

A Note on a Consistency Property for Permutations

Citation for published version (APA):

Derks, J., & Peters, H. J. M. (2002). A Note on a Consistency Property for Permutations. *Discrete Mathematics*, 250, 241-244. [https://doi.org/10.1016/S0012-365X\(01\)00346-6](https://doi.org/10.1016/S0012-365X(01)00346-6)

Document status and date:

Published: 01/01/2002

DOI:

[10.1016/S0012-365X\(01\)00346-6](https://doi.org/10.1016/S0012-365X(01)00346-6)

Document Version:

Publisher's PDF, also known as Version of record

Please check the document version of this publication:

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Note

A note on a consistency property for
permutations

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Received 14 January 1999; received in revised form 3 April 2001; accepted 30 April 2001

Abstract

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In cooperative game theory allocation of earnings to players may take place on the basis of selectors or—more restrictively—consistent selectors, or on the basis of a permutation representing the queueing of the players. This note gives a graph theoretic characterization of those situations in which the latter allocation method results in allocation with consistent selectors.

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Keywords: Selector; Permutation; Consistency; Cycle

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1. Introduction

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For a finite set $N = \{1, \dots, n\}$ we consider functions, the so-called selectors, assigning to each non-empty subset of N an element of that subset; formally, a *selector* is a function $\alpha: 2^N \setminus \{\emptyset\} \rightarrow N$ with $\alpha(S) \in S$ for every non-empty subset S of N .

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In [2] the notion of selector is introduced in a game theoretic context, where the elements of N are the players, and a non-empty subset S of N is a coalition. In this context, a selector assigns a representative to each coalition. We will adopt the notation and terminology from the game theoretic literature since the problem that we tackle in this note is inspired by an application in this field.

27

A selector α is called *consistent* if the representative of any coalition S is also the representative of the subsets of S containing that representative; i.e., if $S, T \subseteq N$, and $T \subseteq S$ so that $\alpha(S) \in T$, then $\alpha(T) = \alpha(S)$.

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1 A selector is mainly used in allocation methods of the total earnings among the
 2 players. Assuming that these earnings (e.g., the so-called dividends of a cooperative
 3 game) are split up over the coalitions, allocation is simply performed by giving the
 4 earnings of each coalition to its representative. If the average is taken over all selectors
 5 or over all consistent selectors, this allocation method results in the well-known Shapley
 6 Value (cf. [3,1]).

7 A different approach towards allocation is the assignment of the earnings according
 8 to a specified queueing $\pi(1), \pi(2), \dots, \pi(n)$ of the players, as follows: allocate to player
 9 $\pi(j)$ all positive earnings of those coalitions S with no member to the left of $\pi(j)$ (so,
 10 $\pi(j)$ is the first of the players in S), and all negative earnings of those coalitions S
 11 with only players to the left of $\pi(j)$ (i.e., $\pi(j)$ is the last player in S). In other words,
 12 if we let the players take their turn from right to left then each player, when it is his
 13 turn, may grab all positive earnings of coalitions containing him and not already taken,
 14 and he may pass on the negative earnings of coalitions as long as there are still players
 15 waiting in that coalition; if not he has to accept also these earnings. Allocations based
 16 on this method are called *greedy* for obvious reasons, and considered first in [1]; there
 17 it is shown that taking the average of all greedy allocations (one for each permutation
 18 π) again results in the Shapley value.

19 It is not hard to see that the greedy allocations correspond to allocations based
 20 on specific selectors. Moreover, in [1] it is shown that the convex hull of all greedy
 21 allocations is equal to the convex hull of all allocations based on arbitrary selectors, the
 22 so-called selectope. Also, the question is raised to characterize those situations where
 23 all greedy allocations correspond to consistent selectors. Because allocations based on
 24 consistent selectors are exactly the marginal values (cf. [4]) this question concerns
 25 the coincidence of the Weber set (i.e., the convex hull of the marginal values) and
 26 the selectope. The purpose of the present note is to give a (hyper)graph theoretic
 27 characterization of this coincidence.

2. The characterization result

29 For a permutation π denote the player in coalition S who has no predecessors in S by
 30 $\min_{\pi}(S)$ and denote the player in S for whom all other players in S are predecessors
 31 by $\max_{\pi}(S)$. Let \mathcal{R} and \mathcal{L} denote two disjoint subsets of coalitions. In the game
 32 theoretic context the elements of \mathcal{R} are those coalitions with negative earnings, and \mathcal{L}
 33 those with positive earnings.

We say that a selector α is an $(\mathcal{L}, \mathcal{R})$ -match for permutation π if

$$35 \quad \alpha(S) = \max_{\pi}(S) \quad \text{for all } S \text{ with } S \in \mathcal{R}, \quad (1)$$

$$36 \quad \alpha(S) = \min_{\pi}(S) \quad \text{for all } S \text{ with } S \in \mathcal{L}. \quad (2)$$

37 Observe that the representatives of the coalitions in \mathcal{R} according to α are the Right-
 38 most players according to π , and the representatives of the coalitions in \mathcal{L} according
 39 to α are the Left-most players according to π . Further, observe that an allocation on

1 the basis of an $(\mathcal{L}, \mathcal{R})$ -match yields the same outcome as the greedy allocation method
 based on queueing according to π .

3 A reformulation of the question at the end of the Introduction is: For which pairs
 $(\mathcal{L}, \mathcal{R})$ do all permutations have consistent $(\mathcal{L}, \mathcal{R})$ -matches?

5 Let \mathcal{R} and \mathcal{L} be disjoint sets of coalitions. A sequence S_1, S_2, \dots, S_k of k different
 coalitions from $\mathcal{R} \cup \mathcal{L}$ is called an $(\mathcal{L}, \mathcal{R})$ -cycle if there are k different players i_1, \dots, i_k
 7 such that

(i) for each $r = 1, \dots, k$, it holds that $i_r \in S_r \cap S_{r+1}$ (where S_{k+1} denotes the coalition
 9 S_1);

(ii) at least one coalition is taken from \mathcal{R} and at least one from \mathcal{L} .

11 $(\mathcal{L}, \mathcal{R})$ -cycle free collections are exactly those pairs that we are looking for:

Theorem. *Let \mathcal{R} and \mathcal{L} be disjoint collections of coalitions. The following two con-
 13 ditions are equivalent:*

(a) *There exists no $(\mathcal{L}, \mathcal{R})$ -cycle.*

15 (b) *For each permutation π of N there exists a consistent $(\mathcal{L}, \mathcal{R})$ -match.*

Proof. For the implication (b) \Rightarrow (a), suppose there exists an $(\mathcal{L}, \mathcal{R})$ -cycle S_1, S_2, \dots, S_k .
 17 Since each $(\mathcal{L}, \mathcal{R})$ -cycle contains two consecutive coalitions, one in \mathcal{L} and one in \mathcal{R} ,
 we may assume without loss of generality that $S_1 \in \mathcal{L}$ and $S_k \in \mathcal{R}$. Choose different
 19 players i_r in the intersection of S_r and S_{r+1} , for every $r = 1, \dots, k$. One may also as-
 21 sume $i_r \notin S_\ell$ for all $r = 1, \dots, k$ and $\ell \neq r, r + 1$ because otherwise at least one of the
 two shorter cycles $S_\ell, S_{\ell+1}, \dots, S_r$ and $S_\ell, S_r, S_{r+1}, \dots, S_{\ell-1}$ is again an $(\mathcal{L}, \mathcal{R})$ -cycle,
 so that the proof can be restarted with the appropriate shorter cycle.

23 With these players i_1, \dots, i_k define the following mapping π :

$$\pi(i_r) = \begin{cases} |\{j: j \geq r \text{ and } S_j \in \mathcal{L}\}| & \text{if } S_r \in \mathcal{L}, \\ n - |\{j: j > r \text{ and } S_j \in \mathcal{R}\}| & \text{if } S_r \in \mathcal{R}. \end{cases}$$

25 Observe first that $\pi(i_r) \in N$ for all i_r , because an $(\mathcal{L}, \mathcal{R})$ -cycle contains at most n
 coalitions. Let L denote $|\{j: j \in \mathcal{L}\}|$, and R denote $|\{j: j \in \mathcal{R}\}|$. With these notations we
 27 have $\pi(i_r) \leq L$ whenever $S_r \in \mathcal{L}$, and $\pi(i_r) > n - R$ whenever $S_r \in \mathcal{R}$. Further, $\pi(i_r) \neq \pi(i_\ell)$
 whenever $S_r, S_\ell \in \mathcal{L}$ or $S_r, S_\ell \in \mathcal{R}$, so that π is injective. By extending π to N and by
 29 taking the positions of the other players arbitrarily among the remaining positions
 $L + 1, \dots, n - R$, we obtain a permutation.

31 We will now show that the permutation π has the property $i_r = \min_\pi(S_r)$ for
 all $S_r \in \mathcal{L}$. For $S_r \in \mathcal{L}$ there are only two players among i_1, \dots, i_k who are mem-
 33 ber of S_r , namely i_{r-1} and i_r (where the index 0 is taken to mean k). If $S_{r-1} \in \mathcal{L}$
 then $\pi(i_{r-1}) = \pi(i_r) + 1$, and if $S_{r-1} \in \mathcal{R}$ then $\pi(i_{r-1}) > n - R \geq L \geq \pi(i_r)$. Therefore,
 35 $\pi(i_{r-1}) > \pi(i_r)$. The other players of S_r obtain positions between $L + 1$ and $n - R$, so
 that we must have $i_r = \min_\pi(S_r)$.

37 The property $i_r = \max_\pi(S_r)$ for all $S_r \in \mathcal{R}$ can be shown similarly.

39 Now suppose that there exists a consistent selector α satisfying (1) and (2). So,
 by construction of π we have $\alpha(S_r) = i_r$ for each $r = 1, \dots, k$. Consider the coalition

1 $S = \bigcup_{r=1}^k S_r$. Then $\alpha(S)$ is a member of one of the coalitions S_1, \dots, S_k , say S_r . Consistency thus implies that $\alpha(S) = i_r$; therefore, $\alpha(S) \in S_{r+1}$, so that, again by consistency,
 3 $\alpha(S) = i_{r+1}$, a contradiction. This proves the implication (b) \Rightarrow (a).

In order to prove the implication (a) \Rightarrow (b), suppose there are no $(\mathcal{L}, \mathcal{R})$ -cycles. Let
 5 π be an arbitrary permutation of the player set. Consider the directed graph (N, E) on N with edge set E equal to the union of the sets $\{(\max_{\pi}(S), j) : j \in S, S \in \mathcal{R}\}$, and
 7 $\{(\min_{\pi}(S), j) : j \in S, S \in \mathcal{L}\}$.

Suppose there exists a directed cycle in this graph, say i_1, \dots, i_k . Then consider
 9 for each edge (i_r, i_{r+1}) in this cycle a coalition $S_r \in \mathcal{R} \cup \mathcal{L}$ such that $i_r, i_{r+1} \in S_r$, and $i_r = \max_{\pi}(S_r)$ if $S_r \in \mathcal{R}$ or $i_r = \min_{\pi}(S_r)$ if $S_r \in \mathcal{L}$. It is impossible that all these coalitions can be chosen from \mathcal{R} , because otherwise $\pi(i_1) > \pi(i_2) > \dots > \pi(i_k) > \pi(i_1)$. Similarly, not all these coalitions can be chosen from \mathcal{L} . This implies that S_1, \dots, S_k
 11 is an $(\mathcal{L}, \mathcal{R})$ -cycle, a contradiction. Hence, there are no directed cycles in (N, E) . Therefore, there is a permutation j_1, \dots, j_n , with the property that each edge (j_l, j_r) in
 13 E satisfies $l > r$. Consider the following selector α which chooses for each coalition S the right-most player:
 15

$$17 \quad \alpha(S) = j_r \quad \text{with } r = \max\{l : j_l \in S\}, \quad S \subseteq N.$$

This α is consistent. Now let $S \in \mathcal{R}$, and suppose that $\alpha(S) \neq \max_{\pi}(S)$. This implies
 19 $(j_l, j_r) \in E$ for $\max_{\pi}(S) = j_l$ and $\alpha(S) = j_r$, and, therefore, $l > r$; but this contradicts the definition of α . Therefore, α satisfies (1). Similarly one shows that α satisfies (2).

21 This concludes the proof of the Theorem. \square

Clearly, no $(\mathcal{L}, \mathcal{R})$ -cycles exist if the carriers of both collections have at most one
 23 player in common, that is, $|(\bigcup\{S : S \in \mathcal{R}\}) \cap (\bigcup\{S : S \in \mathcal{L}\})| \leq 1$.

There is no clear intuition of the existence or non-existence of a $(\mathcal{L}, \mathcal{R})$ -cycle in the
 25 game theoretic context although the very appealing implication of the non-existence is that the set of selector-based allocations coincides with its subset of allocations coming
 27 from consistent selectors. For a detailed discussion the reader is referred to [1].

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