A Complete Algorithm for Generating Landmarks

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Introduction

- multiple uses of landmarks in planning
- most powerful admissible heuristics are based on landmarks
- we know . . .
  - a lot about exploiting landmarks
  - little about generation of landmarks
- this work is about generation of landmarks

Our contribution

- principled algorithm for generating landmarks
- landmarks can be used for different purposes
- a general framework for heuristics based on landmarks:
  - admissible for optimal planning
  - non-admissible for satisfacing planning
- polytime admissible heuristic

Relaxed Planning

Obtained by removing the deletes of each action

Relaxed task characterized by:

- finite set F of facts
- initial facts $I \subseteq F$
- goal facts $G \subseteq F$ that must be reached
- operators of the form $o[4] : a, b \rightarrow c, d$

read: If we already have facts a and b (preconditions $pre(o)$), we can apply o, paying 4 units (cost *cost*(o)), to obtain facts c and d (effects *eff*(o))

Assume WLOG: $I = \{i\}$, $G = \{g\}$, all *pre*$(o) \neq \emptyset$

Example

$o_1[3] : i \rightarrow a, b$
$o_2[4] : i \rightarrow a, c$
$o_3[5] : i \rightarrow b, c$
$o_4[1] : a, b \rightarrow d$
$o_5[1] : a, c, d \rightarrow g$

One way to reach goal $G = \{g\}$ from $I = \{i\}$:

- apply sequence o_1, o_2, o_4, o_5 (plan)
- cost: $3 + 4 + 1 + 1 = 9$ (optimal)

Optimal Relaxed Cost

- h^+ : minimal total cost to reach G from I
- Very good heuristic function for optimal planning
- NP-hard to compute or approximate by constant factor

Landmarks

Most accurate admissible heuristics are based on landmarks

Def: a (disjunctive action) landmark is a set of operators L such that each plan must contain some action in L

Example

$o_1[3] : i \to a, b$
$o_2[4] : i \to a, c$
$o_3[5] : i \to b, c$
$o_4[1] : a, b \to d$
$o_5[1] : a, d, c \to g$

Some landmarks:

- need g: $W = \{o_5\}$ (hence $h^+ \geq 1$)
- need a: $X = \{o_1, o_2\}$ (hence $h^+ \geq 3$)
- need c: $Y = \{o_2, o_3\}$ (hence $h^+ \geq 4$)
- need d: $Z = \{o_4\}$ (hence $h^+ \geq 1$)
- ...

Exploiting Landmarks: Hitting Sets

Given:

- finite set A
- collection $\mathcal{F}$ of subsets from A
- non-negative costs $c : A \to \mathbb{R}_0^+$

Hitting set:

- subset $H \subseteq A$ that hits every $S \in \mathcal{F}$ (i.e. $S \cap H \neq \emptyset$)
- cost of $H = \sum_{a \in H} c(a)$

Minimum-cost Hitting Set (MHS):

- minimizes cost
- classical NP-complete problem

Landmarks and Hitting Sets

Can view collection of landmarks as instance of MHS problem

Example (Landmarks)

$A = \{o_1, o_2, o_3, o_4, o_5\}$

$\mathcal{F} = \{\underbrace{\{o_5\}}_{W}, \underbrace{\{o_1, o_2\}}_{X}, \underbrace{\{o_2, o_3\}}_{Y}, \underbrace{\{o_4\}}_{Z}\}$

costs: $c(o_1) = 3,\ \ c(o_2) = 4,\ \ c(o_3) = 5,\ \ c(o_4) = 1,\ \ c(o_5) = 1$

Minimum hitting set: $\{o_2, o_4, o_5\}$ with cost $4 + 1 + 1 = 6$

Obtaining Landmarks: Justification Graphs

Precondition choice function (pcf): function D that maps operators to preconditions

Justification graph for pcf D: arc-labeled digraph with:

- vertices: the facts F
- arcs: $D(o) \xrightarrow{o} e$ for each operator o and effect $e \in \mathit{eff}(o)$

pcf D:

o	o_1	o_2	o_3	o_4	o_5
$D(o)$	i	i	i	a	a

$o_1[3] : i \rightarrow a, b$

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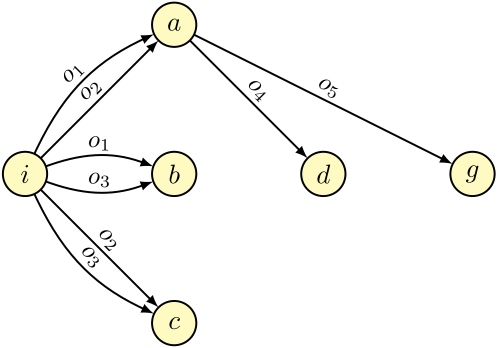

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Landmark (cut): $W = \{o_5\}$

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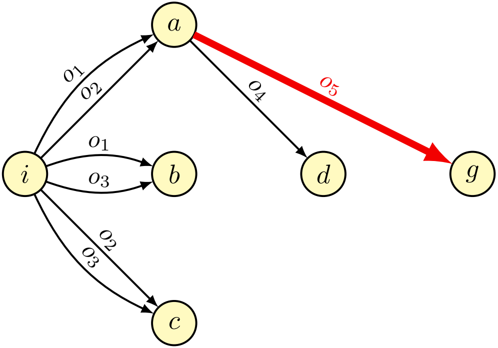

pcf D:

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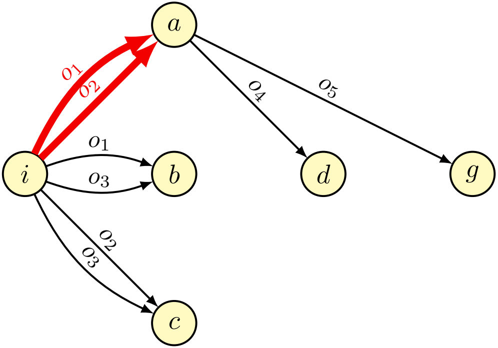

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(new pcf)

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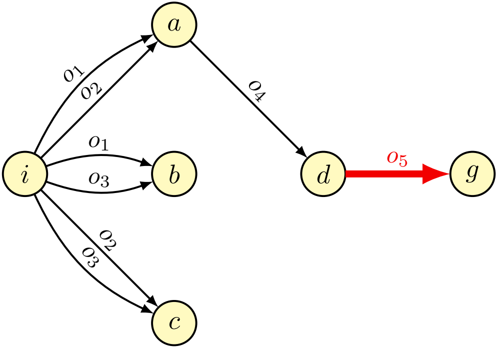

pcf D:

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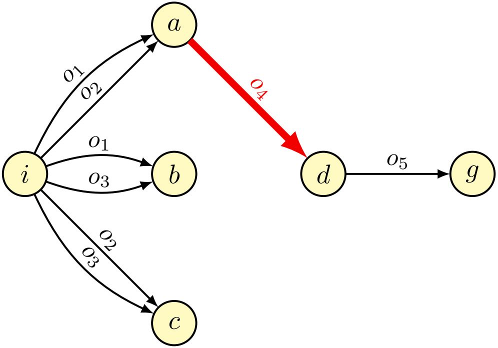

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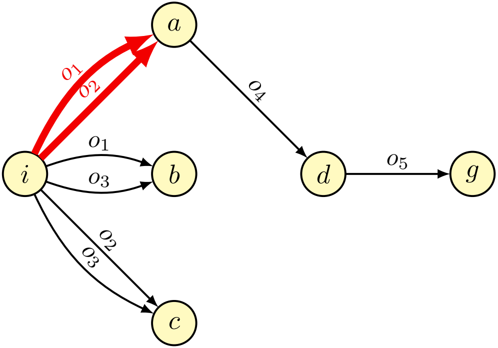

Power of Justification Graph Cuts

Thm (B. & Helmert, 2010): Let $\mathcal{L}$ be all "cut landmarks".
Then, $h^+ =$ cost of MHS for $\mathcal{L}$.

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Impractical to generate all landmarks!

Do we need all of them to get h^+ or a good approximation?

Principled Generation of Landmarks

$H =$ subset of operators

$R =$ fluents reachable from I using only operators in H

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$g \in R \implies H$ "contains" a relaxed plan

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and H does not hit cutset(R, R^c)

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and H does not hit cutset(R, R^c)

Indeed, it's enough to define pcf D as $D(o) = p$ where

$$\begin{cases} p \in \mathit{pre}(o) & \text{if } \mathit{pre}(o) \subseteq R \\ p \in \mathit{pre}(o) \setminus R & \text{if } \mathit{pre}(o) \not\subseteq R \end{cases}$$

For such pcf D,

$$L = \text{cutset}(R, R^c) = \{o : D(o) \in R \text{ and } \textit{eff}(o) \not\subseteq R^c\}$$

is landmark not hit by H!

For such pcf D,

$$L = \mathsf{cutset}(R, R^c) = \{o : D(o) \in R \text{ and } \mathit{eff}(o) \not\subseteq R^c\}$$

is landmark not hit by H!

L **improved by removing from** $G(D)$ **facts irrelevant to** g

Algorithm A

Input: subset H of actions

Output: YES if H contains plan, or landmark not hit by H

Method:

1. $R :=$ set of reachable fluents using actions in H
2. **if** $g \in H$ **then return** YES
3. compute pcf D and justification graph $G(D)$
4. simplify graph $G(D)$
5. **return** cutset of (R, R^c) in simplified graph

Time: linear with correct data structures!

Landmarks $= \emptyset$

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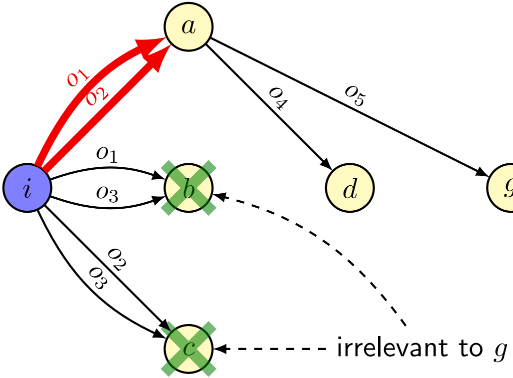
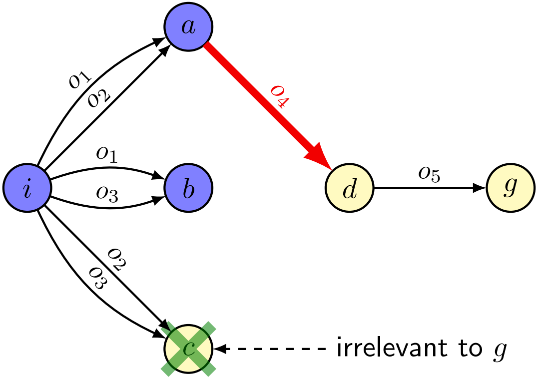
$H = \emptyset$; $R = \{i\}$; $R^c = \{a, b, c, d, g\}$; $L = \{o_1, o_2\}$



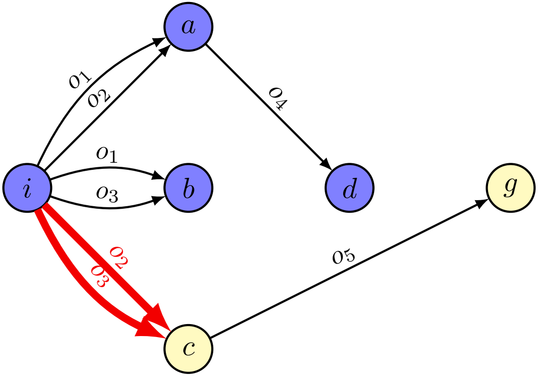
$$\text{Landmarks} = \{\underbrace{\{o_1, o_2\}}_{X}\}$$

$$H = \{o_1\} \; ; \; R = \{i, a, b\} \; ; \; R^c = \{c, d, g\} \; ; \; L = \{o_4\}$$



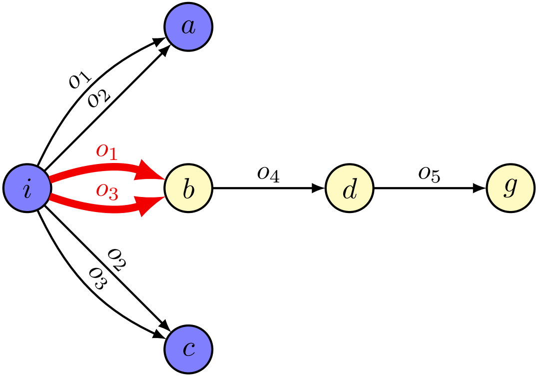
$$\text{Landmarks} = \{\underbrace{\{o_1, o_2\}}_{X}, \underbrace{\{o_4\}}_{Z}\}$$

$$H = \{o_1, o_4\} \; ; \; R = \{i, a, b, d\} \; ; \; R^c = \{c, g\} \; ; \; L = \{o_2, o_3\}$$



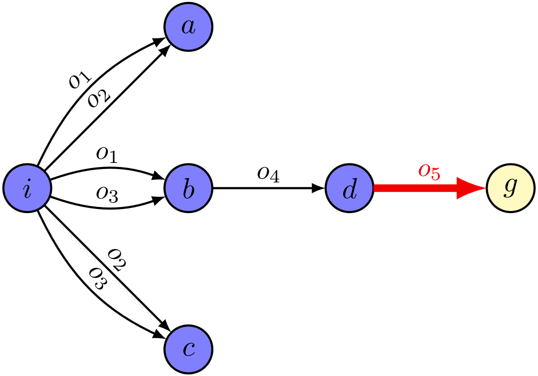
$\text{Landmarks} = \{\underbrace{\{o_1, o_2\}}_{X}, \underbrace{\{o_4\}}_{Z}, \underbrace{\{o_2, o_3\}}_{Y}\}$

$H = \{o_2, o_4\}$; $R = \{i, a, c\}$; $R^c = \{b, g\}$; $L = \{o_1, o_3\}$



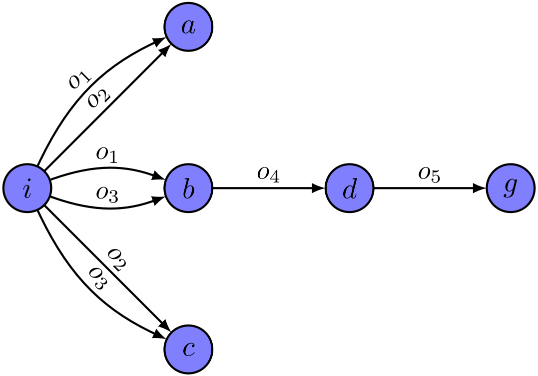
$$\text{Landmarks} = \{\underbrace{\{o_1, o_2\}}_{X}, \underbrace{\{o_4\}}_{Z}, \underbrace{\{o_2, o_3\}}_{Y}, \{o_1, o_3\}\}$$

$$H = \{o_1, o_2, o_4\} \ ; \ R = \{i, a, b, c, d\} \ ; \ R^c = \{g\} \ ; \ L = \{o_5\}$$



Landmarks = $\{\underbrace{\{o_1, o_2\}}_{X}, \underbrace{\{o_4\}}_{Z}, \underbrace{\{o_2, o_3\}}_{Y}, \{o_1, o_3\}, \underbrace{\{o_5\}}_{W}\}$ **complete!**

$H = \{o_1, o_2, o_4, o_5\}$; $R = \{i, a, b, c, d, g\}$; $R^c = \emptyset$



Algorithm $C1$

Input: initial collection $\mathcal{L}$ (maybe empty)

Output: a complete collection and $h^+(I)$

Method:

1. $H :=$ min-cost hitting set for $\mathcal{L}$
2. $L := A(H)$
3. **if** $L =$ YES **then return** $\mathcal{L}$ and cost of H
4. $\mathcal{L} := \mathcal{L} \cup \{L\}$
5. **goto** 2

Algorithm $C1$ does not run in polytime because:

- computing min-cost hitting sets is NP-hard
- number of iterations may be exponential

Flaws can be overcomed to get a polytime approximation by:

- controlling number of iterations
- controlling difficulty of solving MHS problem

See paper for:

- details about algorithm $C1$ and variants $C2$ and $C3$
- how to use A to get heuristics for satisficing planning
- novel polytime admissible heuristics that dominate best-known heuristics **(in number of expanded nodes)**

  slower than state-of-the-art heuristics (i.e. LM-Cut)

Thanks!