Search Strategies for Partial-Order Causal-Link Planning with Preferences

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Search Strategies for POCL Planning with Preferences – Outline

(POCL Planning == Partial-Order Causal-Link Planning)

- Planning with soft goals / at-end preferences (PDDL 3.0)
- Optimize Net-Benefit
- No compilation, but native implementation in PANDA, a POCL Planning Architecture (PhD thesis, Schattenberg)
Search Strategies for POCL Planning with Preferences – Outline

1. Problem Formalization
2. POCL Planning: Basics
3. Flaw Selection Strategies
   - Which Preference Flaw to Select?
   - How to Address a Preference Flaw?
4. Empirical Evaluation
5. Summary & Outlook
A planning domain is a tuple $\mathcal{D} = \langle \mathcal{V}, \mathcal{A} \rangle$ with:

- $\mathcal{V}$ is a finite set of state variables, $s \in 2^\mathcal{V}$ being a state,
- $\mathcal{A}$ is a finite set of actions,

An action $a := \langle \text{pre}, \text{add}, \text{del} \rangle \in \mathcal{A}$ consists of:

- $\text{pre} \subseteq \mathcal{V}$, the precondition of $a$,
- $\text{add} \subseteq \mathcal{V}$, the add list of $a$,
- $\text{del} \subseteq \mathcal{V}$, the delete list of $a$,
- $\text{cost}(a)$, the cost of $a$
A planning domain is a tuple $\mathcal{D} = \langle \mathcal{V}, \mathcal{A} \rangle$ with:

- $\mathcal{V}$ is a finite set of state variables, $s \in 2^\mathcal{V}$ being a state,
- $\mathcal{A}$ is a finite set of actions,
  an action $a := \langle \text{pre}, \text{add}, \text{del} \rangle \in \mathcal{A}$ is applicable:
    - in a state $s \in 2^\mathcal{V}$ iff $\text{pre} \subseteq s$,
    - and generates the state $(s \setminus \text{del}) \cup \text{add}$
    - (applicability of action sequences is defined as usual)
A POCL planning problem is a tuple \( \pi = \langle D, P_{init} \rangle \) with:

- \( D \) is the planning domain
- \( P_{init} \) is the initial plan which contains/encodes:
  - \( s_{init} \in 2^V \), the initial state
  - \( G \subseteq V \), the goal description

A solution to \( \pi \) is a plan \( P \), s.t.:

- for every action sequence \( \bar{a} \) induced by \( P \) holds:
  - \( \bar{a} \) is applicable in \( s_{init} \),
  - \( \bar{a} \) generates a state \( s' \supseteq G \)
A POCL planning problem is a tuple \( \pi = \langle \mathcal{D}, P_{\text{init}} \rangle \) with:

- \( \mathcal{D} \) is the planning domain
- \( P_{\text{init}} \) is the initial plan which contains/encodes:
  - \( s_{\text{init}} \in 2^\mathcal{V} \), the initial state
  - \( G \subseteq \mathcal{V} \), the goal description
  - \( O \subseteq 2^2^\mathcal{V} \), the optional goals, called preferences

A solution to \( \pi \) is a plan \( P \), s.t.:

- for every action sequence \( \bar{a} \) induced by \( P \) holds:
  - \( \bar{a} \) is applicable in \( s_{\text{init}} \),
  - \( \bar{a} \) generates a state \( s' \supseteq G \)
Planning goal: find a plan with best quality:
\[ \rightarrow \text{Optimize the net benefit of a plan } P! \]

- Each \( o \in O, o \subseteq 2^V \) is a formula in disjunctive normal form.
- Each \( o \in O \) has a benefit, \( \text{ben}(o) \)
- The \textit{net benefit} is defined by:
  \[ \text{NetBen}(P) = \sum_{o \in O, P \models o} \text{ben}(o) - \text{cost}(P) \]
A partial plan is a tuple $P = (PS, \prec, CL)$ with:

- $PS$ is a finite set of plan steps, a plan step $l:a \in PS$ is a labeled action,
- $\prec$ is a strict partial order on $PS$, 
- $CL$ is a set of causal links between the plan steps in $PS$

Example for a partial plan:

- $init$: $\underbrace{\text{init}}_{\text{init}}$ 
  - $a \rightarrow b \rightarrow b$

- $l^2:A^2$: $\underbrace{l^2:A^2}_{l^2:A^2}$ 
  - $\neg b \rightarrow a \rightarrow a$

- $l^1:A^1$: $\underbrace{l^1:A^1}_{l^1:A^1}$ 
  - $\neg a \rightarrow c \rightarrow a$

- $goal$: $\underbrace{\text{goal}}_{\text{goal}}$ 
  - $\neg a \rightarrow c \rightarrow a$
A = \{A^1, A^2\} with: A^1 = (a, \neg a \land c) and A^2 = (b, \neg b \land a)
initial state \(s_{init} = a \land b\), goal description \(g = a \land c\)
\[ A = \{A^1, A^2\} \text{ with: } A^1 = (a, \neg a \land c) \text{ and } A^2 = (b, \neg b \land a) \]

initial state \( s_{init} = a \land b \), goal description \( g = a \land c \)

<table>
<thead>
<tr>
<th>Flaws</th>
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POCL Planning: Basics

Partial Plan (Flaws and Modifications)

\( A = \{A^1, A^2\} \) with: \( A^1 = (a, \neg a \land c) \) and \( A^2 = (b, \neg b \land a) \)

initial state \( s_{init} = a \land b \), goal description \( g = a \land c \)

\[ \begin{align*}
\text{init} & \quad \begin{array}{c}
\overline{a} \\
\text{b}
\end{array} \\
\text{goal} & \quad \begin{array}{c}
\overline{a} \\
\text{c}
\end{array}
\end{align*} \]

\( l^1: A^1 \)

Flaws

Open Precondition: \((a, goal)\)

Causal Link: \((A^2, a, goal)\)

Causal Link: \((init, a, goal)\)

Open Precondition: \((c, goal)\)

Causal Link: \((A^1, c, goal)\)
\( \mathcal{A} = \{A^1, A^2\} \) with: 
\[ A^1 = (a, \neg a \land c) \] and 
\[ A^2 = (b, \neg b \land a) \]

initial state \( s_{init} = a \land b \), goal description \( g = a \land c \)

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initial state \( s_{init} = a \land b \), goal description \( g = a \land c \)

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initial state \( s_{init} = a \land b \), goal description \( g = a \land c \)

**Flaws**

- Open Precondition: \((a, goal)\)

**Modifications**

- Causal Link: \((A^2, a, goal)\)
- Causal Link: \((init, a, goal)\)

- Causal Link: \((A^2, a, l^1:A^1)\)
- Causal Link: \((init, a, l^1:A^1)\)

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POCL Planning: Basics

Partial Plan (Flaws and Modifications)

$A = \{A^1, A^2\}$ with: $A^1 = (a, \neg a \land c)$ and $A^2 = (b, \neg b \land a)$

Initial state $s_{init} = a \land b$, goal description $g = a \land c$

Flaws

Open Precondition: $(a, goal)$

Causal Link: $(A^2, a, goal)$

Causal Link: $(init, a, goal)$

Causal Link: $(l^2:A^2, a, goal)$

Open Precondition: $(b, l^2:A^2)$

Causal Link: $(init, b, l^2:A^2)$

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initial state \[ s_{\text{init}} = a \land b \], goal description \[ g = a \land c \]

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initial state \( s_{init} = a \land b \), goal description \( g = a \land c \)

### Flaws

- Open Precondition: \((a, goal)\)

### Modifications

- Causal Link: \((A^2, a, goal)\)
- Causal Link: \((init, a, goal)\)
- Causal Link: \((l^2:A^2, a, goal)\)

- Causal Link: \((init, b, l^2:A^2)\)
Algorithm 1: POCL planning procedure

\( Fringe \leftarrow \{ P_{\text{init}} \} \)

\textbf{while} \( Fringe \neq \emptyset \) \textbf{do}

\hspace{1em} \( P \leftarrow \text{planSel} (\text{Fringe}) \)

\hspace{1em} \( Fringe \leftarrow Fringe \setminus \{ P \} \)

\hspace{1em} \textbf{if} \( \text{Flaws}(P) = \emptyset \) \textbf{then return} \( P \)

\hspace{1em} \( f \leftarrow \text{flawSel} (\text{Flaws}(P)) \)

\hspace{1em} \( Fringe \leftarrow Fringe \cup \{ \text{applyMod}(P, m) \mid m \in \text{Mods}(f) \} \)

\textbf{return} \( \text{fail} \)

→ two choices:

\textbf{plan selection} (\text{planSel}) and \textbf{flaw selection} (\text{flawSel})
plan selection (planSel):
A* or weighted A* with heuristics for POCL plans:

- with preferences: Bercher & Biundo, PuK 2011, FLAIRS 2012
- without preferences: Bercher et al., KI 2013, ICTAI 2013

flaw selection (flawSel):

- with preferences: Bercher et al., PuK 2013
- without preferences: Bercher et al., ???
Flaw selection can never be wrong, but it “forms the search space”.

Let the plan $P$ have the flaws: $f_1, \ldots, f_4$. 

$f_1 \rightarrow f_2 \rightarrow f_3 \rightarrow f_4$  

$f_4 \rightarrow f_1 \rightarrow f_2 \rightarrow f_3$
Flaw selection can never be wrong, but it “forms the search space”.

Let the plan $P$ have the flaws: $f_1, \ldots, f_4$.

$LCFR \to$ Select a flaw with least number of modifications.
In which order to select the preference flaws?
How to combine estimates of a preference?

\[ p_1 = \psi_1 \]
\[ p_2 = \psi_1 \land \psi_2 \]

modifications

2

modifications

1 3

\[ \text{estimate}(p_1) = 2 \]
\[ \text{estimate}(p_2) = 1? \ (\text{min}) / 4? \ (\text{sum}) / 3? \ (\text{product}) \]
**Splitting:** *Focus on disjuncts individually.*

First selection of the preference $p$ (example):

$$p = \psi_1 \lor (\psi_2 \land \psi_2)$$

- $p_1 = \psi_1$
- $p_2 = \psi_2 \land \psi_2$

Each subsequent selection of the preference:

- $p_1 = \psi_1$
- $p_2 = \psi_2 \land \psi_2$

Modifications:
- 1
- 2
- 3
No Splitting: Stay flexible and work on different disjuncts.

\[ p = \psi_1 \lor (\psi_1 \land \psi_2) \]

Example: After a modification for \( \psi_{21} \) was applied, search is not committed to \((\psi_{21} \land \psi_{22})\), but may also support \( \psi_{11} \).
Evaluation compares:

- Solve ordinary goals first vs. solve soft goals first
- *splitting* vs. *no splitting*
- Estimate combination: *min* vs. *sum* vs. *product*
- “A* NetBenefit”, which maximizes $NetBen(P) - h(P)$, 
  $h$ being the additive heuristic for POCL planning.
Evaluation compares:

- Solve ordinary goals first vs. solve soft goals first
- *splitting* vs. *no splitting*
- Estimate combination: *min* vs. *sum* vs. *product*
- “A* NetBenefit”, which maximizes $\text{NetBen}(P) - h(P)$, $h$ being the additive heuristic for POCL planning.

Evaluated planning domains/problems:

- 5 hand-modeled problem instances of one domain
- 120 randomly generated planning problems
Empirical Evaluation

Results (Hand-modeled Domain)

- Solve ordinary goals first vs. solve soft goals first
  - Qualities much better if hard flaws are solved first.
- Splitting vs. no splitting
- Estimate combination: min vs. sum vs. product
  - no clear results
Empirical Evaluation

Results (Random Domain)

- Solve ordinary goals first vs. solve soft goals first
  - 2/120 problems were solved if preferring soft goals first
- $\textit{splitting}$ vs. $\textit{no splitting}$
- Estimate combination: $\textit{min}$ vs. $\textit{sum}$ vs. $\textit{product}$
  - $\textit{splitting}$ with $\textit{minimum}$ produces the worst solutions
  - $\textit{no splitting}$ produces the best solutions
  - $\textit{sum}$ and $\textit{product}$ equally good, $\textit{min}$ performs badly
Summary:

- Introduced how simple preferences can be addressed in a POCL system: splitting vs. no splitting
- Evaluated various strategies:
  - Soft goals first / last
  - How to aggregate flaw cost estimates?

Outlook:

- Evaluate IPC domains
- Integrate heuristic from FLAIRS 2012