

Foundations of Artificial Intelligence

39. Automated Planning: Landmark Heuristics

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Automated Planning: Overview

Chapter overview: 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:

- $a_1 = \langle i \rightarrow x, y \rangle_3$
- $a_2 = \langle i \rightarrow x, z \rangle_4$
- $a_3 = \langle i \rightarrow y, z \rangle_5$
- $a_4 = \langle x, y, z \rightarrow g \rangle_0$

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 $e \in add(a)$

Example: Justification Graph

Example

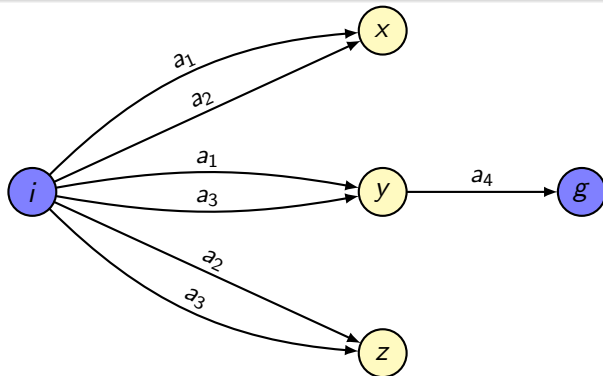
pcf P : $P(a_1) = P(a_2) = P(a_3) = i$, $P(a_4) = y$

$$a_1 = \langle i \rightarrow x, y \rangle_3$$

$$a_2 = \langle i \rightarrow x, z \rangle_4$$

$$a_3 = \langle i \rightarrow y, z \rangle_5$$

$$a_4 = \langle x, y, z \rightarrow g \rangle_0$$



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 .

Cuts

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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

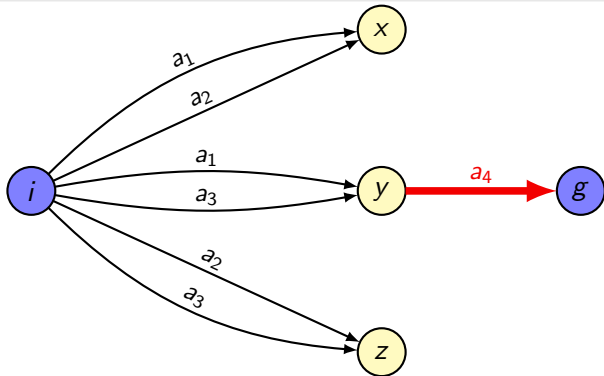
landmark $A = \{a_4\}$ (cost = 0)

$$a_1 = \langle i \rightarrow x, y \rangle_3$$

$$a_2 = \langle i \rightarrow x, z \rangle_4$$

$$a_3 = \langle i \rightarrow y, z \rangle_5$$

$$a_4 = \langle x, y, z \rightarrow g \rangle_0$$



Example: Cuts in Justification Graphs

Example

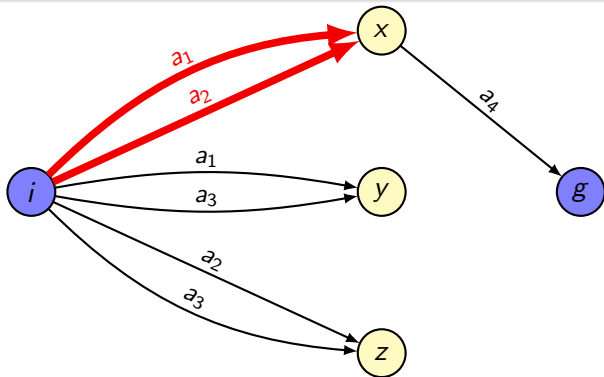
landmark $B = \{a_1, a_2\}$ (cost = 3)

$$a_1 = \langle i \rightarrow x, y \rangle_3$$

$$a_2 = \langle i \rightarrow x, z \rangle_4$$

$$a_3 = \langle i \rightarrow y, z \rangle_5$$

$$a_4 = \langle x, y, z \rightarrow g \rangle_0$$



Example: Cuts in Justification Graphs

Example

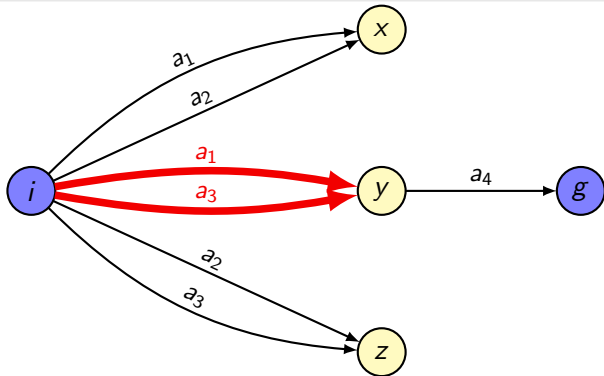
landmark $C = \{a_1, a_3\}$ (cost = 3)

$$a_1 = \langle i \rightarrow x, y \rangle_3$$

$$a_2 = \langle i \rightarrow x, z \rangle_4$$

$$a_3 = \langle i \rightarrow y, z \rangle_5$$

$$a_4 = \langle x, y, z \rightarrow g \rangle_0$$



Example: Cuts in Justification Graphs

Example

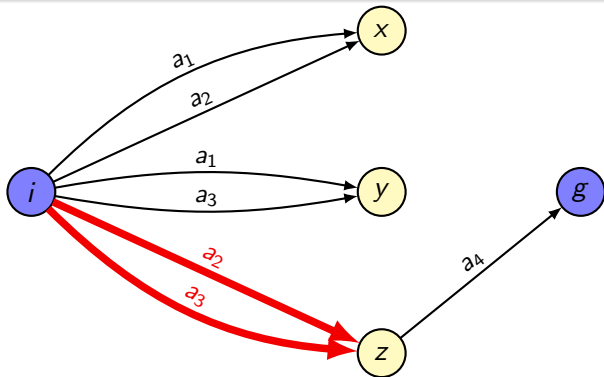
landmark $D = \{a_2, a_3\}$ (cost = 4)

$$a_1 = \langle i \rightarrow x, y \rangle_3$$

$$a_2 = \langle i \rightarrow x, z \rangle_4$$

$$a_3 = \langle i \rightarrow y, z \rangle_5$$

$$a_4 = \langle x, y, z \rightarrow g \rangle_0$$



Power of Cuts in Justification Graphs

- Which landmarks can be computed with the cut method?

Power of Cuts in Justification Graphs

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- **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 $\mathcal{L}$.

$\rightsquigarrow$ 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.
- On the other hand, it can be computed efficiently and is optimal for planning tasks with uniform costs (i.e., $cost(a) = 1$ for all actions).

~> currently the best admissible planning heuristic

The LM-Cut Heuristic

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

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

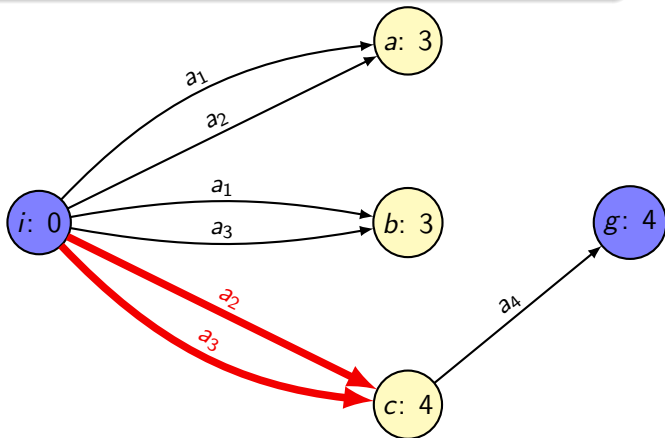
- 1 Compute h^{max} values of the variables.
Stop if $h^{\text{max}}(g) = 0$.
- 2 Let P be a pcf that chooses preconditions with maximal h^{max} value.
- 3 Compute the justification graph for P .
- 4 Compute a cut which guarantees $\text{cost}(L) > 0$ for the corresponding landmark L .
- 5 Increase $h^{\text{LM-cut}}(I)$ 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]

$a_1 = \langle i \rightarrow a, b \rangle_3$
 $a_2 = \langle i \rightarrow a, c \rangle_4$
 $a_3 = \langle i \rightarrow b, c \rangle_5$
 $a_4 = \langle a, b, c \rightarrow g \rangle_0$

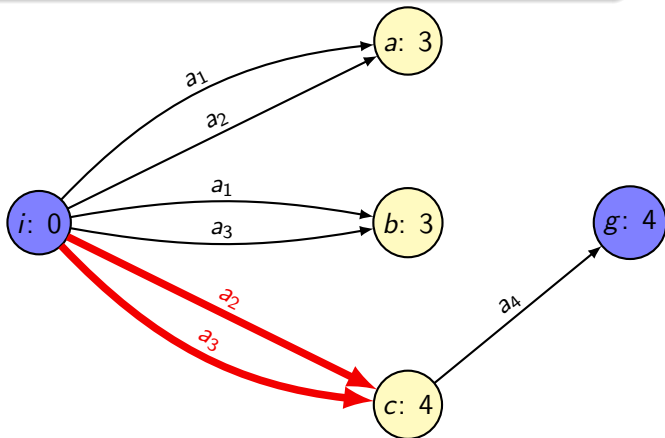


Example: Computation of LM-Cut

Example

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

$a_1 = \langle i \rightarrow a, b \rangle_3$
 $a_2 = \langle i \rightarrow a, c \rangle_0$
 $a_3 = \langle i \rightarrow b, c \rangle_1$
 $a_4 = \langle a, b, c \rightarrow g \rangle_0$

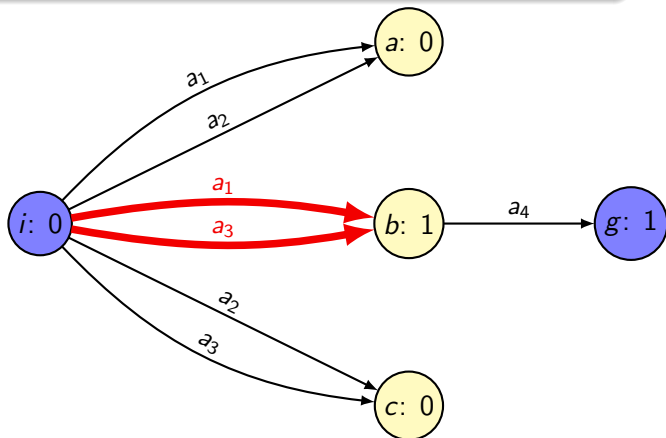


Example: Computation of LM-Cut

Example

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

$a_1 = \langle i \rightarrow a, b \rangle_3$
 $a_2 = \langle i \rightarrow a, c \rangle_0$
 $a_3 = \langle i \rightarrow b, c \rangle_1$
 $a_4 = \langle a, \textcolor{red}{b}, c \rightarrow g \rangle_0$

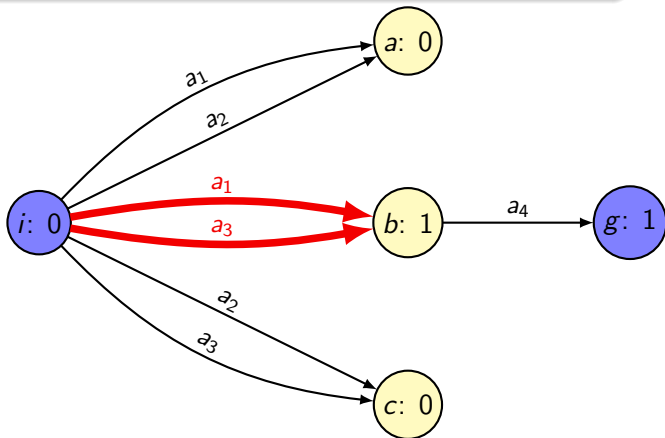


Example: Computation of LM-Cut

Example

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

$a_1 = \langle i \rightarrow a, b \rangle_2$
 $a_2 = \langle i \rightarrow a, c \rangle_0$
 $a_3 = \langle i \rightarrow b, c \rangle_0$
 $a_4 = \langle a, b, c \rightarrow g \rangle_0$

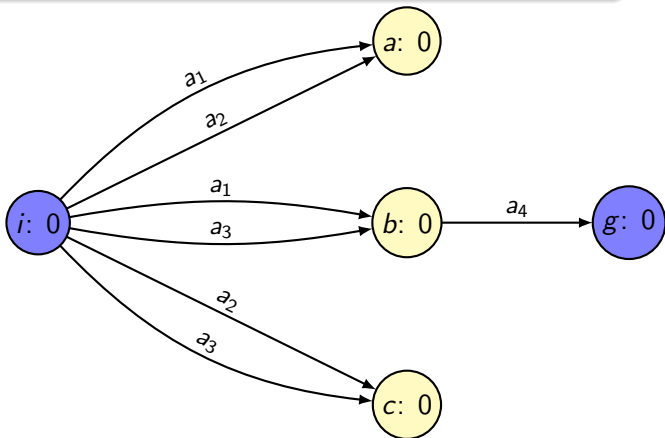


Example: Computation of LM-Cut

Example

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

$a_1 = \langle i \rightarrow a, b \rangle_2$
 $a_2 = \langle i \rightarrow a, c \rangle_0$
 $a_3 = \langle i \rightarrow b, c \rangle_0$
 $a_4 = \langle a, b, c \rightarrow g \rangle_0$



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.