

Foundations of Artificial Intelligence

39. Automated Planning: Landmark Heuristics

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Automated Planning: Overview

Chapter overview: automated planning

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

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

landmark examples:

- ▶ $A = \{a_4\}$ (cost = 0)
- ▶ $B = \{a_1, a_2\}$ (cost = 3)
- ▶ $C = \{a_1, a_3\}$ (cost = 3)
- ▶ $D = \{a_2, a_3\}$ (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 labeled arcs.

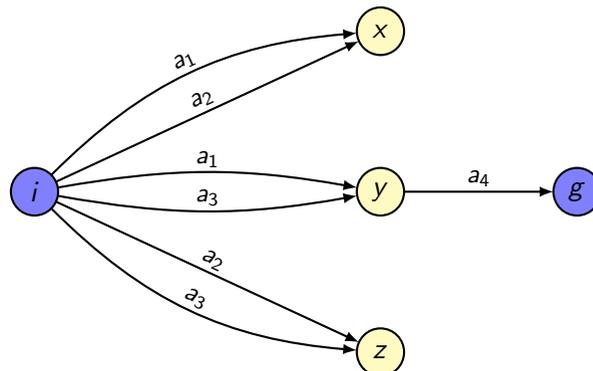
- ▶ **vertices**: the variables V
- ▶ **arcs**: $P(a) \xrightarrow{a} e$ for every action a , every effect $e \in \text{add}(a)$

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 arcs such that all paths from i to g contain an arc in C .

Proposition (cuts are landmarks)

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

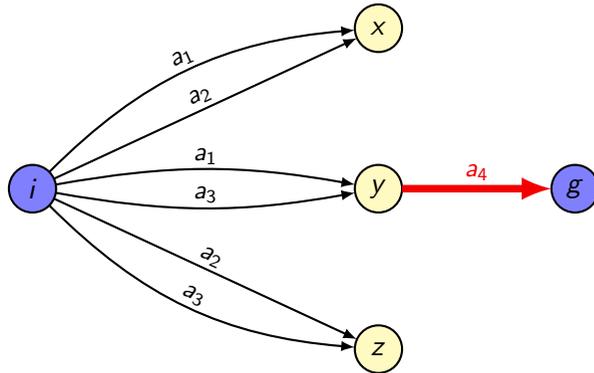
Then the arc labels for C form a landmark.

Example: Cuts in Justification Graphs

Example

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

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

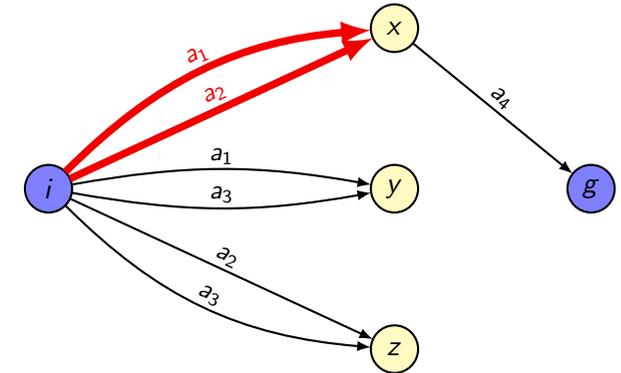


Example: Cuts in Justification Graphs

Example

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

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

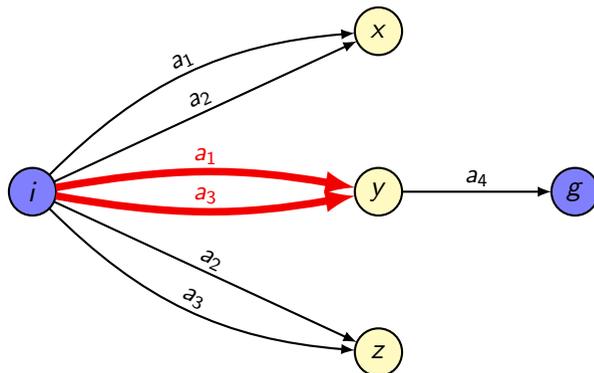


Example: Cuts in Justification Graphs

Example

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

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

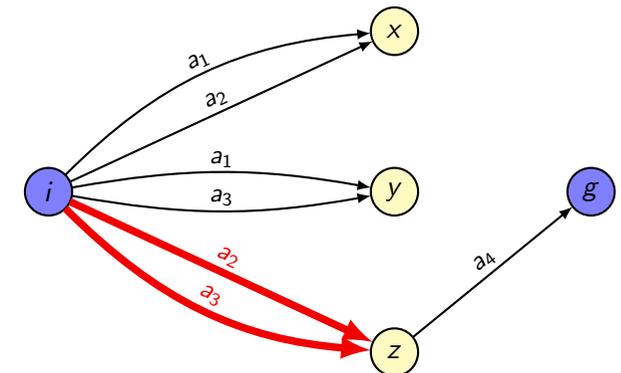


Example: Cuts in Justification Graphs

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 $h^{\text{MHS}}(I) = h^+(I)$ 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., $\text{cost}(a) = 1$ for all actions).

↔ one of the best admissible planning heuristics

LM-Cut Heuristic

$h^{\text{LM-cut}}$: Helmert & Domshlak (2009)

Initialize $h^{\text{LM-cut}}(I) := 0$. Then iterate:

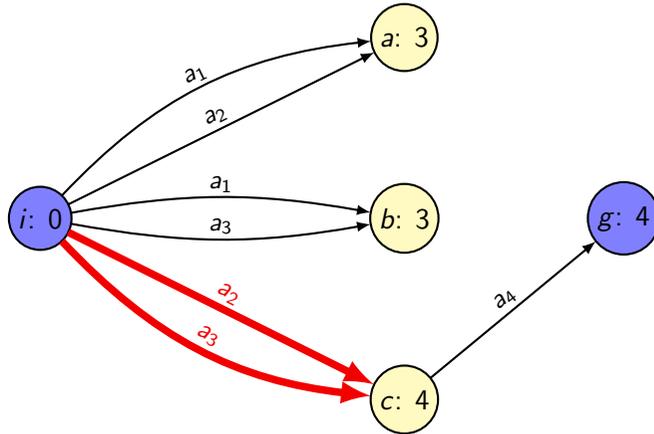
- 1 Compute **h^{max} values** of the variables. Stop if $h^{\text{max}}(g) = 0$.
- 2 Compute justification graph G for a pcf that chooses preconditions with **maximal h^{max} value**. (Requires a tie-breaking policy.)
- 3 Determine the **goal zone** V_g of G that consists of all vertices that have a zero-cost path to g .
- 4 Compute the cut L that contains the labels of all arcs $v \xrightarrow{a} v'$ such that $v \notin V_g$, $v' \in V_g$ and v can be reached from i without traversing a vertex in V_g .
It is guaranteed that **$\text{cost}(L) > 0$** .
- 5 **Increase $h^{\text{LM-cut}}(I)$ by $\text{cost}(L)$** .
- 6 **Decrease $\text{cost}(a)$ by $\text{cost}(L)$ for all $a \in L$** .

Example: Computation of LM-Cut

Example

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

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

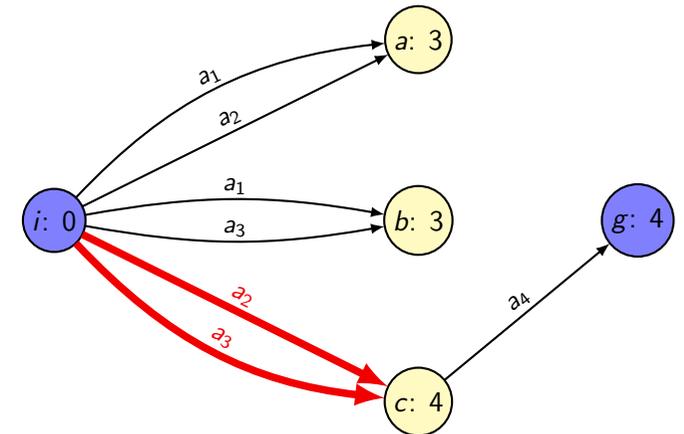


Example: Computation of LM-Cut

Example

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

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

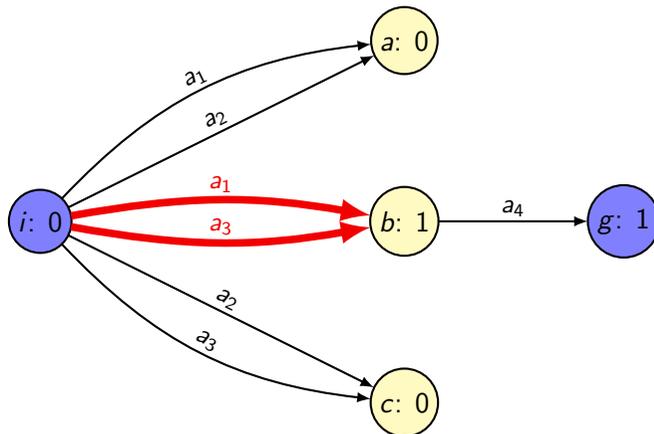


Example: Computation of LM-Cut

Example

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

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

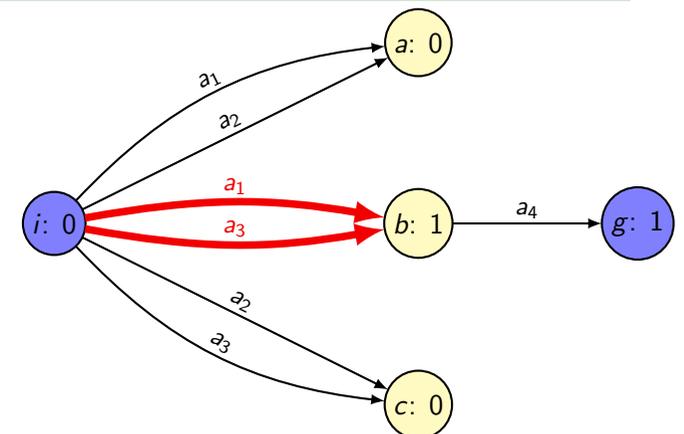


Example: Computation of LM-Cut

Example

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

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

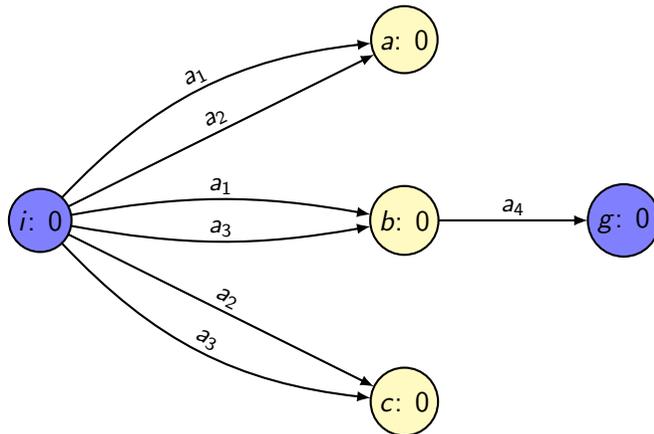


Example: Computation of LM-Cut

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.