Principles of AI Planning
14. Planning as search: Partial-Order Reduction

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January 22nd, 2018

Motivation

Worst case: Heuristic search may explore exponentially more states than necessary, even if heuristic is almost perfect (Helmert and Röger, 2008).
Example: A* search in GRIPPER domain explores all permutations of ball transportations if heuristic is off only by a small constant.
Idea: Complement heuristic search with orthogonal technique(s) to reduce size of explored state space.
Desired properties of this technique: preservation of completeness and, if possible, optimality.

Partial-Order Reduction

Idea:
- Enforce particular ordering among operators.
- Ignore all other orderings.
Example
Preliminaries

Basic Definitions

Definition (Operators)
Let $\Pi = (V, I, O, \gamma)$ be a SAS$^+$ planning task and $o \in O$ an operator. Then

- $\text{prevs}(o) := \text{vars}(\text{pre}(o))$ are the variables that occur in the precondition of $o$.
- $\text{effvars}(o) := \text{vars}(\text{eff}(o))$ are the variables that occur in the effect of $o$.
- $o$ reads $v \in V$ iff $v \in \text{prevs}(o)$.
- $o$ modifies $v \in V$ iff $v \in \text{effvars}(o)$.

Variable $v \in V$ is goal-related iff $v \in \text{vars}(\gamma)$.

Assumption: $\text{effvars}(o) \neq \emptyset$ for all $o \in O$.

Setting

Assumption: For the rest of the chapter, we assume that all planning tasks are SAS$^+$ planning tasks $\Pi = (V, I, O, \gamma)$.

For convenience, we assume that operators have the form $o = \langle \text{pre}(o), \text{eff}(o) \rangle$, where $\text{pre}(o)$ and $\text{eff}(o)$ are both partial states over $V$, i.e., partial functions mapping variables $v$ to values in $\mathcal{D}_v$. Similarly, we assume that $\gamma$ is a partial state describing the goal.

Example
Operator $o = \langle \text{pre}(o), \text{eff}(o) \rangle$ with

- $\text{pre}(o) = \{ v_1 \mapsto d_1, v_5 \mapsto d_5 \}$ and
- $\text{eff}(o) = \{ v_2 \mapsto d_2, v_3 \mapsto d_5 \}$

corresponds to $o = \langle \chi, e \rangle$ with

$\chi = (v_1 = d_1 \land v_5 = d_5)$ and $e = (v_2 := d_2 \land v_3 := d_3)$.

Operator Dependencies

Definition (Operator dependencies)
Let $\Pi = (V, O, I, \gamma)$ be a planning task and $o, o' \in O$.

1. $o$ disables $o'$ iff there exists $v \in \text{effvars}(o) \cap \text{prevs}(o')$ such that $\text{eff}(o)(v) \neq \text{pre}(o')(v)$.
2. $o$ enables $o'$ iff there exists $v \in \text{effvars}(o) \cap \text{prevs}(o')$ such that $\text{eff}(o)(v) = \text{pre}(o')(v)$.
3. $o$ and $o'$ conflict iff there is $v \in \text{effvars}(o) \cap \text{effvars}(o')$ such that $\text{eff}(o)(v) \neq \text{eff}(o')(v)$.
4. $o$ and $o'$ interfere iff $o$ disables $o'$, or $o'$ disables $o$, or $o$ and $o'$ conflict.
5. $o$ and $o'$ are commutative iff $o$ and $o'$ do not interfere, and neither $o$ enables $o'$, nor $o'$ enables $o$.
Necessary Enabling Sets and Disjunctive Action Landmarks

Definition (Necessary enabling set)
Let \( \Pi = \langle V, I, O, \gamma \rangle \) be a planning task, \( s \) a state, and \( o \in O \) an operator that is not applicable in \( s \). A set \( N \) of operators is a necessary enabling set (NES) for \( o \) in \( s \) if all operator sequences that lead from \( s \) to a goal state and include \( o \) contain an operator in \( N \) before the first occurrence of \( o \).

Note: NESs not uniquely determined for given \( o \) and \( s \). (E.g., supersets of NESs are still NESs.)

Proof
Let \( L \) be such a disjunctive action landmark. Then each operator sequence that leads from \( s \) to a state satisfying \( \text{pre}(o) \) contains some operator in \( L \). Thus, each operator sequence that leads from \( s \) to a goal state and includes \( o \) contains an operator in \( L \) before the first occurrence of \( o \).

Therefore, \( L \) is an NES for \( o \) in \( s \).
**Motivation**

If, in state $s$, some set of operators can be applied in any order and the order does not matter, we want to commit to one such order and ignore all other orders.

**Idea:**

Identify operators that can be postponed since they are independent of all operators that are not postponed.

E.g., put-on-right could be postponed, since it is independent of put-on-left (that is not postponed).

**Stubborn Sets**

**Definition (Strong stubborn set)**

Let $\Pi = (V, I, O, \gamma)$ be a planning task and $s$ a state. A set $T_s \subseteq O$ is a strong stubborn set in $s$ if:

1. $T_s$ contains a disjunctive action landmark in $s$, and
2. for all $o \in T_s$ that are not applicable in $s$, $T_s$ contains a necessary enabling set for $o$ and $s$, and
3. for all $o \in T_s$ that are applicable in $s$, $T_s$ contains all operators that interfere with $o$.

Instead of applying all applicable operators in $s$ only apply those that are applicable and contained in $T_s$. 
Strong Stubborn Sets

Example

\[ V = \{u_1, u_2, v, w\}, I = \{u_1 \mapsto u, u_2 \mapsto 0, v \mapsto 0, w \mapsto 0\}, \gamma = \{v \mapsto 0, u_1 \mapsto 1, u_2 \mapsto 1\}, \text{and } O = \{o_1, o_2, o_3\}, \text{where:} \]

\[ o_1 = \langle u_1 = 0, u_1 = 1 \wedge w = 2\rangle, \]
\[ o_2 = \langle u_2 = 0, u_2 = 1 \wedge w = 2\rangle, \]
\[ o_3 = \langle u_1 = 0 \wedge u_2 = 0, v = 1 \wedge w = 1\rangle. \]

Strong stubborn set:

\[ \text{Step 1: Include } o_1 (\text{or } o_2) \text{ in } T_s \text{ as DAL.} \]
\[ \text{Step 2: Include } o_3 \text{ in } T_s \text{ since it interferes with } o_1 \text{ (or } o_2). \]
\[ \text{Step 3: Include } o_2 \text{ (or } o_1) \text{ in } T_s \text{ since it interferes with } o_3. \]

\[ \text{~} \rightarrow \text{ all applicable operators included in } T_s, \text{ no pruning.} \]

Question: Can we do better than that in this example?

Domain Transition Graphs

Definition (Domain transition graph)

Let \( \Pi = (V, I, O, \gamma) \) be a SAS^+ planning task and \( v \in V \). The domain transition graph for \( v \) is the directed graph

\[ DTG(v) = (\mathcal{D}_v, E) \] where \( (d, d') \in E \) iff there is an operator \( o \in O \) with

1. \( \text{eff}(o)(v) = d' \), and
2. \( v \notin \text{prev}(o) \) or \( \text{pre}(o)(v) = d \).

Then \( DTG(pos) \):
Active Operators

**Definition (Active operators)**
Let $\Pi = \langle V, I, O, \gamma \rangle$ be a planning task and let $s$ be a state. The set of active operators $\text{Act}(s) \subseteq O$ in $s$ is defined as the set of operators such that for all $o \in \text{Act}(s)$:

1. For every variable $v \in \text{prevars}(o)$, there is a path in $\text{DTG}(v)$ from $s(v)$ to $\text{pre}(o)(v)$. If $v$ is goal-related, then there is also a path from $\text{pre}(o)(v)$ to the goal value $\gamma(v)$.
2. For every goal-related variable $v \in \text{effvars}(o)$, there is a path in $\text{DTG}(v)$ from $\text{eff}(o)(v)$ to the goal value $\gamma(v)$.

**Remark 1:** Even when excluding inactive operators, this preserves completeness and even optimality of a search algorithm (see proof below).

**Remark 2:** Excluding inactive operators can “cascade” in the sense that additional active operators need not be considered.

Proposition

$\text{Act}(s)$ can be identified efficiently for a given state $s$ by considering paths in the projection of $\Pi$ onto $v$.

Operators not in $\text{Act}(s)$ can be treated as nonexistent when reasoning about $s$ because they are not applicable in all states reachable from $s$, or they lead to a dead-end from $s$.

**Proof**

1. Homework: Specify efficient algorithm for identification of $\text{Act}(s)$.
2. Obvious.

Strong Stubborn Sets

**Definition (Strong stubborn set with active operator pruning)**
Let $\Pi = \langle V, I, O, \gamma \rangle$ be a planning task and $s$ a state. A set $T_s \subseteq O$ is a strong stubborn set in $s$ if

1. $T_s$ contains a disjunctive action landmark in $s$, and
2. for all $o \in T_s$ that are not applicable in $s$, $T_s$ contains a necessary enabling set for $o$ and $s$, and
3. for all $o \in T_s$ that are applicable in $s$, $T_s$ contains all operators that are active in $s$ and interfere with $o$.

Instead of applying all applicable operators in $s$ only apply those that are applicable and contained in $T_s$.
Now, with active operator pruning:

Example

| $I = \{u_1 \mapsto 0, u_2 \mapsto 0, v \mapsto 0, w \mapsto 0\}$, |
| $\gamma = \{v \mapsto 0, u_1 \mapsto 1, u_2 \mapsto 1\}$ |
| $o_1 = \langle u_1 = 0, u_1 = 1 \land w = 2\rangle$ |
| $o_2 = \langle u_2 = 0, u_2 = 1 \land w = 2\rangle$ |
| $o_3 = \langle u_1 = 0 \land u_2 = 0, v = 1 \land w = 1\rangle$ |

Now, with active operator pruning:

- Step 1: Include $o_1$ (or $o_2$) in $T_s$ as DAL.
- Step 2: Operator $o_3$ is not active in any reachable state. $\Rightarrow o_3$ not in $T_s$, although it interferes with $o_1$ (or $o_2$).

Recall the previous example where strong stubborn sets without active operator pruning were useless.

Example (Example, ctd.)

Now, with active operator pruning:

- Step 1: Include $o_1$ (or $o_2$) in $T_s$ as DAL.
- Step 2: Operator $o_3$ is not active in any reachable state. $\Rightarrow o_3$ not in $T_s$, although it interferes with $o_1$ (or $o_2$).
- Hence, e.g., $T_s = \{o_1\}$ strong stubborn set (with active operator pruning) in $I$.
- Even active operator $o_2$ is not included in $T_s = \{o_1\}$.
- $\Rightarrow$ some pruning occurs.

Weak Stubborn Sets

With weak stubborn sets, some operators that disable an operator in $T_s$ need not be included in $T_s$.

Therefore, weak stubborn sets potentially allow more pruning than strong stubborn sets.

Definition (Weak stubborn set)

Let $\Pi = (V, I, O, \gamma)$ be a planning task and $s$ a state. A set $T_s \subseteq O$ is a weak stubborn set in $s$ if

1. $T_s$ contains a disjunctive action landmark in $s$, and
2. for all $o \in T_s$ that are not applicable in $s$, $T_s$ contains a necessary enabling set for $o$ and $s$, and
3. for all $o \in T_s$ that are applicable in $s$, $T_s$ contains the active operators in $s$ that have conflicting effects with $o$ or that are disabled by $o$.

WeakStubbornSets

For weak stubborn sets, it suffices to include active operators $o'$ that are disabled or conflict with applicable operators $o \in T_s$.

However, $o'$ does not need to be included if $o'$ does not disable an applicable operator $o \in T_s$.

No computational overhead of computing weak stubborn sets over computing strong stubborn sets.

Theorem

In the best case, weak stubborn sets admit exponentially more pruning than strong stubborn sets.

Proof

Homework.
Motivation

Preliminaries

Stubborn Sets

Strong Stubborn Sets

Active Operators

Weak Stubborn Sets

Algorithms

Properties of Stubborn Sets

Some Experiments

Conclusion

Algorithms

**compute-DAL**: Compute a disjunctive action landmark.

Procedure compute-DAL

```python
def compute-DAL(γ):
    select v ∈ vars(γ) with s(v) ≠ γ(v)
    L ← {o' ∈ Act(s) | eff(o')(v) = γ(v)}
    return L
```

Selection of v ∈ vars(γ) arbitrary. Any variable will do. Selection heuristics?

Algorithms

**compute-NES**: Compute a necessary enabling set.

Procedure compute-NES

```python
def compute-NES(o, s):
    select v ∈ prevars(o) with s(v) ≠ pre(o)(v)
    N ← {o' ∈ Act(s) | eff(o')(v) = pre(o)(v)}
    return N
```

Selection of v ∈ prevars(o) arbitrary. Any variable will do. Selection heuristics?

Algorithms

**compute-interfering-operators**: Compute interfering operators.

Procedure compute-interfering-operators (for strong SS)

```python
def compute-interfering-operators(o):
    disablers ← {o' ∈ O | o' disables o}
    disablees ← {o' ∈ O | o disables o'}
    conflicting ← {o' ∈ O | o and o' conflict}
    return disablers ∪ disablees ∪ conflicting
```

Procedure compute-interfering-operators (for weak SS)

```python
def compute-interfering-operators(o):
    disablees ← {o' ∈ O | o disables o'}
    conflicting ← {o' ∈ O | o and o' conflict}
    return disablees ∪ conflicting
```

Algorithms

Computing (strong and weak) stubborn sets for planning can be achieved with a fixpoint iteration until the constraints of $T_s$ are satisfied:

**compute-stubborn-set**: Compute (strong or weak) stubborn set.

Procedure compute-stubborn-set

```python
def compute-stubborn-set(s):
    $T_s ← \text{compute-DAL}(γ)$
    while no fixed-point of $T_s$ reached do
        for o ∈ $T_s$ applicable in s:
            $T_s ← T_s ∪ \text{compute-interfering-operators}(o)$
        for o ∈ $T_s$ not applicable in s:
            $T_s ← T_s ∪ \text{compute-NES}(o, s)$
    return $T_s$
```

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Integration into A*

Observation: stubborn sets are state-dependent, but not path-dependent.

This allows filtering the applicable operators in s in graph search algorithms like A* that perform duplicate detection, too.

Instead of applying all applicable operators app(s) in s, only apply operators in \( T_{\text{app}}(s) := T_s \cap \text{app}(s) \).

Preservation of Completeness and Optimality

Theorem

Weak stubborn sets are completeness and optimality preserving.

Proof

Let \( T_{\text{app}}(s) := T_s \cap \text{app}(s) \) for a weak stubborn set \( T_s \).

We show that for all states \( s \) from which an optimal plan consisting of \( n > 0 \) operators exists, \( T_{\text{app}}(s) \) contains an operator that starts such a plan.

We show by induction that A* restricting successor generation to \( T_{\text{app}}(s) \) is optimal.

Let \( T_s \) be a weak stubborn set and \( \pi = o_1, \ldots, o_n \) be an optimal plan that starts in \( s \).

Proof (ctd.)

As \( T_s \) contains a disjunctive action landmark, \( \pi \) must contain an operator from \( T_s \).

Let \( o_k \) be the operator with smallest index in \( \pi \) that is also contained in \( T_s \), i.e., \( o_k \in T_s \) and \( \{ o_1, \ldots, o_{k-1} \} \cap T_s = \emptyset \).

We observe:

1. \( o_k \in \text{app}(s) \): otherwise by definition of weak stubborn sets, a necessary enabling set \( N \) for \( o_k \) in \( s \) would have to be contained in \( T_s \), and at least one operator from \( N \) would have to occur before \( o_k \) in \( \pi \) to enable \( o_k \), contradicting that \( o_k \) was chosen with smallest index.

2. \( o_k \) is does not disable any of the operators \( o_1, \ldots, o_{k-1} \), and all these operators have non-conflicting effects with \( o_k \); otherwise, as \( o_k \in \text{app}(s) \), and by definition of weak stubborn sets, at least one of \( o_1, \ldots, o_{k-1} \) would have to be contained in \( T_s \), again contradicting the assumption.

Hence, we can move \( o_k \) to the front:

\( o_k, o_1, \ldots, o_{k-1}, o_{k+1}, \ldots, o_n \) is also a plan for \( \pi \).

It has the same cost as \( \pi \) and is hence optimal.

Thus, we have found an optimal plan of length \( n \) started by an operator \( o_k \in T_{\text{app}}(s) \), completing the proof.

Proof (ctd.)
Preservation of Completeness and Optimality

Remark: The argument to move \( o_k \) to the front also holds for strong stubborn sets: in this case, \( o_k \) is not even disabled by any of \( o_1, \ldots, o_{k-1} \) (and hence, \( o_k \) is independent of \( o_1, \ldots, o_{k-1} \)), which is a stronger property than needed in the proof.

Corollary

\( \text{Strong stubborn sets are completeness and optimality preserving.} \)

Some Experiments

Weak compared to strong stubborn sets

\[ \begin{array}{cccccc}
\text{Domain (problems)} & \text{Coverage} & \text{Nodes generated} & \# \text{problems w. diff. gen.} \\
& \text{SSS} & \text{WSS} & \text{SSS} & \text{WSS} & \\
\text{OPENSTACKS-OPT08 (30)} & 21 & 152711917 & 99.936\% & 18 \\
\text{OPENSTACKS-OPT11 (20)} & 16 & 152642101 & 99.936\% & 16 \\
\text{PATHWAYS-NONEG (30)} & 5 & 162347 & 99.702\% & 2 \\
\text{PSR-SMALL (50)} & 49 & 18119489 & 99.998\% & 6 \\
\text{SATTELITE (36)} & 12 & 70299721 & 92.804\% & 12 \\
\end{array} \]

In practice (or, at least, in the standard benchmark problems) there is no significant difference between weak and strong stubborn sets.

Some Experiments: Overview

Optimal Planning, A* with LM-cut Heuristic, Selected Domains

<table>
<thead>
<tr>
<th>Domain (problems)</th>
<th>Coverage</th>
<th>Nodes generated</th>
<th>A* +SSS</th>
<th>A* +SSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PARCPRINTER-08 (30)</td>
<td>18 ±12</td>
<td>2455181 &amp; 1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PARCPRINTER-OPT11 (20)</td>
<td>13 ±7</td>
<td>2454533 &amp; 1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WOODWORKING-OPT08 (30)</td>
<td>17 ±10</td>
<td>26796212 &amp; 1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WOODWORKING-OPT11 (20)</td>
<td>12 ±7</td>
<td>26795517 &amp; 1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SATELLITE (36)</td>
<td>7 ±5</td>
<td>5116312 &amp; 2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROVERS (40)</td>
<td>7 ±2</td>
<td>1900691 &amp; 22%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIRPORT (50)</td>
<td>28 ±0</td>
<td>545072 &amp; 93%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPENSTACKS-OPT08 (30)</td>
<td>19 ±2</td>
<td>56884063 &amp; 51%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPENSTACKS-OPT11 (20)</td>
<td>14 ±2</td>
<td>56459699 &amp; 51%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DRIVERLOG (20)</td>
<td>13 ±1</td>
<td>3679376 &amp; 82%</td>
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<tr>
<td>SCANALYZER-OPT08 (30)</td>
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<td>14203012 &amp; 100%</td>
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<td></td>
</tr>
<tr>
<td>SCANALYZER-OPT11 (20)</td>
<td>12 ±3</td>
<td>14202884 &amp; 100%</td>
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</tr>
<tr>
<td>PARKING-OPT11 (20)</td>
<td>3 ±1</td>
<td>560914 &amp; 100%</td>
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</tr>
<tr>
<td>SOKOBAN-OPT08 (30)</td>
<td>30 ±1</td>
<td>20519270 &amp; 100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VISITALL-OPT11 (20)</td>
<td>11 ±1</td>
<td>1991169 &amp; 100%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Remaining domains (980) | 544 ±0 | 436017004 & 93% |

SUM (1396) | 763 ±39 | 670278179 & 77% |

Conclusion

⇒ In practice (or, at least, in the standard benchmark problems) there is no significant difference between weak and strong stubborn sets.
Need for techniques orthogonal to heuristic search, complementing heuristics.

One idea: Commit to one order of operators if they are independent. Prune other orders.

Class of such techniques: partial-order reduction (POR)

One such technique: strong/weak stubborn sets

Can lead to substantial pruning compared to plain A*.

Many other POR techniques exist.

Other pruning techniques exist as well, e.g., symmetry reduction.