A Stubborn Set Algorithm for Optimal Planning

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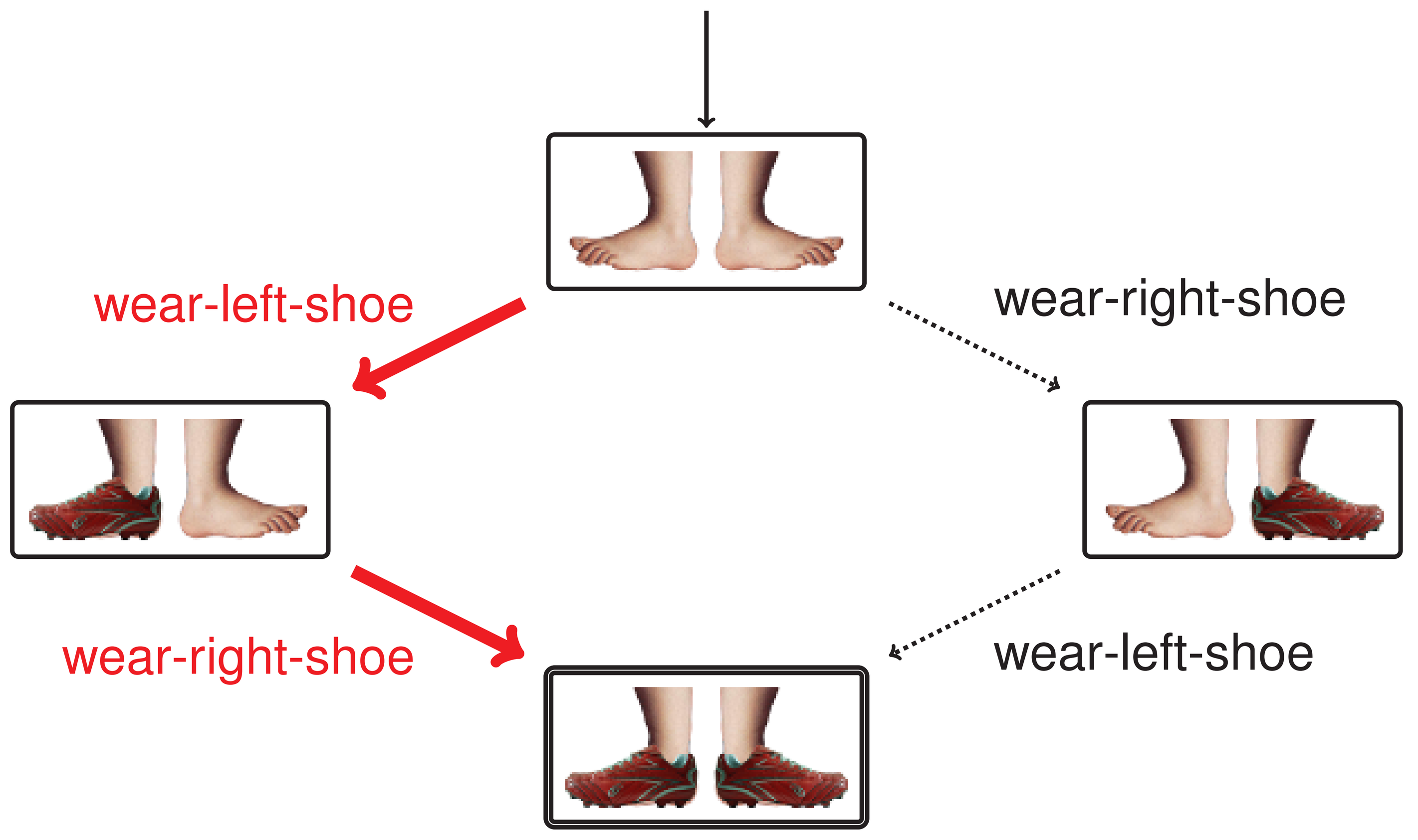
Introduction

Heuristic search

- Popular technique to facilitate planning.
- Drawback: number of state explorations scales exponentially even under generous assumptions [Helmert and Röger 2008].



Partial order reduction

- Observation: unnecessary interleavings of transitions
- Idea: Enforce a particular ordering among operators.
- Problem: Original techniques in model checking are sound [Valmari 1989, Godefroid 1996], but adaptations for planning are not [Chen and Yao 2009, Xu et al. 2011, Chen et al. 2009].
- Objective: Adapt original techniques with as little modification as possible.

Preliminaries

SAS^+ planning tasks

- An SAS^+ planning task Π is a 4-tuple $\langle V, I, O, G\rangle$, where:
  - V is a finite set of finite-domain state variables.
  - I is the initial state.
  - O is a finite set of operators.
  - G is the goal.
- A fact is a pair $\langle v, d\rangle$ with $v \in V$ and $d \in Dom(v)$.
- An operator consists of preconditions and effects.

Dependency of operators

- Operator o_1 disables o_2 if o_2 requires a variable to have a particular value and o_1 assigns another value to the variable.
- Operators o_1 and o_2 conflict if both of them affect a common variable differently.
- Operators o_1 and o_2 are dependent if o_1 disables o_2, or o_2 disables o_1, or o_1 and o_2 conflict.

Disjunctive action landmarks

A disjunctive action landmark for a set of facts F in state s is a set of operators L such that every applicable operator sequence that starts in s and ends in $s' \supseteq F$ contains at least one operator $o \in L$.

Necessary enabling sets

A necessary enabling set for operator $o \notin app(s)$ in state s is a disjunctive action landmark for $pre(o)$ in s.

Strong stubborn sets

Definition

Let Π be a planning task and let s be a state. A strong stubborn set in s is a set of operators $T_s \subseteq O$ such that:

1. T_s contains all the operators that interfere with some applicable operator in T_s.
2. T_s contains a necessary enabling set in s for each inapplicable operator in T_s.
3. T_s contains a disjunctive action landmark for the goal in s.

Strong stubborn set computation (conceptually)

Algorithm 1 Strong stubborn set computation for state s

Input: State s
Output: Strong stubborn set T_s for s

```
T_s ← L_s^G   for some disjunctive action landmark L_s^G for G in s
repeat
    for all o ∈ T_s do
        if o ∈ app(s) then
            T_s ← T_s ∪ dep(o)
        else
            T_s ← T_s ∪ N_s^o  for some nec. enabling set N_s^o for o in s
until T_s reaches a fixed-point
return T_s
```

Experiments

Node generations and coverage of

- Plain A*,
- A* with Expansion Core (EC [Chen and Yao 2009, Xu et al. 2011]), and
- A* with strong stubborn sets (SSS),

all guided by the LM-cut heuristic.

- Nodes and coverage +EC, +SSS relative to plain A*
- green/red: improvement/deterioration compared to plain A*
- **bold**: best result per domain

Domain (problems)	Nodes generated A*	+EC	+SSS	Coverage A*	+EC	+SSS
PARCPRINTER-08 (30)	2461106	100%	**<1%**	18	±0	**+12**
PARCPRINTER-OPT11 (20)	2460475	100%	**<1%**	13	±0	**+7**
WOODWK-OPT08 (30)	7334811	17%	**3%**	17	+5	**+11**
WOODWK-OPT11 (20)	7334070	17%	**3%**	12	+3	**+7**
SATELLITE (36)	4283651	64%	**5%**	7	±0	**+3**
LOGISTICS00 (28)	12855134	100%	**17%**	20	±0	**+1**
OPENSTACKS-OPT08 (30)	34336295	100%	**52%**	18	−2	**+2**
OPENSTACKS-OPT11 (20)	34209201	100%	**52%**	13	−2	**+2**
ELEVATORS-OPT08 (30)	18561161	100%	**55%**	19	±0	**+3**
ELEVATORS-OPT11 (20)	18006303	100%	**55%**	16	±0	**+2**
PSR-SMALL (50)	1859026	100%	**80%**	**49**	−1	±0
MPRIME (35)	921359	100%	**84%**	**22**	−1	±0
ROVERS (40)	1281967	99%	**87%**	7	±0	**+1**
PIPESWORLD-TK (50)	585963	100%	**97%**	**9**	−1	±0
PIPESWORLD-NOTK (50)	2798494	100%	**99%**	**17**	−1	±0
FREECELL (80)	**5543463**	**100%**	**100%**	**15**	−4	−3
GRIPPER (20)	**10807891**	**100%**	**100%**	**7**	−1	±0
PARKING-OPT11 (20)	**39354**	**100%**	**100%**	**2**	−1	−1
SCANALYZER-08 (30)	**7781870**	**100%**	**100%**	**14**	±0	−1
SCANALYZER-OPT11 (20)	**7781742**	**100%**	**100%**	**11**	±0	−1
TRUCKS (30)	**11687203**	**100%**	**100%**	**10**	−1	−1
REMAINING DOMAINS (707)	136716998	100%	**94%**	**425**	±0	±0
OVERALL (1396)	329647537	96%	**72%**	741	−7	**+44**

Future work

- Investigation of other partial order reduction methods and their combination with our POR framework.

References

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