Automated Action Planning

Implicit Planning Task Structure: Landmark Heuristics

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Finite Domain Representation (FDR) Language

Definition (FDR planning tasks)

An FDR planning task is a tuple $\Pi = \langle V, A, I, G \rangle$

- V is a finite set of state variables with finite domains $dom(v_i)$
- initial state I is a complete assignment to V
- goal G is a partial assignment to V
- A is a finite set of actions a specified via pre(a) and eff(a), both being partial assignments to V

In cost-sensitive planning, each action a is also associated with a cost $C(a)$

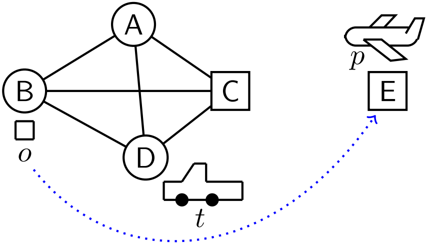
Landmarks

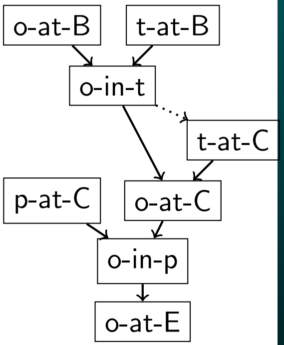
- A landmark is a formula that must be true at some point in every plan
- Landmarks can be (partially) ordered according to the order in which they must be achieved
- Some landmarks and orderings can be discovered automatically
- Most current approaches consider only landmarks that are facts or disjunctions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

Action Landmarks

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

Example Planning Problem - Logistics





Partial landmarks graph

Sound Landmark Orderings

Sound landmark orderings are guaranteed to hold - they do not prune the solution space

- *Natural* ordering $A \rightarrow B$, iff A true some time before B
- *Necessary* ordering $A \rightarrow_n B$, iff A always true one step 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 $A \rightarrow_n B \implies A \rightarrow_{gn} B \implies A \rightarrow B$

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 operators that achieve this fact is unsolvable

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

Landmark Discovery in Theory

Theory

- A is a landmark $\iff \Pi'_A$ is unsolvable
  where Π'_A is Π without the operators that achieve A

- The delete relaxation of Π'_A is unsolvable $\implies \Pi'_A$ is unsolvable (delete-relaxation landmarks)
- An abstraction of Π'_A is unsolvable $\implies \Pi'_A$ is unsolvable (abstraction landmarks)

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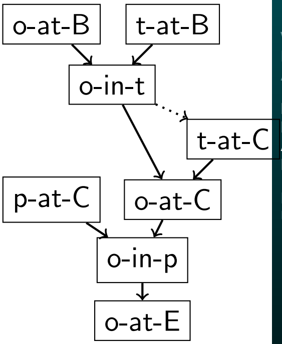
Landmark Discovery I

Delete Relaxation Landmarks

Find landmarks and orderings by backchaining

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

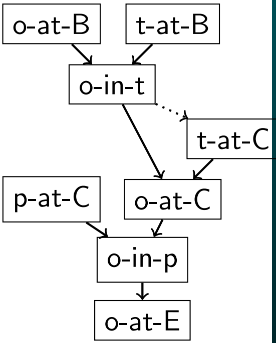


Useful restriction: consider only the case where B is achieved for the first time $\leadsto$ find more landmarks (and $A \rightarrow_{\mathrm{gn}} B$)

Landmark Discovery I
Delete Relaxation Landmarks

PSPACE-complete to find first achievers
$\rightsquigarrow$ 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 $\rightsquigarrow$ possible first achievers



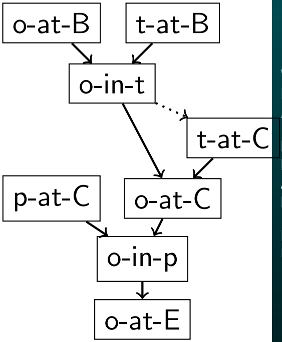
Additionally, if C not in the graph and C later proven to be a landmark, introduce $B \rightarrow C$

Landmark Discovery I

Delete Relaxation Landmarks

Disjunctive landmarks also possible, e.g., (o-in-$\mathrm{p}_1 \vee$ 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)

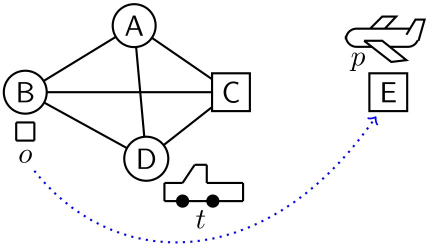
Find landmarks through DTGs (Richter et al. 2008)

The domain transition graph of $v \in V$ (DTG$_v$) represents how the value of v can change.

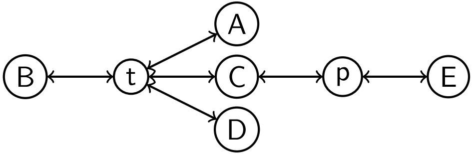
Given: an FDR task $\langle V, A, s_0, G \rangle$
DTG$_v$ is a directed graph with nodes $\mathcal{D}_v$ that has arc $\langle d, d' \rangle$ iff

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

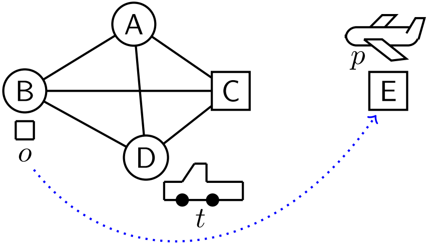
DTG Example



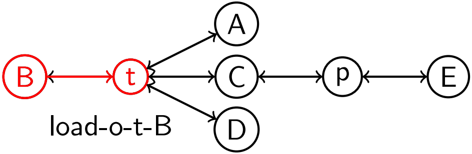
DTG$_{v_o}$:



DTG Example

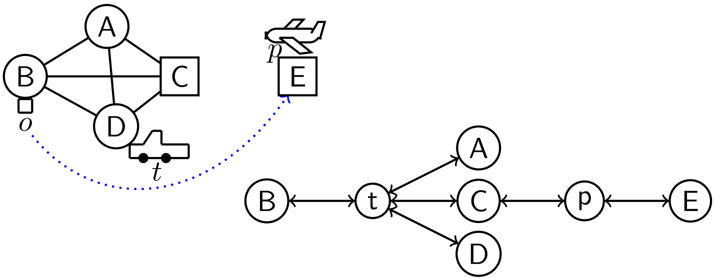


DTG_{v_o}:



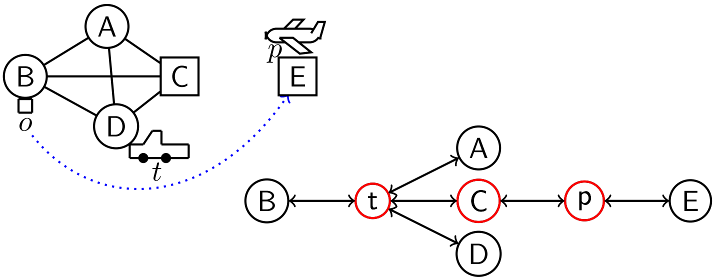
Landmark Discovery II

Abstraction Landmarks



- 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 $\quad (v \mapsto d') \;\rightarrow\; (v \mapsto d)$



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Using Landmarks

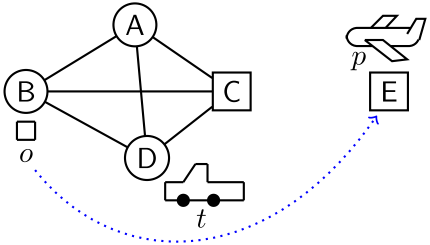
- Some landmarks and orderings can be discovered efficiently
- So what can we do once we have these landmarks?

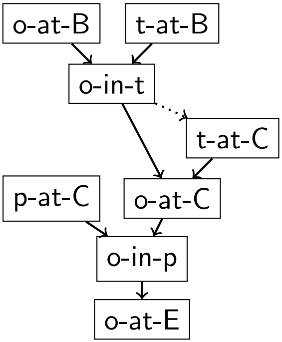
- We assume that landmarks and orderings are discovered in a pre-processing phase, and the same landmark graph is used throughout the planning phase

Using Landmarks as Subgoals

- Landmarks can be used as subgoals for a base planner
- The first layer of landmarks that have not yet been achieved is passed as a disjunctive goal to a base planner

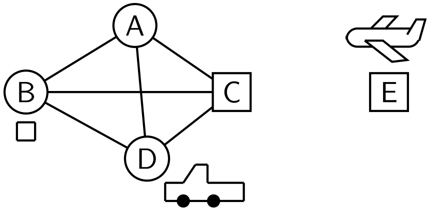
Using Landmarks as Subgoals - Logistics Example

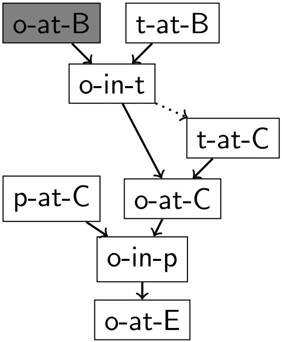




- Partial plan:
- Goal:

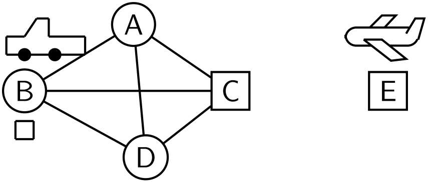
Using Landmarks as Subgoals - Logistics Example

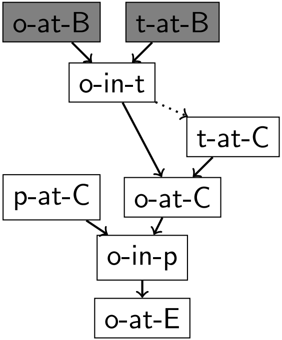




- Partial plan: $\emptyset$
- Goal: t-at-B $\vee$ p-at-C

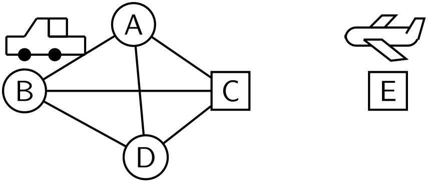
Using Landmarks as Subgoals - Logistics Example

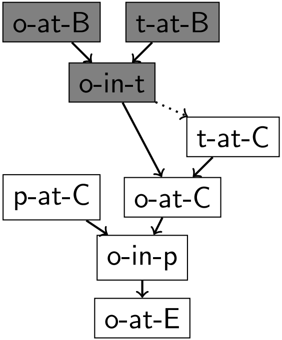




- Partial plan: Drive-t-B
- Goal: o-in-t $\vee$ p-at-C

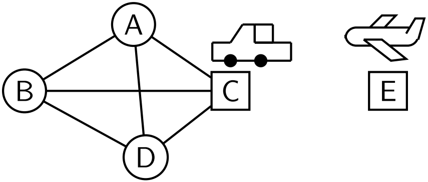
Using Landmarks as Subgoals - Logistics Example

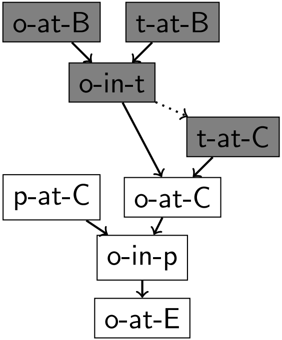




- Partial plan: Drive-t-B, Load-o-B
- Goal: t-at-C $\vee$ p-at-C

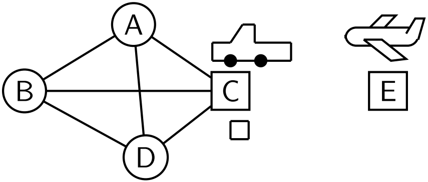
Using Landmarks as Subgoals - Logistics Example

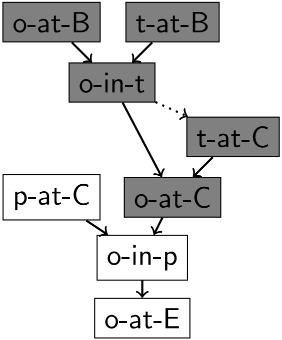




- Partial plan: Drive-t-B, Load-o-B, Drive-t-C
- Goal: o-at-C $\vee$ p-at-C

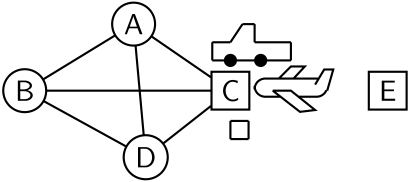
Using Landmarks as Subgoals - Logistics Example

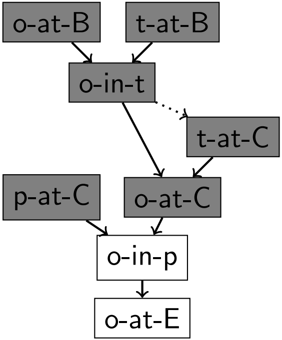




- Partial plan: Drive-t-B, Load-o-B, Drive-t-C, Unload-o-C
- Goal: p-at-C

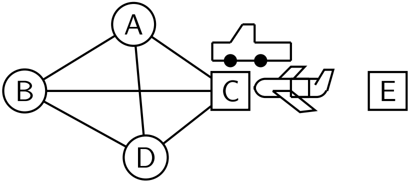
Using Landmarks as Subgoals - Logistics Example

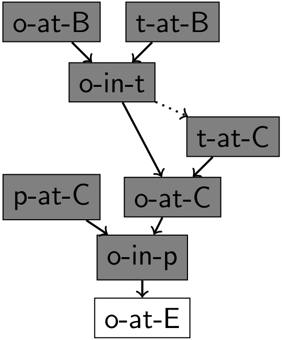




- Partial plan: Drive-t-B, Load-o-B, Drive-t-C, Unload-o-C, Fly-p-C
- Goal: o-in-p

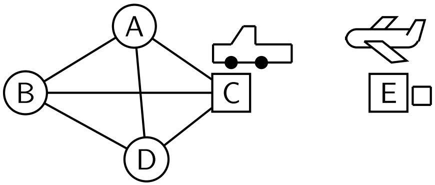
Using Landmarks as Subgoals - Logistics Example

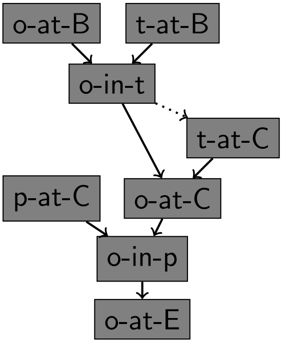




- Partial plan: Drive-t-B, Load-o-B, Drive-t-C, Unload-o-C, Fly-p-C, Load-o-p
- Goal: o-at-E

Using Landmarks as Subgoals - Logistics Example



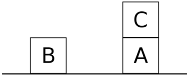


- Partial plan: Drive-t-B, Load-o-B, Drive-t-C, Unload-o-C, Fly-p-C, Load-o-p, Fly-p-E, Unload-o-E
- Goal: $\emptyset$

Using Landmarks as Subgoals

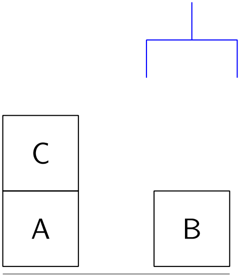
- That was a good example
- Now let's see a bad one

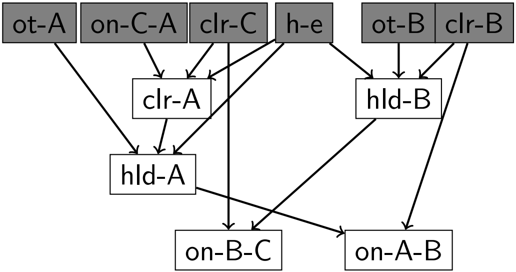
Using Landmarks as Subgoals - Sussman Example

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

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

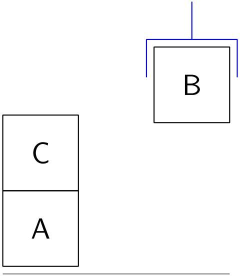
Using Landmarks as Subgoals - Sussman Example

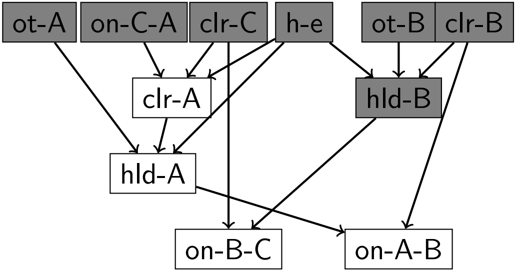




- Partial plan: $\emptyset$
- Goal: clear-A $\vee$ holding-B

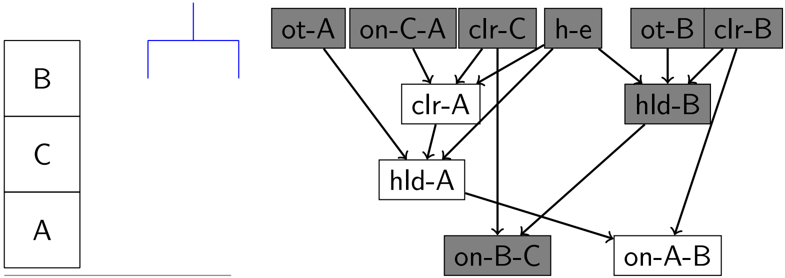
Using Landmarks as Subgoals - Sussman Example





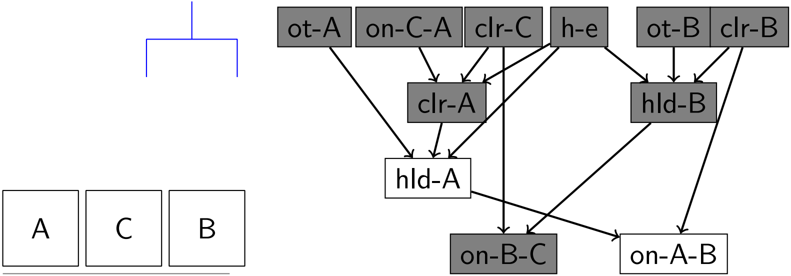
- Partial plan: Pickup-B
- Goal: clear-A $\vee$ on-B-C

Using Landmarks as Subgoals - Sussman Example



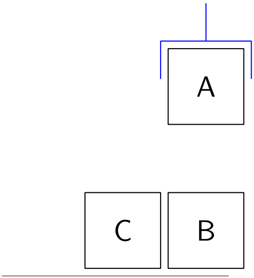
- Partial plan: Pickup-B, Stack-B-C
- Goal: clear-A

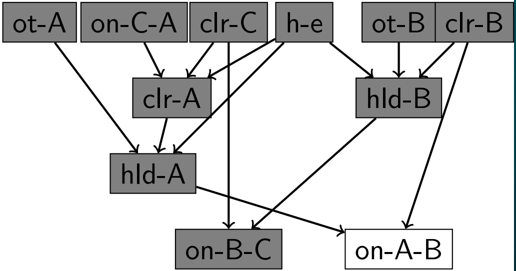
Using Landmarks as Subgoals - Sussman Example



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

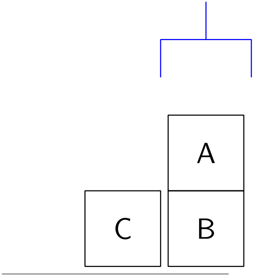
Using Landmarks as Subgoals - Sussman Example

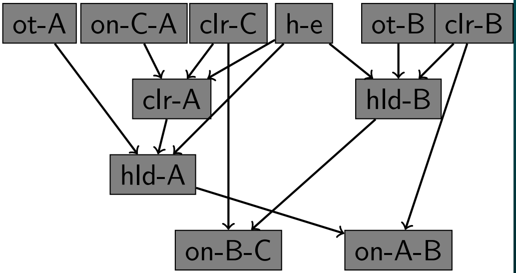




- Partial plan: Pickup-B, Stack-B-C, Unstack-B-C, Putdown-B, Unstack-C-A, Putdown-C, Pickup-A
- Goal: on-A-B

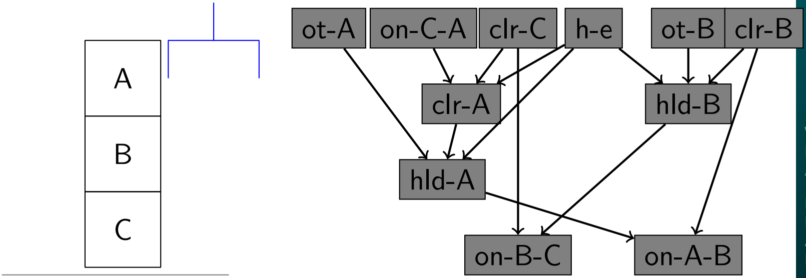
Using Landmarks as Subgoals - Sussman Example





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

Using Landmarks for Heuristic Estimates

- The number of landmarks that still need to be achieved is a heuristic estimate
- Used by LAMA (Richter, Helmert and Westphal 2008), winner of the IPC-2008 and IPC-2011 sequential satisficing track!