP}(\succeq)$ holds immediately by their definitions. To see that the inclusion may be strict, consider the set of alternatives $A = \{x, y, z\}$ and let \succeq be such that $x \succeq y \succeq z$. Then, $\mathcal{SP}(\succeq) \subsetneq \mathcal{SSP}(\succeq)$ because R_i^x such that $zP_i^x y$ belongs to $\mathcal{SSP}(\succeq)$ but not to $\mathcal{SP}(\succeq)$.

Remark 3 When the semilattice \succeq is a linear order over A , condition (i) in Definition 2 still generalizes the usual definition of single-peakedness. Moreover, if condition (i) holds then condition (ii) is redundant since $x \not\preceq w$ implies, by completeness of \succeq , that $x \succ w$ and so $\sup_{\succeq}\{x, w\} = xP_i^x w$ follows trivially.

Example 1 illustrates the notion of semilattice single-peakedness.

Example 1 Let $A = \{x_1, \dots, x_9\}$ be a set with nine alternatives and let \succeq be the semilattice represented in Figure 1 where, for any $x_k, x_{k'} \in A$, an arrow from x_k to $x_{k'}$ means $x_{k'} \succ x_k$, and arrows that would follow from transitivity are deleted.

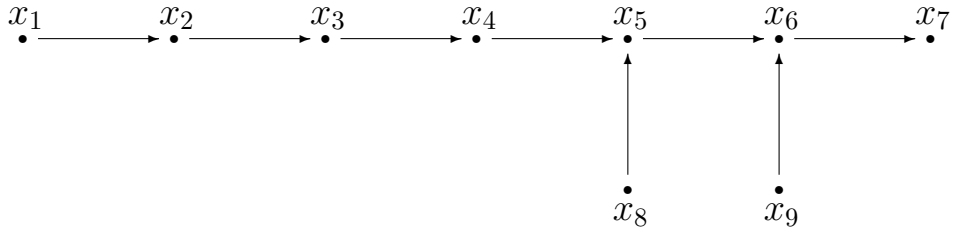


Figure 1

The set of $\mathcal{SSP}(\succeq)$ is large but restricted; in particular, the set of strict preferences listed in Table 1 are semilattice single-peaked on (A, \succeq) ,

while the ones listed in Table 2 are not. Each column represents a strict preference with the convention that an alternative located in a row is strictly preferred to all alternatives located in lower rows.¹⁶

$P_i^{x_3}$	$\widehat{P}_i^{x_3}$	$P_i^{x_8}$	$\widehat{P}_i^{x_8}$	$P_i^{x_5}$
x_3	x_3	x_8	x_8	x_5
x_4	x_2	x_5	x_5	x_3
x_5	x_1	x_6	x_6	x_8
x_1	x_4	x_9	x_7	x_4
x_2	x_5	x_7	x_9	x_6
x_6	x_8	x_1	x_4	x_7
x_7	x_6	x_3	x_3	x_9
x_9	x_9	x_2	x_2	x_2
x_8	x_7	x_4	x_1	x_1

Table 1

$\overline{P}_i^{x_3}$	$\widetilde{P}_i^{x_3}$	$\overline{P}_i^{x_8}$	$\widetilde{P}_i^{x_8}$
x_3	x_3	x_8	x_8
x_5	x_2	x_6	x_4
x_4	x_1	x_9	x_6
x_1	x_4	x_5	x_7
x_2	x_8	x_7	x_9
x_6	x_5	x_1	x_5
x_7	x_6	x_3	x_2
x_9	x_9	x_2	x_3
x_8	x_7	x_4	x_1

Table 2

Preferences $P_i^{x_3}$, $\widehat{P}_i^{x_3}$, $P_i^{x_8}$, $\widehat{P}_i^{x_8}$ and $P_i^{x_5}$ belong to $\mathcal{SSP}(\succeq)$ because, for instance, according to Definition 1, and Remark 1,

- $\sup_{\succeq}\{x_3, x_4\} = x_4 P_i^{x_3} x_5 = \sup_{\succeq}\{x_5, x_4\}$, $\sup_{\succeq}\{x_3, x_8\} = x_5 P_i^{x_3} x_6 = \sup_{\succeq}\{x_9, x_8\}$,
 - $x_3 \prec x_4 \prec x_5$ and $x_4 P_i^{x_3} x_5$, and $\sup_{\succeq}\{x_3, x_8\} = x_5 P_i^{x_3} x_8$.
- $\sup_{\succeq}\{x_8, x_6\} = x_6 P_i^{x_8} x_7 = \sup_{\succeq}\{x_7, x_6\}$, $\sup_{\succeq}\{x_8, x_3\} = x_5 P_i^{x_8} x_6 = \sup_{\succeq}\{x_9, x_3\}$,
 - $x_8 \prec x_6 \prec x_7$ and $x_6 P_i^{x_8} x_7$, and $\sup_{\succeq}\{x_8, x_9\} = x_6 P_i^{x_8} x_9$.

¹⁶To ease the exposition in this and all examples that follow we only consider strict preferences.

Preferences $\overline{P}_i^{x_3}$, $\widetilde{P}_i^{x_3}$, $\overline{P}_i^{x_8}$ and $\widetilde{P}_i^{x_8}$ do not belong to $\mathcal{SSP}(\succeq)$ because, for instance, according to Definition 1, and Remark 1,

- $\sup_{\succeq}\{x_3, x_4\} = x_4$ and $x_5 = \sup_{\succeq}\{x_5, x_4\}$, but $x_5 \overline{P}_i^{x_3} x_4$,
– $x_3 \prec x_4 \prec x_5$ and $x_5 \overline{P}_i^{x_3} x_4$.
- $\sup_{\succeq}\{x_8, x_5\} = x_5$ and $x_6 = \sup_{\succeq}\{x_5, x_9\}$, but $x_6 \overline{P}_i^{x_8} x_5$,
– $x_8 \prec x_5 \prec x_6$ and $x_6 \overline{P}_i^{x_8} x_5$.

However, preference $\widehat{P}_i^{x_3}$ belongs to $\mathcal{SP}(\succeq)$ but preference $P_i^{x_3}$ does not because, for instance, according to Definition 2,

- $x_1 \prec x_2 \prec x_3$ and $x_2 \widehat{P}_i^{x_3} x_1$, but $x_1 P_i^{x_3} x_2$. □

Before moving to the section with our results, we want to comment on the plausibility of semilattice single-peakedness as a meaningful domain restriction. For instance, consider the situation where A is the set of locations along a river and its tributaries, and the semilattice \succeq represents the flow of the water. Then, preferences in $\mathcal{SSP}(\succeq)$ correspond to the situation where agents can move from where they are located (their top locations) only downstream, but not upstream. Thus, any pair of non-top locations $x, y \in A$ that are not connected by the flow of the water can be ordered in any way. In addition of its plausibility, the interest of semilattice single-peakedness lies in the facts that (i) any (rich) domain that admits a strategy-proof and simple rule ought to satisfy this restriction and (ii) the set of all semilattice single-peaked preferences contains many of the restrictions studied in the literature, justified as weakenings of single-peakedness. Our characterization identifies the subset of strategy-proof and simple rules that because they are

strategy-proof on the semilattice single-peaked domain remain strategy-proof in any of its subsets. Hence, this set of rules identified here may be seen as being more robust to misspecifications of the relevant domain restriction.

3 Main result

Our goal in this paper is to characterize, for any semilattice (A, \succeq) , the class of all strategy-proof and simple rules on the domain of semilattice single-peaked preferences $\mathcal{SSP}(\succeq)$. We start by defining, given a semilattice (A, \succeq) , the supremum rule \sup_{\succeq} on the domain $\mathcal{SSP}(\succeq)$. We then argue that the supremum rule is simple and strategy-proof on $\mathcal{SSP}(\succeq)$.

Let (A, \succeq) be a semilattice and let $\mathcal{SSP}(\succeq)$ be the set of semilattice single-peaked preferences on (A, \succeq) . The *supremum rule*, denoted as $\sup_{\succeq} : \mathcal{SSP}(\succeq)^n \rightarrow A$, is defined by setting, for each profile $R = (R_1, \dots, R_n) \in \mathcal{SSP}(\succeq)^n$,

$$\sup_{\succeq}(R_1, \dots, R_n) = \sup_{\succeq}\{t(R_1), \dots, t(R_n)\}.$$

The supremum rule \sup_{\succeq} is unanimous, anonymous and tops-only by definition, and so it is simple. To see that \sup_{\succeq} is strategy-proof first define $t(R) = \{t(R_i) \mid i \in N\}$ as the set of (different) tops at profile R and $t(R_{-i}) = \{t(R_j) \mid j \in N \setminus \{i\}\}$. Next, consider any profile $R \in \mathcal{SSP}(\succeq)^n$, agent $i \in N$ and preference $R'_i \in \mathcal{SSP}(\succeq)$. By semilattice single-peakedness,

$$\sup_{\succeq}(R) = \sup_{\succeq}\{t(R_i), \sup_{\succeq}t(R_{-i})\} \quad R_i \sup_{\succeq}\{t(R'_i), \sup_{\succeq}t(R_{-i})\} = \sup_{\succeq}(R'_i, R_{-i}).$$

Thus, \sup_{\succeq} is strategy-proof.

However, there are semilattices (A, \succeq) for which \sup_{\succeq} is not the unique strategy-proof and simple rule on $\mathcal{SSP}(\succeq)$. Theorem 1 below

identifies the class of all strategy-proof and simple rules on the domain of semilattice single-peaked preferences. To state this characterization we need the following notation and definitions. Given $R \in \mathcal{SSP}(\succeq)^n$ and $x \in A$, define $N(R, x) = \{i \in N \mid t(R_i) = x\}$ as the set of agents whose top is x at profile R . Assume A has a supremum, denoted as $\sup_{\succeq} A = \alpha$.¹⁷ Namely, there is $\alpha \in A$ such that $\alpha \succ x$ for all $x \in A \setminus \{\alpha\}$. Let

$$A^*(\succeq) = \{x \in A \mid \text{for each } y \in A \setminus \{\alpha\}, x \not\succeq y \text{ and } y \not\succeq x\}$$

be the set of alternatives that, according to \succeq , are not related to any other alternative but α . Observe that $\alpha \notin A^*(\succeq)$; for instance, for $A = \{x, y, z\}$ and the semilattice $x \succ y$, $x \succ z$, $y \not\succeq z$ and $z \not\succeq y$, $\sup_{\succeq} A = x$ and $A^*(\succeq) = \{y, z\}$. Moreover, $A^*(\succeq)$ may be empty; for instance, in the case of the semilattice considered in Example 1.

Definition 3 *Let \succeq be a semilattice over A such that $\sup_{\succeq} A$ exists. The rule $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ is a **quota-supremum** rule if there are $x \in A^*(\succeq)$ and integer q^x with $1 \leq q^x < n$ such that, for every $R \in \mathcal{SSP}(\succeq)^n$,*

$$f(R) = \begin{cases} x & \text{if } |N(R, x)| \geq q^x \\ \sup_{\succeq} t(R) & \text{otherwise.} \end{cases}$$

We refer to the alternative $x \in A^*(\succeq)$, whose existence makes f to be a quota-supremum rule, as the *alternative associated to f* , and to q^x as the *quota* of x . Given $x \in A^*(\succeq)$ we can generate a new semilattice, the one obtained from the original one by declaring x to be above α , and maintaining all the other binary comparisons not involving x as in the original semilattice. Example 2 below illustrates this procedure.

¹⁷We are abusing a bit the notation and use \sup_{\succeq} to denote the supremum rule and $\sup_{\succeq} X$ to denote the supremum of a set $X \subseteq A$.

Denote by $\mathcal{Q}(\succeq)$ the set of quota-supremum rules defined on $\mathcal{SSP}(\succeq)$, and by $\mathcal{F}(\succeq)$ the set of strategy-proof and simple rules defined on $\mathcal{SSP}(\succeq)$. We know that $\mathcal{F}(\succeq) \neq \emptyset$ since we have just argued that \sup_{\succeq} is strategy-proof and simple. In contrast, $\mathcal{Q}(\succeq)$ is ill-defined whenever $A^*(\succeq)$ is empty; by convention, we define $\mathcal{Q}(\succeq) = \emptyset$ if $A^*(\succeq) = \emptyset$. The main result of the paper is the following.

Theorem 1 *Let \succeq be a semilattice over A . The rule $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ is strategy-proof and simple if and only if $f = \sup_{\succeq}$ or f is a quota-supremum; i.e.,*

$$\mathcal{F}(\succeq) = \{\sup_{\succeq}\} \cup \mathcal{Q}(\succeq).$$

PROOF See Appendix 7.3. ■

Corollary 1 *Let \succeq be a semilattice over A such that $\sup_{\succeq} A$ does not exist. Then, $\mathcal{Q}(\succeq) = \emptyset$ and $\mathcal{F}(\succeq) = \{\sup_{\succeq}\}$.*

Example 2 illustrates the content of Theorem 1 when $n = 2$ and indicates a procedure to identify for this case, the full class of strategy-proof and simple rules on the domain $\mathcal{SSP}(\succeq)$; namely, all quota-supremum rules.

Example 2 Let $A = \{x, y, z\}$ be the set of alternatives and let $N = \{1, 2\}$ be the set of agents. Consider the semilattice (A, \succeq_1) , where $x \succ_1 y$, $x \succ_1 z$, $y \not\succ_1 z$ and $z \not\succ_1 y$. Obviously, $\sup_{\succeq_1} A = x$ and the supremum rule $\sup_{\succeq_1} = f_1$ can be described by

$$f_1(x, y) = x$$

$$f_1(x, z) = x$$

$$f_1(y, z) = x$$

together with the corresponding choices required by unanimity and anonymity. Observe that $A^*(\succeq_1) = \{y, z\}$. Then, the set of (strict)

semilattice single-peaked preferences $\mathcal{SSP}(\succeq_1)$ on (A, \succeq_1) contains the four preferences listed in Table 3 where, for any pair $a, b \in \{x, y, z\}$, P_i^{ab} refers to the unique strict preference $aP_i^{ab}bP_i^{ab}c$.

P_i^{xy}	P_i^{xz}	P_i^{yx}	P_i^{zx}
x	x	y	z
y	z	x	x
z	y	z	y

Table 3

Consider now the two semilattices (A, \succeq_2) and (A, \succeq_3) , where \succeq_2 and \succeq_3 are obtained from \succeq_1 by setting $y \succ_2 x$ and $z \succ_3 x$, respectively, and adding the relations implied by transitivity. Figure 2 represents \succeq_1 , \succeq_2 and \succeq_3 , where an arrow between two alternatives points to their supremum, and arrows that would follow by transitivity are omitted.

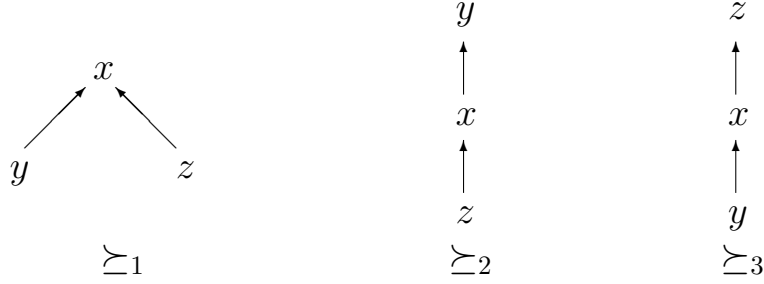


Figure 2

Hence, the rules $\sup_{\succeq_2} = f_2$ and $\sup_{\succeq_3} = f_3$ can be described by

$$\begin{array}{ll}
 f_2(x, y) = y & f_3(x, y) = x \\
 f_2(x, z) = x & \text{and} \quad f_3(x, z) = z \\
 f_2(y, z) = y & f_3(y, z) = z
 \end{array}$$

together with the corresponding choices required by unanimity and anonymity. Observe that $A^*(\succeq_2) = A^*(\succeq_3) = \emptyset$ and $f_2, f_3 \in \mathcal{Q}(\succeq_1)$,

where f_2 and f_3 can also be seen as the quota-supremum rules associated respectively to y and z (in this case, and since there are only two agents, the only admissible quota for any quota-supremum rule is equal to 1). Given the semilattice \succeq_1 , the set of strategy-proof and simple rules on $\mathcal{SSP}(\succeq_1)$ is the set $\mathcal{F}(\succeq_1) = \{f_1, f_2, f_3\}$. \square

For any $n \geq 2$, a quota-supremum rule with associated alternative $x \in A^*(\succeq)$ and quota $q^x = 1$ can also be described as the supremum of a slightly modified semilattice. Let (A, \succeq) be a semilattice and let $x \in A^*(\succeq)$. Define the semilattice \succeq^x on A obtained from \succeq by setting $x \succ^x y$ for all $y \in A \setminus \{x\}$ and, for all $y, z \in A \setminus \{x\}$, $y \succ^x z$ if and only if $y \succ z$. If $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ is a quota-supremum rule with associated alternative x and quota $q^x = 1$, then $f(R) = \sup_{\succeq^x} t(R)$ for all $R \in \mathcal{SSP}(\succeq)^n$. Asking for the support of at least one agent for x , and otherwise selecting the supremum of all tops according to \succeq , is equivalent to obtaining directly the supremum of all tops, according to \succeq^x .

To see that all quota-supremum rules with quota one are strategy-proof, fix a quota-supremum rule $f : \mathcal{SSP}(\succeq)^n \rightarrow A$, where $x \in A^*(\succeq)$ is its associated alternative and $q^x = 1$. Let $R_i^y \in \mathcal{SSP}(\succeq)$ and $R_{-i} \in \mathcal{SSP}(\succeq)^{n-1}$ be arbitrary. If $y = x$ then $f(R_i^y, R_{-i}) = y$, and i cannot manipulate f at (R_i^y, R_{-i}) . If $y \neq x$, we distinguish between two cases. First, suppose $x \in t(R_i^y, R_{-i})$; then, $f(R_i^y, R_{-i}) = x$ and $f(R'_i, R_{-i}) = x$ for all $R'_i \in \mathcal{SSP}(\succeq)$, and i cannot manipulate f at (R_i^y, R_{-i}) . Second, suppose $x \notin t(R_i^y, R_{-i})$; then, $f(R_i^y, R_{-i}) = \sup_{\succeq} t(R_i^y, R_{-i})$. If $\sup_{\succeq} t(R_i^y, R_{-i}) = y$, agent i cannot manipulate f at (R_i^y, R_{-i}) . If $\sup_{\succeq} t(R_i^y, R_{-i}) \neq y$ we distinguish between two subcases. First, suppose $t(R'_i) \neq x$; then,

$$y \prec f(R_i^y, R_{-i}) \preceq \sup_{\succeq} t(R'_i, R_{-i}) = f(R'_i, R_{-i}),$$

but by semilattice single-peakedness, $f(R_i^y, R_{-i})R_i^y f(R_i', R_{-i})$, and i cannot manipulate f at (R_i^y, R_{-i}) with R_i' . Second, suppose $t(R_i') = x$; then $f(R_i', R_{-i}) = x$ and since

$$y \prec f(R_i^y, R_{-i}) \prec \sup_{\succeq} t(R_i', R_{-i}) = \sup_{\succeq} A$$

and $y \not\preceq f(R_i', R_{-i}) = x$, by (ii) in Remark 1 characterizing semilattice single-peakedness and transitivity of R_i^y , $f(R_i^y, R_{-i})R_i^y f(R_i', R_{-i}) = x$, and i cannot manipulate f at (R_i^y, R_{-i}) with R_i' . Thus, f is strategy-proof and trivially simple. In the proof of Theorem 1, in Appendix 7.3, we extend this argument from the case $q^x = 1$ to any quota $1 < q^x < n$, and show that any strategy-proof and simple rule $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ is either the \sup_{\succeq} rule if $\sup_{\succeq} A$ does not exist or else a quota-supremum rule.

4 Two examples

In this section we illustrate our result by applying it to the setting of two well-known restricted domains of preferences. The example in Subsection 4.1 corresponds to the domain of single-peaked preferences over a subset of real numbers. The example in Subsection 4.2 corresponds to the domain of separable preferences over the family of all subsets of a given set of objects. In each of the two examples we identify the semilattices and their corresponding rules that, among the class of all strategy-proof and simple rules on the single-peaked or separable domains, remain strategy-proof on the larger domain of semilattice single-peaked preferences. Moreover we show how, according to our result, these rules can be described either as the supremum of the underlying semilattice or as quota-supremum rules.

4.1 Median voters

The set of alternatives A is a subset of real numbers. We distinguish between two cases, depending on whether A is equal to the real line \mathbb{R} (as in Moulin (1980)) or A is finite (as the one-dimensional case in Barberà, Güel and Stacchetti (1993)).

4.1.1 Moulin (1980)

The set A is the set of real numbers \mathbb{R} , linearly ordered by the binary relation \geq (“to be larger or equal than”), and agents preferences are single-peaked (relative to \geq) over \mathbb{R} .¹⁸ We first consider the case where the semilattice on \mathbb{R} coincides with the binary relation \geq . Then, the semilattice (\mathbb{R}, \geq) does not have supremum and the set of semilattice single-peaked preferences on (\mathbb{R}, \geq) is

$$\mathcal{SSP}(\geq) = \{R_i \in \mathcal{R} \mid t(R_i) = x \text{ for some } x \in \mathbb{R} \text{ and } x < y < z \text{ implies } yR_iz\}.$$

That is, a semilattice single-peaked preference $R_i \in \mathcal{SSP}(\geq)$ is decreasing on the right of its top alternative, and it is unrestricted between pairs of alternatives that are either on the left of the top or on different sides of the top. Figure 3 depicts a semilattice single-peaked preference $R_i \in \mathcal{SSP}(\geq)$ with top on alternative x .¹⁹

¹⁸Namely, the preference R_i over \mathbb{R} is *single-peaked (relative to \geq)* if (i) R_i has a unique top alternative $t(R_i)$ and (ii) $y < x < t(R_i)$ or $t(R_i) < x < y$ implies xR_iz .

¹⁹Preferences in $\mathcal{SSP}(\geq)$ would arise naturally when agents are willing to consume the public good only at higher levels of their top alternatives. For instance, and using the river metaphore suggested at the end of Subsection 2.3, if the linear order \geq represents the flow of a river (without tributaries), semilattice single-peakedness would reflect the fact that agents are able to move (*i.e.*, consume the good) using only the flow of the river. Semilattice single-peakedness does not impose restrictions on how agents order alternatives upstream of their top alternatives but it requires monotonicity downstream.

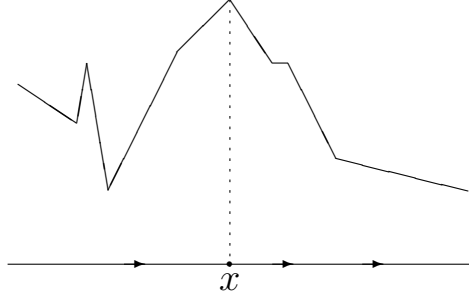


Figure 3

Since $A^*(\geq) = \emptyset$, Theorem 1 says that the unique strategy-proof and simple rule on $\mathcal{SSP}(\geq)^n$ is the \sup_{\geq} rule, which corresponds in Moulin (1980)'s characterization of all strategy-proof and simple rules on the domain of single-peaked preferences (relative to \geq) to the median voter rule where $n - 1$ fixed votes are located at $+\infty$; that is, for each $R \in \mathcal{SSP}(\geq)^n$,

$$\begin{aligned} \sup_{\geq}(R) &= \sup_{\geq}\{t(R_1), \dots, t(R_n)\} \\ &= \text{median}_{\geq}\{t(R_1), \dots, t(R_n), \underbrace{+\infty, \dots, +\infty}_{(n-1)\text{-times}}\}. \end{aligned}$$

We now consider other cases where the semilattice over \mathbb{R} does not coincide with the binary relation \geq and the supremum rule can be identified with a median voter rule. For any fixed $\alpha \in \mathbb{R}$, consider the semilattice \succeq where $y < x \leq \alpha$ or $\alpha \leq x < y$ implies $x \succ y$ and $x < \alpha < y$ implies $x \not\succeq y$ and $y \not\succeq x$. Thus, $\sup_{\succeq} = \alpha$ and the set of semilattice single-peaked preferences on (\mathbb{R}, \succeq) is

$$\begin{aligned} \mathcal{SSP}(\succeq) = \{ & R_i \in \mathcal{R} \mid t(R_i) = x \text{ for some } x \in \mathbb{R}, \\ & t(R_i) < y < z \leq \alpha \text{ or } \alpha \leq z < y < t(R_i) \text{ implies } y R_i z \text{ and} \\ & t(R_i) \not\succeq y \text{ and } y \not\succeq t(R_i) \text{ imply } \sup_{\succeq}\{t(R_i), y\} = \alpha R_i y\}. \end{aligned}$$

That is, a semilattice single-peaked preference $R_i \in \mathcal{SSP}(\succeq)$ is decreasing from $t(R_i)$ towards α and the preference between pairs of alternatives after α , all according to \succeq , are unrestricted but none is strictly

preferred to α . Figure 4 represents this semilattice (as arrows pointing to α) and depicts a semilattice single-peaked preference $R_i \in \mathcal{SSP}(\succeq)$ on (\mathbb{R}, \succeq) .

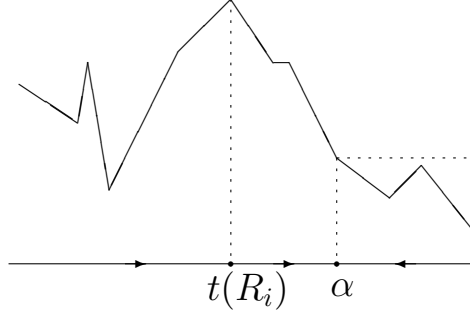


Figure 4

Since $A^*(\succeq) = \emptyset$ also holds, Theorem 1 says that the unique strategy-proof and simple rule on $\mathcal{SSP}(\succeq)^n$ is the \sup_{\succeq} , which corresponds, in the previously mentioned Moulin (1980)'s characterization, to the median voter rule (relative to \succeq) where $n - 1$ fixed votes are located at α ; that is, for each $R \in \mathcal{SSP}(\succeq)^n$,

$$\begin{aligned} \sup_{\succeq}(R) &= \sup_{\succeq}\{t(R_1), \dots, t(R_n)\} \\ &= \text{median}_{\succeq}\{t(R_1), \dots, t(R_n), \underbrace{\alpha, \dots, \alpha}_{(n-1)\text{-times}}\}. \end{aligned}$$

4.1.2 Barberà, Güel and Stacchetti (1993)

The set A is a finite subset of real numbers. Without loss of generality suppose that $A = \{x_1, \dots, x_M\}$, where $x_1 < \dots < x_M$. We distinguish between two types of semilattices over A , depending on whether or not the semilattice has the property that there is one alternative that is related only to the supremum.

First consider any semilattice \succeq with the property that, for some m such that $1 \leq m \leq M$, $\sup_{\succeq} A = x_m$ and $A^*(\succeq) = \emptyset$; for instance the case $m = M$ and $x_1 \prec \dots \prec x_M$ or the case $2 < m < M - 1$

and $x_1 \prec x_2 \prec \dots \prec x_m$ and $x_M \prec x_{M-1} \prec \dots \prec x_m$. Then, the set $\mathcal{SSP}(\succeq)$ of semilattice single-peaked preferences on (A, \succeq) is the natural extension of the set for the continuous case to this discrete setting. Again, Theorem 1 says that the unique strategy-proof and simple rule on $\mathcal{SSP}(\succeq)^n$ is the \sup_{\succeq} rule. This rule can also be represented as the median_{\succeq} , according to the ordering \succeq , of the set of the profile of tops and $(n-1)$ fixed votes located at x_m .²⁰ Namely, for each $R \in \mathcal{SSP}(\succeq)^n$,

$$\begin{aligned} \sup_{\succeq}(R) &= \sup_{\succeq}\{t(R_1), \dots, t(R_n)\} \\ &= \text{median}_{\succeq}\{t(R_1), \dots, t(R_n), \underbrace{x_m, \dots, x_m}_{(n-1)\text{-times}}\}. \end{aligned}$$

Suppose now that $M \geq 4$ and consider the semilattice such that and $x_1 \prec x_2 \prec \dots \prec x_{M-1}$ and $x_M \prec x_{M-1}$. Figure 5 depicts the case $M = 6$.

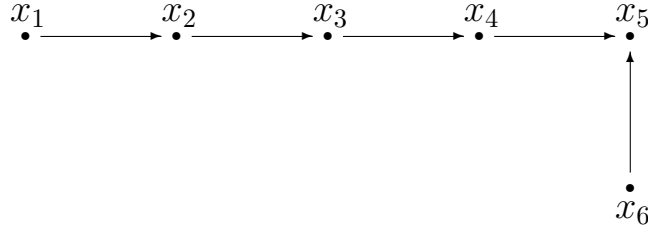


Figure 5

Then, $\sup_{\prec} A = x_{M-1}$, $A^*(\succeq) = x_M$ and the set of semilattice single-peaked preferences on (\mathbb{R}, \succeq) is

$$\begin{aligned} \mathcal{SSP}(\succeq) = \{ & R_i \in \mathcal{R} \mid t(R_i) = x_m \text{ for some } x_m \in A, \\ & \text{if } m = M \text{ then } x_{M-1} R_i x_j \text{ for all } j < M-1 \text{ and} \\ & \text{if } m < M-1 \text{ then } x_m \prec x_j \prec x_{j'} \preceq x_{M-1} \text{ implies } x_j R_i x_{j'} \text{ and } x_{M-1} R_i \} \end{aligned}$$

²⁰Moreover, and according to the description of median voters by means of left-coalition systems used in Barberà, Güel and Stachetti (1993), this rule corresponds to the case (using also the ordering $x_1 < \dots < x_M$ to define the left-coalition system) where the family of winning coalitions for all alternatives $x_j < x_m$ is equal to N , while the family of winning coalitions for all alternatives $x_j \geq x_m$ is equal to $2^N \setminus \{\emptyset\}$.

Observe that when $t(R_i) = x_{M-1}$, R_i is unrestricted. It is easy to see that the family of quota-supremum rules on the domain $\mathcal{SSP}(\succeq)^n$ with associated alternative x_M and quota $1 \leq q < n$, denoted by $\{f^q\}_{q=1}^{q=n-1}$, can be described as median voter rules, where the $n - 1$ fixed votes $\alpha_1, \dots, \alpha_{n-1}$ are given in Table 4, and by setting for each $R \in \mathcal{SSP}(\succeq)^n$, $f^q(R) = \text{median}_{\succeq}\{t(R_1, \dots, t(R_n), \alpha_1, \dots, \alpha_{n-1})\}$, where the fixed votes $\alpha_1, \dots, \alpha_{n-1}$ are given by the row corresponding to quota q in Table 4.

Quota	Fixed votes at x_{M-1}	Fixed votes at x_M
$q = 1$	none	$\alpha_1 = \dots = \alpha_{n-1} = x_M$
$q = 2$	$\alpha_1 = x_{M-1}$	$\alpha_2 = \dots = \alpha_{n-1} = x_M$
\vdots	\vdots	\vdots
$q = k$	$\alpha_1 = \dots = \alpha_{k-1} = x_{M-1}$	$\alpha_k = \dots = \alpha_{n-1} = x_M$
\vdots	\vdots	\vdots
$q = n - 1$	$\alpha_1 = \dots = \alpha_{n-2} = x_{M-1}$	$\alpha_{n-1} = x_M$

Table 4

4.2 Voting by committees

Consider the special case of voting by quota studied by Barberà, Sonnenschein and Zhou (1991) with two objects.²¹ A society has to choose a subset from a given set of two objects $\{a, b\}$. Namely, the set of alternatives is $A = \{\{\emptyset\}, \{a\}, \{b\}, \{a, b\}\}$ which can be identified with the unit vertices of the two-dimensional cube $A = \{(0, 0), (1, 0), (0, 1), (1, 1)\}$. Moreover, agents' preferences are separable: adding an object to a set that does not contain the object makes the set strictly preferred to the original set if and only the added object is strictly preferred to the empty set (as a singleton set, the object is good). Denote by \mathcal{S} the set

²¹For the illustration that we want to make here two objects is enough; the extension to the case with three or more objects is straightforward.

of all strict and separable preferences over A . Let \succeq be the semilattice represented in Figure 5, where an arrow between two alternatives points to their supremum, and the arrow that would follow from transitivity is omitted. It holds that $\mathcal{S} \subsetneq \mathcal{SSP}(\succeq)$; for instance, the preference $P_i^{(1,1)}$ where $(1,1)P_i^{(1,1)}(0,0)P_i^{(1,1)}(1,0)P_i^{(1,1)}(0,1)$ is not separable over the two-dimensional cube but it is semilattice single-peaked over (A, \succeq) .

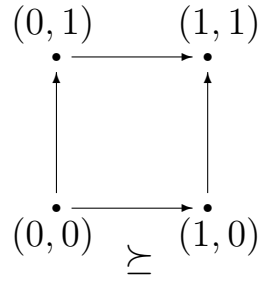


Figure 5

Let k^a and k^b be two integers such that $1 \leq k^a \leq n$ and $1 \leq k^b \leq n$. According to the terminology in Barberà, Sonnenschein and Zhou (1991), applied to the case with two objects, a rule $f : \mathcal{D}^n \rightarrow A$ is *voting by quota* (k^a, k^b) if, for all $P \in \mathcal{D}^n$, object $x \in \{a, b\}$ is an element of the chosen set at P (*i.e.*, $x \in f(P)$) if and only if $|N(R, x)| \geq k^x$. Barberà, Sonnenschein and Zhou (1991) show that $f : \mathcal{S}^n \rightarrow A$ is strategy-proof, anonymous and onto if and only if f is voting by quota.

For the semilattice depicted in Figure 5, and since $A^*(\succeq) = \emptyset$, the unique strategy-proof and simple rule on $\mathcal{SSP}(\succeq)^n$ is voting by quota $(k^a, k^b) = (1, 1)$, which corresponds to the \sup_{\succeq} rule. Figure 6 depicts three other semilattices over A .

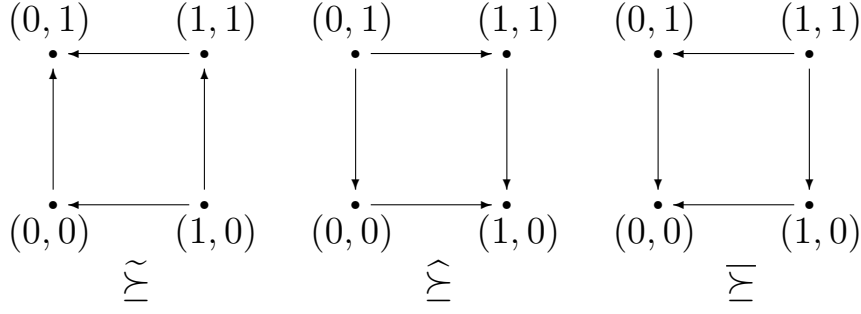


Figure 6

Since $A^*(\widetilde{\succeq}) = A^*(\widehat{\succeq}) = A^*(\overline{\succeq}) = \emptyset$, the unique strategy-proof and simple rule in each of the three cases is the one that corresponds to voting by quota $(\widetilde{k}^a, \widetilde{k}^b) = (n, 1)$, $(\widehat{k}^a, \widehat{k}^b) = (1, n)$ and $(\overline{k}^a, \overline{k}^b) = (n, n)$, or to $\text{sup}_{\widetilde{\succeq}}$, $\text{sup}_{\widehat{\succeq}}$ and $\text{sup}_{\overline{\succeq}}$, respectively, each corresponding to the unique strategy-proof and simple rule on the respective domains $\mathcal{SSP}(\widetilde{\succeq})^n$, $\mathcal{SSP}(\widehat{\succeq})^n$ and $\mathcal{SSP}(\overline{\succeq})^n$.

5 Rich domains and additional results

Chatterji and Massó (2018) shows that semilattice single-peakedness is a necessary condition of a domain \mathcal{D} admitting a strategy-proof and simple rule $f : \mathcal{D}^n \rightarrow A$, provided that n is even and \mathcal{D} is rich.²² Here, we first present the Chatterji and Massó (2018) notion of rich domain and show that, given any semilattice (A, \succeq) , the domain $\mathcal{SP}(\succeq)$ is indeed rich, and hence $\mathcal{SSP}(\succeq)$ is rich as well (richness is a property inherited by supersets).

Definition 4 *Let \succeq be a binary relation over A . The domain \mathcal{D} is **rich** on (A, \succeq) if, for all $x, y, z \in A$ with $z \notin [x, y] \neq \emptyset$, there exist $R_i^x, R_i^y \in \mathcal{D}$ such that $yP_i^x z$ and $xP_i^y z$.*

To illustrate richness return to Example 1 and consider, for instance,

²²Note that our results in this paper hold for any $n \geq 2$, independently on whether n is odd or even.

alternatives $x_3, x_5, x_8 \in A$ for which $x_8 \notin [x_3, x_5] \neq \emptyset$. In this case, $P_i^{x_3}, P_i^{x_5} \in \mathcal{SSP}(\preceq)$ are such that $x_5 P_i^{x_3} x_8$ and $x_3 P_i^{x_5} x_8$.

Well-known domains of preferences satisfying generalized notions of single-peakedness studied in the literature are rich (see Chatterji and Massó (2018)). However, subsets of single-peaked domains may not be rich, if they are substantially restricted; for example, the Euclidean preference domain is not rich.²³ Nevertheless, the set of all single-peaked preferences $\mathcal{SP}(\succeq)$ is rich on (A, \succeq) . This result is stated as Lemma 1.

Lemma 1 *Let \succeq be a semilattice over A . Then, the domain $\mathcal{SP}(\succeq)$ is rich on (A, \succeq) .*

PROOF Let $x, y, z \in A$ be such that $z \notin [x, y] \neq \emptyset$. Note that $x \neq z$ and $y \neq z$. We show that there is $R_i^x \in \mathcal{SP}(\succeq)$ such that $y P_i^x z$ (to show that there is $R_i^y \in \mathcal{SP}(\succeq)$ such that $x P_i^y z$ follows an analogous argument and it is omitted). If $x = y$ then all preferences $R_i^x \in \mathcal{SP}(\succeq)$ trivially fulfill $y P_i^x z$, so assume $x \neq y$. There are three cases to consider:

1. $y \prec z$. Then, $x \prec y \prec z$. By assumption, there exists at least one $R_i^x \in \mathcal{SP}(\succeq)$, and by part (i) of Definition 2, $y P_i^x z$.
2. $z \prec y$. If $z \prec x$, then $z \prec x \prec y$ and there is $R_i^x \in \mathcal{SP}(\succeq)$ such that $y P_i^x z$, since Definition 2 imposes no restriction on how R_i^x should order y and z . Otherwise, when $z \not\prec x$, if $y = \sup_{\succeq} \{x, z\}$ we have $y P_i^x z$ by part (ii) of Definition 2, whereas if $y \neq \sup_{\succeq} \{x, z\}$ Definition 2 imposes no restriction on how R_i^x should order y and z , and so we can always take $R_i^x \in \mathcal{SP}(\succeq)$ such that $y P_i^x z$.

²³Let A be a subset of an Euclidean space, let $\|\cdot\|$ be the Euclidean norm and let $x \in A$. We say that R_i^x is an *Euclidean* preference if, for all $y, z \in A$, $y R_i^x z$ if and only if $\|x - y\| \leq \|x - z\|$. Euclidean domains are not rich: for each $x \in A$, there is only one Euclidean preference whose top is x .

3. $y \not\preceq z$ or $z \not\preceq y$. Notice that, in this case, $y \neq \sup_{\preceq}\{x, z\}$. Again, Definition 2 imposes no restriction on how R_i^x should order y and z , and so we can always take $R_i^x \in \mathcal{SP}(\preceq)$ such that $yP_i^x z$.

Hence, the domain $\mathcal{SP}(\preceq)$ is rich on (A, \preceq) . ■

As we have already said, richness is a property inherited by larger domains. Hence, we obtain, as a consequence of Lemma 1, that the domain $\mathcal{SSP}(\preceq)$ is rich on (A, \preceq) .

Corollary 2 *Let \preceq be a semilattice over A . Then, the domain $\mathcal{SSP}(\preceq)$ is rich on (A, \preceq) .*

We finish this section by showing that the domain $\mathcal{SSP}(\preceq)$ is a maximal domain for the \sup_{\preceq} rule.

Definition 5 *Let $\mathcal{D} \subseteq \mathcal{R}$ be a domain and let $f : \mathcal{R}^n \rightarrow A$ be a simple rule such that $f : \mathcal{D}^n \rightarrow A$ is strategy-proof. The domain \mathcal{D} is **maximal** for f if for any $\tilde{\mathcal{D}}$ such that $\mathcal{D} \subsetneq \tilde{\mathcal{D}} \subseteq \mathcal{R}$, the rule $f : \tilde{\mathcal{D}}^n \rightarrow A$ is not strategy-proof.*

Proposition 1 *Let \preceq be a semilattice over A and let $\sup_{\preceq} : \mathcal{SSP}(\preceq)^n \rightarrow A$ be the supremum rule. Then, $\mathcal{SSP}(\preceq)$ is maximal for \sup_{\preceq} .*

PROOF See Appendix 7.2. ■

We return to Example 2 (continued) to illustrate two facts. First, $\mathcal{SSP}(\preceq)$ may not be maximal for some rule. Second, the converse of Proposition 1 does not hold for $n > 2$ (it is easy to see that it does for $n = 2$); namely, there exists a simple and strategy-proof rule $f : \mathcal{SSP}(\preceq)^3 \rightarrow A$ such that $\mathcal{SSP}(\preceq)$ is maximal for f but $f \neq \sup_{\preceq}$.

Example 2 (continued) The domain $\mathcal{SSP}(\preceq_1)$ is not maximal for f_2 and f_3 , but either rule can be represented as the supremum of their

respective induced semilattice (with quota 1); namely, $f_2 = \sup_{\succeq_2}$ and $f_3 = \sup_{\succeq_3}$. Moreover, the maximal domains for the rules f_2 and f_3 , that coincide with their associated semilattice single-peaked domains, are obtained by adding to $\mathcal{SSP}(\succeq_1)$ the preference P_i^{yz} for rule f_2 and the preference P_i^{zy} for rule f_3 ; namely,

$$\begin{aligned}\mathcal{SSP}(\succeq_1) &= \{P_i^{xy}, P_i^{xz}, P_i^{yx}, P_i^{zx}\} \\ \mathcal{SSP}(\succeq_2) &= \{P_i^{xy}, P_i^{xz}, P_i^{yx}, P_i^{zx}, P_i^{yz}\} = \mathcal{SSP}(\succeq_1) \cup \{P_i^{yz}\} \\ \mathcal{SSP}(\succeq_3) &= \{P_i^{xy}, P_i^{xz}, P_i^{yx}, P_i^{zx}, P_i^{zy}\} = \mathcal{SSP}(\succeq_1) \cup \{P_i^{zy}\}.\end{aligned}$$

It is easy to check that $f_1(R) = \sup_{\succeq_1} t(R)$ for all $R \in \mathcal{SSP}(\succeq_1)^2$. Moreover, $\mathcal{SSP}(\succeq_1)$ is a maximal domain for f_1 but $\mathcal{SSP}(\succeq_2)$ is not because $f_1 : \mathcal{SSP}(\succeq_2)^2 \rightarrow A$ is not strategy-proof since

$$z = f_1(P_1^{zx}, P_2^{zx})P_1^{yz}f_1(P_1^{yz}, P_2^{zx}) = x,$$

which means that agent 1 can manipulate f_1 at (P_1^{yz}, P_2^{zx}) by declaring P_1^{zx} instead of P_1^{yz} . Observe that $P_1^{yz} \notin \mathcal{SSP}(\succeq_1)$ and indeed, $f_1(P_1^{yz}, P_2^{zx}) = x \neq y = \sup_{\succeq_2} \{y, z\}$ where $\{y, z\} = t(P_1^{yz}, P_2^{zx})$. Similarly, $\mathcal{SSP}(\succeq_3)$ is not a maximal domain for $f_1 : \mathcal{SSP}(\succeq_3)^2 \rightarrow A$ because it is not strategy-proof since

$$y = f_1(P_1^{yx}, P_2^{yx})P_1^{zy}f_1(P_1^{zy}, P_2^{yx}) = x,$$

which means that agent 1 can manipulate f_1 at (P_1^{zy}, P_2^{yx}) by declaring P_1^{yx} instead of P_1^{zy} . Observe that $P_1^{zy} \notin \mathcal{SSP}(\succeq_1)$ and indeed, $f_1(P_1^{zy}, P_2^{yx}) = x \neq z = \sup_{\succeq_3} \{y, z\}$ where $\{y, z\} = t(P_1^{zy}, P_2^{yx})$.

Consider the rule $f_4 : \mathcal{SSP}(\succeq_1)^3 \rightarrow A$ described by

$$\begin{array}{ll} f_4(y, y, z) = y & f_4(x, x, y) = x \\ f_4(x, y, y) = y & \text{and} \quad f_4(x, y, z) = x \\ f_4(y, z, z) = x & f_4(x, z, z) = x \\ & f_4(x, x, z) = x \end{array}$$

together with the corresponding choices required by unanimity and anonymity. It is easy to check that $f_4 : \mathcal{SSP}(\succeq_1)^3 \rightarrow A$ is strategy-proof. Then, $f_4 \neq \sup_{\succeq_1}$ but $\mathcal{SSP}(\succeq_1)$ is maximal for f_4 , since the addition in the domain of either P_i^{yz} or P_i^{zy} would induce a manipulation by some of the agents. To see that, suppose P_i^{yz} or P_i^{zy} is available to agent 1. Then,

$$z = f_4(P_1^{zx}, P_2^{zx}, P_3^{zx})P_1^{yz} f_4(P_1^{yz}, P_2^{zx}, P_3^{zx}) = x$$

or

$$y = f_4(P_1^{yx}, P_2^{yx}, P_3^{zx})P_1^{zy} f_4(P_1^{zy}, P_2^{yx}, P_3^{zx}) = x,$$

contradicting strategy-proofness. Hence, the converse of Proposition 1 does not hold for $n > 2$. \square

6 Final remarks

We finish the paper with four remarks.

First, we have assumed, and intensively used from the very beginning, that $|A| \geq 3$. The case $A = \{x, y\}$ is special since there are only two semilattices over A , $x \succ^x y$ or $y \succ^y x$, and they are somehow equivalent since the two corresponding semilattice single-peaked domains coincide with the universal domain of strict preferences over A ; namely, $\mathcal{SSP}(\succ^x) = \mathcal{SSP}(\succ^y) = \{P_i^x, P_i^y\} = \mathcal{R}$. It is well-known that when the set of alternatives has cardinality two, the class of all strategy-proof and simple rules is voting by quota $(t^x, t^y) \in \{1, \dots, n\}^2$, where $t^x + t^y = n + 1$.²⁴ When x is used as the reference alternative, and

²⁴This is equivalent to the one-object case of voting by committees in Barberà, Sonnenschein and Zhou (1991), after identifying either y with the empty set (“ x is not elected”) or x with the empty set (“ y is not elected”). Then, the domain of separable (and additive) preferences coincides with the universal domain of strict preferences.

y is identified with the empty set (“ x is not elected”), for all $R \in \mathcal{R}^n$,

$$f^x(R) = \begin{cases} x & \text{if } |N(R, x)| \geq t^x \\ y & \text{otherwise,} \end{cases} \quad (1)$$

or when y is used as a references alternative, and x is identified with the empty set (“ y is not elected”), for all $R \in \mathcal{R}^n$,

$$f^y(R) = \begin{cases} y & \text{if } |N(R, y)| \geq t^y \\ x & \text{otherwise.} \end{cases} \quad (2)$$

Since $t^x + t^y = n + 1$, the two rules coincide because

$$\begin{aligned} |N(R, x)| &\geq t^x \\ \iff |N(R, x)| + t^y &\geq n + 1 = |N(R, x)| + |N(R, y)| + 1 \\ \iff t^y &\geq |N(R, y)| + 1 \\ \iff t^y &> |N(R, y)|. \end{aligned}$$

Hence, for all $R \in \mathcal{R}^n$, $f^x(R) = f^y(R)$. For the semilattice \succ^x , $A^*(\succ^x) = \{y\}$ and $f^y : \mathcal{R}^n \rightarrow \{x, y\}$ in (2) is the description of voting by quota (t^x, t^y) as a quota-supremum rule for y with quota t^y , and for the semilattice \succ^y , $A^*(\succ^y) = \{x\}$ and $f^x : \mathcal{R}^n \rightarrow \{x, y\}$ in (1) is the description of voting by quota (t^x, t^y) as a quota-supremum rule for x with quota t^x . Hence, the characterization in Theorem 1 remains valid even when $|A| = 2$.

Second, one may wonder whether our analysis of strategy-proof rules on semilattice single-peaked domains could be straightforwardly extended to the analysis of group strategy-proof rules on the same domain.²⁵ The answer to this query is negative. The domain of semilattice single-peaked preferences does not satisfy indirect sequential inclusion, the weaker condition on a domain identified by Barberà, Berga

²⁵If this would have been the case, some arguments in the proofs of our results would be simpler, since instead of replacing the preferences of agents sequentially they could be replaced simultaneously all together.

and Moreno (2010) as being sufficient for the equivalence of individual and group strategy-proofness. To see that in general strategy-proofness is strictly weaker than group strategy-proofness on semilattice single-peaked domains, consider again the special case of voting by quota studied by Barberà, Sonnenschein and Zhou (1991) with two objects (see Subsection 4.2). Then, voting by quota 1 for the two objects is not efficient since $\sup_{\succeq} \{(1, 0), (0, 1)\} = (1, 1)$ but there are separable preferences $P_1^{(1,0)}$ and $P_2^{(0,1)}$ for which $(0, 0)P_1^{(1,0)}(1, 1)$ and $(0, 0)P_2^{(0,1)}(1, 1)$. Hence, the \sup_{\succeq} rule although strategy-proof on the domain $\mathcal{SSP}(\succeq)$ it is not efficient, and so it is not group strategy-proof, even on the set of separable preferences \mathcal{S} over the two-dimensional cube, a subdomain of semilattice single-peaked preferences on (A, \succeq) .

Third, a natural question to ask is whether the characterization in Theorem 1 remains valid without the tops-only condition. It is well known that, in different settings, strategy-proof and unanimous rules (or random rules) on domains related to single-peakedness have to be tops-only.²⁶ In particular, for the case of a finite set of alternatives, Chatterji and Sen (2011) identify conditions on a domain that are sufficient for strategy-proofness and unanimity to imply tops-onlyness. It is not difficult to exhibit a simple example showing that $\mathcal{SSP}(\succeq)$ does not satisfy the most general of their conditions. Unfortunately, for the semilattice single-peaked domain, we have neither a proof that tops-only follows from strategy-proofness and unanimity nor an example of a strategy-proof and unanimous rule on a domain of semilattice single-peaked preferences that is not tops-only. We conjecture that the

²⁶See for example Barberà, Güel and Stacchetti (1993), Barberà and Jackson (1994), Barberà, Massó and Neme (1997 and 2005), Barberà, Massó and Serizawa (1998), Barberà, Sonnenschein and Zhou (1991), Border and Jordan (1983), Chatterji and Sen (2011), Chatterji and Zeng (2018), Ching (1997), Ehlers, Peters and Storcken (2002), Pycia and Ünver (2015), Reffgen (2015), Reffgen and Svensson (2012), Saporiti (2009), Sprumont (1995) and Weymark (2008 and 2011).

former is correct and that its proof is difficult.²⁷ In our setting, several reasons add further difficulties to obtain such proof. The semilattice structure of the set A is much weaker than the linear and Euclidean structure of the set of alternatives, often assumed in this literature. Moreover, we admit the possibility that the set of alternatives A be infinite and that semilattice single-peaked preferences display indifferences (in particular, along any path that, leaving the top alternative, follows the semilattice in the up direction). Most of this literature on tops-onlyness assumes that A is finite and preferences are linear orders over A . To see the additional difficulty coming from indifferences, consider the simplest case where $A = \{x, y, z\}$, $x \prec y \prec z$ and $n = 2$. Let $R_1, R'_1, R_2 \in \mathcal{SSP}(\succeq)$ be such that $t(R_1) = t(R'_1)$ and, to obtain a contradiction with tops-onlyness, assume $f(R_1, R_2) = y \neq z = f(R'_1, R_2)$. If $t(R_1) = y$, 1 manipulates f at (R'_1, R_2) with R_1 . If $t(R_1) = z$, 1 manipulates at (R_1, R_2) with R'_1 . Hence $t(R_1) = t(R'_1) = x \notin \{y, z\}$. However, the definition of semilattice single-peakedness only requires that $yR_i^x z$. Therefore, if $yI_i^x z$ a contradiction does not follow immediately. Accordingly, we leave the general proof for further research.

Fourth, random rules have been proposed with the objective of achieving equity or fairness; for instance, in settings like voting, matching or the assignment of indivisible objects. For the voting case with single-peaked preferences, Ehlers, Peters and Storcken (2002) characterizes the family of strategy-proof and unanimous random rules based on Moulin (1980)'s characterization of deterministic rules.²⁸ Pycia and Ünver (2015) asks under which circumstances desirable properties of random rules survive decomposition of the rule as a probability

²⁷Sprumont (1995, p. 77) has noted that: "Proving this fact constitutes a key step in many papers in the literature. Unfortunately, the proofs remain model specific and are often quite complicated."

²⁸In the single-peaked domain, all strategy-proof and unanimous deterministic rules are tops-only.

distribution over deterministic rules that satisfy the same properties. The approach in the latter paper is based on two key things. First, the possibility of expressing a property of a random rule as a family of constraints. Second, on whether or not the matrix associated to the constraints is totally unimodular. In particular, Theorem 7 in Pycia and Ünver (2015) states that a strategy-proof, unanimous and anonymous random rule is decomposable. Observe that the family of rules that we characterize here is significantly smaller than the class of rules characterized in Moulin (1980); indeed, the domain of semilattice single-peaked preferences constitutes a substantial enlargement of the single-peaked domain and accordingly, many strategy-proof rules on the smaller domain become manipulable on the larger domain. Hence, a natural and interesting road that we leave for further research is to extend our analysis to random rules on the semilattice single-peaked domain, as Ehlers, Peters and Storcken (2002) and Pycia and Ünver (2015) have done for the single-peaked domain.

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7 Appendix

7.1 Preliminary remarks and lemmata

Remarks 4 and 5 identify circumstances under which, given any three different alternatives $x, y, z \in A$, the set $\mathcal{SSP}(\succeq)$ contains preferences with top on x that may or may not freely order y and z . The two remarks will be useful in some of the proofs that follow.

Remark 4 *Let $x, y, z \in A$ be three different alternatives and let \succeq be a semilattice over A . If $x \succ y$, then*

- (i) *there exists $R_i^x \in \mathcal{SSP}(\succeq)$ such that $zP_i^x y$,*
- (ii) *there exists $R_i^x \in \mathcal{SSP}(\succeq)$ such that $yP_i^x z$.*

PROOF Suppose $x, y, z \in A$ are three different alternatives with $x \succ y$. We first show that part (i) of the Remark holds. If $z \in [y, x]$, then $y \notin [z, x] \neq \emptyset$ and the result follows from *richness*. If $z \notin [y, x]$, we will show that neither condition (i) nor condition (ii) in Remark 1 characterizing *semilattice single-peakedness* imply $yR_i^x z$. First, notice that since $x \succ y$, condition (i) in Remark 1 cannot be applied, and hence the ordering between y and z is unrestricted. Second, notice that although $y \not\preceq x$,

condition (ii) in Remark 1 only implies $x = \sup_{\succeq} \{x, y\} R_i^x y$, and hence the ordering between y and z is also unrestricted. Thus, there exists $R_i^x \in \mathcal{SSP}(\succeq)$ such that $z P_i^x y$. To show that part (ii) holds, notice that if $z \notin [y, x]$ the result follows from *richness*; whereas if $z \in [y, x]$ it follows that $x \succ z \succ y$ and parts (i) and (ii) of Remark 1 can not be applied, and hence the ordering between y and z is unrestricted. Thus, there exists $R_i^x \in \mathcal{SSP}(\succeq)$ such that $y P_i^x z$. ■

Remark 5 Let $x, y, z \in A$ be three different alternatives and let \succeq be a semilattice over A . If $x \not\succ y$, $y \not\succ x$ and $z \notin [x, \sup_{\succeq} \{x, y\}]$, then there is $R_i^x \in \mathcal{SSP}(\succeq)$ such that $y P_i^x z$.

PROOF Let $x, y, z \in A$ be three different alternatives and suppose $x \not\succ y$, $y \not\succ x$ and $z \notin [x, \sup_{\succeq} \{x, y\}]$. We will show that neither condition (i) nor condition (ii) in Remark 1 characterizing *semilattice single-peakedness* imply that, for each $R_i^x \in \mathcal{SSP}(\succeq)$, $z R_i^x y$ holds. First, notice that since $x \not\succ y$, condition (i) in Remark 1 cannot be applied. Second, notice that since $x \not\succ y$, condition (ii) in Remark 1 only implies that $\sup_{\succeq} \{x, y\} R_i^x y$. But since $z \neq \sup_{\succeq} \{x, y\}$, there exists $R_i^x \in \mathcal{SSP}(\succeq)$ such that $y P_i^x z$. ■

To illustrate the content of Remarks 4 and 5 return again to Example 1 and observe, for instance, that

- $x_3 \succ x_1$ and there exist $P_i^{x_3}, \hat{P}_i^{x_3} \in \mathcal{SSP}(\succeq)$ such that $x_1 P_i^{x_3} x_2$ and $x_2 \hat{P}_i^{x_3} x_1$.
- $x_8 \not\succ x_9$, $x_9 \not\succ x_8$, $\sup_{\succeq} \{x_8, x_9\} = x_6$ and $x_4 \notin [x_8, x_6]$ and there is $P_i^{x_8} \in \mathcal{SSP}(\succeq)$ such that $x_9 P_i^{x_8} x_4$.

We next state and prove several lemmata that will be used in the proofs of the Propositions and Theorem 1.

Lemma 2 Let \succeq be a semilattice over A , let $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ be a strategy-proof and simple rule, and let $R \in \mathcal{SSP}(\succeq)^n$. Assume $x, y \in A$ are such that $x \succ y$ or $y \succ x$ and $t(R) = \{x, y\}$. Then, $f(R) \in \{x, y\}$.

PROOF Let the hypothesis of the Lemma hold. Without loss of generality, assume $x \succ y$. The proof is by induction on the cardinality of $N(R, x)$. Consider first $N(R, x) = \{i\}$ (this implies $N(R, y) = N \setminus \{i\}$) and assume $f(R) = z \notin \{x, y\}$. By Remark 4 (ii), there is $R_i^x \in \mathcal{SSP}(\succeq)$ such that $yP_i^x z$. By *tops-onlyness*, $f(R_i^x, R_{-i}) = f(R) = z$. Furthermore, by *unanimity*, $f(R_i^y, R_{-i}) = y$ for any $R_i^y \in \mathcal{SSP}(\succeq)$. Then,

$$f(R_i^y, R_{-i}) = yP_i^x z = f(R_i^x, R_{-i}),$$

contradicting *strategy-proofness*. Hence, $f(R) \in \{x, y\}$. Now, suppose $R \in \mathcal{SSP}(\succeq)^n$ is such that, for all $1 \leq k \leq n - 2$, $|N(R, x)| = k$ and $f(R) = \{x, y\}$. We want to see that if $R' \in \mathcal{SSP}(\succeq)^n$ is such that $|N(R', x)| = k + 1$, then $f(R') \in \{x, y\}$. To obtain a contradiction, suppose $f(R') = z \notin \{x, y\}$. Let $i \in N(R', x)$. By Remark 4 (ii), there is $R_i^x \in \mathcal{SSP}(\succeq)$ such that $yP_i^x z$. By *tops-onlyness*, $f(R_i^x, R'_{-i}) = f(R') = z$. Furthermore, by the inductive hypothesis and *tops-onlyness*, $f(R_i^y, R'_{-i}) \in \{x, y\}$ for any $R_i^y \in \mathcal{SSP}(\succeq)$. Then, in both case,

$$f(R_i^y, R'_{-i})P_i^x z = f(R_i^x, R'_{-i}),$$

contradicting *strategy-proofness*. Hence, $f(R') \in \{x, y\}$. ■

Lemma 3 Let \succeq be a semilattice over A , let $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ be a strategy-proof and simple rule and let k be such that $1 \leq k < n$. Assume $x, y \in A$ are such that $x \succ y$ and there is $R \in \mathcal{SSP}(\succeq)^n$ such that $t(R) = \{x, y\}$, $|N(R, y)| = k$ and $f(R) = y$. Then, $f(\tilde{R}) = y$ for each $\tilde{R} \in \mathcal{SSP}(\succeq)^n$ such that $|N(\tilde{R}, y)| \geq k$.

PROOF Let the hypothesis of the Lemma hold. Let $\tilde{R} \in \mathcal{SSP}(\succeq)^n$ be such that $|N(\tilde{R}, y)| \geq k$. We want to show that $f(\tilde{R}) = y$. Let $S \subset N$ be such that $S \subseteq N(\tilde{R}, y)$ and $|S| = k$. By *anonymity*, we can assume that $N(R, y) = S$. By *tops-onlyness*, $f(\tilde{R}_S, R_{-S}) = y$. Let $i \in N \setminus S$. We claim that $f(\tilde{R}_{S \cup \{i\}}, R_{-(S \cup \{i\})}) = y$. If not, $f(\tilde{R}_{S \cup \{i\}}, R_{-(S \cup \{i\})}) = w \neq y$ and, as $x \succ y$, by Remark 4 (i) there is $R_i^x \in \mathcal{SSP}(\succeq)$ such that $w P_i^x y$. Since $N(R, y) = S$, $t(R_i) = x$. By *tops-onlyness*, $f(\tilde{R}_S, R_i^x, R_{-(S \cup \{i\})}) = f(\tilde{R}_S, R_{-S})$. Therefore,

$$f(\tilde{R}_{S \cup \{i\}}, R_{-(S \cup \{i\})}) = w P_i^x y = f(\tilde{R}_S, R_i^x, R_{-(S \cup \{i\})}),$$

contradicting *strategy-proofness*. Hence, $f(\tilde{R}_{S \cup \{i\}}, R_{-(S \cup \{i\})}) = y$. Continuing in the same way, we can successively change the preferences of each of the remaining agents in $N \setminus S$ to finally obtain $f(\tilde{R}) = y$. ■

Lemma 4 *Let \succeq be a semilattice over A and let $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ be a strategy-proof and simple rule. Then, for each $R \in \mathcal{SSP}(\succeq)^n$,*

$$f(R) \in \bigcup_{i \in N} [t(R_i), \sup_{\succeq} t(R)].$$

PROOF Let the hypothesis of the Lemma hold. The proof is by induction on the cardinality of $t(R)$. If $R \in \mathcal{SSP}(\succeq)^n$ is such that $|t(R)| = 1$, then the result is trivially true by *unanimity*. Suppose that the result holds for any $R \in \mathcal{SSP}(\succeq)^n$ such that $|t(R)| = k$ and $1 \leq k < n$. Consider now a profile $R \in \mathcal{SSP}(\succeq)^n$ such that $t(R) = \{x_1, \dots, x_{k+1}\}$ and assume $f(R) = y \notin \cup_{j=1}^{k+1} [x_j, \sup_{\succeq} t(R)]$. There are two cases to consider.

1. $\sup_{\succeq} t(R) \in t(R)$. Without loss of generality, assume $\sup_{\succeq} t(R) = x_{k+1}$. Then,

$$\cup_{j=1}^{k+1} [x_j, \sup_{\succeq} t(R)] = \cup_{j=1}^k [x_j, x_{k+1}].$$

If $|N(R, x_{k+1})| > 1$, take any $i \in N(R, x_{k+1})$ and consider $R'_i \in \mathcal{SSP}(\succeq)$ such that $t(R'_i) \in t(R) \setminus \{x_{k+1}\}$. We claim that $f(R'_i, R_{-i}) = z \notin \cup_{j=1}^k [x_j, x_{k+1}]$. If $z = y$ this is obvious, by the contradiction hypothesis, so assume $z \neq y$ and, to obtain a contradiction, suppose $z \in \cup_{j=1}^k [x_j, x_{k+1}]$. We now show that $z \neq x_{k+1}$, because otherwise,

$$f(R'_i, R_{-i}) = z = x_{k+1} P_i^{x_{k+1}} y = f(R_i^{x_{k+1}}, R_{-i}),$$

contradicting *strategy-proofness*. Thus, $x_{k+1} \succ z$. By Remark 4 (ii) there is $R_i^{x_{k+1}} \in \mathcal{SSP}(\succeq)$ such that $z P_i^{x_{k+1}} y$. Notice that, by *tops-onlyness*, $f(R_i^{x_{k+1}}, R_{-i}) = f(R) = y$. Therefore,

$$f(R'_i, R_{-i}) = z P_i^{x_{k+1}} y = f(R_i^{x_{k+1}}, R_{-i}),$$

contradicting *strategy-proofness*. Hence, $f(R'_i, R_{-i}) \notin \cup_{j=1}^k [x_j, x_{k+1}]$. If necessary (*i.e.*, if there are still several agents with top at x_{k+1}), we repeat this process until we obtain a profile \tilde{R} such that $t(\tilde{R}) = \{x_1, \dots, x_{k+1}\}$, $|N(\tilde{R}, x_{k+1})| = 1$, and $f(\tilde{R}) = t \notin \cup_{j=1}^k [x_j, x_{k+1}]$. Hence, let $N(\tilde{R}, x_{k+1}) = \{i\}$ and consider $R'_i \in \mathcal{SSP}(\succeq)$ such that $t(R'_i) \in t(\tilde{R}) \setminus \{x_{k+1}\}$. Let $f(R'_i, \tilde{R}_{-i}) = w$ and $\tilde{x} = \sup_{\succeq} \{x_1, \dots, x_k\}$. Then, by the inductive hypothesis, $w \in \cup_{j=1}^k [x_j, \tilde{x}]$. Therefore, $x_{k+1} \succ \tilde{x} \succeq w$ and, by Remark 4 (ii), there is $R_i^{x_{k+1}} \in \mathcal{SSP}(\succeq)$ such that $w P_i^{x_{k+1}} t$. By *tops-onlyness*, $f(R_i^{x_{k+1}}, \tilde{R}_{-i}) = f(\tilde{R}) = t$. Therefore,

$$f(R'_i, \tilde{R}_{-i}) = w P_i^{x_{k+1}} t = f(R_i^{x_{k+1}}, \tilde{R}_{-i}),$$

contradicting *strategy-proofness*.

- 2. $\sup_{\succeq} t(R) \notin t(R)$.** Let $\tilde{x} = \sup_{\succeq} t(R)$. Consider any $x^* \in t(R)$ and let $t^*(R) = \{x \in t(R) \mid x \succeq x^* \text{ or } x^* \succeq x\}$. Notice that, since $\sup_{\succeq} t(R) \notin t(R)$, $1 \leq |t^*(R)| < |t(R)|$. Let $N^* = \{i \in N \mid t(R_i) \in t^*(R)\}$ and let $i^* \in N(R, x^*)$.

Claim: Let $i \in N^*$ and let $R'_i \in \mathcal{SSP}(\succeq)$ be such that $t(R'_i) \in t(R) \setminus t^*(R)$. Then, $f(R'_i, R_{-i}) \notin \cup_{j=1}^{k+1}[x_j, \tilde{x}]$.

Let $i \in N^*$, $x_i = t(R_i)$, and $z = f(R'_i, R_{-i})$. If $z = y$ this is obvious, by the contradiction hypothesis, so assume $z \neq y$ and, to obtain a contradiction, suppose $z \in \cup_{j=1}^{k+1}[x_j, \tilde{x}]$. Then, there is $R_i^{x_i} \in \mathcal{SSP}(\succeq)$ such that

$$z P_i^{x_i} y, \quad (3)$$

where, remember, $y = f(R)$. To see that (3) holds, there are two cases to consider. First, assume that $z \succeq x_i$. As $y \notin \cup_{j=1}^{k+1}[x_j, \tilde{x}]$, it follows that $y \notin [x_i, z]$ and (3) is implied by *richness*. Second, assume that $z \not\succeq x_i$. If $x_i \succeq z$, (3) follows from Remark 4 (ii). If $x_i \not\succeq z$, and since $y \notin [x_i, \tilde{x}]$, (3) follows from Remark 5. By *tops-onlyness*, $f(R_i^{x_i}, R_{-i}) = f(R) = y$. Therefore,

$$f(R'_i, R_{-i}) = z P_i^{x_i} y = f(R_i^{x_i}, R_{-i}),$$

contradicting *strategy-proofness*. Hence, $f(R'_i, R_{-i}) \notin \cup_{j=1}^{k+1}[x_j, \tilde{x}]$ and the Claim is proved.

Using the Claim, we proceed by changing the preferences of all the members of N^* except i^* . We obtain a new profile $\tilde{R} \in \mathcal{SSP}(\succeq)$ such that $t(\tilde{R}) \subset t(R)$, $N(\tilde{R}, x^*) = \{i^*\}$, and $f(\tilde{R}) \notin \cup_{j=1}^{k+1}[x_j, \tilde{x}]$.

To finish the proof, consider $R'_{i^*} \in \mathcal{SSP}(\succeq)$ such that $t(R'_{i^*}) \in t(R) \setminus t^*(R)$. Let $t = f(\tilde{R})$, $w = f(R'_{i^*}, \tilde{R}_{-i^*})$ and $\hat{x} = \sup_{\succeq}[t(R) \setminus t^*(R)]$. Then, by the inductive hypothesis, $w \in \cup_{x_j \in t(R) \setminus t^*(R)}[x_j, \hat{x}]$. Since $\sup_{\succeq}\{x^*, w\} = \tilde{x}$ and $t \notin [x^*, \tilde{x}]$, by Remark 5, there is $R_{i^*}^{x^*} \in \mathcal{SSP}(\succeq)$ such that $w P_{i^*}^{x^*} t$. By *tops-onlyness*, $f(R_{i^*}^{x^*}, \tilde{R}_{-i^*}) = f(\tilde{R}) = t$. Therefore,

$$f(R'_{i^*}, \tilde{R}_{-i^*}) = w P_{i^*}^{x^*} t = f(R_{i^*}^{x^*}, \tilde{R}_{-i^*}),$$

contradicting *strategy-proofness*.

Hence, $f(R) \in \cup_{j=1}^{k+1} [x_j, \sup_{\succeq} t(R)]$. ■

Lemma 5 *Let \succeq be a semilattice over A and let $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ be a strategy-proof and simple rule. Let $R \in \mathcal{SSP}(\succeq)^n$, $x \in A$, $i \in N$ and $R_i^x \in \mathcal{SSP}(\succeq)$. If $x \succ t(R_i)$, $x \succ f(R)$ and $f(R) \notin [t(R_i), x]$, then*

$$f(R_i^x, R_{-i}) = f(R).$$

PROOF Let the hypothesis of the Lemma hold. First, notice that

$$f(R_i^x, R_{-i}) \in \{f(R), x\}. \quad (4)$$

Otherwise, since $x \succ f(R)$, by Remark 4 (ii) there is $\tilde{R}_i^x \in \mathcal{SSP}(\succeq)$ such that $f(R) \tilde{P}_i^x f(R_i^x, R_{-i})$. By *tops-onlyness*, $f(R_i^x, R_{-i}) = f(\tilde{R}_i^x, R_{-i})$. Therefore,

$$f(R) \tilde{P}_i^x f(\tilde{R}_i^x, R_{-i}),$$

contradicting *strategy-proofness*. Second, assume $f(R_i^x, R_{-i}) = x$. Since $f(R) \notin [t(R_i), x]$, by *richness* there is $\tilde{R}_i \in \mathcal{SSP}(\succeq)$ such that $t(\tilde{R}_i) = t(R_i)$ and $x \tilde{P}_i f(R)$. By *tops-onlyness*, $f(R) = f(\tilde{R}_i, R_{-i})$. Therefore,

$$f(R_i^x, R_{-i}) \tilde{P}_i f(\tilde{R}_i, R_{-i}),$$

contradicting *strategy-proofness*. To conclude, as (4) holds and $f(R_i^x, R_{-i}) \neq x$, the result follows. ■

Lemma 6 *Let \succeq be a semilattice over A and let $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ be a strategy-proof and simple rule. If $R \in \mathcal{SSP}(\succeq)^n$ is such that $\sup_{\succeq} t(R) \notin t(R)$ and $\sup_{\succeq} t(R) \succ f(R)$, then there is $\tilde{R} \in \mathcal{SSP}(\succeq)^n$ such that $\sup_{\succeq} t(\tilde{R}) = \sup_{\succeq} t(R)$, $\sup_{\succeq} t(\tilde{R}) \in t(\tilde{R})$, and $f(\tilde{R}) = f(R)$.*

PROOF Let the hypothesis of the Lemma hold. Take $i \in N$ such that $f(R) \notin [t(R_i), \sup_{\succeq} t(R)]$ (such i exists, because otherwise $f(R) =$

$\sup_{\succeq} t(R)$). Let $R'_i \in \mathcal{SSP}(\succeq)$ be such that $t(R'_i) = \sup_{\succeq} t(R)$ and consider the profile $\tilde{R} = (R'_i, R_{-i})$. Then, $\sup_{\succeq} t(\tilde{R}) = \sup_{\succeq} t(R) \in t(\tilde{R})$ and since $f(R) \notin [t(R_i), \sup_{\succeq} t(R)]$ holds, by Lemma 5, $f(\tilde{R}) = f(R)$. ■

Lemma 7 *Let \succeq be a semilattice over A , let $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ be a strategy-proof and simple rule and let k be such that $1 \leq k < n$. Assume $x, y \in A$ are such that $x \succ y$ and there is $R \in \mathcal{SSP}(\succeq)^n$ such that $t(R) = \{x, y\}$, $|N(R, y)| = k$ and $f(R) = y$. Then, $f(\tilde{R}) \in \{y, \sup_{\succeq} t(\tilde{R})\}$ for all $\tilde{R} \in \mathcal{SSP}(\succeq)^n$ such that $|N(\tilde{R}, y)| < k$.*

PROOF Let the hypothesis of the Lemma hold. Let $\tilde{R} \in \mathcal{SSP}(\succeq)^n$ be such that $|N(\tilde{R}, y)| = k - 1$. If $k = 1$ then $t(\tilde{R}) = \{x\}$, and by *unanimity*, $f(\tilde{R}) = x = \sup_{\succeq} t(\tilde{R})$ and the statement holds trivially. Suppose $k > 1$. Let $i \in N(R, y)$ and set $S \equiv N(R, y) \setminus \{i\}$. By *anonymity*, we can assume $S = N(\tilde{R}, y)$. By *tops-onlyness*, $f(\tilde{R}_S, R_{-S}) = f(R)$. Let $j \in N(R, x)$. First, we show that

$$f(\tilde{R}_{S \cup \{j\}}, R_{-(S \cup \{j\})}) = y. \quad (5)$$

Otherwise, since $x \succ y$, by Remark 4 (i) there is $R_j^x \in \mathcal{SSP}(\succeq)$ such that

$$f(\tilde{R}_{S \cup \{j\}}, R_{-(S \cup \{j\})}) P_j^x y.$$

By *tops-onlyness*, $f(\tilde{R}_S, R_j^x, R_{-(S \cup \{j\})}) = f(\tilde{R}_S, R_{-S}) = y$. Therefore,

$$f(\tilde{R}_{S \cup \{j\}}, R_{-(S \cup \{j\})}) P_j^x (\tilde{R}_S, R_j^x, R_{-(S \cup \{j\})}),$$

contradicting *strategy-proofness*. Thus, (5) holds. Continuing in the same way, we can change the preferences of each of the remaining agents in $N(R, x)$ to obtain

$$f(\tilde{R}_{-i}, R_i) = y. \quad (6)$$

Next, we show that $f(\tilde{R}) \in \{y, \sup_{\succeq} t(\tilde{R})\}$. Let $s \equiv \sup_{\succeq} t(\tilde{R})$ and, to get a contradiction, suppose $f(\tilde{R}) \notin \{y, s\}$. Then, as $f(\tilde{R}) \prec s$ by Lemma 4, we can assume that \tilde{R} is such that $s \in t(\tilde{R})$ by Lemma 6. By *anonymity*, assume $i \in N(R, s)$. Since $s \succ f(\tilde{R})$, by Remark 4 (i) there is $R_i^s \in \mathcal{SSP}(\succeq)$ such that $y P_i^s f(\tilde{R})$. By *tops-onlyness*, $f(\tilde{R}) = f(R_i^s, \tilde{R}_{-i})$. Therefore, using (6),,

$$f(R_i, \tilde{R}_{-i}) P_i^s f(R_i^s, \tilde{R}_{-i}),$$

contradicting *strategy-proofness*. Hence, $f(\tilde{R}) \in \{y, s\}$.

We just proved the Lemma when \tilde{R} is such that $|N(\tilde{R}, y)| = k - 1$. In order to prove the statement for a profile \hat{R} such that $N(\hat{R}, y) = k - 2$ we use a similar reasoning and the fact that the result is true whenever there are $k - 1$ tops in y . We successively apply the same reasoning to profiles in which the cardinality of the set of agents with top in y is smaller. ■

Lemma 8 *Let \succeq be a semilattice over A such that there is $\sup_{\succeq} A \equiv \alpha$ and let $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ be a strategy-proof and simple rule. Assume $f(R) = \alpha$ whenever $\alpha \in t(R)$. Then, $f(R) = \sup_{\succeq} t(R)$ for each $R \in \mathcal{SSP}(\succeq)^n$.*

PROOF Let the hypothesis of the Lemma hold. To obtain a contradiction, assume there is $R \in \mathcal{SSP}(\succeq)^n$ such that $f(R) \neq \sup_{\succeq} t(R)$. Since $f(R) \in \cup_{i \in N} [t(R_i), \sup_{\succeq} t(R)]$ by Lemma 4,

$$\sup_{\succeq} t(R) \succ f(R). \tag{7}$$

By Lemma 6, it is without loss of generality to assume that $\sup_{\succeq} t(R) \in t(R)$. Let $i \in N(R, \sup_{\succeq} t(R))$. As $\alpha \succeq \sup_{\succeq} t(R) \succ f(R)$, by *richness*, there is $R'_i \in \mathcal{SSP}(\succeq)$ such that $t(R'_i) = \sup_{\succeq} t(R)$ and $\alpha P'_i f(R)$. By

tops-onlyness, $f(R'_i, R_{-i}) = f(R)$. By the hypothesis, $f(R_i^\alpha, R_{-i}) = \alpha$ for any $R_i^\alpha \in \mathcal{SSP}(\succeq)$. Therefore,

$$f(R_i^\alpha, R_{-i}) = \alpha P'_i f(R) = f(R'_i, R_{-i}),$$

contradicting *strategy-proofness*. Hence, $f(R) = \sup_{\succeq} t(R)$. ■

Lemma 9 *Let \succeq be a semilattice over A such that $\sup_{\succeq} A$ does not exist and let $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ be a strategy-proof and simple rule. Then, $f(R) = \sup_{\succeq} t(R)$ for each $R \in \mathcal{SSP}(\succeq)^n$.*

PROOF Let the hypothesis of the Lemma hold. Notice first that, if $|t(R)| = 1$ then the result follows by *unanimity*. To obtain a contradiction, let $R \in \mathcal{SSP}^n$, with $|t(R)| > 1$, be such that $f(R) \neq \sup_{\succeq} t(R)$. Since $f(R) \in \cup_{i \in N} [t(R_i), \sup_{\succeq} t(R)]$ by Lemma 4,

$$\sup_{\succeq} t(R) \succ f(R). \quad (8)$$

By Lemma 6, it is without loss of generality to assume that $\sup_{\succeq} t(R) \in t(R)$. Let

$$s \equiv \sup_{\succeq} t(R). \quad (9)$$

First, notice that there is $x \in A$ such that $x \succ s$. Since, by the hypothesis, there is no $\sup_{\succeq} A$, there exists $y \in A$ such that $s \not\preceq y$. If $y \succ s$, take $x = y$; whereas if $s \not\preceq y$ and $y \not\preceq s$, take $x = \sup_{\succeq} \{s, y\}$. We now proceed through several steps.

Claim 1: If $S \subseteq N(R, s)$ and $\tilde{R}_S \in \mathcal{SSP}(\succeq)^{|S|}$ is such that $t(\tilde{R}_i) = x$ for each $i \in S$, then $f(\tilde{R}_S, R_{-S}) = f(R)$.

The proof is by induction on the cardinality of S . Suppose first that $S = \{i\}$ and consider any $\tilde{R}_i \in \mathcal{SSP}(\succeq)$ such that $t(\tilde{R}_i) = x$. As $f(R) \notin [s, x]$, by Lemma 5,

$$f(\tilde{R}_i, R_{-i}) = f(R). \quad (10)$$

Suppose now that $f(\tilde{R}_S, R_{-S}) = f(R)$ and consider $i \in N(R, s) \setminus S$. Let $\tilde{R}_i \in \mathcal{SSP}(\succeq)$ be such that $t(\tilde{R}_i) = x$. As $f(\tilde{R}_S, R_{-S}) \notin [s, x]$, by Lemma 5,

$$f(\tilde{R}_{S \cup \{i\}}, R_{-(S \cup \{i\})}) = f(\tilde{R}_S, R_{-S}). \quad (11)$$

Thus, $f(\tilde{R}_{S \cup \{i\}}, R_{-(S \cup \{i\})}) = f(R)$ and the Claim holds.

Claim 2: If $S \supseteq N(R, s)$ and $\tilde{R}_S \in \mathcal{SSP}(\succeq)^{|S|}$ is such that $t(\tilde{R}_i) = x$ for each $i \in S$, then $f(\tilde{R}_S, R_{-S}) = f(R)$.

The proof is by induction on the cardinality of S . Let $\tilde{N} \equiv N(R, s)$, $i \notin \tilde{N}$ and consider $\tilde{R}_{\tilde{N}} \in \mathcal{SSP}(\succeq)^{|\tilde{N}|}$ with $t(\tilde{R}_j) = x$ for each $j \in \tilde{N}$ and $R'_i \in \mathcal{SSP}(\succeq)$ with $t(R'_i) = s$. Since $s \succ f(R)$ and $f(R_{\tilde{N}}, R_{-\tilde{N}}) = f(R)$ by Claim 1, by Lemma 5 it follows that

$$f(R'_i, \tilde{R}_{\tilde{N}}, R_{-(\tilde{N} \cup \{i\})}) = f(\tilde{R}_{\tilde{N}}, R_{-\tilde{N}}).$$

Now consider $\tilde{R}_i \in \mathcal{SSP}(\succeq)$ such that $t(\tilde{R}_i) = x$. Since $x \succ f(R)$ and $f(\tilde{R}_{\tilde{N}}, R_{-\tilde{N}}) = f(R)$ by Claim 1, by Lemma 5 it follows that

$$f(\tilde{R}_{\tilde{N} \cup \{i\}}, R_{-(\tilde{N} \cup \{i\})}) = f(\tilde{R}_{\tilde{N}}, R_{-\tilde{N}}).$$

To finish the proof of Claim 2, suppose next that $S \supsetneq N(R, s)$, $\tilde{R}_S \in \mathcal{SSP}(\succeq)^{|S|}$ is such that $t(\tilde{R}_i) = x$ for each $i \in S$ and $f(\tilde{R}_S, R_{-S}) = f(R)$. Let $i \notin S$. First, let $R'_i \in \mathcal{SSP}(\succeq)$ such that $t(R'_i) = s$. By an analogous reasoning as the one presented to obtain (10), we can prove that $f(R'_i, \tilde{R}_S, R_{-(S \cup \{i\})}) = f(\tilde{R}_S, R_{-S})$. Second, let $\tilde{R}_i \in \mathcal{SSP}(\succeq)$ be such that $t(\tilde{R}_i) = x$. By an analogous reasoning as the one presented to obtain (11), we can prove that $f(\tilde{R}_{S \cup \{i\}}, R_{-(S \cup \{i\})}) = f(\tilde{R}_S, R_{-S})$. Therefore, $f(\tilde{R}_{S \cup \{i\}}, R_{-(S \cup \{i\})}) = f(R)$ and the inductive proof is complete.

Concluding. Let $\tilde{R} \in \mathcal{SSP}(\succeq)^n$ be such that $t(\tilde{R}_i) = x$ for each $i \in N$. By *unanimity*, $f(\tilde{R}) = x$. Applying Claim 2 when $S = N$ we get $f(\tilde{R}) = f(R)$. Then, $f(R) = x$. But, as $x \succ s$ and $s \succ f(R)$,

it follows by (8) and (9) that $f(R) \succ f(R)$, a contradiction. Hence, $f(R) = \sup_{\succeq} t(R)$ for each $R \in \mathcal{SSP}(\succeq)^n$. \blacksquare

7.2 Proof of Proposition 1

Let the hypothesis of the Proposition hold. Assume $\mathcal{SSP}(\succeq)$ is not *maximal* for \sup_{\succeq} . Then, there is $\hat{R}_i \in \mathcal{R} \setminus \mathcal{SSP}(\succeq)$ such that $\sup_{\succeq} : [\mathcal{SSP}(\succeq) \cup \{\hat{R}_i\}]^n \rightarrow A$ is *simple* and *strategy-proof*. By Remark 1 characterizing *semilattice single-peakedness*, there are two cases to consider:

1. **There are $x, y, z \in A$ with $z \succ y \succ x$, $t(\hat{R}_i) = x$ and $z\hat{P}_i y$.**

Let $R_{-i} \in \mathcal{SSP}(\succeq)^{n-1}$ be such that $t(R_j) = y$ for each $j \in N \setminus \{i\}$ and let $R_i^z \in \mathcal{SSP}(\succeq)$ be arbitrary. As $z \succ y \succ x$,

$$\sup_{\succeq}(R_i^z, R_{-i}) = z\hat{P}_i y = \sup_{\succeq}(\hat{R}_i, R_{-i}),$$

contradicting *strategy-proofness*.

2. **There are $x, w \in A$ such that $w \not\succeq x$, $t(\hat{R}_i) = x$ and $w\hat{P}_i \sup_{\succeq}\{x, w\}$.**

First, notice that $x \not\succeq w$ also. Otherwise $w\hat{P}_i x$, contradicting the fact that $t(\hat{R}_i) = x$. Let $t = \sup_{\succeq}\{x, w\}$ and consider $R_{-i} \in \mathcal{SSP}(\succeq)^{n-1}$ such that $t(R_j) = w$ for each $j \in N \setminus \{i\}$ and any $R_i^w \in \mathcal{SSP}(\succeq)$. Then,

$$\sup_{\succeq}(R_i^w, R_{-i}) = w\hat{P}_i t = \sup_{\succeq}(\hat{R}_i, R_{-i}),$$

contradicting *strategy-proofness*.

Hence, $\mathcal{SSP}(\succeq)$ is *maximal* for \sup_{\succeq} . \blacksquare

7.3 Proof of Theorem 1

(\implies) Assume $f : \mathcal{SSP}(\succeq)^n \rightarrow A$ is a *strategy-proof* and *simple* rule.

If there is no $\sup_{\succeq} A$, by Lemma 9, $f(R) = \sup_{\succeq} t(R)$ for each $R \in$

$\mathcal{SSP}(\succeq)^n$, and therefore $f = \sup_{\succeq}$. So let us assume there is $\sup_{\succeq} A$. Let $\alpha \equiv \sup_{\succeq} A$ and consider $f \neq \sup_{\succeq}$. By Lemma 8, there is $R^* \in \mathcal{SSP}(\succeq)^n$ such that $\alpha \in t(R^*)$ and $f(R^*) \neq \alpha$. Let $x \equiv f(R^*)$ and let

$$k^* \equiv \min_k \{k = |N(R, x)| \mid R \in \mathcal{SSP}(\succeq)^n \text{ with } t(R) = \{\alpha, x\} \text{ and } f(R) = x\}.$$

Step 1: $x \in A^*(\succeq)$. We need to prove that, for $y \in A \setminus \{\alpha, x\}$, $x \not\succeq y$ and $y \not\succeq x$. In order to get a contradiction, first suppose $y \succeq x$. Let $R \in \mathcal{SSP}(\succeq)^n$ be such that $t(R) = \{x, \alpha\}$ and $|N(R, x)| = k^*$. Then, $f(R) = x$ by the definition of k^* . Let $i \in N(R, x)$ and consider any $R_i^y \in \mathcal{SSP}(\succeq)$. By Lemma 7, $f(R_i^y, R_{-i}) \in \{x, \alpha\}$. There are two cases to consider:

1.1. $f(R_i^y, R_{-i}) = x$. As $y \succ x$, by Remark 4 (i) there is $\tilde{R}_i^y \in \mathcal{SSP}(\succeq)$ such that $\alpha \tilde{P}_i^y x$. By *tops-onlyness*, $f(\tilde{R}_i^y, R_{-i}) = f(R_i^y, R_{-i})$. Let $R_i^\alpha \in \mathcal{SSP}(\succeq)$ be arbitrary. By the definition of k^* and Lemma 2, $f(R_i^\alpha, R_{-i}) = \alpha$. Therefore,

$$f(R_i^\alpha, R_{-i}) = \alpha \tilde{P}_i^y x = f(\tilde{R}_i^y, R_{-i}),$$

contradicting *strategy-proofness*.

1.2. $f(R_i^y, R_{-i}) = \alpha$. As $y \succ x$, by Remark 4 (ii) there is $\tilde{R}_i^y \in \mathcal{SSP}(\succeq)$ such that $x \tilde{P}_i^y \alpha$. By *tops-onlyness*, $f(\tilde{R}_i^y, R_{-i}) = f(R_i^y, R_{-i})$. Therefore,

$$f(R) = x \tilde{P}_i^y \alpha = f(\tilde{R}_i^y, R_{-i}),$$

contradicting *strategy-proofness*.

Thus, $y \not\succeq x$. The case $x \succeq y$ follows a similar argument, interchanging the roles of x and y . Hence, $x \in A^*(\succeq)$.

Step 2: $f \in \mathcal{Q}(\succeq)$ with associated alternative x and quota $q^x = k^*$. Let $R \in \mathcal{SSP}(\succeq)^n$. There are two cases to consider:

2.1. $|N(\mathbf{R}, x)| \geq k^*$. Then $f(R) = x$ by Lemma 3.

2.2. $|N(\mathbf{R}, x)| < k^*$. We want show that $f(R) = \sup_{\succeq} t(R)$. Notice that, by Lemma 7, $f(R) \in \{x, \sup_{\succeq} t(R)\}$. In order to get a contradiction, assume $f(R) = x$. Let $N^x \equiv N(R, x)$ and $N^\alpha \equiv N(R, \alpha)$. Consider first the case $N^\alpha = \emptyset$. Let $i \in N \setminus N^x$. As $\alpha \succ t(R_i)$ and $f(R) \notin [t(R_i), \alpha]$ (since $f(R) \in A^*(\succeq)$), by Lemma 5, $f(R_i^\alpha, R_{-i}) = f(R) = x$. Continuing in the same way, we successively change preferences of all the remaining agents in $N \setminus N^x$ to obtain $f(R_{N^x}, R_{-N^x}^\alpha) = x$. But this contradicts the definition of k^* .

To finish, consider the case $N^\alpha \neq \emptyset$. Let $R_{N^\alpha}^\alpha \in \mathcal{SSP}(\succeq)^{|N^\alpha|}$. By *tops-onlyness*, $f(R_{N^\alpha}^\alpha, R_{-N^\alpha}) = f(R) = x$. Next, let $i \in N \setminus (N^x \cup N^\alpha)$, which exists because otherwise $N \setminus (N^x \cup N^\alpha) = \emptyset$ would imply $f(R) = \alpha$, a contradiction. As $\alpha \succ t(R_i)$ and $f(R_{N^\alpha}^\alpha, R_{-N^\alpha}) \notin [t(R_i), \alpha]$, by Lemma 5, $f(R_{N^\alpha \cup \{i\}}^\alpha, R_{-(N^\alpha \cup \{i\})}) = x$. Continuing in the same way, we successively change preferences of all the remaining agents in $N \setminus (N^x \cup N^\alpha)$ to obtain $f(R_{N^x \cup N^\alpha}, R_{-(N^x \cup N^\alpha)}^\alpha) = x$. But this also contradicts the definition of k^* .

(\Leftarrow) That \sup_{\succeq} is *strategy-proof* and *simple* has been presented in the main text (see Section 3). Let f be a quota-supremum rule with associated alternative x and quota q^x . By definition, f is *unanimous*, *anonymous* and *tops-only*, and therefore *simple*. We know show that f is also *strategy-proof*. Let $R \in \mathcal{SSP}(\succeq)^n$, $i \in N$ and $R'_i \in \mathcal{SSP}(\succeq)$ be arbitrary, and assume $f(R) \neq t(R_i)$. There are two cases to consider:

1. **$f(\mathbf{R}) = \mathbf{x}$.** Since $x \in A^*(\succeq)$, $|N(R, x)| \geq k$. As $t(R_i) \neq x$, $f(R'_i, R_{-i}) = x$ because $|N((R'_i, R_{-i}), x)| \geq |N(R, x)|$. Thus, there is no profitable manipulation from agent i .

2. $f(R) = \sup_{\succeq} t(R)$. We want to show that

$$f(R)R_i f(R'_i, R_{-i}). \quad (12)$$

If $f(R'_i, R_{-i}) = \sup_{\succeq} (R'_i, R_{-i})$, then by *semilattice single-peakedness* and associativity of the supremum,

$$f(R) = \sup_{\succeq} \{t(R_i), \sup_{\succeq} t(R_{-i})\} R_i \sup_{\succeq} \{t(R'_i), \sup_{\succeq} t(R_{-i})\} = f(R'_i, R_{-i}),$$

so (12) holds. If $f(R'_i, R_{-i}) = x$, as $x \in A^*(\succeq)$, it follows that $t(R_i) \not\preceq x$ and, by Remark 1 (ii),

$$\alpha = \sup_{\succeq} \{t(R_i), x\} R_i x. \quad (13)$$

Also, since $t(R_i) \preceq \sup_{\succeq} t(R) \preceq \alpha$, by Remark 1 (i),

$$\sup_{\succeq} t(R) R_i \alpha. \quad (14)$$

Therefore, by hypothesis and using (13) and (14) we obtain

$$f(R) = \sup_{\succeq} t(R) R_i x = f(R'_i, R_{-i}),$$

so (12) holds.

Hence, the quota-supremum rule f is *strategy-proof*. ■