Learning Partial Lexicographic Preference Trees over Combinatorial Domains

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Motivation

Preferences over options are ubiquitous in real life.

1. People have preferences over dinners offered in a restaurant.
2. In political elections voters cast ballots over candidates.
3. Customers rate their purchased items on websites such as Bestbuy.com and Amazon.com.

 $\succ$  $\succ$  $\succ \cdots$

Figure: What do I like for dinner?

Motivation

 $\succ$  $\succ$  $\succ \cdots$

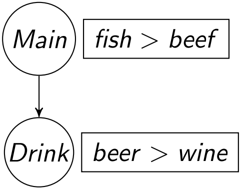
1. Preferences are **qualitative**.
2. Domains are **combinatorial**.
3. Can we model such preferences **compactly**?
4. If so, can we learn a compact model **efficiently**?

Motivation

1. What is the problem?
   – Qualitative preference modeling and learning over combinatorial domains.
2. Why is it important?
   - Predict preferences between unseen options.
   - Support preference reasoning tasks, such as dominance testing, optimization and aggregation.

Contributions

1. Propose *partial lexicographic preference trees* (PLP-trees):
   – lexicographic, compact, extending LP-trees[1]



 $\succ$  $\succ$ 

[1] Booth et al., *Learning Conditionally Lexicographic Preference Relations*, 2010.

Contributions

1. Propose *partial lexicographic preference trees* (PLP-trees):
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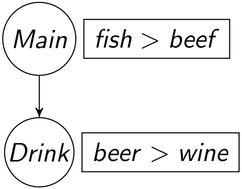

UI-UP PLP-tree

 $\succ$  $\succ$ 

[1] Booth et al., *Learning Conditionally Lexicographic Preference Relations*, 2010.

Contributions

1. Propose *partial lexicographic preference trees* (PLP-trees):
   – lexicographic, compact, extending LP-trees
2. Show results on *passive learning problems*, where all training examples ($o_i \succ o_i'$ or $o_k \approx o_k'$) are provided upfront, in the setting of PLP-trees:
   – ConsLearn, SmallLearn, MaxLearn

CONSLEARN UI-UP PLP-trees

1. Let $\mathcal{I} = \{X_1, \ldots, X_p\}$ be a set of binary issues, and $CD(\mathcal{I})$ be the combinatorial domain $\prod_{1 \leq i \leq p} \mathcal{D}_i$, where $\mathcal{D}_i = \{0_i, 1_i\}$. Given an example set $\mathcal{E} = \{e_1, \ldots, e_m\}$, where e_i is of form either $\alpha_i \succ \beta_i$ or $\alpha_i \approx \beta_i$ for $\alpha_i, \beta_i \in CD(\mathcal{I})$, the CONSLEARN problem is to learn a PLP-tree T (of a particular type) consistent with $\mathcal{E}$.
2. Denote by $\mathcal{E}^{\succ} = \{e_i \in \mathcal{E} : \alpha_i \succ \beta_i\}$ the set of *strict examples*, and $\mathcal{E}^{\approx} = \{e_i \in \mathcal{E} : \alpha_i \approx \beta_i\}$ the set of *equivalent examples*.
3. Denote by (X_i, x_i) a node label in a UI-UP PLP-tree, where X_i is an issue from $\mathcal{I}$ and x_i is the preferred value, either 0_i or 1_i, in $\mathcal{D}_i$.

4. $NEQ(\mathcal{E},\mathcal{I})$: set of issues in $\mathcal{I}$ that incorrectly handle at least one equivalent example in $\mathcal{E}$, i.e.,

$$NEQ(\mathcal{E},\mathcal{I}) = \{X_i \in \mathcal{I} : \exists \alpha \approx \beta \in \mathcal{E}, \alpha(X_i) \neq \beta(X_i)\}.$$

5. $EQ(\mathcal{E},\mathcal{I})$: set of issues in $\mathcal{I}$ that do not order any of the strict examples in $\mathcal{E}$, i.e.,

$$EQ(\mathcal{E},\mathcal{I}) = \{X_i \in \mathcal{I} : \forall \alpha \succ \beta \in \mathcal{E}, \alpha(X_i) = \beta(X_i)\}.$$

6. $AVI(\mathcal{E}, S)$: set of issues in S ($S \subseteq \mathcal{I} \setminus (NEQ(\mathcal{E},\mathcal{I}) \cup EQ(\mathcal{E},\mathcal{I}))$) available for selection as the next important issue, i.e.,

$$AVI(\mathcal{E}, S) = \{X_i \in S : \forall \alpha \succ \beta \in \mathcal{E}, \alpha(X_i) \geq \beta(X_i) \vee \\ \forall \alpha \succ \beta \in \mathcal{E}, \alpha(X_i) \leq \beta(X_i)\}.$$

ConsLearn UI-UP PLP-trees (cont'd)

1. $1_1 1_2 1_3 0_4 0_5 \approx 1_1 1_2 1_3 1_4 0_5$
2. $0_1 0_2 1_3 1_4 1_5 \approx 0_1 0_2 1_3 0_4 1_5$
3. $1_1 0_2 0_3 0_4 1_5 \succ 0_1 1_2 0_3 1_4 1_5$
4. $1_1 1_2 0_3 1_4 0_5 \succ 1_1 1_2 1_3 0_4 0_5$
5. $0_1 1_2 0_3 0_4 1_5 \succ 0_1 0_2 1_3 0_4 1_5$
6. $0_1 1_2 1_3 1_4 0_5 \succ 0_1 0_2 1_3 1_4 0_5$

$NEQ = \{X_4\}, EQ = \{X_5\},$

$S = \{X_1, X_2, X_3\}$

Input: A set $\mathcal{E}$ of examples over $\mathcal{I}$
Output: A sequence T of pairs (X_ℓ, x_ℓ), or FAILURE if a UI-UP tree does not exist

$S = \mathcal{I} \setminus (NEQ(\mathcal{E}, \mathcal{I}) \cup EQ(\mathcal{E}, \mathcal{I}))$;
$T \leftarrow$ empty sequence;
while $\mathcal{E}^{\succ} \neq \emptyset$ **do**
  Construct $AVI(\mathcal{E}, S)$;
  if $AVI(\mathcal{E}, S) = \emptyset$ **then**
    return FAILURE;
  end
  $X_\ell \leftarrow$ an element from $AVI(\mathcal{E}, S)$;
  Construct (X_ℓ, x_ℓ);
  $T \leftarrow T, (X_\ell, x_\ell)$;
  $\mathcal{E} \leftarrow \mathcal{E} \setminus \{e \in \mathcal{E}^{\succ} : e \text{ is decided on } X_\ell\}$;
  $S \leftarrow S \setminus \{X_\ell\}$;
end
return T;

ConsLearn UI-UP PLP-trees (cont'd)

1. ~~$1_1 1_2 1_3 0_4 0_5 \approx 1_1 1_2 1_3 1_4 0_5$~~
2. ~~$0_1 0_2 1_3 1_4 1_5 \approx 0_1 0_2 1_3 0_4 1_5$~~
3. $1_1 0_2 0_3 0_4 1_5 \succ 0_1 1_2 0_3 1_4 1_5$
4. $1_1 1_2 0_3 1_4 0_5 \succ 1_1 1_2 1_3 0_4 0_5$
5. $0_1 1_2 0_3 0_4 1_5 \succ 0_1 0_2 1_3 0_4 1_5$
6. $0_1 1_2 1_3 1_4 0_5 \succ 0_1 0_2 1_3 1_4 0_5$

1st: $S = \{X_1, X_2, X_3\}$,
$AVI = \{X_1, X_3\}, X_\ell = X_3$

Input: A set $\mathcal{E}$ of examples over $\mathcal{I}$
Output: A sequence T of pairs (X_ℓ, x_ℓ), or FAILURE if a UI-UP tree does not exist
$S = \mathcal{I} \setminus (NEQ(\mathcal{E}, \mathcal{I}) \cup EQ(\mathcal{E}, \mathcal{I}))$;
$T \leftarrow$ empty sequence;
while $\underline{\mathcal{E}^{\succ} \neq \emptyset}$ **do**
  Construct $AVI(\mathcal{E}, S)$;
  if $\underline{AVI(\mathcal{E}, S) = \emptyset}$ **then**
    return FAILURE;
  end
  $X_\ell \leftarrow$ an element from $AVI(\mathcal{E}, S)$;
  Construct (X_ℓ, x_ℓ);
  $T \leftarrow T, (X_\ell, x_\ell)$;
  $\mathcal{E} \leftarrow \mathcal{E} \setminus \{e \in \mathcal{E}^{\succ} : e$ is decided on $X_\ell\}$;
  $S \leftarrow S \setminus \{X_\ell\}$;
end
return T;

1. $\cancel{1_1 1_2 1_3 0_4 0_5 \approx 1_1 1_2 1_3 1_4 0_5}$
2. $\cancel{0_1 0_2 1_3 1_4 1_5 \approx 0_1 0_2 1_3 0_4 1_5}$
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4. $1_1 1_2 0_3 1_4 0_5 \succ 1_1 1_2 1_3 0_4 0_5$
5. $0_1 1_2 0_3 0_4 1_5 \succ 0_1 0_2 1_3 0_4 1_5$
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1st: $S = \{X_1, X_2, X_3\}$,
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6. $0_1 1_2 1_3 1_4 0_5 \succ 0_1 0_2 1_3 1_4 0_5$

1st: $S = \{X_1, X_2, X_3\}$,
$AVI = \{X_1, X_3\}, X_\ell = X_3$

$(X_3, 0_3)$

Input: A set $\mathcal{E}$ of examples over $\mathcal{I}$
Output: A sequence T of pairs (X_ℓ, x_ℓ), or FAILURE if a UI-UP tree does not exist

```
S = I \ (NEQ(E, I) ∪ EQ(E, I));
T ← empty sequence;
while E^≻ ≠ ∅ do
    Construct AVI(E, S);
    if AVI(E, S) = ∅ then
        return FAILURE;
    end
    X_ℓ ← an element from AVI(E, S);
    Construct (X_ℓ, x_ℓ);
    T ← T, (X_ℓ, x_ℓ);
    E ← E\{e ∈ E^≻ : e is decided on X_ℓ};
    S ← S\{X_ℓ};
end
return T;
```

ConsLearn UI-UP PLP-trees (cont'd)

1. ~~$1_1 1_2 1_3 0_4 0_5 \approx 1_1 1_2 1_3 1_4 0_5$~~
2. ~~$0_1 0_2 1_3 1_4 1_5 \approx 0_1 0_2 1_3 0_4 1_5$~~
3. $1_1 0_2 0_3 0_4 1_5 \succ 0_1 1_2 0_3 1_4 1_5$
4. ~~$1_1 1_2 0_3 1_4 0_5 \succ 1_1 1_2 1_3 0_4 0_5$~~
5. ~~$0_1 1_2 0_3 0_4 1_5 \succ 0_1 0_2 1_3 0_4 1_5$~~
6. $0_1 1_2 1_3 1_4 0_5 \succ 0_1 0_2 1_3 1_4 0_5$

1st: $S = \{X_1, X_2, X_3\}$,
$AVI = \{X_1, X_3\}, X_\ell = X_3$

$(X_3, 0_3)$

$S = \{X_1, X_2\}$

Input: A set $\mathcal{E}$ of examples over $\mathcal{I}$
Output: A sequence T of pairs (X_ℓ, x_ℓ), or FAILURE if a UI-UP tree does not exist

$S = \mathcal{I} \setminus (NEQ(\mathcal{E}, \mathcal{I}) \cup EQ(\mathcal{E}, \mathcal{I}))$;
$T \leftarrow$ empty sequence;
while $\mathcal{E}^{\succ} \neq \emptyset$ **do**
  Construct $AVI(\mathcal{E}, S)$;
  if $AVI(\mathcal{E}, S) = \emptyset$ **then**
    return FAILURE;
  end
  $X_\ell \leftarrow$ an element from $AVI(\mathcal{E}, S)$;
  Construct (X_ℓ, x_ℓ);
  $T \leftarrow T, (X_\ell, x_\ell)$;
  $\mathcal{E} \leftarrow \mathcal{E} \backslash \{e \in \mathcal{E}^{\succ}$: e is decided on $X_\ell\}$;
  $S \leftarrow S \backslash \{X_\ell\}$;
end
return T;

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6. $0_1 1_2 1_3 1_4 0_5 \succ 0_1 0_2 1_3 1_4 0_5$

2nd: $S = \{X_1, X_2\}$,
$AVI = \{X_1\}, X_\ell = X_1$

$(X_3, 0_3)$
$\downarrow$
$(X_1, 1_1)$

Input: A set $\mathcal{E}$ of examples over $\mathcal{I}$
Output: A sequence T of pairs (X_ℓ, x_ℓ), or FAILURE if a UI-UP tree does not exist

$S = \mathcal{I} \setminus (NEQ(\mathcal{E},\mathcal{I}) \cup EQ(\mathcal{E},\mathcal{I}))$;
$T \leftarrow$ empty sequence;
while $\underline{\mathcal{E}^{\succ} \neq \emptyset}$ **do**
  Construct $AVI(\mathcal{E}, S)$;
  if $\underline{AVI(\mathcal{E}, S) = \emptyset}$ **then**
    return FAILURE;
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  $S \leftarrow S \setminus \{X_\ell\}$;
end
return T;

ConsLearn UI-UP PLP-trees (cont'd)

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2. ~~$0_1 0_2 1_3 1_4 1_5 \approx 0_1 0_2 1_3 0_4 1_5$~~
3. ~~$1_1 0_2 0_3 0_4 1_5 \succ 0_1 1_2 0_3 1_4 1_5$~~
4. ~~$1_1 1_2 0_3 1_4 0_5 \succ 1_1 1_2 1_3 0_4 0_5$~~
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6. $0_1 1_2 1_3 1_4 0_5 \succ 0_1 0_2 1_3 1_4 0_5$

2nd: $S = \{X_1, X_2\}$,

$AVI = \{X_1\}, X_\ell = X_1$

$$\begin{array}{c} (X_3, 0_3) \\ \downarrow \\ (X_1, 1_1) \end{array}$$

$S = \{X_2\}$

Input: A set $\mathcal{E}$ of examples over $\mathcal{I}$

Output: A sequence T of pairs (X_ℓ, x_ℓ), or FAILURE if a UI-UP tree does not exist

$S = \mathcal{I} \setminus (NEQ(\mathcal{E},\mathcal{I}) \cup EQ(\mathcal{E},\mathcal{I}))$;

$T \leftarrow$ empty sequence;

while $\mathcal{E}^{\succ} \neq \emptyset$ **do**

  Construct $AVI(\mathcal{E}, S)$;

  if $AVI(\mathcal{E}, S) = \emptyset$ **then**

    return FAILURE;

  end

  $X_\ell \leftarrow$ an element from $AVI(\mathcal{E}, S)$;

  Construct (X_ℓ, x_ℓ);

  $T \leftarrow T, (X_\ell, x_\ell)$;

  $\mathcal{E} \leftarrow \mathcal{E} \setminus \{e \in \mathcal{E}^{\succ} : e \text{ is decided on } X_\ell\}$;

  $S \leftarrow S \setminus \{X_\ell\}$;

end

return T;

ConsLearn UI-UP PLP-trees (cont'd)

~~1. $1_1 1_2 1_3 0_4 0_5 \approx 1_1 1_2 1_3 1_4 0_5$~~

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~~3. $1_1 0_2 0_3 0_4 1_5 \succ 0_1 1_2 0_3 1_4 1_5$~~

~~4. $1_1 1_2 0_3 1_4 0_5 \succ 1_1 1_2 1_3 0_4 0_5$~~

~~5. $0_1 1_2 0_3 0_4 1_5 \succ 0_1 0_2 1_3 0_4 1_5$~~

6. $0_1 1_2 1_3 1_4 0_5 \succ 0_1 0_2 1_3 1_4 0_5$

3rd: $S = \{X_2\}$,
$AVI = \{X_2\}, X_\ell = X_2$

$$(X_3, 0_3)$$
$$\downarrow$$
$$(X_1, 1_1)$$
$$\downarrow$$
$$(X_2, 1_2)$$

```
Input: A set 𝓔 of examples over 𝓘
Output: A sequence T of pairs (X_ℓ, x_ℓ), or FAILURE if a
        UI-UP tree does not exist
S = 𝓘 \ (NEQ(𝓔, 𝓘) ∪ EQ(𝓔, 𝓘));
T ← empty sequence;
while 𝓔^≻ ≠ ∅ do
    Construct AVI(𝓔, S);
    if AVI(𝓔, S) = ∅ then
        return FAILURE;
    end
    X_ℓ ← an element from AVI(𝓔, S);
    Construct (X_ℓ, x_ℓ);
    T ← T, (X_ℓ, x_ℓ);
    𝓔 ← 𝓔\{e ∈ 𝓔^≻ : e is decided on X_ℓ};
    S ← S\{X_ℓ};
end
return T;
```

~~1. $1_1 1_2 1_3 0_4 0_5 \approx 1_1 1_2 1_3 1_4 0_5$~~

~~2. $0_1 0_2 1_3 1_4 1_5 \approx 0_1 0_2 1_3 0_4 1_5$~~

~~3. $1_1 0_2 0_3 0_4 1_5 \succ 0_1 1_2 0_3 1_4 1_5$~~

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3rd: $S = \{X_2\}$,

$AVI = \{X_2\}, X_\ell = X_2$

$$(X_3, 0_3)$$
$$\downarrow$$
$$(X_1, 1_1)$$
$$\downarrow$$
$$(X_2, 1_2)$$

$S = \emptyset$

Input: A set $\mathcal{E}$ of examples over $\mathcal{I}$

Output: A sequence T of pairs (X_ℓ, x_ℓ), or FAILURE if a UI-UP tree does not exist

$S = \mathcal{I} \setminus (NEQ(\mathcal{E},\mathcal{I}) \cup EQ(\mathcal{E},\mathcal{I}))$;
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  $S \leftarrow S \setminus \{X_\ell\}$;
end
return T;

ConsLearn UI-UP PLP-trees (cont'd)

~~1. $1_1 1_2 1_3 0_4 0_5 \approx 1_1 1_2 1_3 1_4 0_5$~~

~~2. $0_1 0_2 1_3 1_4 1_5 \approx 0_1 0_2 1_3 0_4 1_5$~~

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~~4. $1_1 1_2 0_3 1_4 0_5 \succ 1_1 1_2 1_3 0_4 0_5$~~

~~5. $0_1 1_2 0_3 0_4 1_5 \succ 0_1 0_2 1_3 0_4 1_5$~~

~~6. $0_1 1_2 1_3 1_4 0_5 \succ 0_1 0_2 1_3 1_4 0_5$~~

$\mathcal{E}^{\succ} = \emptyset$,

Done!

$(X_3, 0_3)$

$\downarrow$

$(X_1, 1_1)$

$\downarrow$

$(X_2, 1_2)$

Input: A set $\mathcal{E}$ of examples over $\mathcal{I}$
Output: A sequence T of pairs (X_ℓ, x_ℓ), or FAILURE if a UI-UP tree does not exist

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  $\mathcal{E} \leftarrow \mathcal{E} \setminus \{e \in \mathcal{E}^{\succ} : e \text{ is decided on } X_\ell\}$;
  $S \leftarrow S \setminus \{X_\ell\}$;
end
return T;

Results

	FP	UP	CP
UI	P	P	*NP*
CI	P	NPC[2]	P

(a) ConsLearn

	FP	UP	CP
UI	NPC	NPC	NPC
CI	NPC	NPC	NPC

(b) SmallLearn

	FP	UP	CP
UI	NPC[3]	NPC	NPC
CI	NPC	NPC	NPC

(c) MaxLearn

Figure: Complexity results for passive learning problems

[2] Booth et al., *Learning Conditionally Lexicographic Preference Relations*, 2010.

[3] Schmitt and Martignon, *On the Complexity of Learning Lexicographic Strategies*, 2006.

Ongoing and Future Research

1. Settle the complexity for the ConsLearn problem for UI-CP.
2. Implement algorithms handling issues of multi-valued domains.
3. Compare PLP-tree empirically[4] with other models.

[4] Available datasets: UCI machine learning repository, preference-learning.org, and PrefLib.

Q&A

Thank you!

Related Work: Qual. Pref. Models

1. Graphical models: ceteris paribus[5] models (CP-nets[6], TCP-nets[7]), lexicographic models (lexicographic strategies[8], LP-trees[9], CLP-trees[10]).
2. Non-graphical models: ASO-theories[11], Possibilistic logic[12], CP-theories[13].

[5] Latin, it means "everything else being equal."

[6] Boutilier et al., *CP-nets: A Tool for Representing and Reasoning with Conditional Ceteris Paribus Preference Statements*, 2004.

[7] Brafman and Domshlak, *Introducing Variable Importance Tradeoffs into CP-nets*, 2002.

[8] Schmitt and Martignon, *On the Complexity of Learning Lexicographic Strategies*, 2006.

[9] Booth et al., *Learning Conditionally Lexicographic Preference Relations*, 2010.

[10] Bräuning and Eyke, *Learning Conditional Lexicographic Preference Trees*, 2012

[11] Brewka, Niemelä and Truszczynski, *Answer Set Optimization*, 2003.

[12] Dubois, Lang and Prade, *A brief overview of possibilistic logic*, 1991.

[13] Wilson, *Extending CP-Nets with Stronger Conditional Preference Statements*, 2004.