

Foundations of Artificial Intelligence

39. Automated Planning: Landmark Heuristics

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Automated Planning: Overview

Chapter overview: automated planning

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- 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:

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

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)

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.

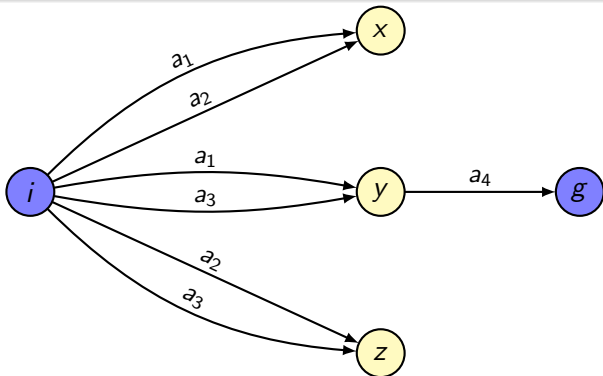
- **vertices**: the variables V
- **edges**: $P(a) \xrightarrow{a} e$ for every action a , every effect $e \in \text{add}(a)$

Example: Justification Graph

Example

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

$a_1 = i \xrightarrow{3} x, y$
 $a_2 = i \xrightarrow{4} x, z$
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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 .

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Proposition (cuts are landmarks)

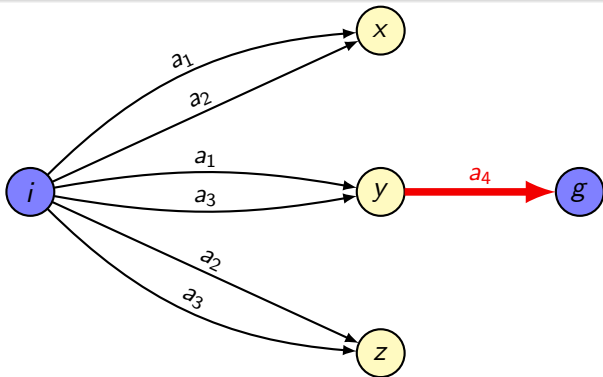
*Let C be a cut in a justification graph for an arbitrary pcf.
Then the edge annotations for C form a landmark.*

Example: Cuts in Justification Graphs

Example

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

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

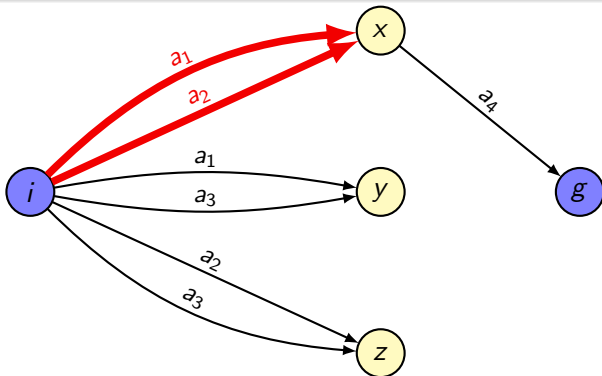


Example: Cuts in Justification Graphs

Example

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

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

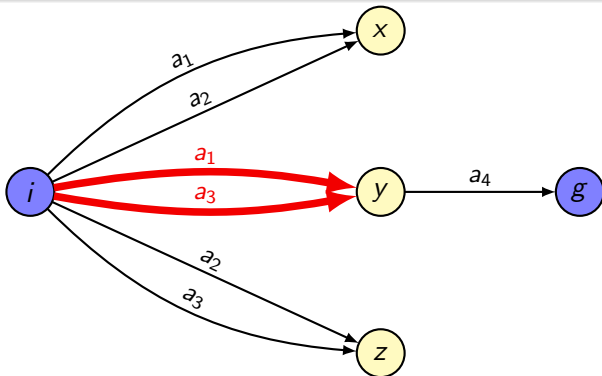


Example: Cuts in Justification Graphs

Example

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

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

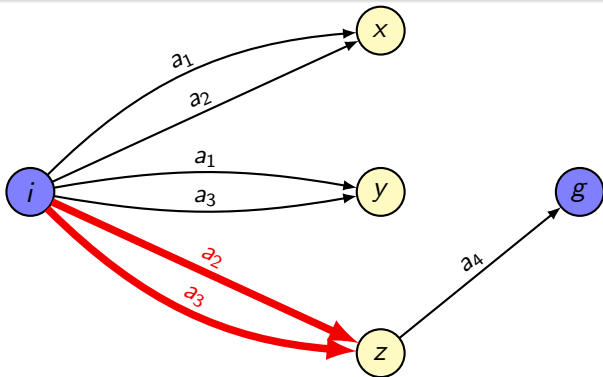


Example: Cuts in Justification Graphs

Example

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

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



Power of Cuts in Justification Graphs

- Which landmarks can be computed with the cut method?

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**.

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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.

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

The LM-Cut Heuristic

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

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

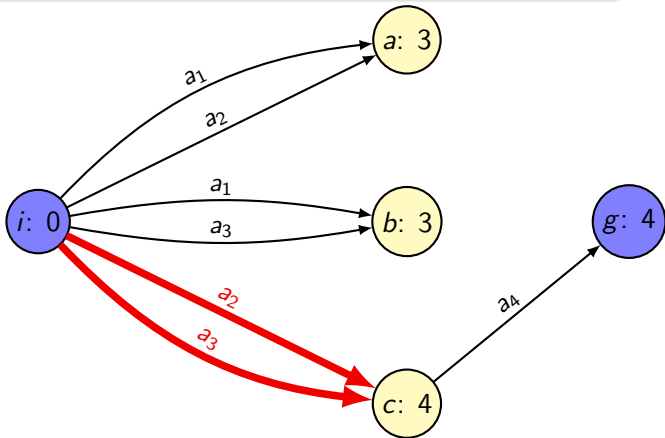
- 1 Compute h^{max} values of the variables.
Stop if $h^{\text{max}}(g) = 0$.
- 2 Let P be a pcf that chooses preconditions with maximal h^{max} value. (Requires a tie-breaking policy.)
- 3 Compute the justification graph for P .
- 4 Compute a cut which guarantees $\text{cost}(L) > 0$ for the corresponding landmark L .
(We omit the details of how this is done.)
- 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]

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

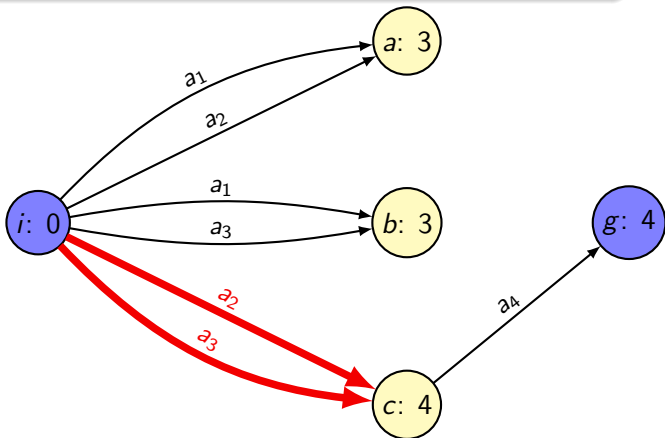


Example: Computation of LM-Cut

Example

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

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

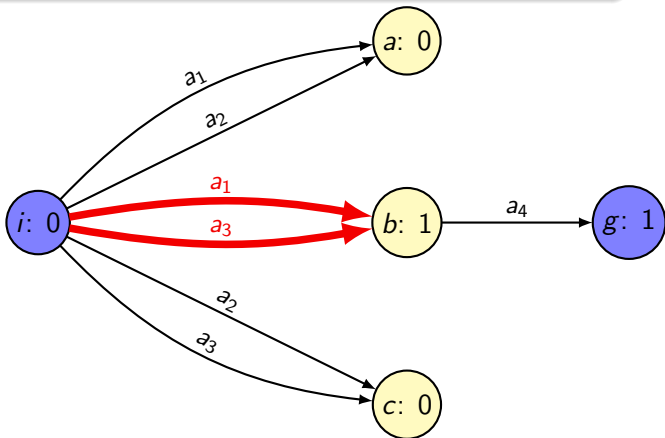


Example: Computation of LM-Cut

Example

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

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

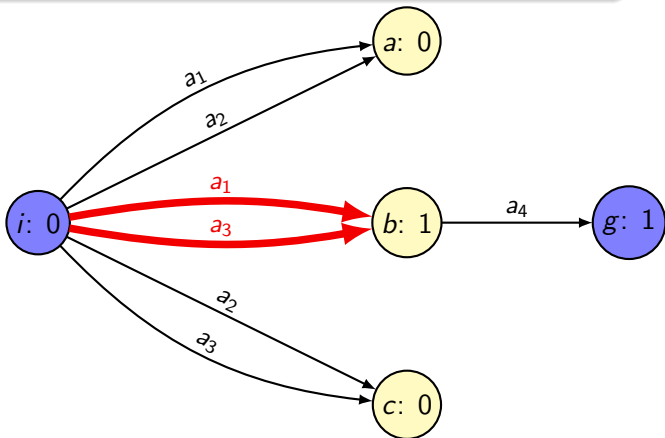


Example: Computation of LM-Cut

Example

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

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

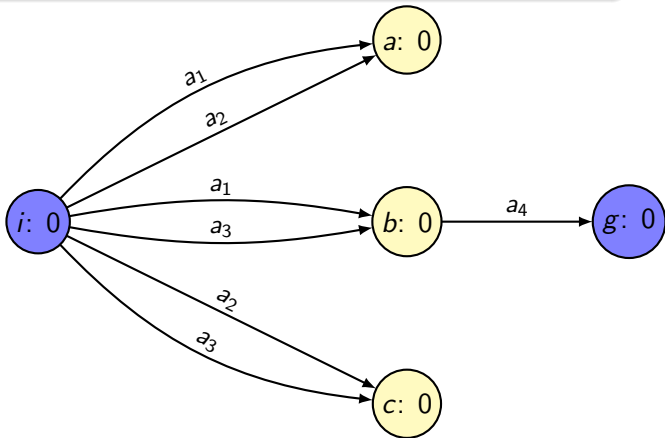


Example: Computation of LM-Cut

Example

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

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



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.