Foundations of Artificial Intelligence

39. Automated Planning: Landmark Heuristics

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May 6, 2020

39.1 Finding Landmarks

39.2 The LM-Cut Heuristic

39.3 Summary

Automated Planning: Overview

Chapter overview: automated planning

- 33. Introduction
- 34. Planning Formalisms
- 35.–36. Planning Heuristics: Delete Relaxation
- 37 Planning Heuristics: Abstraction
- 38.–39. Planning Heuristics: Landmarks
    - 38. Landmarks
    - 39. Landmark Heuristics

Formalism and Example

- As in the previous chapter, we consider delete-free planning tasks in normal form.
- We continue with the example from the previous chapter:

> **Example**
>
> actions: landmark examples:
>
> - $a_1 = i \xrightarrow{3} x, y$ - $A = \{a_4\}$ (cost $= 0$)
> - $a_2 = i \xrightarrow{4} x, z$ - $B = \{a_1, a_2\}$ (cost $= 3$)
> - $a_3 = i \xrightarrow{5} y, z$ - $C = \{a_1, a_3\}$ (cost $= 3$)
> - $a_4 = x, y, z \xrightarrow{0} g$ - $D = \{a_2, a_3\}$ (cost $= 4$)

39.1 Finding Landmarks

Justification Graphs

Definition (precondition choice function)

A precondition choice function (pcf) $P : A \rightarrow V$
maps every action to one of its preconditions.

Definition (justification graph)

The justification graph for pcf P is a directed graph
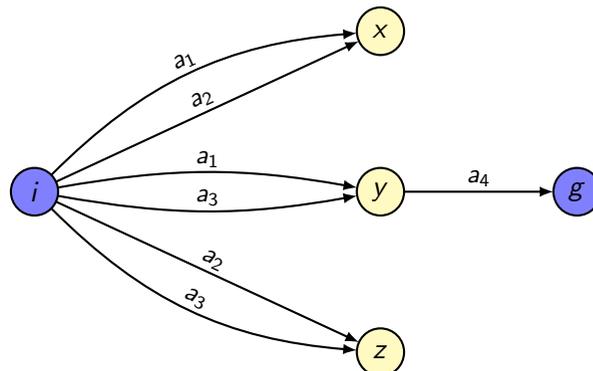with annotated edges.

- ▶ vertices: the variables V
- ▶ edges: $P(a) \xrightarrow{a} e$ for every action a, every effect $e \in add(a)$

Example: Justification Graph

Example

pcf P: $P(a_1) = P(a_2) = P(a_3) = i$, $P(a_4) = y$

$a_1 = i \xrightarrow{3} x, y$
$a_2 = i \xrightarrow{4} x, z$
$a_3 = i \xrightarrow{5} y, z$
$a_4 = x, y, z \xrightarrow{0} g$

Cuts

Definition (cut)

A cut in a justification graph is a subset C of its edges
such that all paths from i to g contain an edge in C.
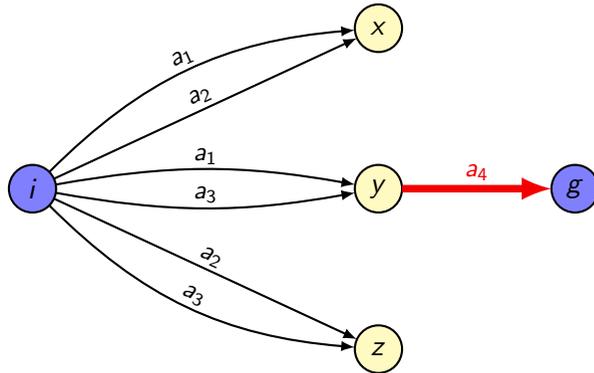
Proposition (cuts are landmarks)

Let C be a cut in a justification graph for an arbitrary pcf.

Then the edge annotations for C form a landmark.

Example: Cuts in Justification Graphs

Example

landmark $A = \{a_4\}$ (cost $= 0$)

$a_1 = i \xrightarrow{3} x, y$
$a_2 = i \xrightarrow{4} x, z$
$a_3 = i \xrightarrow{5} y, z$
$a_4 = x, y, z \xrightarrow{0} g$

Example: Cuts in Justification Graphs

Example

landmark $B = \{a_1, a_2\}$ (cost $= 3$)

$a_1 = i \xrightarrow{3} x, y$
$a_2 = i \xrightarrow{4} x, z$
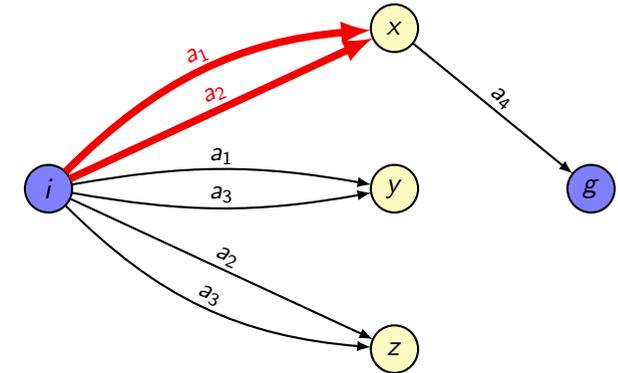$a_3 = i \xrightarrow{5} y, z$
$a_4 = x, y, z \xrightarrow{0} g$

Example: Cuts in Justification Graphs

Example

landmark $C = \{a_1, a_3\}$ (cost $= 3$)

$a_1 = i \xrightarrow{3} x, y$
$a_2 = i \xrightarrow{4} x, z$
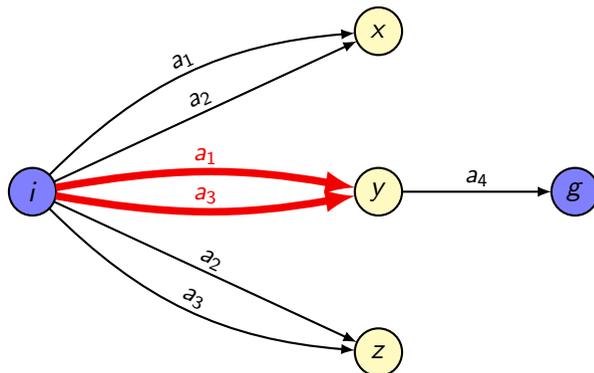$a_3 = i \xrightarrow{5} y, z$
$a_4 = x, y, z \xrightarrow{0} g$

Example: Cuts in Justification Graphs

Example

landmark $D = \{a_2, a_3\}$ (cost $= 4$)

$a_1 = i \xrightarrow{3} x, y$
$a_2 = i \xrightarrow{4} x, z$
$a_3 = i \xrightarrow{5} y, z$
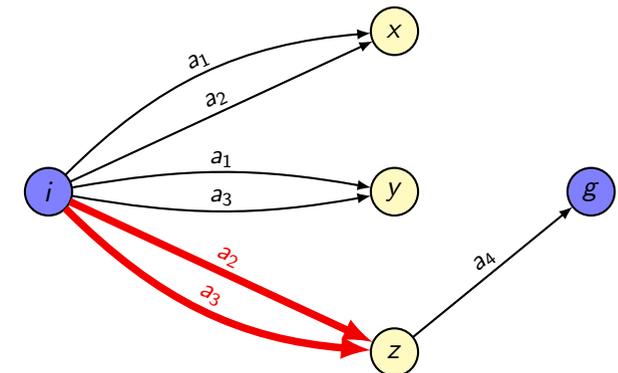$a_4 = x, y, z \xrightarrow{0} g$

Power of Cuts in Justification Graphs

▶ Which landmarks can be computed with the cut method?

▶ all interesting ones!

> **Proposition (perfect hitting set heuristics)**
> Let $\mathcal{L}$ be the set of all "cut landmarks" of a given planning task.
> Then $h^{\mathrm{MHS}}(I) = h^+(I)$ for $\mathcal{L}$.

⤳ hitting set heuristic for $\mathcal{L}$ is perfect.

proof idea:

▶ Show 1:1 correspondence of hitting sets H for $\mathcal{L}$ and plans,
i.e., each hitting set for $\mathcal{L}$ corresponds to a plan,
and vice versa.

39.2 The LM-Cut Heuristic

LM-Cut Heuristic: Motivation

▶ In general, there are exponentially many pcfs, hence
computing all relevant landmarks is not tractable.

▶ The LM-cut heuristic is a method that chooses pcfs
and computes cuts in a goal-oriented way.

▶ A cost partitioning is computed as a side effect
and is usually not optimal.

▶ However, the cost partitioning can be computed efficiently
and is optimal for planning tasks with uniform costs
(i.e., $cost(a) = 1$ for all actions).

⤳ currently one of the best admissible planning heuristics

LM-Cut Heuristic

> **$h^{\mathrm{LM\text{-}cut}}$: Helmert & Domshlak (2009)**
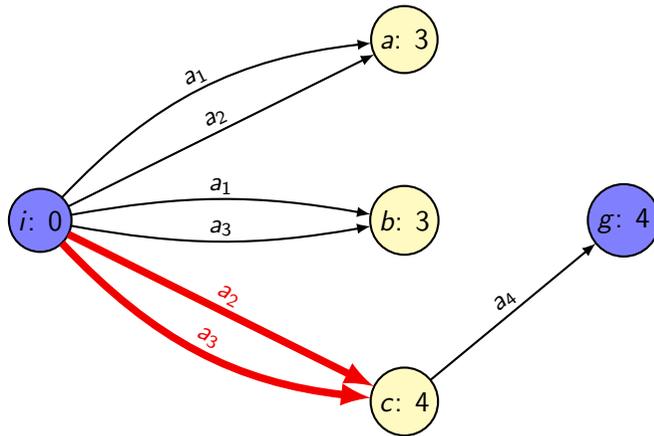> Initialize $h^{\mathrm{LM\text{-}cut}}(I) := 0$. Then iterate:
> 1. Compute $h^{\max}$ values of the variables. Stop if $h^{\max}(g) = 0$.
> 2. Compute justification graph G for a P that chooses
>   preconditions with maximal $h^{\max}$ value.
> 3. Determine the goal zone V_g of G that consists of all nodes
>   that have a zero-cost path to g.
> 4. Compute the cut L that contains the labels of all edges
> $\langle v, o, v' \rangle$ such that $v \notin V_g$, $v' \in V_g$ and v can be reached
>   from i without traversing a node in V_g.
>   It is guaranteed that $cost(L) > 0$.
> 5. Increase $h^{\mathrm{LM\text{-}cut}}(I)$ by $cost(L)$.
> 6. Decrease $cost(o)$ by $cost(L)$ for all $o \in L$.

Slide 1 (17/23)

Example: Computation of LM-Cut

Example

round 1: $P(a_4) = c \rightsquigarrow L = \{a_2, a_3\}$ [4]

$a_1 = i \xrightarrow{3} a, b$
$a_2 = i \xrightarrow{4} a, c$
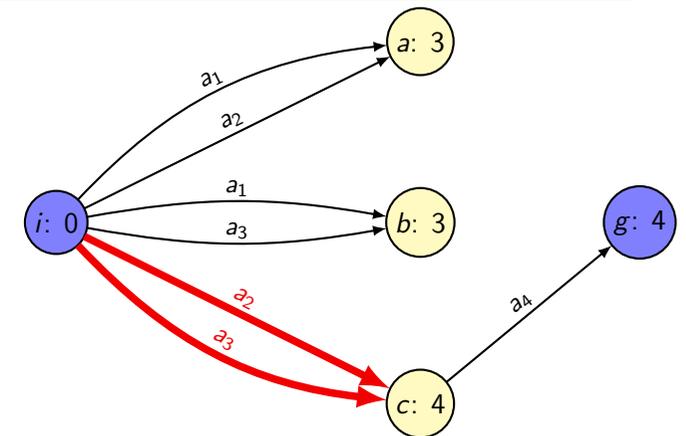$a_3 = i \xrightarrow{5} b, c$
$a_4 = a, b, c \xrightarrow{0} g$

(graph with nodes $i{:}\,0$, $a{:}\,3$, $b{:}\,3$, $c{:}\,4$, $g{:}\,4$; edges a_1, a_2, a_3, a_4)

Slide 2 (18/23)

Example: Computation of LM-Cut

Example

round 1: $P(a_4) = c \rightsquigarrow L = \{a_2, a_3\}$ [4] $\rightsquigarrow h^{\text{LM-cut}}(I) := 4$

$a_1 = i \xrightarrow{3} a, b$
$a_2 = i \xrightarrow{0} a, c$
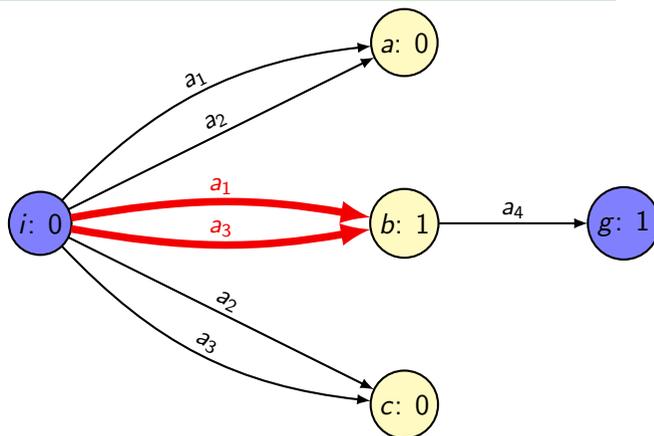$a_3 = i \xrightarrow{1} b, c$
$a_4 = a, b, c \xrightarrow{0} g$

(graph with nodes $i{:}\,0$, $a{:}\,3$, $b{:}\,3$, $c{:}\,4$, $g{:}\,4$; edges a_1, a_2, a_3, a_4)

Slide 3 (19/23)

Example: Computation of LM-Cut

Example

round 2: $P(a_4) = b \rightsquigarrow L = \{a_1, a_3\}$ [1]

$a_1 = i \xrightarrow{3} a, b$
$a_2 = i \xrightarrow{0} a, c$
$a_3 = i \xrightarrow{1} b, c$
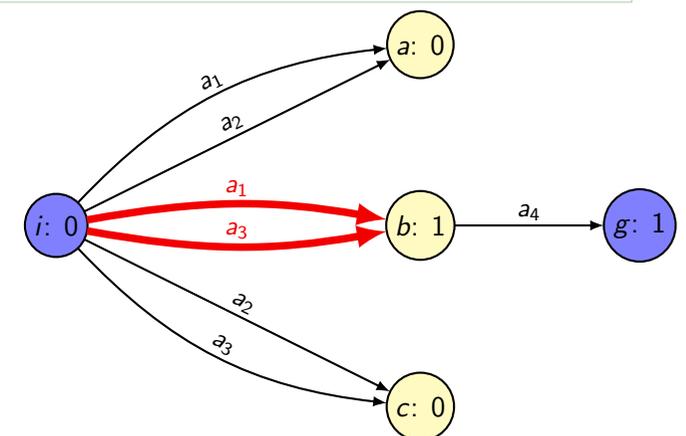$a_4 = a, b, c \xrightarrow{0} g$

(graph with nodes $i{:}\,0$, $a{:}\,0$, $b{:}\,1$, $c{:}\,0$, $g{:}\,1$; edges a_1, a_2, a_3, a_4)

Slide 4 (20/23)

Example: Computation of LM-Cut

Example

round 2: $P(a_4) = b \rightsquigarrow L = \{a_1, a_3\}$ [1] $\rightsquigarrow h^{\text{LM-cut}}(I) := 4 + 1 = 5$

$a_1 = i \xrightarrow{2} a, b$
$a_2 = i \xrightarrow{0} a, c$
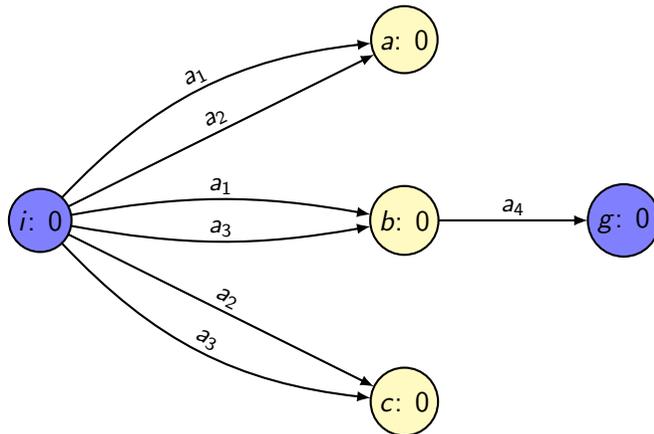$a_3 = i \xrightarrow{0} b, c$
$a_4 = a, b, c \xrightarrow{0} g$

(graph with nodes $i{:}\,0$, $a{:}\,0$, $b{:}\,1$, $c{:}\,0$, $g{:}\,1$; edges a_1, a_2, a_3, a_4)

Example: Computation of LM-Cut

Example

round 3: $h^{\max}(g) = 0 \rightsquigarrow$ done! $\rightsquigarrow h^{\text{LM-cut}}(I) = 5$

$a_1 = i \xrightarrow{2} a, b$
$a_2 = i \xrightarrow{0} a, c$
$a_3 = i \xrightarrow{0} b, c$
$a_4 = a, b, c \xrightarrow{0} g$

39.3 Summary

Summary

▶ Cuts in justification graphs
  are a general method to find landmarks.
▶ Hitting sets over all cut landmarks yield a perfect heuristic
  for delete-free planning tasks.
▶ The LM-cut heuristic is an admissible heuristic
  based on these ideas.