TREE OF ORIENTATIONS ON A NESTED COLLECTION OF CUTS

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1. Introduction

Let $\mathcal{C} \subseteq 2^X$ be a collection of non-empty subsets of a set X. With the definitions in Section 2, we prove the following

Theorem 1.1. *If $\mathcal{C}$ is nested, then the graph $\mathcal{T}_\mathcal{C}$, whose:*

- *Vertices are finitely-based orientations on $\mathcal{C}$; and whose*
- *Neighbors of $\mathcal{U} \in V(\mathcal{T}_\mathcal{C})$ are $\mathcal{U} \triangle \{A, A^c\}$ for every minimal $A \in \mathcal{U}$ with $A^c \in \mathcal{C}$;*

is acyclic. Furthermore, $\mathcal{T}_\mathcal{C}$ is a tree iff $\mathcal{C}$ is closed under complements.

In particular, this applies to when (X, G) is a graph and $\mathcal{C}$ is a nested collection of cuts on X.

2. Preliminaries

2.1. **Orientations.** Since we do not assume that $\mathcal{C}$ is closed under complements, we slightly modify the definition of orientations, as follows.

Definition 2.1. An *orientation* on $\mathcal{C}$ is a subset $\mathcal{U} \subseteq \mathcal{C}$ such that

1. *(Upward-closure).* If $A \in \mathcal{U}$ and $B \in \mathcal{C}$ contains A, then $B \in \mathcal{U}$.
2. *(Ultra).* If $A, A^c \in \mathcal{C}$, then either $A \in \mathcal{U}$ or $A^c \in \mathcal{U}$, but not both.

Remark 2.2. This coincides with the standard definition when $\mathcal{C}$ is a subpocset of 2^X.

Lemma 2.3. *If $\mathcal{U} \subseteq \mathcal{C}$ is an orientation, then for any $\subseteq$-minimal $A \in \mathcal{U}$ with $A^c \in \mathcal{C}$, so is $\mathcal{U} \triangle \{A, A^c\}$.*

Proof. That $\mathcal{V} := \mathcal{U} \triangle \{A, A^c\} = \mathcal{U} \cup \{A^c\} \setminus \{A\}$ is upward-closed follows from $\subseteq$-minimality of A. Now, if $B, B^c \in \mathcal{C}$ and $B^c \notin \mathcal{V}$, we need to show that $B \in \mathcal{V}$.

To this end, note that $B^c \notin \mathcal{V}$ implies $A \neq B$ and either $B = A^c$ or $B^c \notin \mathcal{U}$. The former case follows from $A^c \in \mathcal{V}$, and for the latter, we have $B \in \mathcal{U} \setminus \{A\}$ since $\mathcal{U}$ is ultra. ∎

Remark 2.4. In the above notations, clearly $\mathcal{U} \neq \mathcal{U} \triangle \{A, A^c\}$. Furthermore, for any other such orientation $\mathcal{U}'$ and $A' \in \mathcal{U}'$, that $\mathcal{U} = \mathcal{U}'$ and $\mathcal{U} \triangle \{A, A^c\} = \mathcal{U}' \triangle \{A', A'^c\}$ together imply $A = A'$.

Definition 2.5. A *base* for an orientation $\mathcal{U} \subseteq \mathcal{C}$ is a $\subseteq$-minimal subset $\mathcal{B} \subseteq \mathcal{U}$ such that $\mathcal{U} = \uparrow\mathcal{B}$, where

$$\uparrow\mathcal{B} := \bigcup_{B \in \mathcal{B}} \uparrow B := \bigcup_{B \in \mathcal{B}} \{A \in \mathcal{C} : A \supseteq B\}.$$

Definition 2.6. A collection $\mathcal{C}$ is said to be *nested* if every $C_1, C_2 \in \mathcal{C}$ has an empty corner, i.e., $C_1^i \cap C_2^j = \varnothing$ for some $i, j \in \{1, -1\}$, where $C^i := C$ if $i = 1$ and $C^i := C^c$ if $i = -1$.

Remark 2.7. If $\mathcal{C}$ is nested, then every $\subseteq$-minimal $B \in \mathcal{C}$ induces an orientation $\uparrow B := \{A \in \mathcal{C} : A \supseteq B\}$, called the *principal* orientation. Indeed, $\uparrow B$ is clearly upward-closed, and if $A, A^c \in \mathcal{C}$, then, by $\subseteq$-minimality of B and nestedness of $\mathcal{C}$, either $A \supseteq B$ or $A^c \supseteq B$ (but clearly not both).

This construction generalizes to any collection $\mathcal{B} \subseteq \mathcal{C}$ with each $B \in \mathcal{B}$ being $\subseteq$-minimal, in that $\uparrow\mathcal{B}$ is an orientation on $\mathcal{C}$.

Definition 2.8. An orientation $\mathcal{U} \subseteq \mathcal{C}$ is said to be *finitely-based* if it admits a finite base.

Remark 2.9. If $\mathcal{U} = \uparrow\{B_1, \dots, B_n\}$ is finitely-based, then for any $\subseteq$-minimal $A \in \mathcal{U}$ with $A^c \in \mathcal{C}$, so is the orientation $\mathcal{V} := \mathcal{U} \triangle \{A, A^c\}$. Indeed, $A = B_i$ for some $1 \leq i \leq n$, and $\mathcal{V} = \uparrow(\{A\} \cup \{B_j\}_{j \neq i})$.

3. The graph $\mathcal{T}_\mathcal{C}$

Fix a nested collection of non-empty subsets of a set X. Using Lemma 2.3 and Remarks 2.4 and 2.9, we construct a graph $\mathcal{T}_\mathcal{C}$ whose:

- *Vertices* of $\mathcal{T}_\mathcal{C}$ are finitely-based orientations on $\mathcal{C}$.
- *Neighbors* of $\mathcal{U} \in V(\mathcal{T}_\mathcal{C})$ are $\mathcal{U} \triangle \{A, A^c\}$ for every minimal $A \in \mathcal{U}$ with $A^c \in \mathcal{C}$.

The goal of this section is to establish Theorem 1.1, stating that $\mathcal{T}_\mathcal{C}$ is acyclic (Proposition 3.5), and furthermore, $\mathcal{T}_\mathcal{C}$ is a tree precisely when $\mathcal{C}$ is closed under complements (Proposition 3.6).

3.1. Paths in $\mathcal{T}_\mathcal{C}$.

To show that $\mathcal{T}_\mathcal{C}$ is acyclic, we characterize backtracking paths in $\mathcal{T}_\mathcal{C}$ as follows.

Definition 3.1. Fix $\mathcal{U}_0 \in V(\mathcal{T}_\mathcal{C})$ and $\alpha \leq \omega$. A sequence $(A_n)_{n<\alpha} \subseteq \mathcal{C}$ is said to *represent a path from* $\mathcal{U}_0$ if $(\mathcal{U}_n)_{n\leq\alpha}$, defined by $\mathcal{U}_n \coloneqq \mathcal{U}_{n-1} \triangle \{A_{n-1}\}$ for every $1 \leq n \leq \alpha$, is a path in $\mathcal{T}_\mathcal{C}$ with each $A_n \in \mathcal{U}_n$.

Remark 3.2. Any path in $\mathcal{T}_\mathcal{C}$ is represented by its sequence of flipped basis elements.

Lemma 3.3. *Let $\alpha \geq 3$. A path in $\mathcal{T}_\mathcal{C}$ from $\mathcal{U}_0$ represented by $(A_n)_{n\leq\alpha}$ has no backtracking iff $A_n \neq A_{n-1}^c$ for every $1 \leq n < \alpha$.*

Proof. Take $2 \leq n \leq \alpha$. It suffices to show that $\mathcal{U}_{n-2} = \mathcal{U}_n$ iff $A_{n-1} = A_{n-2}^c$.

- ($\Rightarrow$). We have by definition that $\mathcal{U}_n = \mathcal{U}_{n-2} \cup \left\{A_{n-1}^c, A_{n-2}^c\right\} \setminus \{A_{n-1}, A_{n-2}\}$, so since $A_{n-2} \in \mathcal{U}_{n-2} = \mathcal{U}_n$, we have $A_{n-2} = A_{n-1}^c$ as desired.
- ($\Leftarrow$). Again by definition, by noting that the basis-flipping cancels out. ∎

Lemma 3.4. *If $(A_n)_{n<\alpha}$ represents a path in $\mathcal{T}_\mathcal{C}$ with no backtracking, then $(A_n)_{n<\alpha}$ is strictly increasing.*

Proof. By Lemma 3.3, we have $A_n \neq A_{n-1}^c$ for every $1 \leq n < \alpha$. Thus, since $A_n \in \mathcal{U}_n = \mathcal{U}_{n-1} \cup \left\{A_{n-1}^c\right\} \setminus \{A_{n-1}\}$, we see that $A_n \in \mathcal{U}_{n-1}$. Clearly $A_n \neq A_{n-1}$. It suffices to remove the three cases when $A_n \subseteq A_{n-1}$, $A_{n-1} \subseteq A_n^c$, and $A_n^c \subseteq A_{n-1}$, since then nestedness of $\mathcal{C}$ gives us $A_{n-1} \subset A_n$, as desired.

- If $A_n \subseteq A_{n-1}$, then $A_{n-1} \in \mathcal{U}_n$, contradicting the definition of $\mathcal{U}_n$.
- If $A_{n-1} \subseteq A_n^c$, then $A_n^c \in \mathcal{U}_{n-1}$ by upward-closure of $\mathcal{U}_{n-1}$, a contradiction.
- If $A_n^c \subseteq A_{n-1}$, then $A_{n-1} \in \mathcal{U}_{n+1}$ by upward-closure of $\mathcal{U}_{n+1} \ni A_n^c$. But since $A_{n-1} \neq A_n^c$, we have by definition of $\mathcal{U}_{n+1}$ that $A_{n-1} \in \mathcal{U}_n$, a contradiction. ∎

Proposition 3.5. *$\mathcal{T}_\mathcal{C}$ is acyclic.*

Proof. Let $(\mathcal{U}_i)_{i\leq n}$ be a cycle in $\mathcal{T}_\mathcal{C}$, say represented by $(A_i)_{i\leq n}$. Then $A_0 = A_n$, a contradiction since $(A_i)_{i\leq n}$ is strictly-increasing by Lemma 3.4. ∎

Proposition 3.6. *If $\mathcal{C}$ is closed under complements, then $\mathcal{T}_\mathcal{C}$ is connected (and hence a tree).*

Proof. If $\mathcal{U}, \mathcal{U}' \in V(\mathcal{T}_\mathcal{C})$ are two finitely-based orientations on $\mathcal{C}$, then swapping their basis elements one by one as in Remark 2.9 gives us a path between $\mathcal{U}$ and $\mathcal{U}'$; the closure of $\mathcal{C}$ is needed to ensure that those basis elements represent a path between those vertices. ∎