Planning for Artificial Intelligence

Lukáš Chrpa

Landmarks and LM-Cut Heuristic

Landmarks

Landmarks

- In general, a **landmark** is a formula that must be true at some point for every plan
- Landmarks can be (partially) **ordered**
- A **fact landmark** is a fact (or atom) that must be true at some point for every plan
- An **action landmark** is an action that must occur in every plan
- A **disjunctive** fact (action) landmark stands for that at least one of the fact must be true (at least one action must occur) in every plan
- A **conjunctive** fact landmark stands for that all the facts must be true at the same time in every plan

Fact and Action Landmarks

- A fact landmark implies an action landmark if the action is the only one achieving it
- An action landmark implies fact landmarks (action's preconditions and effects)
- Deciding fact or action landmark in PSPACE-complete
  - The same as deciding whether a task without actions achieving the fact landmark, or an action standing for an action landmark, respectively, is solvable
- Subsets of fact or action landmarks can be identified easily

Landmark Orderings

- For landmarks p and q we define the following types of ordering
  - **Natural ordering** $p \rightarrow q$ iff p is true some time before q
  - **Greedy necessary ordering** $p \rightarrow_{gn} q$ iff p is true one step before q becomes true for the first time
  - **Necessary ordering** $p \rightarrow_{n} q$ iff p is always true one step before q becomes true
- Deciding all types of orderings is PSPACE-complete
- Again, some landmark orderings can be identified easily

Landmark Graph

- Let LG=(V,E) be a directed graph, where V are landmarks and $(v_i,v_j)\in E$ if $v_i \rightarrow v_j$ (natural ordering between landmarks v_i and v_j). LG is a **landmark graph**

- Note that landmark graphs are often partial (as we don't know all the landmarks as well as some of their orderings)

Towards (Fact) Landmark Discovery

- Let $\Pi=(P,A,I,G)$ be a planning task and $p \in P$ be a fact. We denote Π_{-p} a planning task, where $\Pi_{-p}=(P,A \setminus \{a \mid p \in add(a)\},I,G)$.

Theorem: p is a fact landmark iff Π_{-p} is unsolvable

- It also holds that if the (delete-)relaxed task Π^{+}_{-p} is unsolvable, then Π_{-p} is unsolvable
  - Let's find some (fact) landmarks by leveraging **delete-relaxation !**

Landmark Discovery by the Backchaining Method

- Let Π=(P,A,I,G) be a planning task, then

  1) for each **$p \in G$**, it is the case that **p** is a **fact landmark**

  2) if **p** is a **fact landmark** and $p \notin I$, then for each

  $q \in \bigcap_{a \in \{a' | a' \in A,\ p \in add(a')\}} pre(a)$ it is the case that **q** is a **fact landmark** and **$q \rightarrow_n p$**

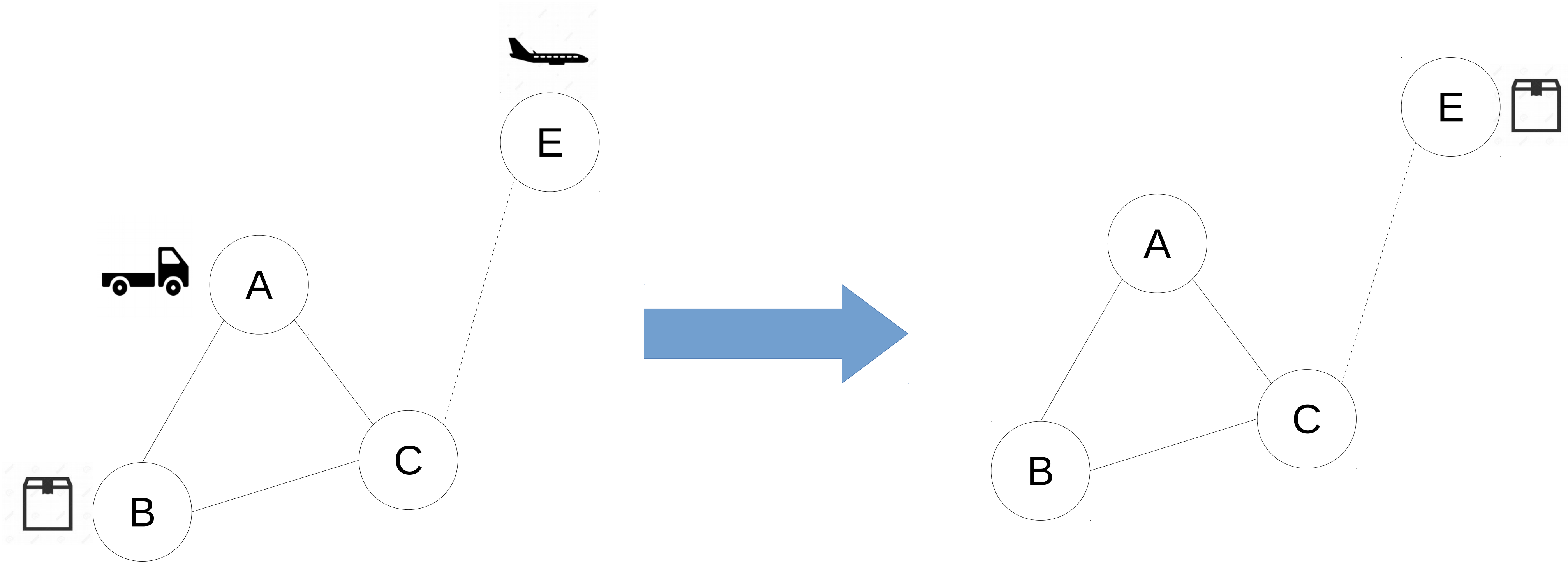
    - q is in preconditions of all actions achieving p

- Can we improve ?

Concerning First Achievers

- An action is a **first achiever** of a fact (or atom) if it achieves (adds) it for the first time
- For a planning task Π and a fact landmark p, we construct a **reachability graph** for Π_{-p} (p won't be reachable unless p∈I)
  - Any action applicable in this graph can possibly be applied before p becomes true → **possible first achievers**
  - The rule 2) of the backchaining method is enhanced by **considering only actions applicable in the last atom layer of the reachability graph**
    - we then get $q \rightarrow_{gn} p$
    - also, more fact landmarks can be identified, why ?

(Enhanced) Logistics Example



Initial state

Goal

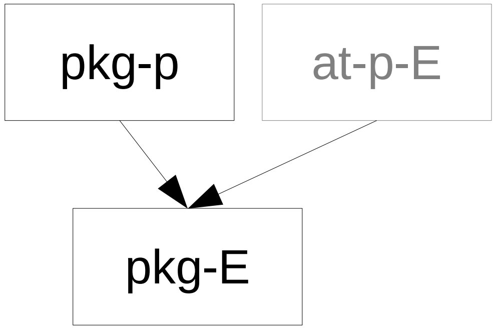
(Enhanced) Logistics Example – Landmark Identification

Goal fact: pkg-E

- achieved only by unload-p-E
- pkg-p, at-p-E are preconditions of unload-p-E and thus fact landmarks

Landmark: pkg-p

- achieved by load-p-C and load-p-E
- no shared preconditions …



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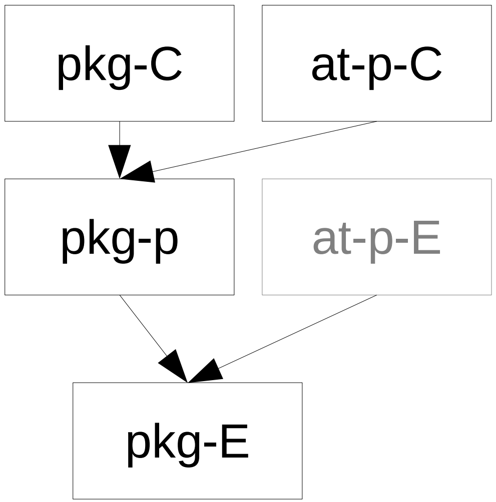
Landmark: pkg-p

- achieved by load-p-C and ~~load-p-E~~
- pkg-C, at-p-C are preconditions of load-p-C and thus fact landmarks



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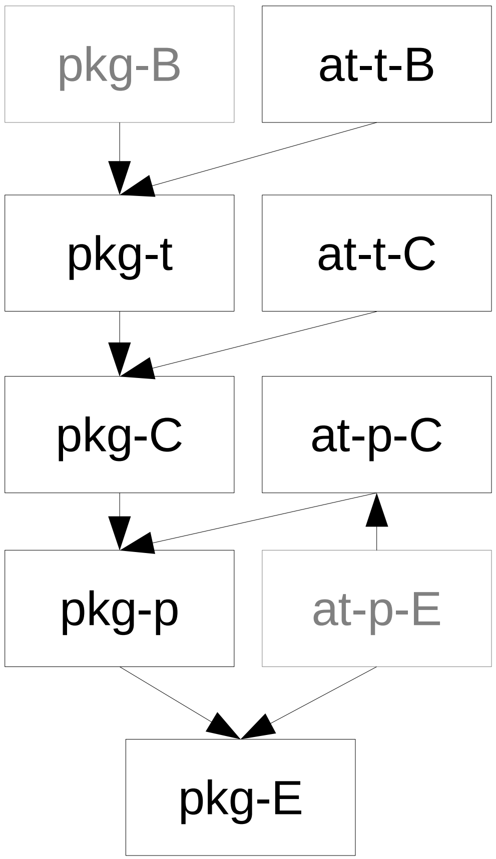


Domain Transition Graph

- A **Domain Transition Graph** of a variable v (DTG_v) represents how the value of v can change
- For a planning task (V,A,I,G) and a variable $v \in V$, DTG_v is defined as follows:
  - Nodes are D(v)
  - (d,d') is an edge iff
    - $d \neq d'$
    - $\exists a \in A$:$(v=d') \in eff(a)$ and $(v=d) \in pre(a)$, or a has no precondition on v

Landmark Discovery via DTG

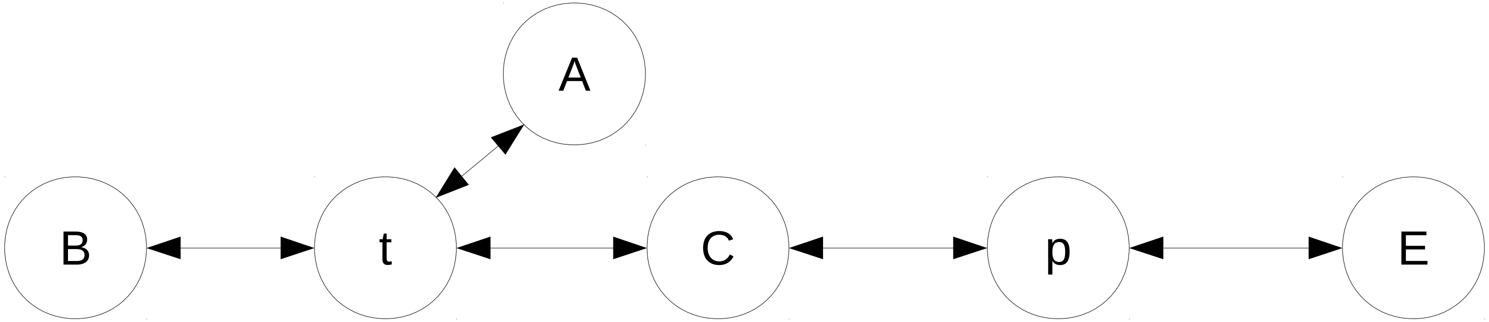
Having DTG_v, where:

- $I[v]=d_0$
- $v=d$ is a fact landmark
- d' is on every path from d_0 to d in DTG_v

then, **v=d’ is a fact landmark** and $(v=d') \rightarrow (v=d)$

(Enhanced) Logistics Example – Landmark Identification from DTG

Let's consider DTG_v (where v represent a position of the package)



(Enhanced) Logistics Example – Landmark Identification from DTG

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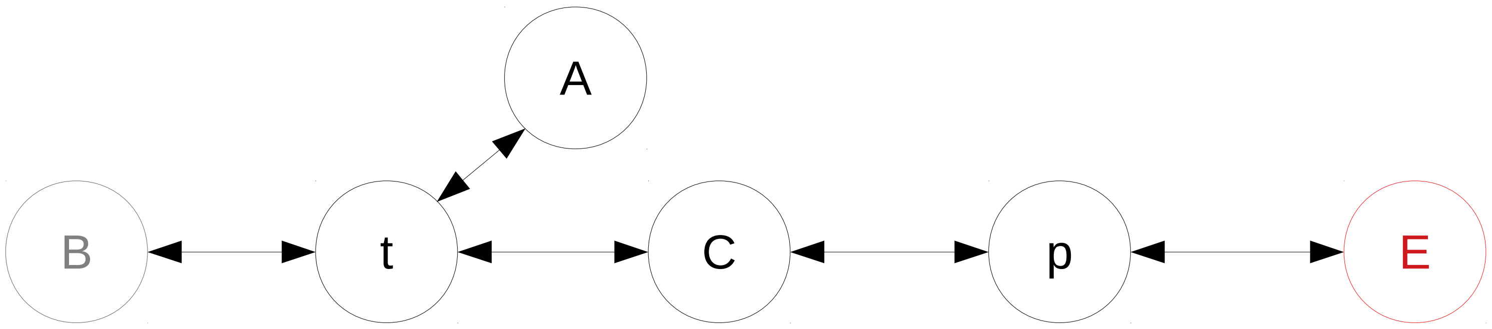

Initial state: v=B

Goal: v=E

(Enhanced) Logistics Example – Landmark Identification from DTG

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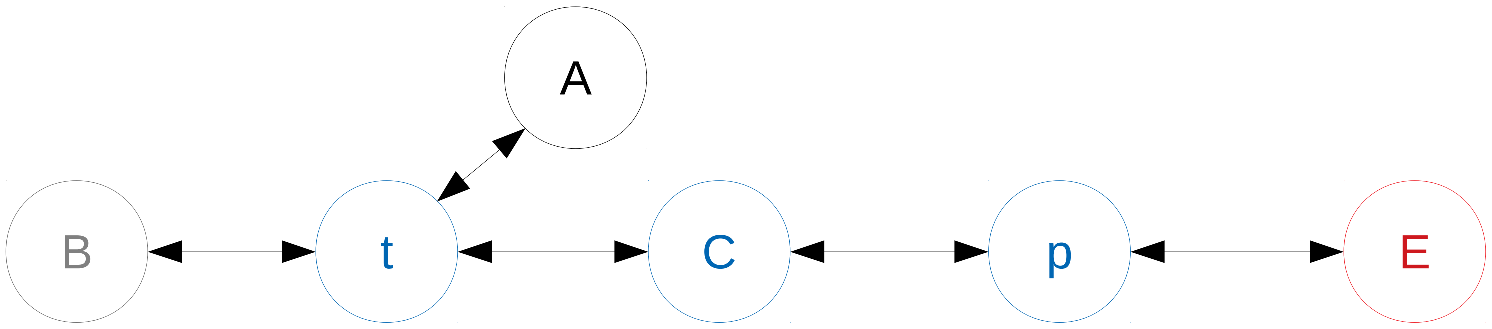

Initial state: v=B

Goal: v=E

Identified landmarks: v=t, v=C, v=p

How to use Landmarks ?

- Assume that we constructed a landmark graph in a preprocessing phase
- Intuitively, landmarks can be used as subgoals (according to their ordering)
  - works well in the Logistic example
  - recall Sussman anomaly (not so good)
  - prone to dead-ends
- For **heuristics**

Landmark Heuristics

Landmark Heuristic

- The landmarks that have yet to be achieved after reaching a state s via a sequence of actions π

$$L(s,\pi)=|(L \setminus Accepted(s,\pi)) \cup ReqAgain(s,\pi)|$$

- L is the set of **all discovered (fact) landmarks**
- $Accepted(s,\pi) \subseteq L$ is the set of **accepted** landmarks
- $ReqAgain(s,\pi) \subseteq Accepted(s,\pi)$ is the set of accepted landmarks that have to be **achieved again**

Accepted Landmarks

- A landmark p is accepted wrt s and π if
  - p becomes true in s
  - all predecessors of p (in the landmark graph) have been accepted
- One a landmark is accepted, it remains accepted

Required Again Landmarks

- A landmark p is required again wrt s and π if at least one of the following holds
  - p is false in s while being a goal (*false goal*)
  - p is false in s while being a greedy-necessary predecessors of some unaccepted landmark (*open-prerequisite*)

Multi-path Dependence

- Assume that a state s was achieved by two sequences of actions π_1 and π_2 such that
  - π_1 achieved a landmark p while π_2 did not
  - do we need to achieve p after s ?

Multi-path Dependence

- Assume that a state s was achieved by two sequences of actions π_1 and π_2 such that
  - π_1 achieved a landmark p while π_2 did not
  - do we need to achieve p after s ?
    - Yes, because p has to become true at some point in **all** plans (including those starting with π_2)

Landmark Heuristic

- Introduced in the well known LAMA planner (LAMA won IPC 2008 and 2011)
  - One component of LAMA
- **Inadmissible**
  - because a single action can achieve multiple landmarks
- Can be very informative in some domains
  - recall our Logistics example

LM-Cut Heuristic

i-g form of Relaxed Planning Tasks

- A relaxed planning task (P,A,i,g) is in **i-g form** if
  - $i, g \in P$
  - every action has at least one precondition
  - convention: an i-g form action will be represented in form $a = (pre(a) \rightarrow add(a))_{c(a)}$
- How "normal" relaxed planning tasks can be converted to i-g form ?

i-g form of Relaxed Planning Tasks

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  - $i,g \in P$
  - every action has at least one precondition
  - convention: an i-g form action will be represented in form $a=(pre(a) \rightarrow add(a))_{c(a)}$
- How “normal” relaxed planning tasks can be converted to i-g form ?
- Introducing **initial and goal actions**, i.e., $a_I=(i \rightarrow I)_0$ and $a_G=(G \rightarrow g)_0$
- Actions with empty preconditions will get i into their preconditions

Justification Graph

- A **precondition choice function (pcf)** $X: A \to P$ for a relaxed planning task in i-g form (P,A,i,g) maps each action to one of its preconditions, i.e., $X(a) \in pre(a)$ for each $a \in A$

- Let X be pcf for (P,A,i,g). The **justification graph** for X in the directed edge-labeled, graph $J=(V,E)$, where
  - $V=P$ (vertices are atoms from P)
  - For each $a \in A$ and $p \in add(a)$, $(X(a),a,p) \in E$

Example

$a_1=(i \rightarrow x,y)_3$

$a_2=(i \rightarrow x,z)_4$

$a_3=(i \rightarrow y,z)_5$

$a_4=(x,y,z \rightarrow g)_0$

Example – Justification Graph

$a_1=(i \rightarrow x,y)_3$

$a_2=(i \rightarrow x,z)_4$

$a_3=(i \rightarrow y,z)_5$

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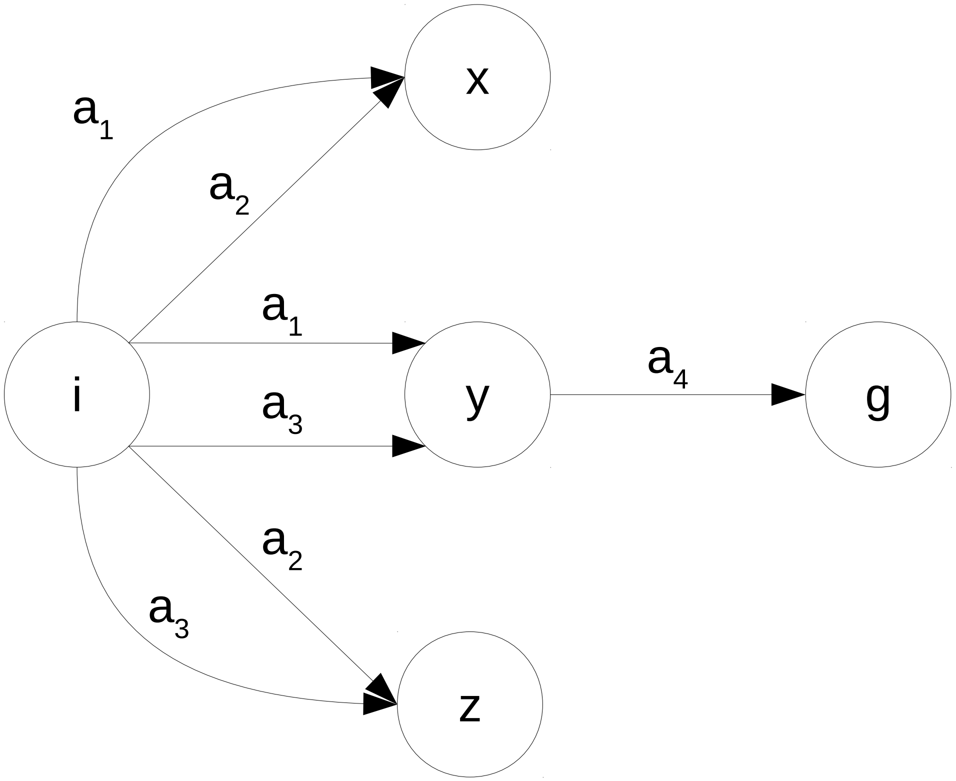
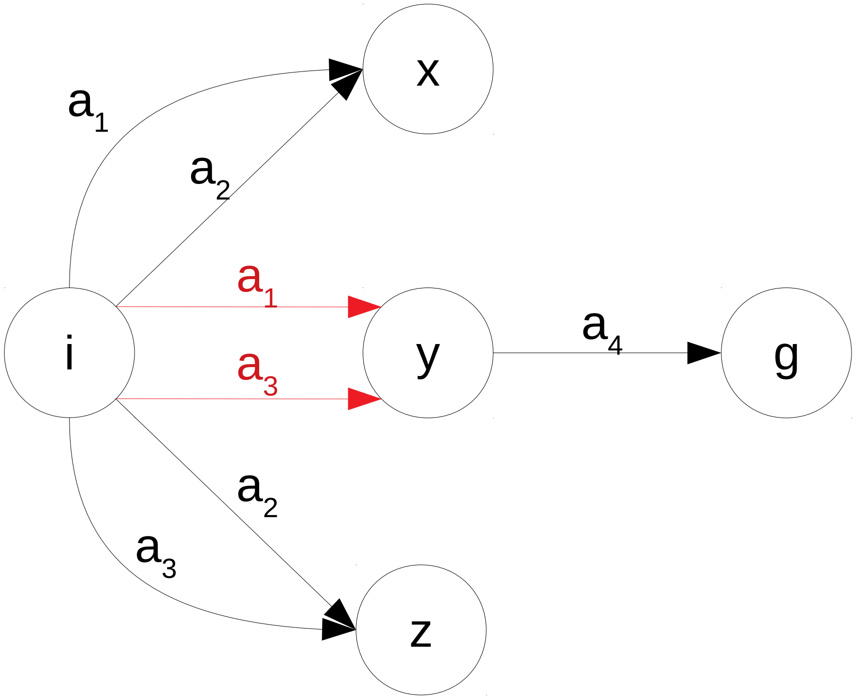
pcf in red



Cuts

- A **cut** in a justification graph is a subset C of its edges such that all paths from i to g contain an edge from C



Disjunctive Action Landmarks

Theorem: Let C be a cut in the justification graph for pcf X. The set of edge-labels from C in a **disjunctive action landmark**

- Note that the justification graph represents a simpler problem (only one action precondition is considered)
- Cuts are disjunctive action landmarks for the simplified problem and thus also for the original problem
- With all “cut landmarks” we can compute the value of h^+
  - However, the number of pcfs is exponential

LM-Cut

- Set $h^{LM\text{-}Cut}(I)=0$, then iterate

1) Compute $\mathbf{h^{max}}$ for all atoms. If $h^{max}(g)=0$, terminate

2) Let X be a pcf choosing preconditions with **maximal $\mathbf{h^{max}}$ value**

3) Compute the **justification graph** for X

4) Compute a **cut** L such that **cost(L)>0** (details on the next slide)

5) $h^{LM\text{-}Cut}(I) \mathrel{+}= cost(L)$

6) For each action $a \in L$, $c(a) \mathrel{-}= cost(L)$

LM-Cut

- Compute a cut L such that cost(L)>0 as follows
  - The **goal zone** V_g of the justification graph consists of all vertices having a path to g with all edges (on that path) having zero-cost actions
  - The cut contains all edges (v,a,v') such that $v \notin V_g$ and $v' \in V_g$ and v can be reached from I without traversing a goal zone node
  - $cost(L)=min_{a \in L} c(a)$

Example – Computing LM-cut

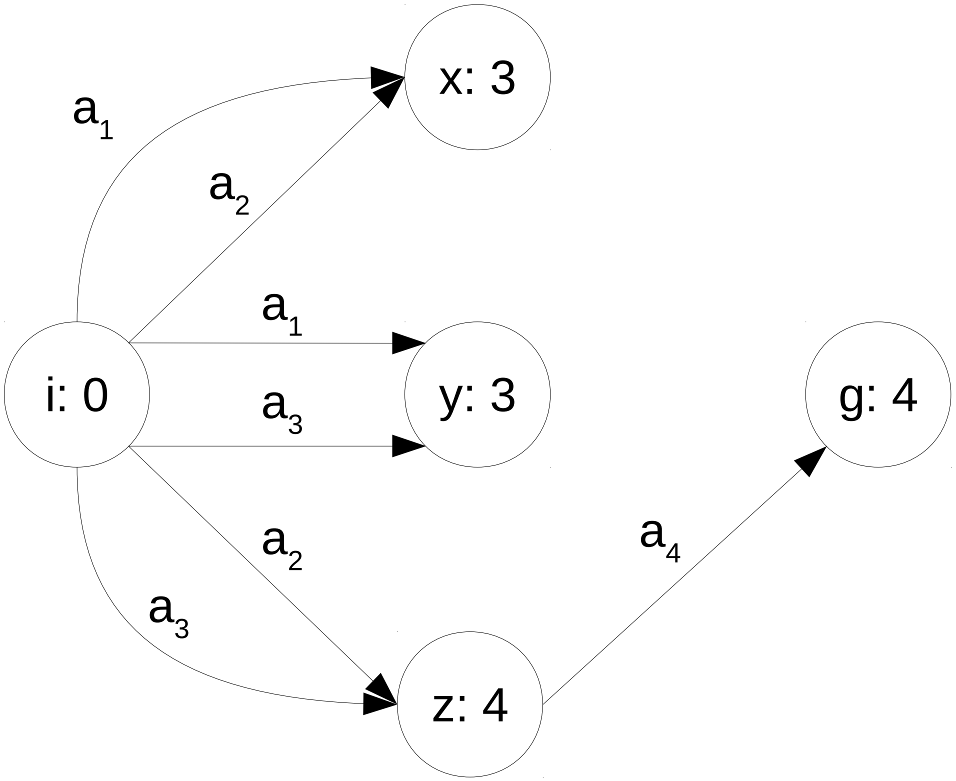
$a_1=(\textcolor{red}{i} \rightarrow x,y)_3$

$a_2=(\textcolor{red}{i} \rightarrow x,z)_4$

$a_3=(\textcolor{red}{i} \rightarrow y,z)_5$

$a_4=(x,y,\textcolor{red}{z} \rightarrow g)_0$

pcf in red



Example – Computing LM-cut

$a_1 = (i \rightarrow x, y)_3$

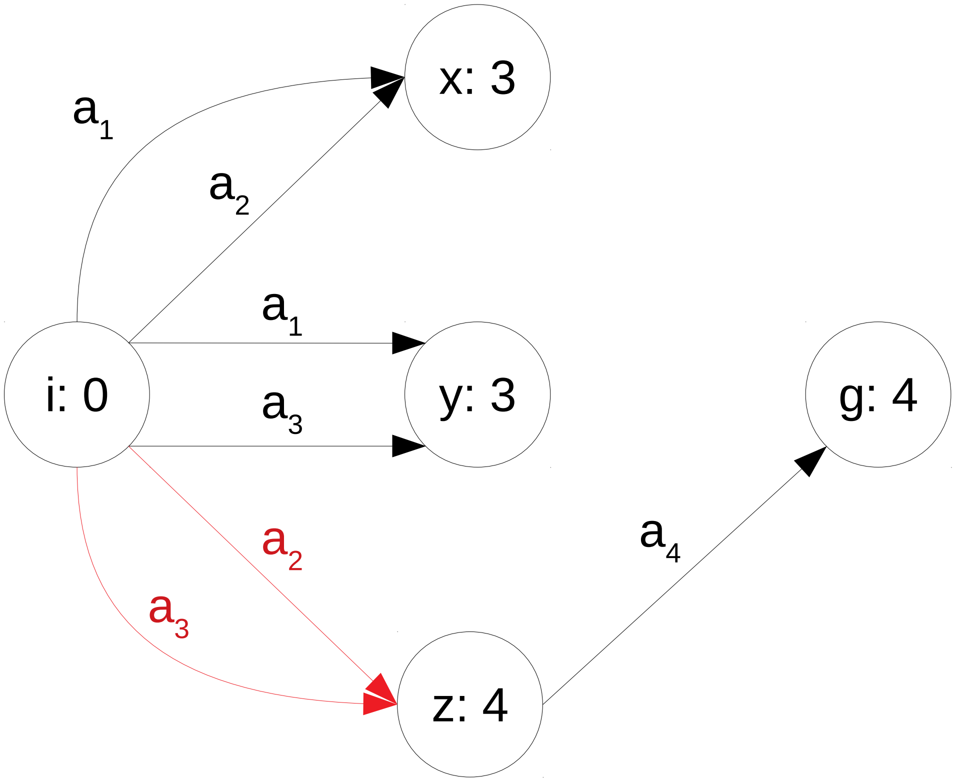
$a_2 = (i \rightarrow x, z)_4$

$a_3 = (i \rightarrow y, z)_5$

$a_4 = (x, y, z \rightarrow g)_0$

pcf in red

$L = \{a_2, a_3\}$
$cost(L) = 4$
$h^{LM\text{-}cut}(I) = 4$



Example – Computing LM-cut

$a_1 = (i \rightarrow x, y)_3$

$a_2 = (i \rightarrow x, z)_0$

$a_3 = (i \rightarrow y, z)_1$

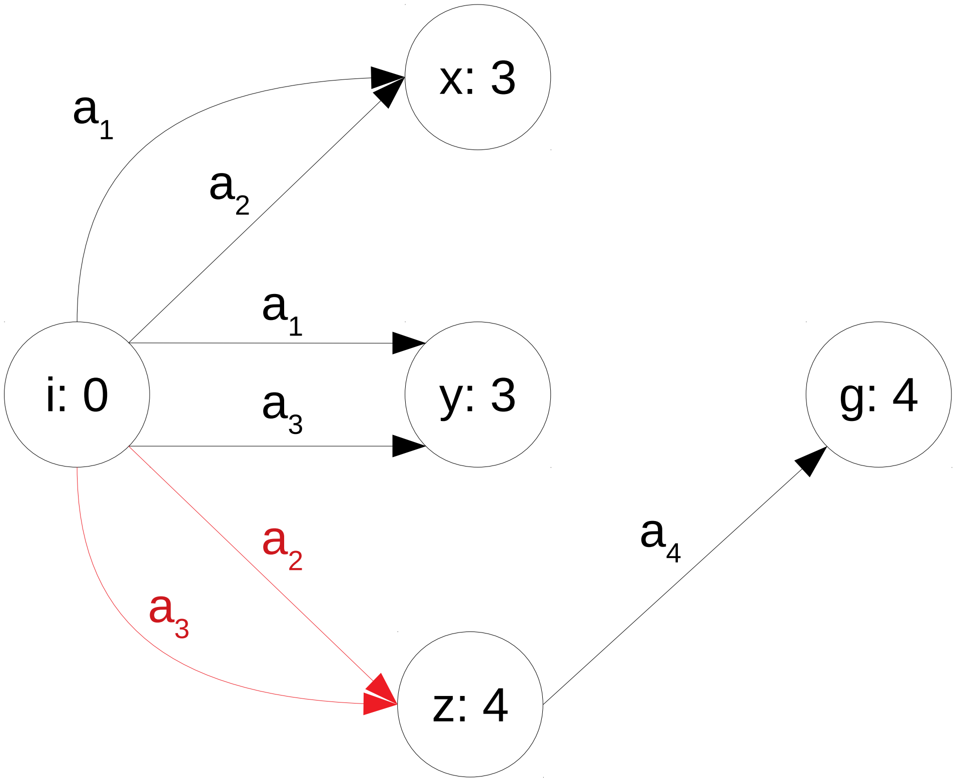
$a_4 = (x, y, z \rightarrow g)_0$

pcf in red

$L = \{a_2, a_3\}$

$cost(L) = 4$

$h^{LM\text{-}cut}(I) = 4$



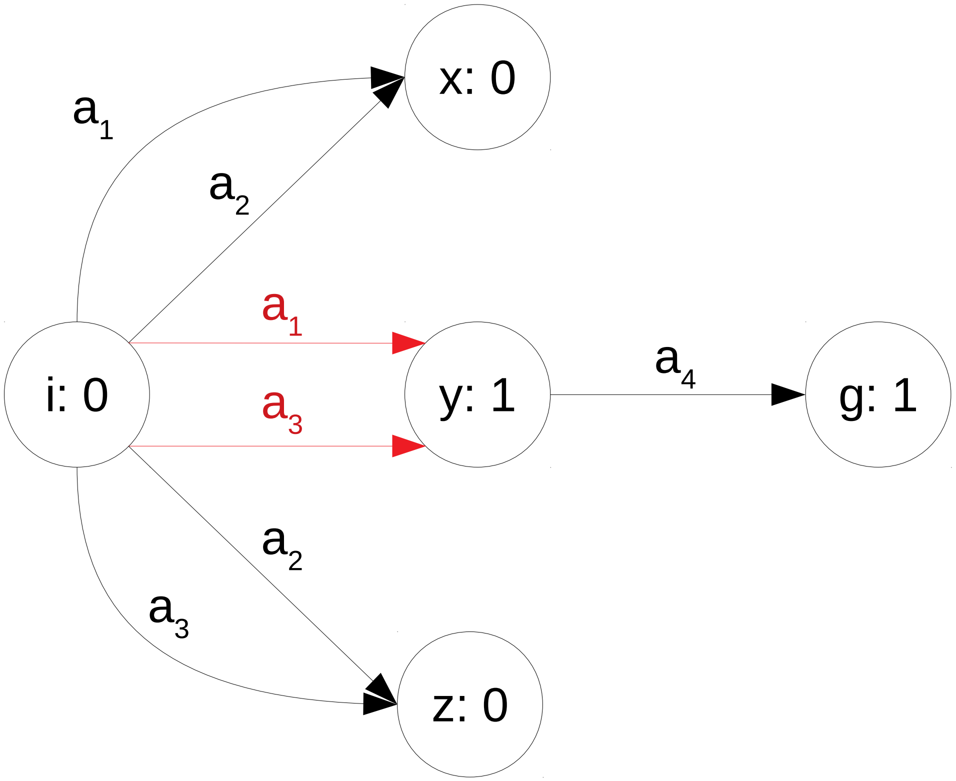
Example – Computing LM-cut

a_1=(i → x,y)$_3$

a_2=(i → x,z)$_0$

a_3=(i → y,z)$_1$

a_4=(x,y,z → g)$_0$



pcf in red

L={a_1,a_3}
cost(L)=1
$h^{LM\text{-}cut}(I)=5$

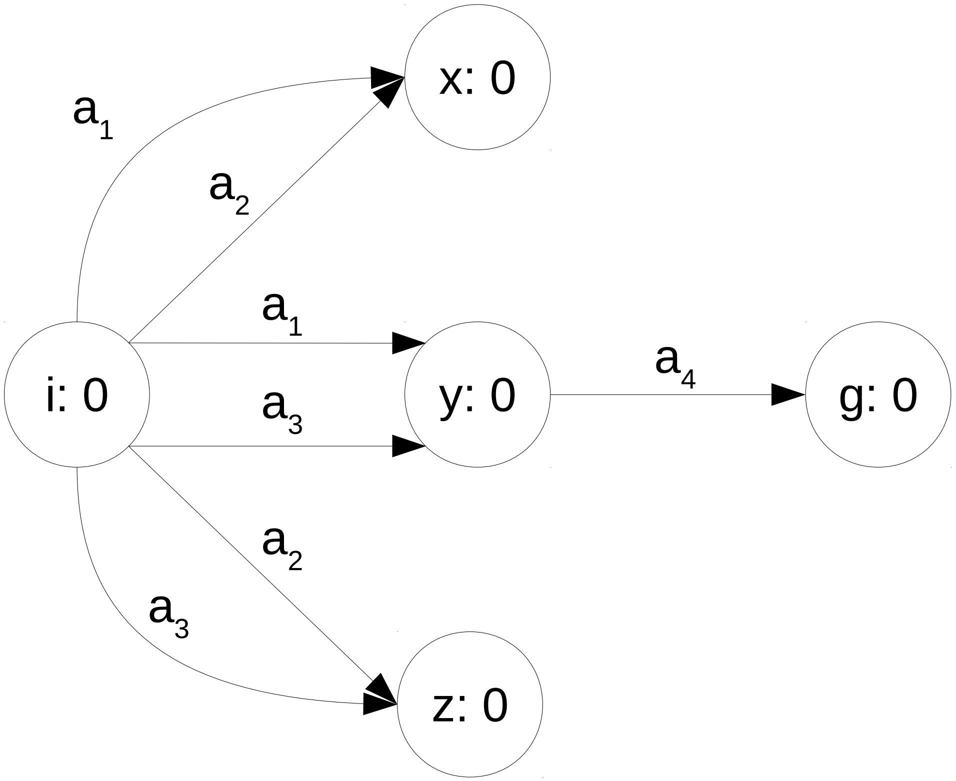
Example – Computing LM-cut

a_1=(i → x,y)$_2$

a_2=(i → x,z)$_0$

a_3=(i → y,z)$_0$

a_4=(x,y,z → g)$_0$



$h^{max}(g)=0$ → done !

pcf in red

$h^{LM\text{-}cut}(I)=5$

LM-cut – Final Remarks

- LM-cut finds (some) **disjunctive action landmarks**
- It can be proven that $h^{LM\text{-}cut} \leq h^{+}$
- LM-cut heuristic is thus **admissible**

- LM-cut heuristic extracts landmarks for each (visited) state
- Other methods extracts landmarks once and then propagate them over the course of the search