

Planning and Optimization

C21. Landmarks: And/Or Landmarks

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November 28, 2016

Reminder

Definition (Disjunctive Action Landmark)

Let s be a state of planning task $\Pi = \langle V, I, O, \gamma \rangle$.

A **disjunctive action landmark** for s is a set of operators $L \subseteq O$ such that every label path from s to a goal state contains an operator from L .

Definition (Formula and Fact Landmark)

Let s be a state of planning task $\Pi = \langle V, I, O, \gamma \rangle$.

A **formula landmark** for s is a formula λ over V such that every state path from s to a goal state contains a state s' with $s' \models \lambda$.

If $\lambda \in V$ then λ is a **fact landmark**.

Landmarks from RTGs

Incidental Landmarks

Example (Incidental Landmarks)

$\Pi = \langle \{a, b, c, d, e, f\}, \{a, b, e\}, \{o_1, o_2\}, \{e, f\} \rangle$ with

$o_1 = \langle \{a\}, \{c, d, e\}, \{b\}, 1 \rangle$, and

$o_2 = \langle \{d, e\}, \{f\}, \{a, b, c, d\}, 1 \rangle$.

Single plan $\langle o_1, o_2 \rangle$ with state path $\{a, b, e\}, \{a, c, d, e\}, \{e, f\}$.

- All variables are fact landmarks for the initial state.
- Variable b is initially true but irrelevant for the plan.
- Variable c gets true as “side effect” of o_1 but it is not necessary for the goal or to make an operator applicable.

Causal Landmarks (1)

Definition (Causal Formula Landmark)

Let $\Pi = \langle V, I, O, \gamma \rangle$ be a planning task.

A formula λ over V is a **causal formula landmark** for I if $\gamma \models \lambda$ or if for all plans $\pi = \langle o_1, \dots, o_n \rangle$ there is an o_i with $pre(o_i) \models \lambda$.

Causal Landmarks (2)

Special case: Fact Landmark for STRIPS task

Definition (Causal Fact Landmark)

Let $\Pi = \langle V, I, O, G \rangle$ be a STRIPS planning task (in set representation).

A variable $v \in V$ is a **causal fact landmark** for I if $v \in G$ or if for all plans $\pi = \langle o_1, \dots, o_n \rangle$ there is an o_i with $v \in \text{pre}(o_i)$.

Causal Landmarks: Example

Example (Causal Landmarks)

$\Pi = \langle \{a, b, c, d, e, f\}, \{a, b, e\}, \{o_1, o_2\}, \{e, f\} \rangle$ with

$$o_1 = \langle \{a\}, \{c, d, e\}, \{b\}, 1 \rangle, \text{ and}$$

$$o_2 = \langle \{d, e\}, \{f\}, \{a, b, c, d\}, 1 \rangle.$$

Single plan $\langle o_1, o_2 \rangle$ with state path $\{a, b, e\}, \{a, c, d, e\}, \{e, f\}$.

- All variables are fact landmarks for the initial state.
- Only a, d, e and f are causal landmarks.

What We Are Doing Next

- Causal landmarks are the desirable landmarks.
- For STRIPS, we can use (a simpler version of) RTGs to compute them.
- We will define landmarks of AND/OR graphs, ...
- and show how they can be computed.
- Afterwards we establish that these are landmarks of the planning task.

Simplified Relaxed Task Graph

Definition

For a STRIPS planning task $\langle V, I, O, G \rangle$ (in set representation), the **simplified relaxed task graph** $sRTG(\Pi^+)$ is the AND/OR graph $\langle V_{\text{and}}, V_{\text{or}}, E \rangle$ with

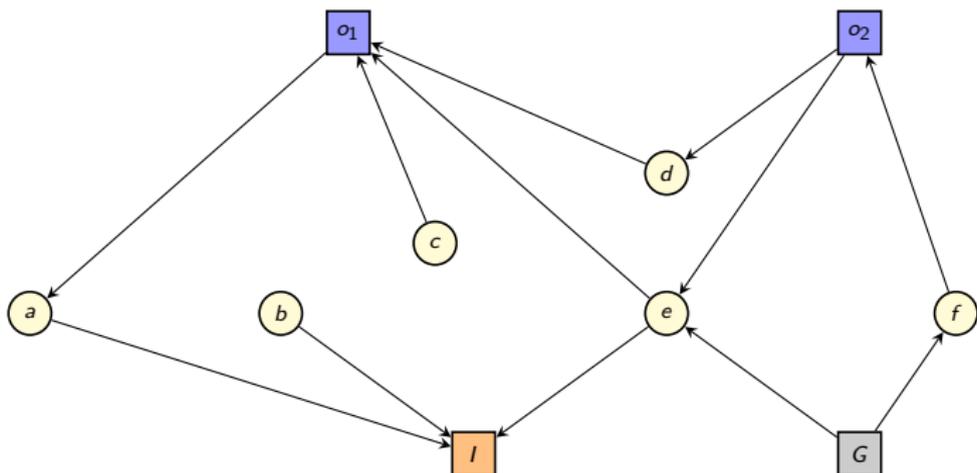
- AND nodes $V_{\text{and}} = \{n_o \mid o \in O\} \cup \{v_I, v_G\}$,
- OR nodes $V_{\text{or}} = \{n_v \mid v \in V\}$, and
- $E = \{ \langle n_a, n_o \rangle \mid o \in O, a \in \text{add}(o) \} \cup$
 $\{ \langle n_o, n_p \rangle \mid o \in O, p \in \text{pre}(o) \} \cup$
 $\{ \langle n_v, n_I \rangle \mid v \in I \} \cup$
 $\{ \langle n_G, n_v \rangle \mid v \in G \}$

Simplified RTG: Example

$\Pi = \langle \{a, b, c, d, e, f\}, \{a, b, e\}, \{o_1, o_2\}, \{e, f\} \rangle$ with

$o_1 = \langle \{a\}, \{c, d, e\}, \{b\}, 1 \rangle$, and

$o_2 = \langle \{d, e\}, \{f\}, \{a, b, c, d\}, 1 \rangle$.



Justification

Definition (Justification)

Let $G = \langle V_{\text{and}}, V_{\text{or}}, E \rangle$ be an AND/OR graph.

A subgraph $J = \langle V^J, E^J \rangle$ with $V^J \subseteq V_{\text{and}} \cup V_{\text{or}}$ and $E^J \subseteq E$ **justifies** $n_\star \in V_{\text{and}} \cup V_{\text{or}}$ iff

- $n_\star \in V^J$,
- $\forall n \in V^J \cap V_{\text{and}} : \forall \langle n, n' \rangle \in E : n' \in V^J$ and $\langle n, n' \rangle \in E^J$
- $\forall n \in V^J \cap V_{\text{or}} : \exists \langle n, n' \rangle \in E : n' \in V^J$ and $\langle n, n' \rangle \in E^J$, and
- J is acyclic.

“Proves” that n_\star is forced true.

Landmarks in AND/OR Graphs

Definition (Landmarks in AND/OR Graphs)

Let $G = \langle V_{\text{and}}, V_{\text{or}}, E \rangle$ be an AND/OR graph. A node n is a **landmark** for reaching $n_\star \in V_{\text{and}} \cup V_{\text{or}}$ if $n \in V^J$ for all justifications J for n_\star .

But: exponential number of possible justifications

Characterizing Equation System

Theorem

Let $G = \langle V_{\text{and}}, V_{\text{or}}, E \rangle$ be an AND/OR graph. Consider the following system of equations:

$$LM(n) = \{n\} \cup \bigcap_{\langle n, n' \rangle \in E} LM(n') \quad n \in V_{\text{or}}$$

$$LM(n) = \{n\} \cup \bigcup_{\langle n, n' \rangle \in E} LM(n') \quad n \in V_{\text{and}}$$

The equation system has a unique maximal solution (maximal with regard to set inclusion), and for this solution it holds that

$n' \in LM(n)$ iff n' is a landmark for reaching n in G .

Computation of Maximal Solution

Theorem

Let $G = \langle V_{\text{and}}, V_{\text{or}}, E \rangle$ be an AND/OR graph. Consider the following system of equations:

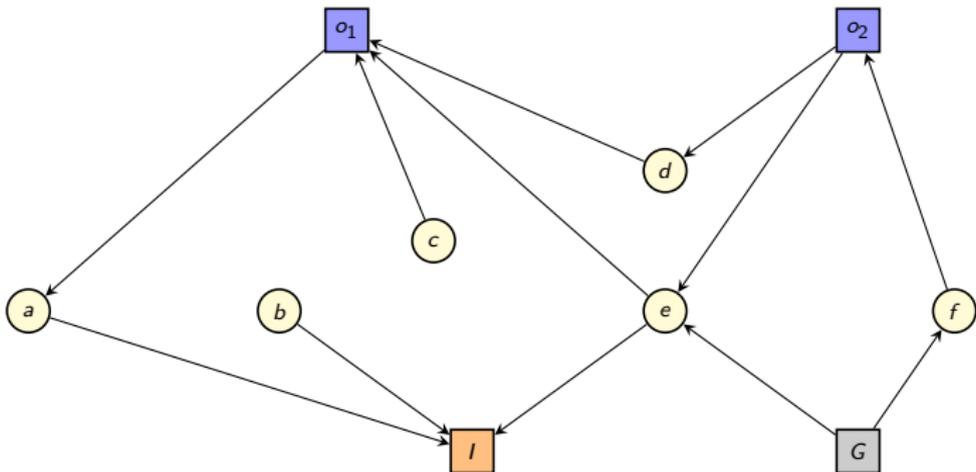
$$LM(n) = \{n\} \cup \bigcap_{\langle n, n' \rangle \in E} LM(n') \quad n \in V_{\text{or}}$$

$$LM(n) = \{n\} \cup \bigcup_{\langle n, n' \rangle \in E} LM(n') \quad n \in V_{\text{and}}$$

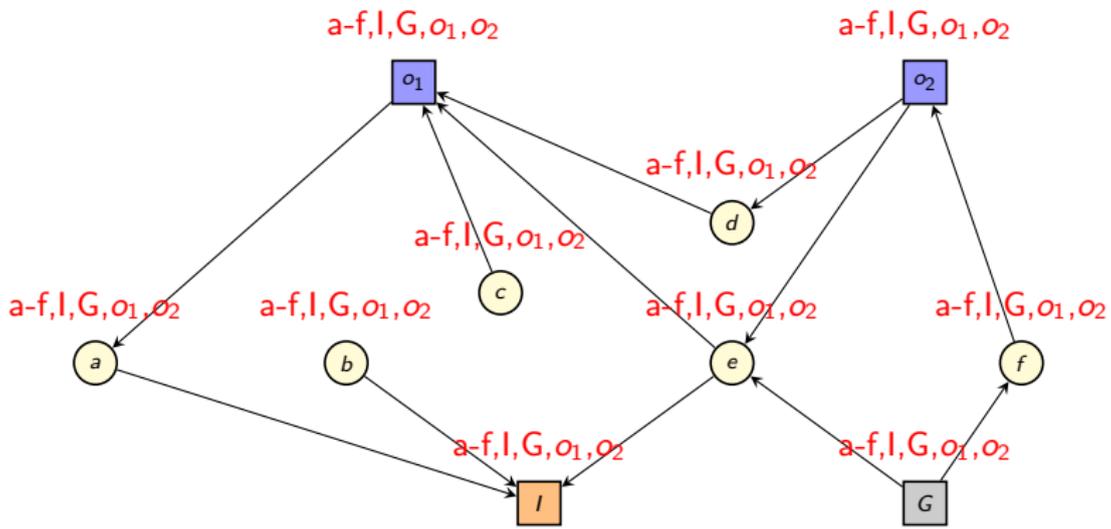
The equation system has a unique maximal solution (maximal with regard to set inclusion).

Computation: Initialize landmark sets as $LM(n) = V_{\text{and}} \cup V_{\text{or}}$ and apply equations as update rules until fixpoint.

Computation: Example

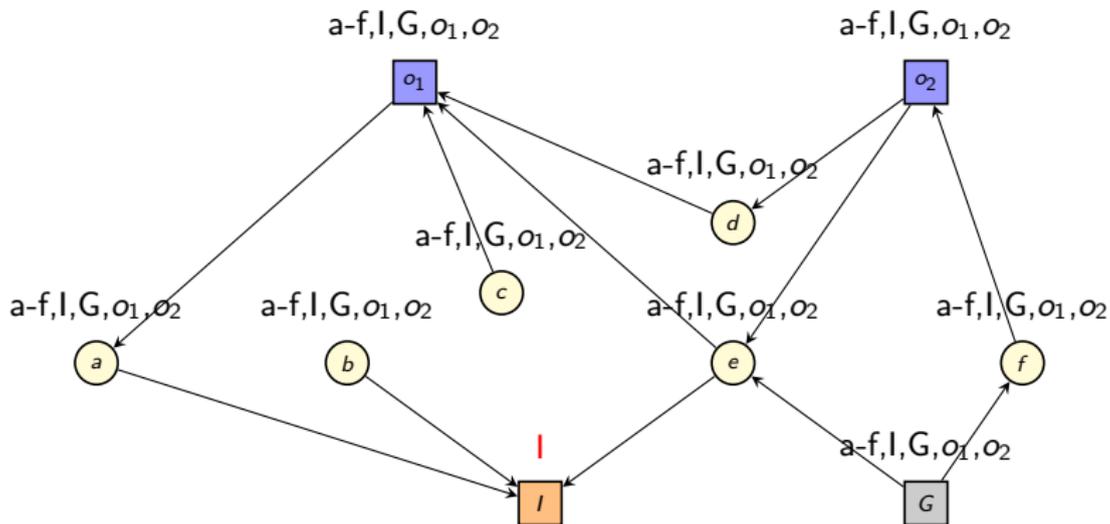


Computation: Example



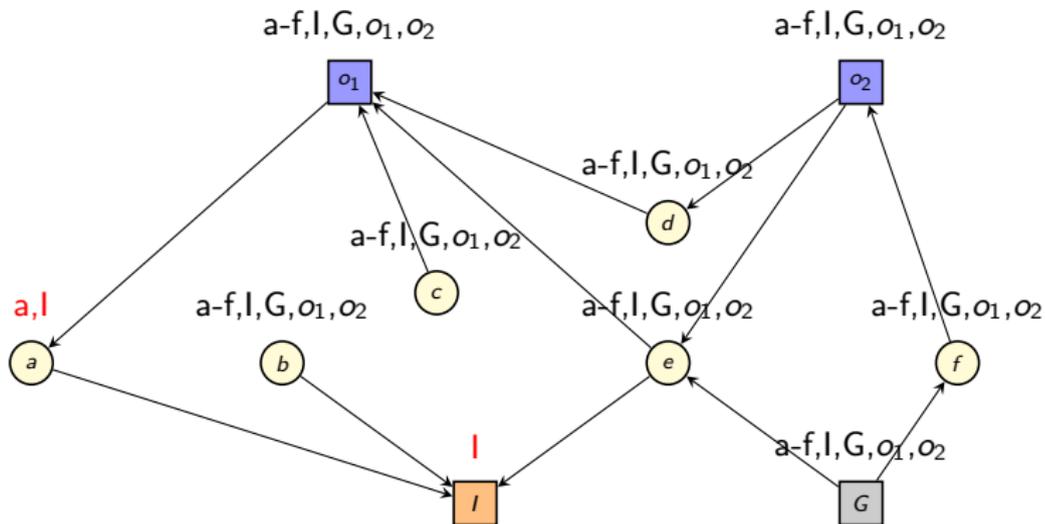
Initialize with all nodes

Computation: Example



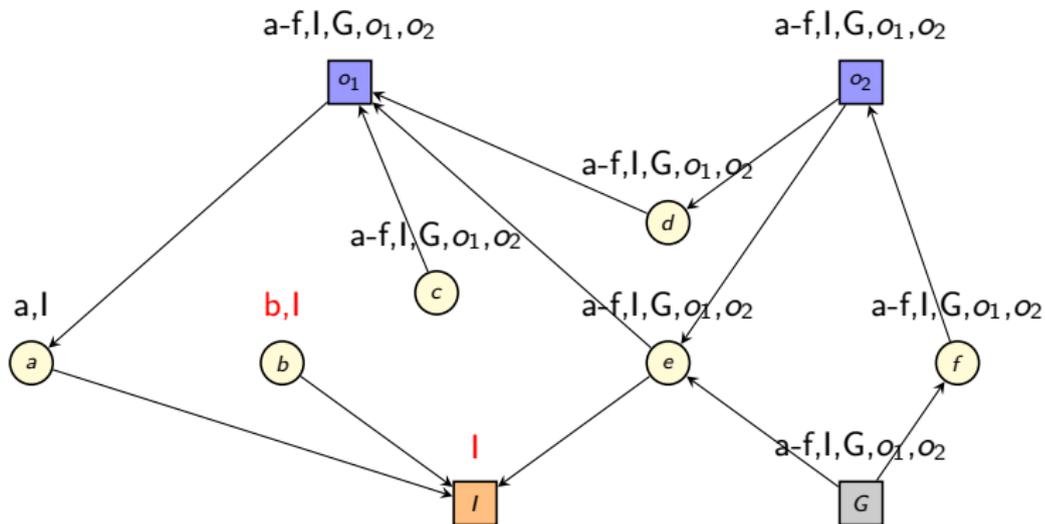
$$LM(I) = \{I\}$$

Computation: Example



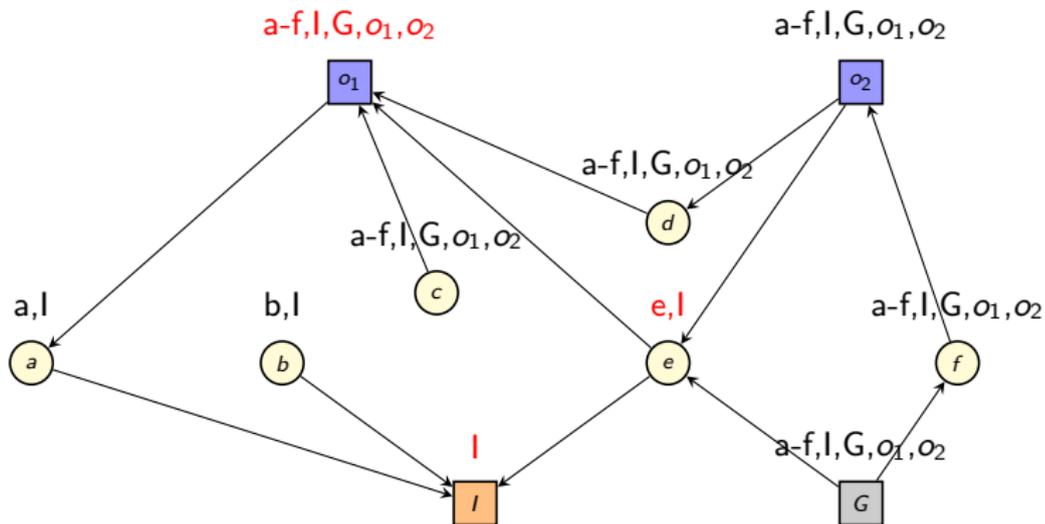
$$LM(a) = \{a\} \cup LM(I)$$

Computation: Example



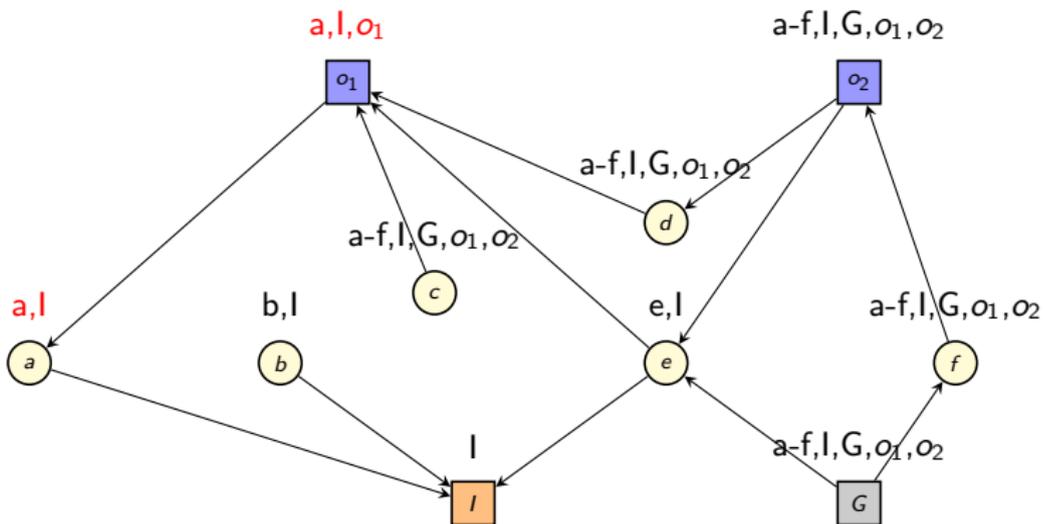
$$LM(b) = \{b\} \cup LM(I)$$

Computation: Example



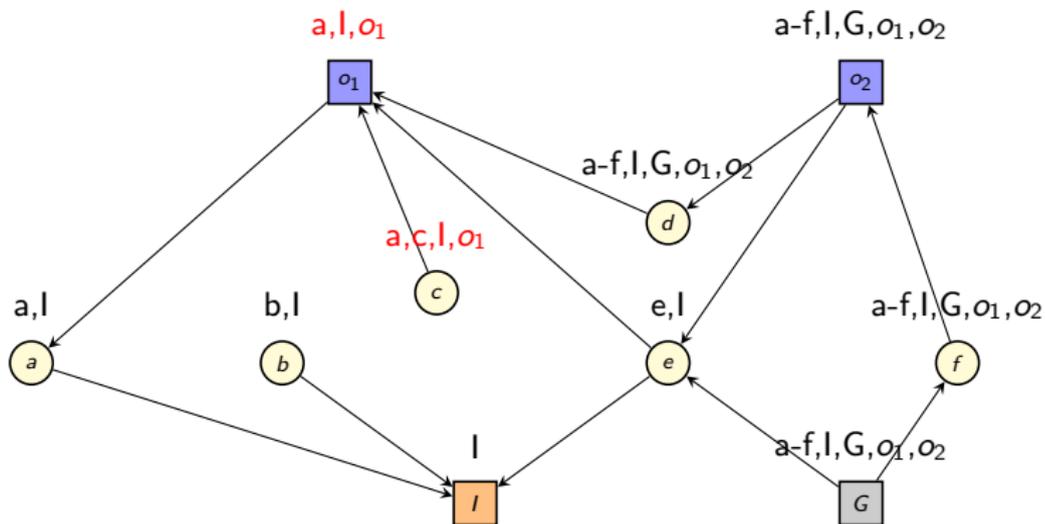
$$LM(e) = \{e\} \cup (LM(l) \cap LM(o_1))$$

Computation: Example



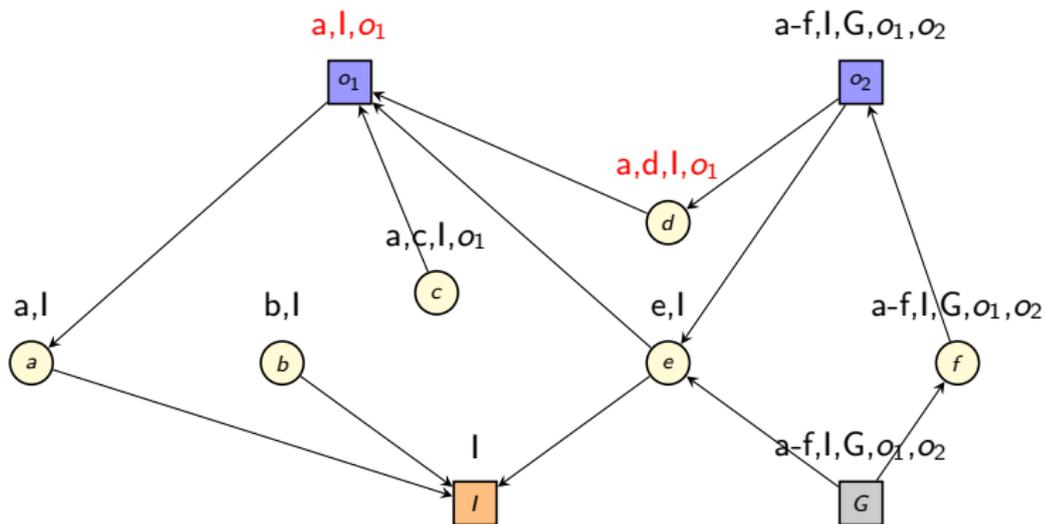
$$LM(o_1) = \{o_1\} \cup LM(a)$$

Computation: Example



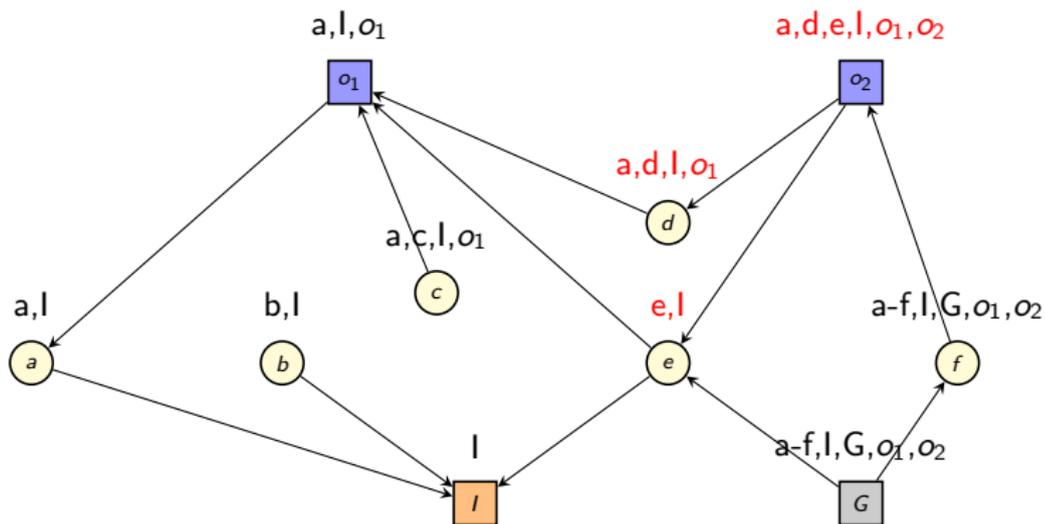
$$LM(c) = \{c\} \cup LM(o_1)$$

Computation: Example



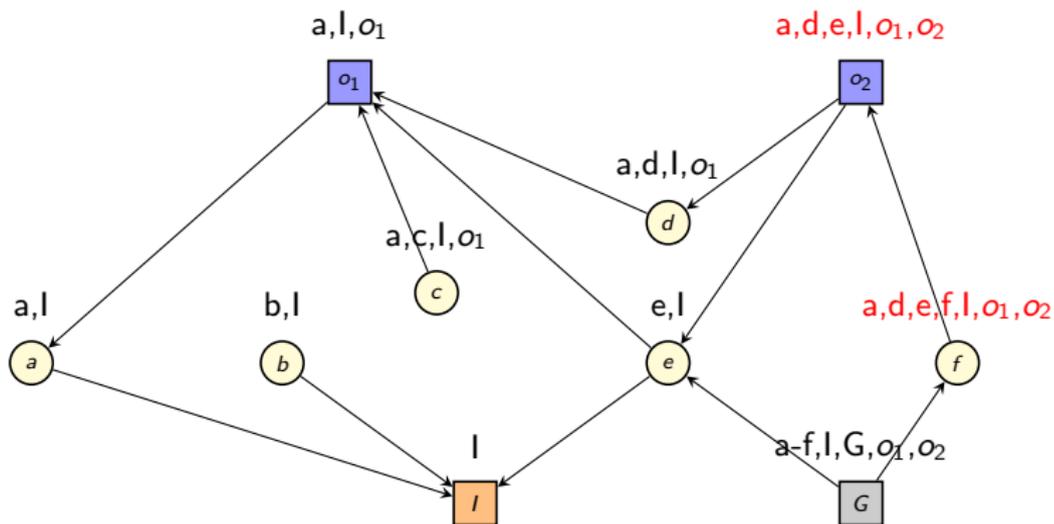
$$LM(d) = \{d\} \cup LM(o_1)$$

Computation: Example



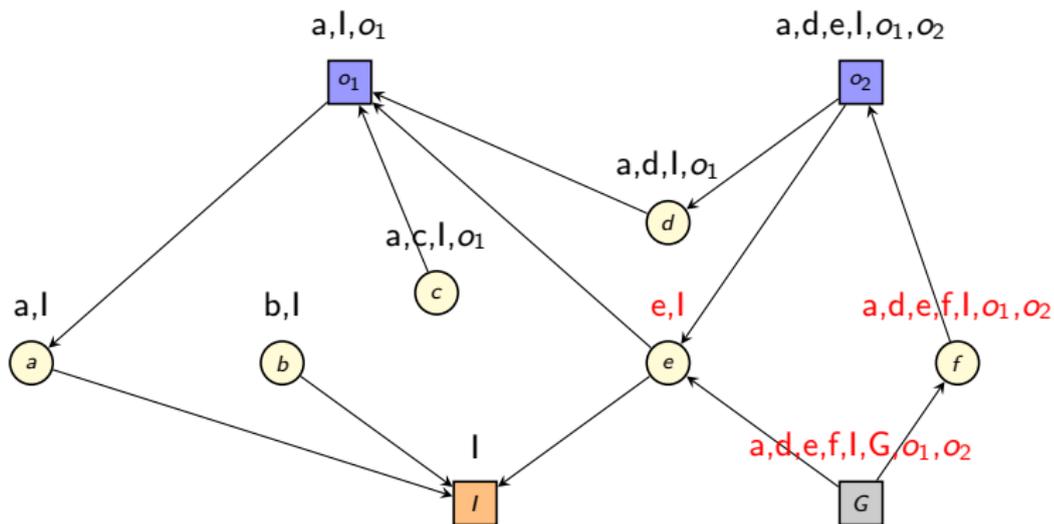
$$LM(o_2) = \{o_2\} \cup LM(d) \cup LM(e)$$

Computation: Example



$$LM(f) = \{f\} \cup LM(o_2)$$

Computation: Example



$$LM(G) = \{G\} \cup LM(e) \cup LM(f)$$

Relation to Planning Task Landmarks

Theorem

Let $\Pi = \langle V, I, O, G \rangle$ be a STRIPS planning task and let \mathcal{L} be the set of landmarks for reaching n_G in $sRTG(\Pi^+)$.

The set $\{v \in V \mid n_v \in \mathcal{L}\}$ is exactly the set of *causal fact landmarks* for I in Π^+ .

For operators $o \in O$, if $n_o \in \mathcal{L}$ then $\{o\}$ is a *disjunctive action landmark* for I in Π^+ . There are no other disjunctive action landmarks of size 1.

(Proofs omitted.)

Example

Example

$\Pi = \langle \{a, b, c, d, e, f\}, \{a, b, e\}, \{o_1, o_2\}, \{e, f\} \rangle$ with

$o_1 = \langle \{a\}, \{c, d, e\}, \{b\}, 1 \rangle$, and

$o_2 = \langle \{d, e\}, \{f\}, \{a, b, c, d\}, 1 \rangle$.

- $LM(n_G) = \{a, d, e, f, l, G, o_1, o_2\}$
- a, d, e , and f are causal fact landmarks of Π^+ .
- They are the only causal fact landmarks of Π^+ .
- $\{o_1\}$ and $\{o_2\}$ are disjunctive action landmarks of Π^+ .

(Some) Landmarks of Π^+ Are Landmarks of Π

Theorem

Let Π be a STRIPS planning task.

All fact landmarks of Π^+ are fact landmarks of Π and all disjunctive action landmarks of Π^+ are disjunctive action landmarks of Π .

Proof.

Let L be a disjunctive action landmark of Π^+ and π be a plan for Π . Then π is also a plan for Π^+ and, thus, π contains an operator from L .

Let f be a fact landmark of Π^+ . If f is already true in the initial state, then it is also a landmark of Π . Otherwise, every plan for Π^+ contains an operator that adds f and the set of all these operators is a disjunctive action landmark of Π^+ . Therefore, also each plan of Π contains such an operator, making f a fact landmark of Π . \square

Not All Landmarks of Π^+ are Landmarks of Π

Example

Consider STRIPS task $\langle \{a, b, c\}, \emptyset, \{o_1, o_2\}, \{c\} \rangle$ with $o_1 = \langle \{\}, \{a\}, \{\}, 1 \rangle$ and $o_2 = \langle \{a\}, \{c\}, \{a\}, 1 \rangle$.

$a \wedge c$ is a formula landmark of Π^+ but not of Π .

Landmarks from Π^m

Reminder: Π^m Compilation

Definition (Π^m)

Let $\Pi = \langle V, I, O, G \rangle$ be a STRIPS planning task.

For $m \in \mathbb{N}_1$, the task Π^m is the STRIPS planning task $\langle V^m, I^m, O^m, G^m \rangle$, where

$$O^m = \{a_{o,S} \mid o \in O, S \subseteq V, |S| < m, S \cap (\text{add}(o) \cup \text{del}(o)) = \emptyset\}$$

with

- $\text{pre}(a_{o,S}) = (\text{pre}(o) \cup S)^m$
- $\text{add}(a_{o,S}) = \{v_Y \mid Y \subseteq \text{add}(o) \cup S, |Y| \leq m, Y \cap \text{add}(o) \neq \emptyset\}$
- $\text{del}(a_{o,S}) = \emptyset$
- $\text{cost}(a_{o,S}) = \text{cost}(o)$

Landmarks from the Π^m Compilation (1)

Idea:

- Π^m is delete-free, so we can compute all causal (meta-)fact landmarks from the AND/OR graph.
- These landmarks correspond to formula landmarks of the original problem.

Landmarks from the Π^m Compilation (2)

Theorem

*Let $\Pi = \langle V, I, O, G \rangle$ be a STRIPS planning task.
If meta-variable v_S is a fact landmark of I^m in Π^m then $\bigwedge_{v \in S} v$ is a formula landmark of I in Π .*

(Proof omitted.)

Π^m Landmarks: Example

Consider again our running example:

Example

$\Pi = \langle \{a, b, c, d, e, f\}, \{a, b, e\}, \{o_1, o_2\}, \{e, f\} \rangle$ with

$$o_1 = \langle \{a\}, \{c, d, e\}, \{b\}, 1 \rangle, \text{ and}$$

$$o_2 = \langle \{d, e\}, \{f\}, \{a, b, c, d\}, 1 \rangle.$$

Meta-variable $v_{\{d,e\}}$ is a causal fact landmark for l^2 in Π^2 , so $d \wedge e$ is a causal formula landmark for Π .

Landmarks from the Π^m Compilation (3)

Theorem

Let $\Pi = \langle V, I, O, G \rangle$ be a STRIPS planning task. For $m \in \mathbb{N}_1$ let $\mathcal{L}^m = \{ \bigwedge_{v \in C} v \mid C \subseteq V, v_C \text{ is a causal fact landmark of } \Pi^m \}$ be the set of formula landmarks derived from Π^m .

Let λ be a conjunction over V that is a formula landmark of Π . For sufficiently large m , \mathcal{L}^m contains λ' with $\lambda' \equiv \lambda$.

(Proof omitted.)

\rightsquigarrow can find all causal conjunctive formula landmarks

Π^m Landmarks: Discussion

- With the Π^m compilation, we can find causal fact landmarks of Π that are not causal fact landmarks of Π^+ .
- In addition we can find conjunctive formula landmarks.
- The approach takes to some extent delete effects into account.
- However, the approach takes exponential time in m .
- Even for small m , the additional cost for computing the landmarks often outweighs the time saved from better heuristic guidance.

Summary

Summary

- We can efficiently compute all causal fact landmarks of a delete-free task from the (simplified) RTG.
- Fact landmarks of the delete relaxed task are also landmarks of the original task.
- We can use the Π^m compilation to find more landmarks.