TREE OF ORIENTATIONS ON A NESTED COLLECTION OF SETS

ZHAOSHEN ZHAI

Let $H \subseteq 2^X$ be a sub-pocset for some fixed set X (so that, in particular, H is closed under complements). With the definitions in Section 1, we prove the following

Theorem A (Propositions 2.5, 2.6, 2.7)**.** *If H is nested, then the graph $\mathcal{T}_H$, whose:*
- *Vertices are finitely-based orientations $p \subseteq H$;*
- *Edges are pairs $\{p, q\}$ such that $q = p \triangle \{h, \neg h\}$ for some $\subseteq$-minimal $h \in H$;*

is acyclic. Furthermore, if H is finitely-separating (or more generally, chain-vanishing), then $\mathcal{T}_H$ is a tree.

In particular, this applies to when (X, G) is a graph and H is a nested collection of cuts on X. No further assumptions on X (like local-finiteness) is needed.

1. Preliminaries

Let $H \subseteq 2^X$ be a sub-pocset for some fixed set X, whose elements $h \in H$ we call *half-spaces*.

Definition 1.1. Two elements $h, k \in H$ are *nested* if $h^i \cap k^j = \varnothing$ for some $i, j \in \{1, -1\}$, where $h^i := h$ for $i = 1$ and $h^i := h^c$ otherwise. We say that H is *nested* if every pair $h, k \in H$ are nested.

1.1. Orientations.
We give the standard definition of orientations on H and characterize them as 'consistent assignments of half-spaces to hyperplanes'.

Definition 1.2. An *orientation* on H is a subset $U \subseteq H$ such that
1. *(Upward-closure).* If $h \in U$ and $k \in H$ contains h, then $k \in U$.
2. *(Ultra).* For each $h \in H$, exactly one of h, h^c is contained in U.

Consider the equivalence relation $\sim$ on H generated by $h \sim h^c$ for all $h \in H$, whose classes are called *hyperplanes* $\partial h := \{h, h^c\}$ where $\partial : H \to H/\sim$ is the projection. We show that an orientation on H is just a choice $\varphi : H/\sim \to H$ of a half-space for each hyperplane, that is consistent in the sense below.

Proposition 1.3. *An orientation $p \subseteq H$ is exactly the data of a function $\varphi : H/\sim \to H$ such that $\varphi(\partial h) \in \partial h$ and $\varphi(\partial h) \not\subseteq \varphi(\partial k)^c$ for every $h, k \in H$.*

Proof. Given an orientation $p \subseteq H$, let $\varphi_p(\partial h) := h^i \in U$ for the unique $i \in \{1, -1\}$. That $\varphi_p(\partial h) \in \partial h$ is clear, and if $\varphi_p(\partial h) \subseteq \varphi_p(\partial k)^c$, then U contains both $\varphi_p(\partial k)$ and $\varphi_p(\partial k)^c$ by upward-closure, a contradiction.

Conversely, given such a function $\varphi : H/\sim \to H$, let $p_\varphi := \operatorname{im} \varphi \subseteq H$. This is ultra since if $h \in H$ and $h^c \notin p_\varphi$, then $\varphi(\partial h) \in \partial h = \{h, h^c\}$ implies $h \in p_\varphi$. Furthermore, if $p_\varphi \ni h \subseteq k$, then $k^c \in p_\varphi$ implies $\varphi(\partial h) = h \subseteq k = \varphi(\partial k)^c$, a contradiction, so $k \in p_\varphi$ by the above.

Finally, given an orientation $p \subseteq H$, we have $h \in p$ iff $\varphi_p(\partial h) = h$, which occurs iff $h \in \operatorname{im} \varphi_p = p_{\varphi_p}$. Thus $p_{\varphi_p} = p$. Conversely, given $\varphi : H/\sim \to H$, and $h \in H$, we have $\varphi_{p_\varphi}(\partial h) = h^i$ iff $h^i \in p_\varphi = \operatorname{im} \varphi$, which occurs iff $\varphi(\partial h) = h^i$. Thus $\varphi_{p_\varphi} = \varphi$ too, as desired. ∎

Definition 1.4. A *base* for an orientation $p \subseteq H$ is a $\subseteq$-minimal subset $p_0 \subseteq p$ such that $p = \uparrow p_0$, where

$$\uparrow p_0 := \bigcup_{h \in p_0} \uparrow h := \bigcup_{h \in p_0} \{k \in H : k \supseteq h\}.$$

We say that p is *finitely-based* if it admits a finite basis.

In the above correspondence, a base for $\varphi : H/\sim \to H$ is a function $\varphi_0 \subseteq \varphi$ where $\operatorname{dom} \varphi_0$ is a $\subseteq$-minimal subset of hyperplanes such that φ_0 extends uniquely to φ. Thus, the finitely-based orientations are the ones determined by a choice of half-spaces from finitely-many hyperplanes.

1.2. **Flipping basis elements.** We now investigate the behaviour of orientation when its choice on a single half-space is modified. Although the proofs work without the characterization in Proposition 1.3, it makes orientations a lot more intuitive to me, and so will be phrased this way.

Lemma 1.5. *Let $p \subseteq H$ be an orientation. Then $q \coloneqq p \triangle \{h, h^c\}$ is an orientation iff $h \in p$ is $\subseteq$-minimal. Furthermore, if p is finitely-based, then so is q.*

Proof. First, note that $\varphi_q(\partial h) = \varphi_p(h)^c = h^c$ and $\varphi_q = \varphi_p$ away from ∂h.

($\Rightarrow$). If q is an orientation and $p \ni k \subset h$, then we have a contradiction since
$$\varphi_q(\partial k) = \varphi_p(\partial k) = k \subseteq h = \varphi_q(\partial h)^c.$$

($\Leftarrow$). Conversely, let $h \in p$ be $\subseteq$-minimal and suppose that q is not an orientation. Since only $\varphi_q(\partial h) = h^c$ differs from φ_p, this can only occur if $\varphi_q(\partial h) \subseteq \varphi_q(\partial k)^c$ for some $k \in H$. But then
$$h^c = \varphi_q(\partial h) \subseteq \varphi_q(\partial k)^c = k^i \notin p$$
for some unique $i \in \{1, -1\}$, so that $p \ni k^{-i} \subseteq h$ and contradicts that $h \in p$ is $\subseteq$-minimal.

Finally, suppose that p is finitely-based. ??? ∎

Remark 1.6. If $h \in p$ is $\subseteq$-minimal and $p_0 \subseteq p$ is any basis, then $h \in p_0$. Indeed, if $h \notin p_0$, then there is some $h_0 \in p_0 \subseteq p$ with $h \supset h_0$, contradicting minimality.

2. The graph $\mathcal{T}_H$

Let $H \subseteq 2^X$ be a nested sub-pocset as before. Using Lemma 1.5, we construct a graph $\mathcal{T}_H$ whose:
- *Vertices* are finitely-based orientations $p \subseteq H$;
- *Edges* are pairs $\{p, q\}$ such that $q = p \triangle \{h, h^c\}$ for some $\subseteq$-minimal $h \in H$.

The goal of this section is to establish Theorem A, stating that $\mathcal{T}_H$ is acyclic (Proposition 2.5), and furthermore, that $\mathcal{T}_H$ is a tree when P is finitely-separating (Proposition 2.6), or more generally, when P is chain-vanishing (Proposition 2.7).

2.1. **Acyclicity of $\mathcal{T}_H$.** Essentially, this is because any path in $\mathcal{T}_H$ (without backtracking) is induced by a sequence of the flipped half-spaces, and those form a *strictly*-increasing chain.

Definition 2.1. Fix $p_0 \in V(\mathcal{T}_H)$ and $n \in \mathbb{N}$. A sequence $(h_i)_{i<n} \subseteq H$ is said to *induce a path from p_0* if $(p_i)_{i<n}$, defined by $p_i \coloneqq p_{i-1} \triangle \{h_{i-1}, h_{i-1}^c\}$ for every $1 \leq i < n$, is a path in $\mathcal{T}_H$ with each $h_i \in p_i$.

Remark 2.2. Any path in $\mathcal{T}_H$ is induced by its sequence of flipped basis elements.

Lemma 2.3. *A path from p_0 induced by $(h_i)_{i<n}$, $n \geq 3$, has no backtracking iff $h_i \neq h_{i-1}^c$ for every $1 \leq i < n$.*

Proof. Take $2 \leq i \leq n$. It suffices to show that $p_{i-2} = p_i$ iff $h_{i-1} = h_{i-2}^c$.

($\Rightarrow$). We have by definition that $p_i = p_{i-2} \cup \{h_{i-1}^c, h_{i-2}^c\} \setminus \{h_{i-1}, h_{i-2}\}$, so since $h_{i-2} \in p_{i-2} = p_i$, we have $h_{i-2} = h_{i-1}^c$ as desired.

($\Leftarrow$). Again by definition, by noting that the basis-flipping cancels out. ∎

Lemma 2.4. *If $(h_i)_{i<n}$ induces a path in $\mathcal{T}_H$ with no backtracking, then $(h_i)_{i<n}$ is strictly increasing.*

Proof. By Lemma 2.3, we have $h_i \neq h_{i-1}^c$ for every $1 \leq i < n$. Thus, since $h_i \in p_i = p_{i-1} \cup \{h_{i-1}^c\} \setminus \{h_{i-1}\}$, we see that $h_i \in p_{i-1}$. Clearly $h_i \neq h_{i-1}$. It suffices to remove the three cases when $h_i \subseteq h_{i-1}$, $h_{i-1} \subseteq h_i^c$, and $h_i^c \subseteq h_{i-1}$, since then nestedness of H gives us $h_{i-1} \subsetneq h_i$, as desired.
- If $h_i \subseteq h_{i-1}$, then $h_{i-1} \in p_i$, contradicting the definition of p_i.
- If $h_{i-1} \subseteq h_i^c$, then $h_i^c \in p_{i-1}$ by upward-closure of p_{i-1}, a contradiction.
- If $h_i^c \subseteq h_{i-1}$, then $h_{i-1} \in p_{i+1}$ by upward-closure of $p_{i+1} \ni h_i^c$. But since $h_{i-1} \neq h_i^c$, we have by definition of p_{i+1} that $h_{i-1} \in p_i$, a contradiction. ∎

Proposition 2.5. *$\mathcal{T}_H$ is acyclic.*

Proof. Let $(p_i)_{i<n}$ be a cycle in $\mathcal{T}_H$ induced by $(h_i)_{i<n}$. Since cycles are non-backtracking, we have $h_0 \subsetneq h_0$ by Lemma 2.4, a contradiction. ∎

Proposition 2.6. *If P is chain-vanishing, then $\mathcal{T}_H$ is connected (and hence a tree).*

Proposition 2.7.

Proposition 2.8. *If P is closed under complements, then $\mathcal{T}_H$ is connected (and hence a tree).*

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