Landmarks

Definitions, Discovery Methods and Uses

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ICAPS 2010 Tutorial

Outline

SAS$^+$

- SAS$^+$ is a language for describing planning tasks compactly
- A SAS$^+$ task is given by a 4-tuple $\Pi = \langle \mathscr{V}, \mathscr{A}, s_0, G \rangle$
  - $\mathscr{V} = \{v_1, \ldots, v_n\}$ is a set of state variables, each associated with a finite domain $dom(v_i)$. By $v \mapsto d$ we denote that variable v is assigned value $d \in dom(v)$
  - Each complete assignment s to $\mathscr{V}$ is called a *state*
  - s_0 is an *initial state*
  - *goal* G is a partial assignment to $\mathscr{V}$
  - $\mathscr{A}$ is a finite set of *actions*
  - Each action a is a pair $\langle \text{pre}(a), \text{eff}(a) \rangle$ of partial assignments to $\mathscr{V}$ called *preconditions* and *effects*
- In cost-sensitive planning, each action a is also associated with a cost $C(a)$

Outline

1. What Landmarks Are
2. How Landmarks Are Discovered
3. Landmark Uses
   - Subgoals
   - Heuristic Estimates
   - Admissible Heuristic Estimates
   - Enriching the Problem
   - Beyond Classical Planning
4. Summary

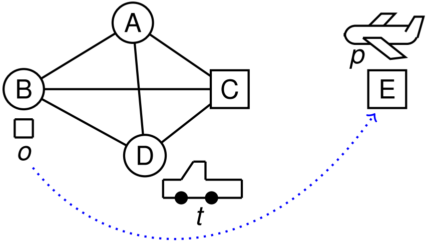
Landmarks

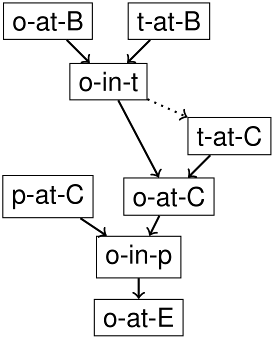
- A landmark is a formula that must be true at some point in every plan (Hoffmann, Porteous & Sebastia 2004)
- Landmarks can be (partially) ordered according to the order in which they must be achieved
- Some landmarks and orderings can be discovered automatically
- Current approaches consider only landmarks that are facts or disjunctions of facts
  (work on conjunctive landmarks to appear)

Action Landmarks

- An action landmark is an action which occurs in every plan
- Landmarks may imply actions landmarks (e.g., sole achievers)
- Action landmarks imply landmarks (e.g., preconditions and effects)
- Action landmarks might capture even more information
- Some action landmarks can be discovered automatically

Example Planning Problem - Logistics





Partial landmarks graph

Types of Landmark Orderings

- Sound landmark orderings are guaranteed to hold - they do not prune the solution space
- Unsound landmark orderings are additional constraints on plans - they may prune the solution space
- It is even possible that no plan exists that respects the unsound orderings
- However, unsound orderings are likely to hold and may save effort in planning

Sound Landmark Orderings

- *Natural* ordering $A \rightarrow B$, iff A true some time before B
- *Necessary* ordering $A \rightarrow_n B$, iff A always true before B becomes true
- *Greedy-necessary* ordering $A \rightarrow_{gn} B$, iff A true one step before B becomes true for the first time

Note that $A \rightarrow_n B \implies A \rightarrow_{gn} B \implies A \rightarrow B$

Reasonable Orderings

- Not sound - not guaranteed to hold in all plans
- *Reasonable* ordering $A \rightarrow_r B$, iff given B was achieved before A, any plan must delete B on the way to A, and re-achieve achieve B after or at the same time as A

$$B \rightsquigarrow \neg B \rightsquigarrow A \rightsquigarrow B \implies A \rightarrow_r B$$

- Initial state landmarks can be reasonably ordered after other landmarks (e. g., if they must be made false and true again)
- This can never happen with sound orderings

Obedient-Reasonable Orderings

- Assume that a plan obeys reasonable orderings $\Rightarrow$ find more orderings
- *Obedient-reasonable* ordering $A \rightarrow_{or} B$, iff given B was achieved before A, any plan that obeys reasonable orderings must delete B on the way to A and re-achieve B after or at the same time as A
- Not sound

Landmark Complexity

- Everything is PSPACE-complete

- Deciding if a given fact is a landmark is PSPACE-complete
- Proof Sketch: it's the same as deciding if the problem without actions that achieve this fact is unsolvable

- Deciding if there is a natural / necessary / greedy-necessary / reasonable ordering between two landmarks is PSPACE-complete

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Landmark Discovery in Theory

Theory

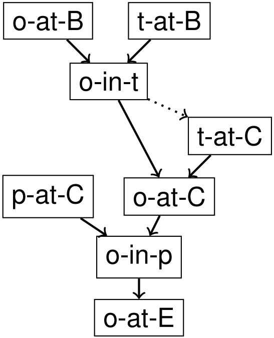
- A is a landmark $\iff \pi'_A$ is unsolvable
  where π'_A is π without the actions that achieve A

- The delete relaxation of π'_A is unsolvable $\Longrightarrow \pi'_A$ is unsolvable (delete-relaxation landmarks) – but better methods exist
- Other heuristics can be used to prove π'_A unsolvable: h^m, structural patterns, ...

Landmark Discovery I

Find landmarks and orderings by backchaining (Hoffmann et al. 2004, Porteous & Cresswell 2002)

- Every goal is a landmark
- If B is landmark and all actions that achieve B share A as precondition, then
  - A is a landmark
  - $A \rightarrow_n B$



Useful restriction: consider only the case where B is achieved for the first time $\rightsquigarrow$ find more landmarks (and $A \rightarrow_{\mathrm{gn}} B$)

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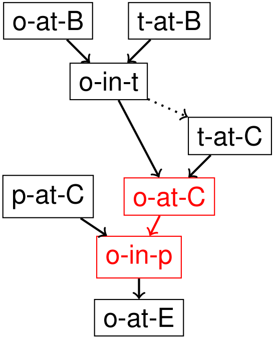

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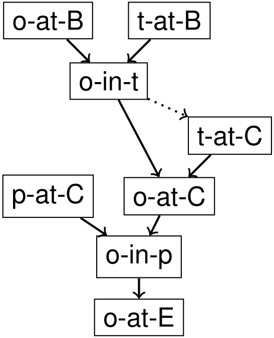
Landmark Discovery I (ctd.)

PSPACE-complete to find first achievers
$\leadsto$ over-approximation by building relaxed planning graph for π'_B

- This graph contains no actions that add B
- Any action applicable in this graph can possibly be executed before B first becomes true $\leadsto$ possible first achievers

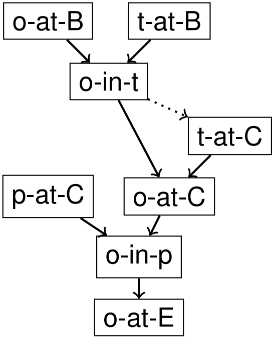


Additionally, if C not in the graph and C later proven to be a landmark, introduce $B \rightarrow C$

Landmark Discovery I (ctd.)

Disjunctive landmarks also possible,
e.g., (o-in-p_1 $\vee$ o-in-p_2):

- If B is landmark and all actions that (first) achieve B have A or C as precondition, then $A \vee C$ is a landmark
- Generalises to any number of disjuncts
- Large number of possible disjunctive landmarks $\rightsquigarrow$ must be restricted



Domain Transition Graphs (DTGs)

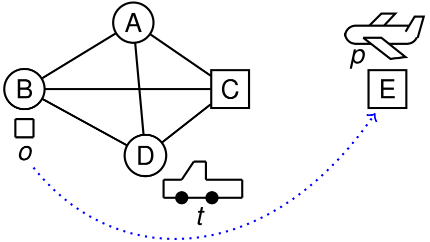
Find landmarks through DTGs (Richter et al. 2008)

The domain transition graph of $v \in \mathscr{V}$ (DTG_v) represents how the value of v can change.

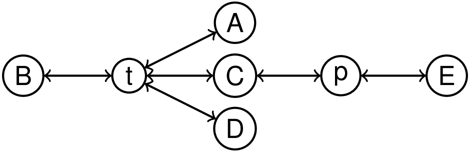
Given: a SAS^+ task $\langle \mathscr{V}, \mathscr{A}, s_0, G \rangle$
DTG_v is a directed graph with nodes $\mathscr{D}_v$ that has arc $\langle d, d' \rangle$ iff

- $d \neq d'$, and
- $\exists$ action with $v \mapsto d'$ as effect, and either
  - $v \mapsto d$ as precondition, or
  - no precondition on v

DTG Example



DTG for v_o:



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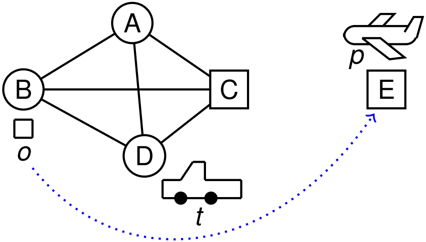

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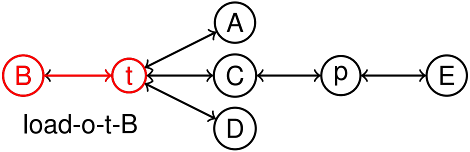
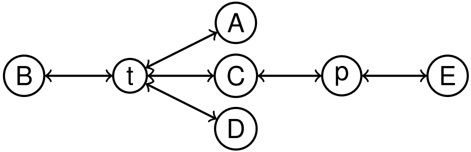


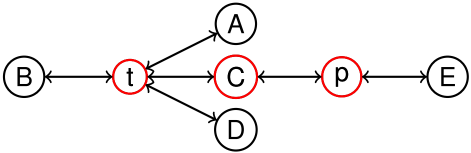
Landmark Discovery II



- Find landmarks through DTGs: if
  - $s_0(v) = d_0$,
  - $v \mapsto d$ landmark, and
  - every path from d_0 to d passes through d',

then $v \mapsto d'$ landmark, and $(v \mapsto d') \rightarrow (v \mapsto d)$

Landmark Discovery II



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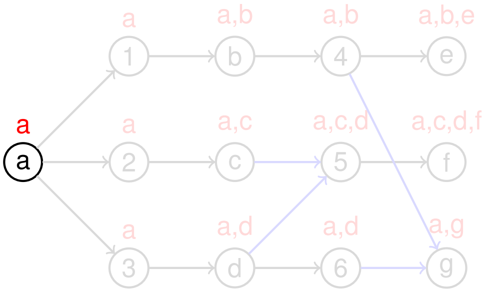
Landmark Discovery III

Find landmarks through forward propagation in relaxed planning graph (Zhu & Givan 2003)

- Finds causal landmarks only (preconditions for actions)
- Finds all causal delete-relaxation landmarks in polynomial time
- Propagate information on necessary predecessors
    - Label each fact node with itself
    - Propagate labels along arcs

Landmark Discovery III (ctd.)

Actions (numbers): propagate union over labels on preconditions
— all preconditions are necessary
Facts (letters): propagate intersection over labels on achievers
— only what's necessary for all achievers is necessary for a fact



No-ops and repeated nodes not shown

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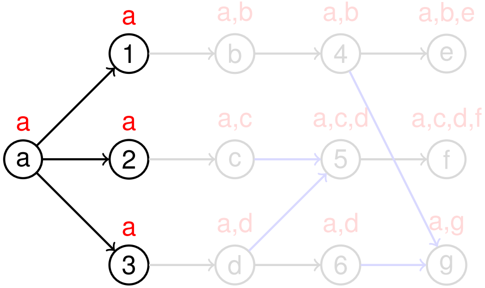

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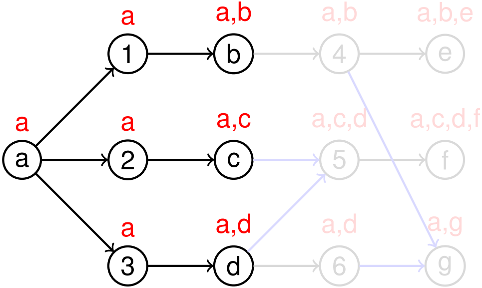

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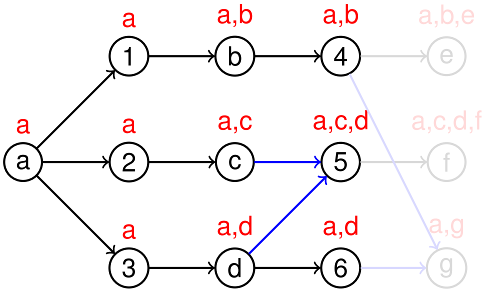

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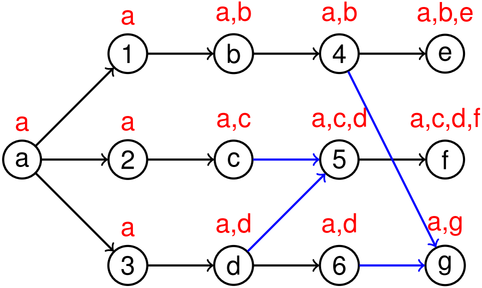


No-ops and repeated nodes not shown

Landmark Discovery III (ctd.)

- Goal nodes in final layer: labels are landmarks
- $A \longrightarrow B$ if A forms part of the label for B in the final layer
- $A \longrightarrow_{\text{gn}} B$ if A is precondition for all possible first achievers of B
- Possible first achievers of B are achievers that do not have B in their label (Keyder, Richter & Helmert 2010)

Advanced version of this method counts re-occurrences of landmarks

Approximating reasonable orderings

We want to introduce $A \rightarrow_{\mathrm{r}} B$ if

1. B must be true after or at the same time as A's first occurrence, and
2. Achieving B first means losing it on the way to A

Approximating reasonable orderings (ctd.)

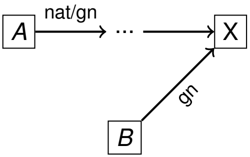
1. *B* must be true after or at the same time as *A*'s first occurrence

   Holds if

   - *B* is a goal

     or
   - there is a chain of natural/greedy-nec. orderings

     $A \rightarrow \ldots \rightarrow X$, and $B \rightarrow_{\mathrm{gn}} X$



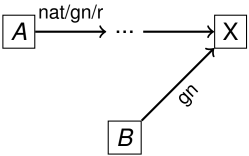
Approximating obedient reasonable orderings

1. B must be true after or at the same time as A's first occurrence

   Holds if

   - B is a goal

     or
   - there is a chain of natural/greedy-nec./reasonable orderings $A \rightarrow \ldots \rightarrow X$, and $B \rightarrow_{\text{gn}} X$



Approximating reasonable orderings (ctd.)

2. Achieving B first means losing it on the way to A

   Holds if

   - A and B are inconsistent (mutually exclusive), or
   - All actions achieving A have an effect inconsistent with B, or
   - There is a landmark X inconsistent with B and $X \rightarrow_{\mathrm{gn}} A$

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Using Landmarks

- Some landmarks and orderings can be discovered efficiently
- So what can we do once we have these landmarks?

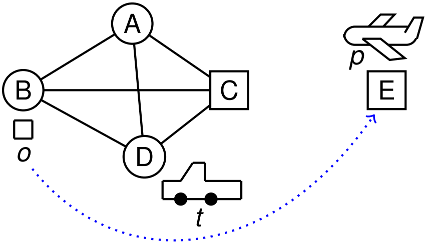
- We assume that landmarks and orderings are discovered in a pre-processing phase, and the same landmark graph is used throughout the planning phase

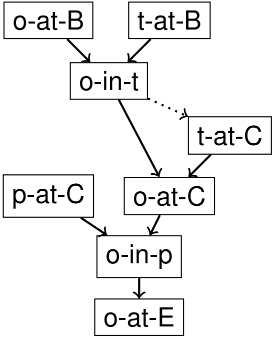
Outline

Using Landmarks as Subgoals

- Landmarks can be used as subgoals for a base planner
- The landmarks which could be achieved in the next iteration are passed as a disjunctive goal to a base planner
- After a landmark is achieved, repeat

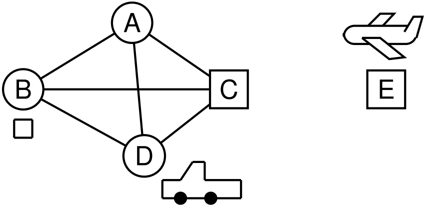
Using Landmarks as Subgoals - Logistics Example

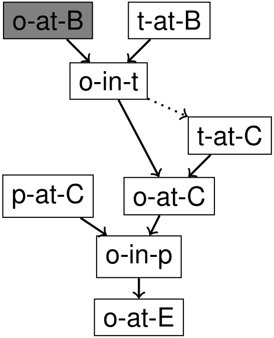




- Partial plan:
- Goal:

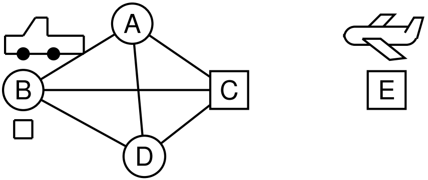
Using Landmarks as Subgoals - Logistics Example

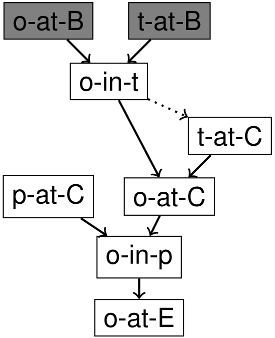




- Partial plan: $\emptyset$
- Goal: t-at-B $\vee$ p-at-C

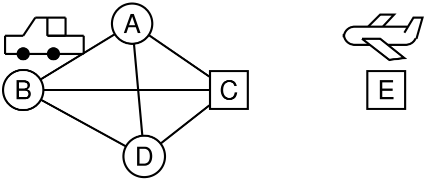
Using Landmarks as Subgoals - Logistics Example

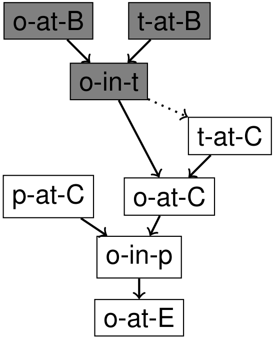




- Partial plan: Drive-t-B
- Goal: o-in-t ∨ p-at-C

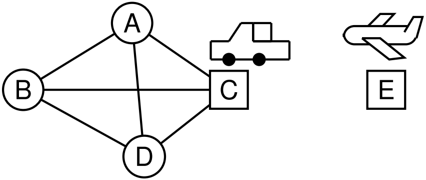
Using Landmarks as Subgoals - Logistics Example

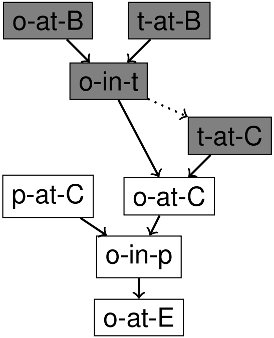




- Partial plan: Drive-t-B, Load-o-B
- Goal: t-at-C $\lor$ p-at-C

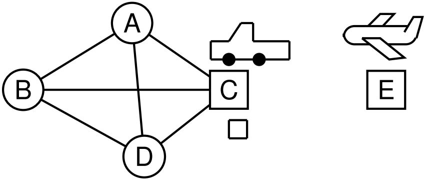
Using Landmarks as Subgoals - Logistics Example

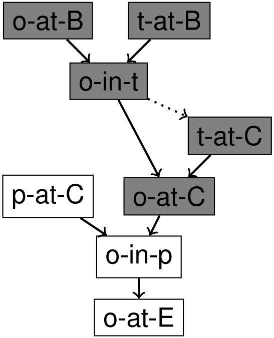




- Partial plan: Drive-t-B, Load-o-B, Drive-t-C
- Goal: o-at-C $\lor$ p-at-C

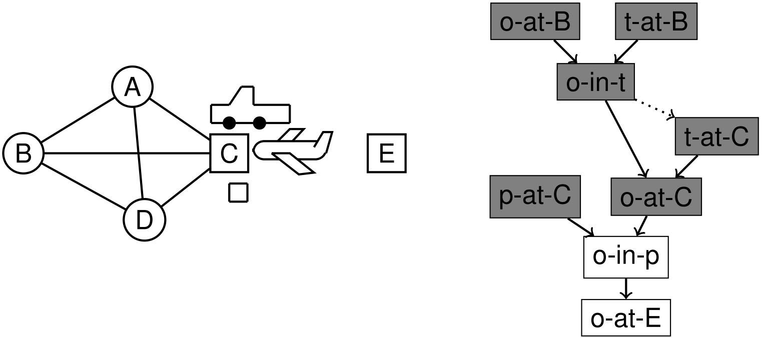
Using Landmarks as Subgoals - Logistics Example





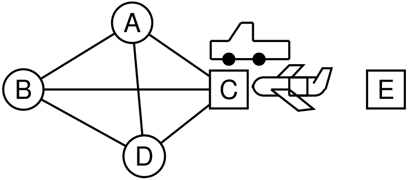
- Partial plan: Drive-t-B, Load-o-B, Drive-t-C, Unload-o-C
- Goal: p-at-C

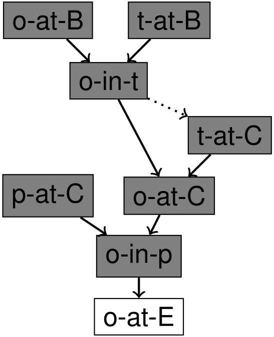
Using Landmarks as Subgoals - Logistics Example



- Partial plan: Drive-t-B, Load-o-B, Drive-t-C, Unload-o-C, Fly-p-C
- Goal: o-in-p

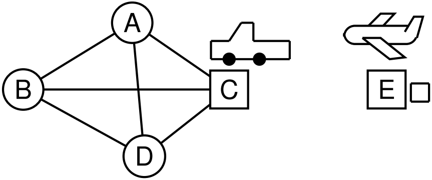
Using Landmarks as Subgoals - Logistics Example

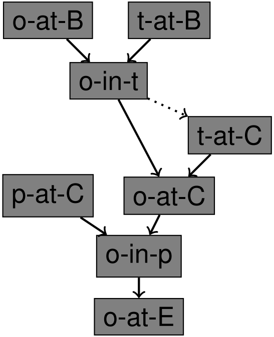




- Partial plan: Drive-t-B, Load-o-B, Drive-t-C, Unload-o-C, Fly-p-C, Load-o-p
- Goal: o-at-E

Using Landmarks as Subgoals - Logistics Example



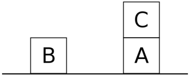


- Partial plan: Drive-t-B, Load-o-B, Drive-t-C, Unload-o-C, Fly-p-C, Load-o-p, Fly-p-E, Unload-o-E
- Goal: $\emptyset$

Using Landmarks as Subgoals

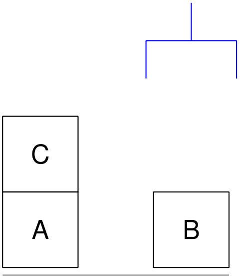
- That was a good example
- Now let's see a bad one

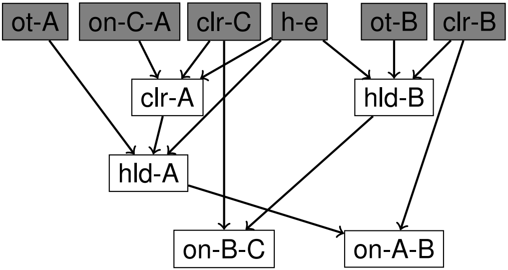
Using Landmarks as Subgoals - Sussman Example

- Consider the following blocks problem ("The Sussman Anomaly")
- Initial State 

- Goal: *on-A-B*, *on-B-C*

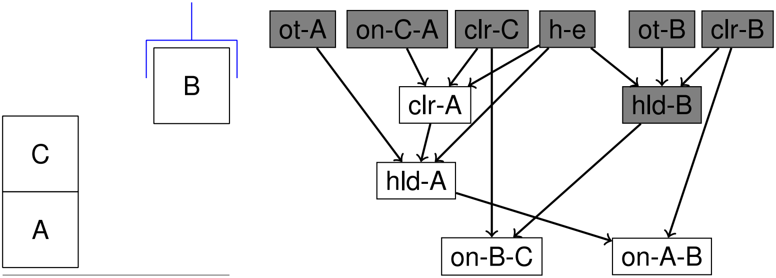
Using Landmarks as Subgoals - Sussman Example





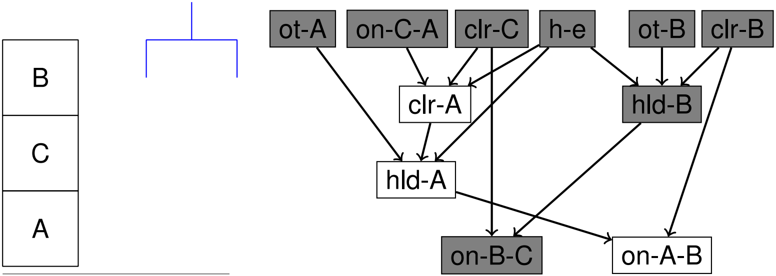
- Partial plan: $\emptyset$
- Goal: clear-A $\vee$ holding-B

Using Landmarks as Subgoals - Sussman Example



- Partial plan: Pickup-B
- Goal: clear-A $\vee$ on-B-C

Using Landmarks as Subgoals - Sussman Example



- Partial plan: Pickup-B, Stack-B-C
- Goal: clear-A

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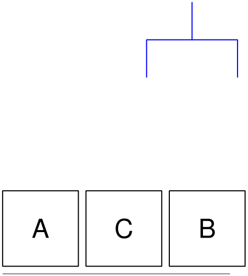

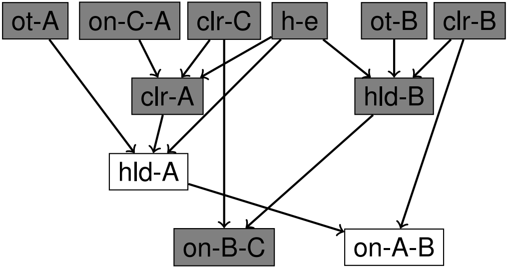

- Partial plan: Pickup-B, Stack-B-C, Unstack-B-C, Putdown-B, Unstack-C-A, Putdown-C
- Goal: holding-A

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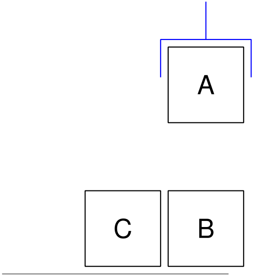

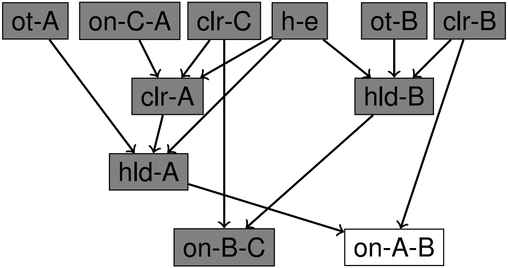

- Partial plan: Pickup-B, Stack-B-C, Unstack-B-C, Putdown-B, Unstack-C-A, Putdown-C, Pickup-A
- Goal: on-A-B

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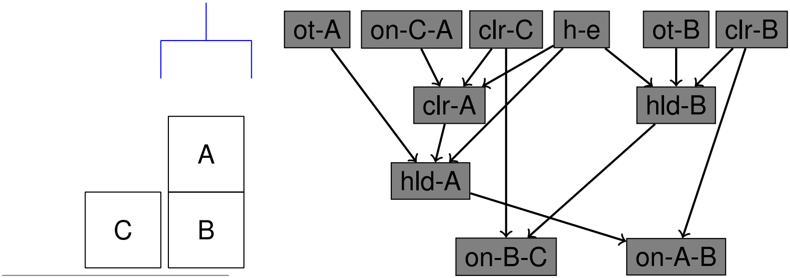
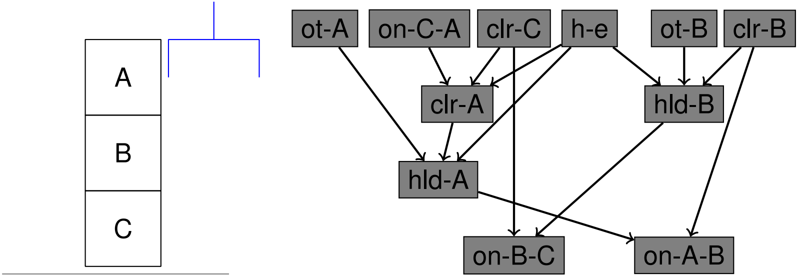


- Partial plan: Pickup-B, Stack-B-C, Unstack-B-C, Putdown-B, Unstack-C-A, Putdown-C, Pickup-A, Stack-A-B
- Goal: Still need to achieve on-B-C

Using Landmarks as Subgoals - Sussman Example



- Partial plan: Pickup-B, Stack-B-C, Unstack-B-C, Putdown-B, Unstack-C-A, Putdown-C, Pickup-A, Stack-A-B, Unstack-A-B, Putdown-A, Pickup-B, Stack-B-C, Pickup-A, Stack-A-B
- Goal: $\emptyset$

Using Landmarks as Subgoals - Pros and Cons

- Pros:
  - Planning is very fast - the base planner needs to plan to a lesser depth
- Cons:
  - Can lead to much longer plans
  - Not complete in the presence of dead-ends

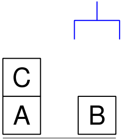
Outline

Using Landmarks for Heuristic Estimates

- The number of landmarks that still need to be achieved is a heuristic estimate (Richter, Helmert and Westphal 2008)
- Used by *LAMA* - winner of the IPC-2008 sequential satisficing track

Path-dependent Heuristics

- Suppose we are in state s. Did we achieve landmark A yet?
- Example: did we achieve holding(B)?



- There is no way to tell just by looking at s
- Achieved landmarks are a function of path, not state
- The number of landmarks that still need to be achieved is a path-dependent heuristic

The Landmark Heuristic

- The landmarks that still need to be achieved after reaching state s via path π are

$$L(s,\pi) = (L \setminus \mathrm{Accepted}(s,\pi)) \cup \mathrm{ReqAgain}(s,\pi)$$

- L is the set of all (discovered) landmarks
- $\mathrm{Accepted}(s,\pi) \subset L$ is the set of *accepted* landmarks
- $\mathrm{ReqAgain}(s,\pi) \subseteq \mathrm{Accepted}(s,\pi)$ is the set of *required again* landmarks - landmarks that must be achieved again

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Accepted Landmarks

- In LAMA, a landmark A is first accepted by path π in state s if
  - all predecessors of A in the landmark graph have been accepted, and
  - A becomes true in s
- Once a landmark has been accepted, it remains accepted

Required Again Landmarks

- A landmark A is required again by path π in state s if:

  false-goal: A is false in s and is a goal, or

  open-prerequisite: A is false in s and is a greedy-necessary predecessor of some landmark B that is not accepted

- It's also possible to use (Buffet and Hoffmann, 2010):

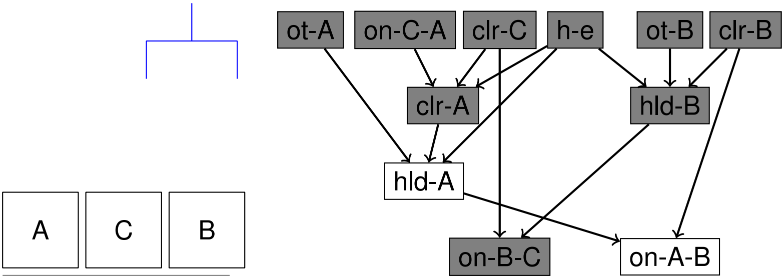
  doomed-goal: A is true in s and is a goal, but one of its greedy-necessary successors was not accepted, and is inconsistent with A

- Unsound rule:

  required-ancestor: is the transitive closure of *open-prerequisite*

Accepted and Required Again Landmarks - Example

- In the Sussman anomaly, after performing: Pickup-B, Stack-B-C, Unstack-B-C, Putdown-B, Unstack-C-A, Putdown-C



- on-B-C is a *false-goal*, and so it is required again

Problems With Reasonable Orderings

- Heuristic value of a goal state may be non-zero
  (if the plan found does not obey all reasonable orderings, and consequently not all landmarks are accepted).
  Solution: explicitely test states for goal condition
- The definition of reasonable orderings allows an ordering $A \rightarrow_r B$ if A and B become true simultaneously.
  Two solutions:
  - Accept a landmark if it has been made true at the same time as its predecessor (Buffet and Hoffmann, 2010)
  - Modify the definition of reasonable orderings to disallow such orderings

Outline

Admissible Heuristic Estimates

- LAMA's heuristic: the number of landmarks that still need to be achieved (Richter, Helmert and Westphal 2008)
- LAMA's heuristic is inadmissible - a single action can achieve multiple landmarks
  - Example: *hand-empty* and *on-A-B* can both be achieved by *stack-A-B*
- Admissible heuristic: assign a cost to each landmark, sum over the costs of landmarks (Karpas and Domshlak, 2009)

Conditions for Admissibility

- Each action shares its cost between all the landmarks it achieves

$$\forall a \in \mathscr{A} : \sum_{B \in L(a|s,\mathscr{P})} cost(a, B) \leq \mathrm{C}(a)$$

$cost(a, B)$: cost “assigned” by action a to B
$L(a|s, \mathscr{P})$: the set of landmarks achieved by a

- Each landmark is assigned at most the cheapest cost any action assigned it

$$\forall B \in L(s, \mathscr{P}) : \ cost(B) \leq \min_{a \in \mathrm{ach}(B|s,\mathscr{P})} cost(a, B)$$

$cost(B)$: cost assigned to landmark B
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Admissible Cost Sharing

- Idea: the cost of a set of landmarks is no greater than the cost of any single action that achieves them
- Given that, the sum of costs of landmarks that still need to be achieved is an admissible heuristic, h_L

$$h_L(s,\pi) := cost(L(s,\pi)) = \sum_{B \in L(s,\pi)} cost(B)$$

- Proof: left up to the reader $\ddot\smile$

Cost Partitioning - how?

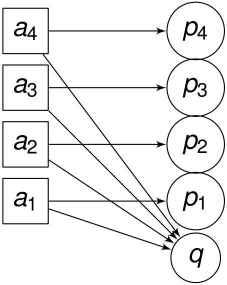
- How can we find such a partitioning?
- Easy answer - uniform cost sharing - each action shares its cost equally between the landmarks it achieves

$$cost(a, B) = \frac{C(a)}{|L(a|s, \pi)|}$$

$$cost(B) = \min_{a \in \text{ach}(B|s,\pi)} cost(a, B)$$

Uniform Cost Sharing

- Advantage: Easy and fast to compute
- Disadvantage: can be much worse than the optimal cost partitioning



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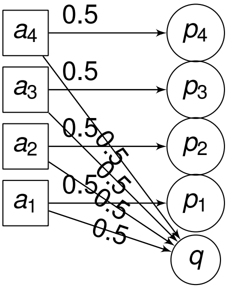

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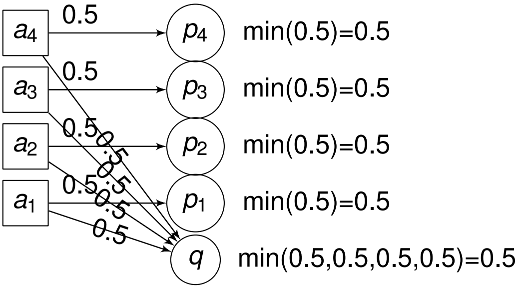

Uniform Cost Sharing

- Advantage: Easy and fast to compute
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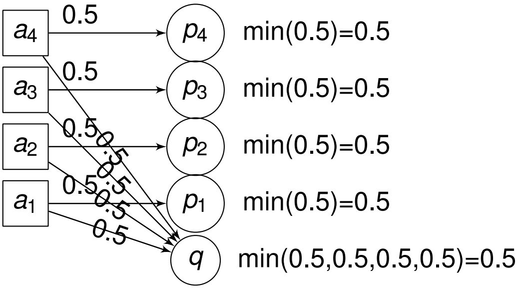
Uniform cost sharing $h_L = 2.5$



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- Advantage: Easy and fast to compute
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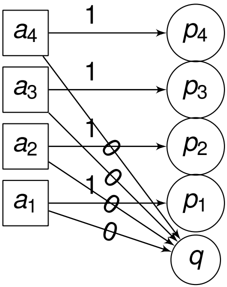
Optimal cost sharing

uniform $h_L = 2.5$



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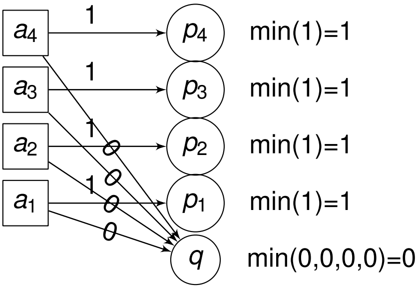
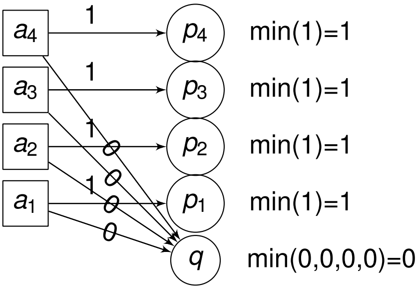


Uniform Cost Sharing

- Advantage: Easy and fast to compute
- Disadvantage: can be much worse than the optimal cost partitioning

Optimal cost sharing $h_L = 4$ uniform $h_L = 2.5$



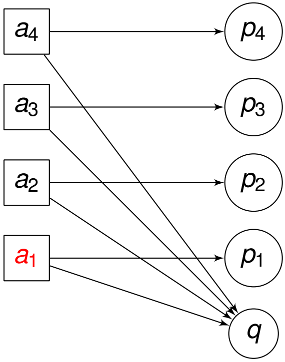
Optimal Cost Sharing

- The good news: the optimal cost partitioning is poly-time to compute
  - The constraints for admissibility are linear, and can be used in a Linear Program (LP)
  - Objective: maximize the sum of landmark costs
  - The solution to the LP gives us the optimal cost partitioning
- The bad news: poly-time can still take a long time

How can we do better?

- So far:
  - Uniform cost sharing is easy to compute, but suboptimal
  - Optimal cost sharing takes a long time to compute
- Q: How can we get better heuristic estimates that don't take a long time to compute?
- A: Exploit additional information - action landmarks

Using Action Landmarks - by Example



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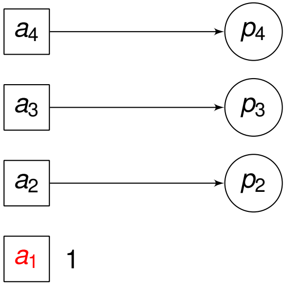
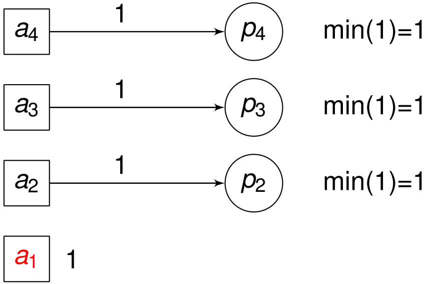


Using Action Landmarks - by Example

Uniform Cost Sharing

$h_{LA} = 4$



Outline

Using Landmarks to Enrich the Problem

- Landmarks are, in essence, implicit goals
- We can make these explicit by reformulating the planning problem
- Two different methods for doing this have been proposed (Wang, Baier and McIlraith, 2009 and Domshlak, Katz and Lefler, 2010)

Viewing Landmarks as Temporally Extended Goals

- Landmarks and their orderings can be viewed as temporally extended goals (Wang, Baier and McIlraith, 2009)
- These temporally extended goals can be expressed in Linear Temporal Logic (LTL)
- Each LTL formula can be compiled into a finite-state automaton
- Each FSA can be encoded as a single variable in an enriched planning problem

A Simpler Approach

- A simpler approach of encoding landmarks into a planning problem is to encode the landmarks directly (Domshlak, Katz and Lefler, 2010)
  - Each landmark is represented by a single binary state variable
  - The two values represent landmark accepted / not accepted
  - Each action that achieves the landmark has an additional effect added to it, changing the landmark variable value to accepted
  - The accepting value of each landmark variable is added to the goal state

Why Enrich Problems?

- Landmarks and orderings are implicit, encoding them into the problem makes them explicit
- Allows other heuristics to use landmark information
- Example: structural pattern heuristic on the enriched problem accounts not only for explicit goals (Domshlak, Katz and Lefler, 2010)
- In fact, the landmark count heuristic can be seen as the goal count heuristic on the landmark enriched problem
- Caveat - since current landmark discovery procedures are based on delete-relaxation, this adds no information to delete-relaxation based heuristics

Outline

Landmarks in Probabilistic Planning

- Landmarks can also be adapted to probabilistic planning (Buffet and Hoffmann, 2010)
- In a probabilistic planning task, a landmark is a fact which must be true in every successful trajectory (possible execution)
- Using the landmark count heuristic in FPG yields good results

Outline

Summary

- Landmarks provide a way to utilize the implicit structure of a planning problem
- They can (and have been) used successfully for both satisficing and optimal planning

Challenges

- Discover more landmarks and orderings using different techniques (why use only relaxed planning?)
- Discover and exploit more complex types of landmarks (conjunctive, CNF, first order logic . . .)
- Discover and exploit landmarks in a problem-independent manner (for example, in Logistics - a package that is not at its destination must always be loaded on a truck or an airplane)

More Challenges

- A landmark / ordering must be true in every plan
- An optimal landmark / ordering must be true in every optimal plan
  - All landmarks are also optimal landmarks, but can we find facts which are optimal landmarks and NOT landmarks?
- An existential landmark / ordering must be true in a plan
  - We must be careful not to mix between existential landmarks from different plans
- An existential optimal landmark / ordering must be true in an optimal plan

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Thank You

Enjoy ICAPS!

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