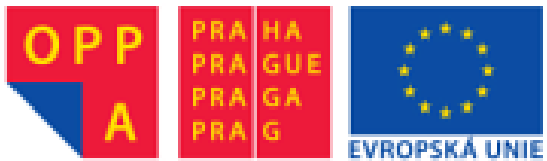
# Automated Action Planning

## Implicit Planning Task Structure: Landmark Heuristics

Carmel Domshlak



# 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 $C(a)$

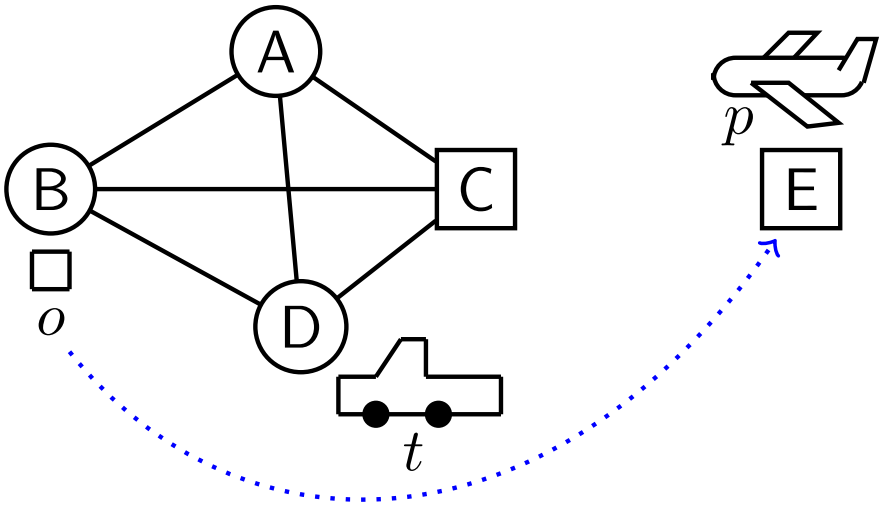
# Landmarks

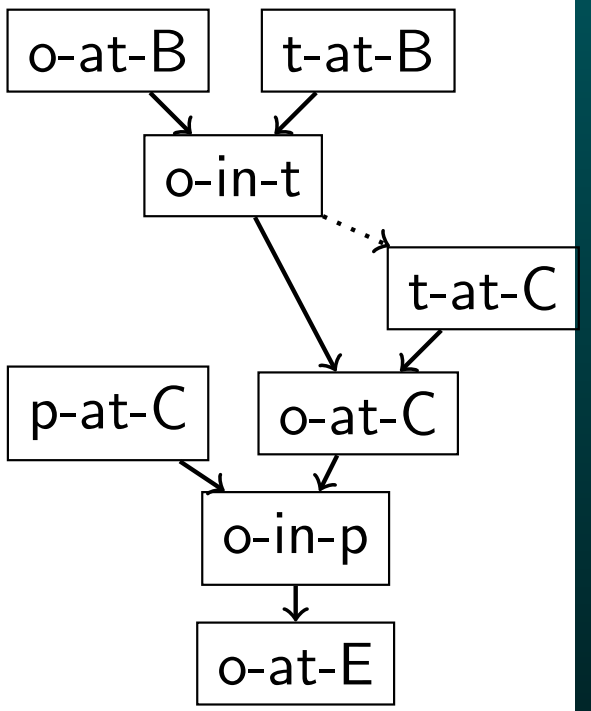
- A landmark is a formula that must be true at some point in every plan
- Landmarks can be (partially) ordered according to the order in which they must be achieved
- Some landmarks and orderings can be discovered automatically
- Most current approaches consider only landmarks that are facts or disjunctions 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 $\Pi'_A$ is $\Pi$ without the operators that achieve $A$

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

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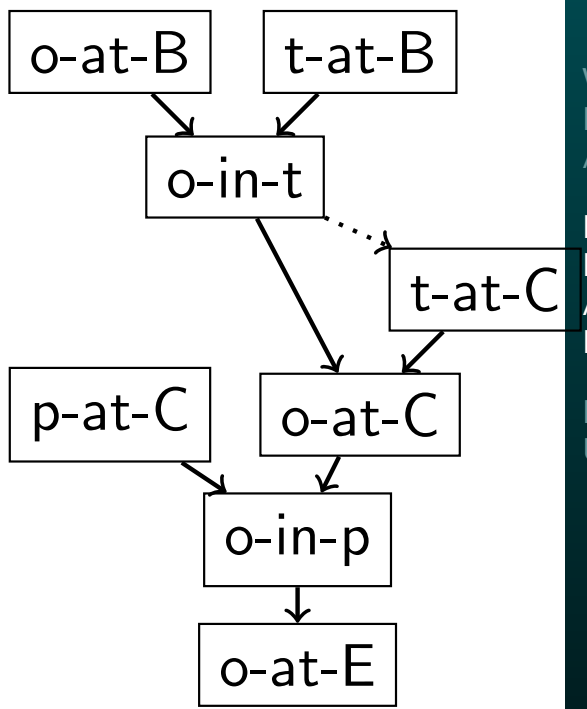
# Landmark Discovery I
## Delete Relaxation Landmarks

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
  - $A \rightarrow_n B$

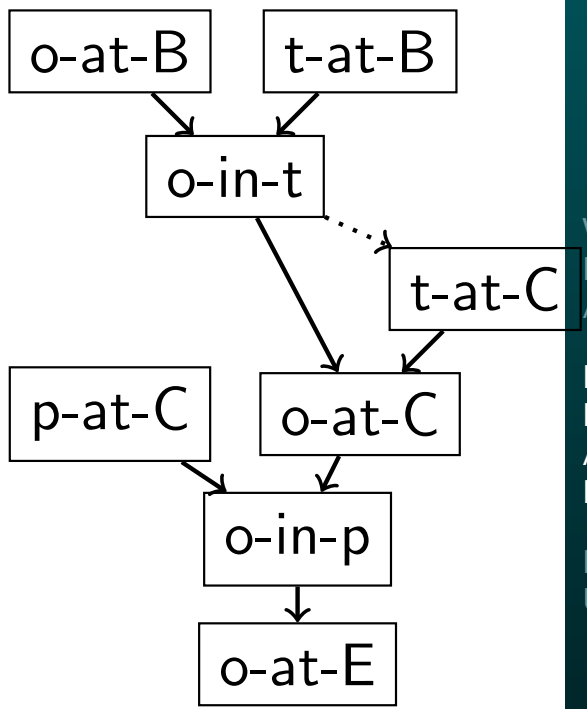



Useful restriction: consider only the case where $B$ is achieved for the first time $\rightsquigarrow$ find more landmarks (and $A \rightarrow_{\mathrm{gn}} B$)

# Landmark Discovery I
## Delete Relaxation Landmarks

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

- 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

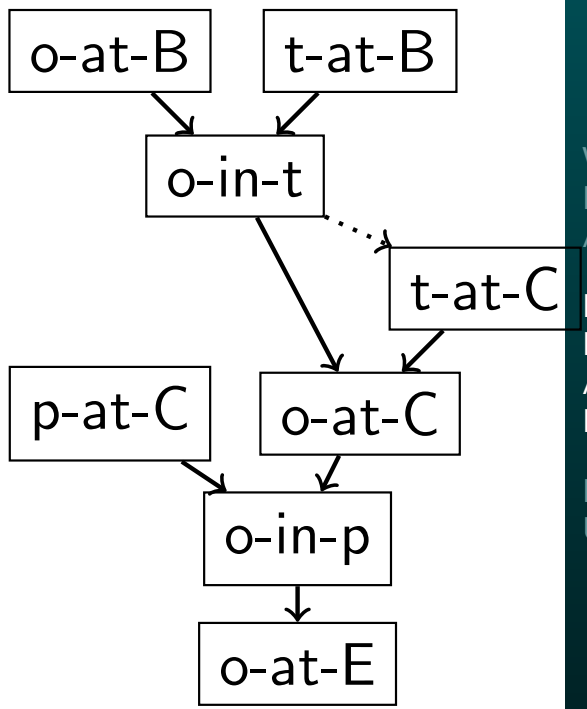



Additionally, if $C$ not in the graph and $C$ later proven to be a landmark, introduce $B \rightarrow C$

# Landmark Discovery I
## Delete Relaxation Landmarks

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

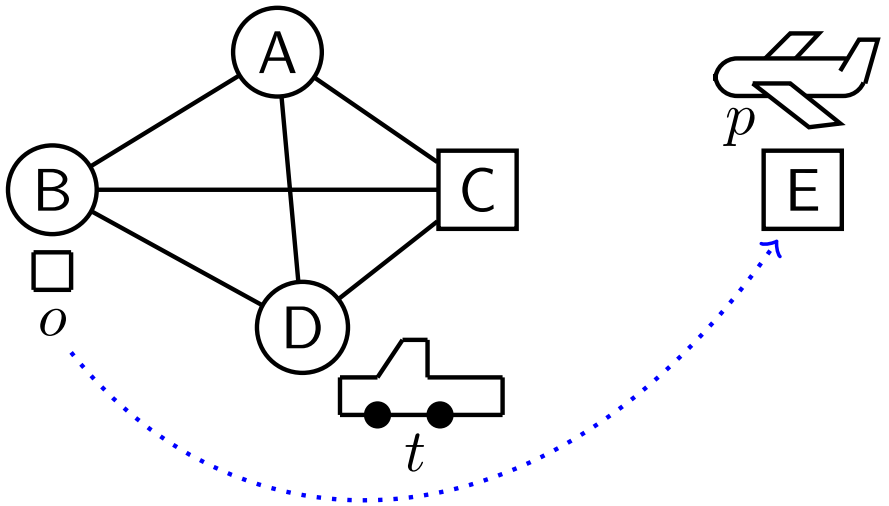
Find landmarks through DTGs (Richter et al. 2008)

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

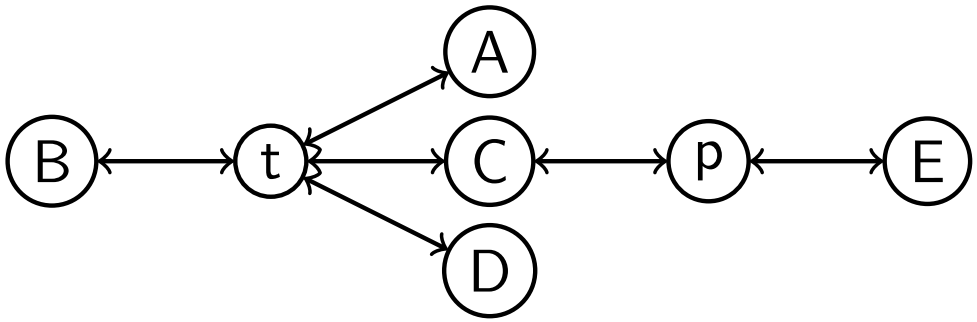
Given: an FDR task $\langle V, A, s_0, G \rangle$
$\text{DTG}_v$ is a directed graph with nodes $\mathcal{D}_v$ that has arc $\langle d, d' \rangle$ iff

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

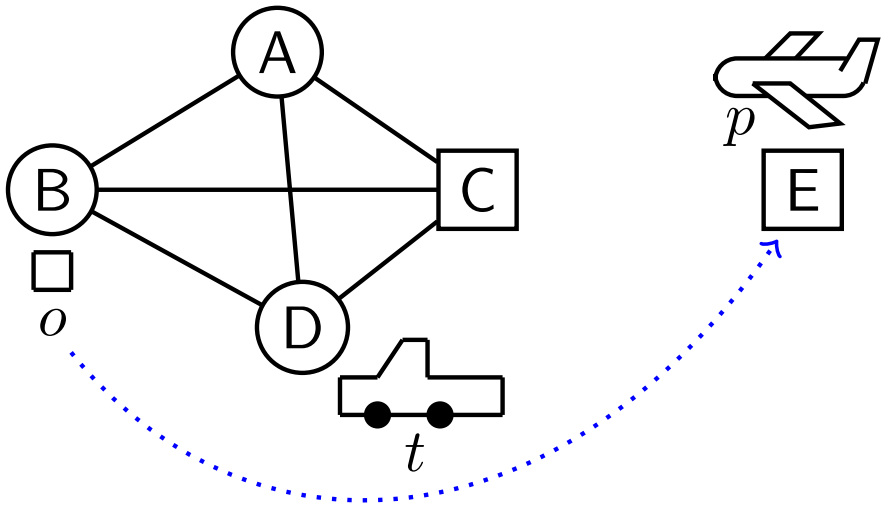
# DTG Example



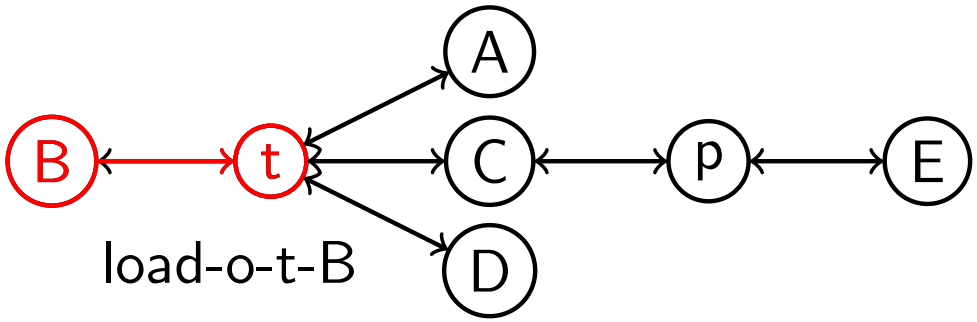

$DTG_{v_o}$:



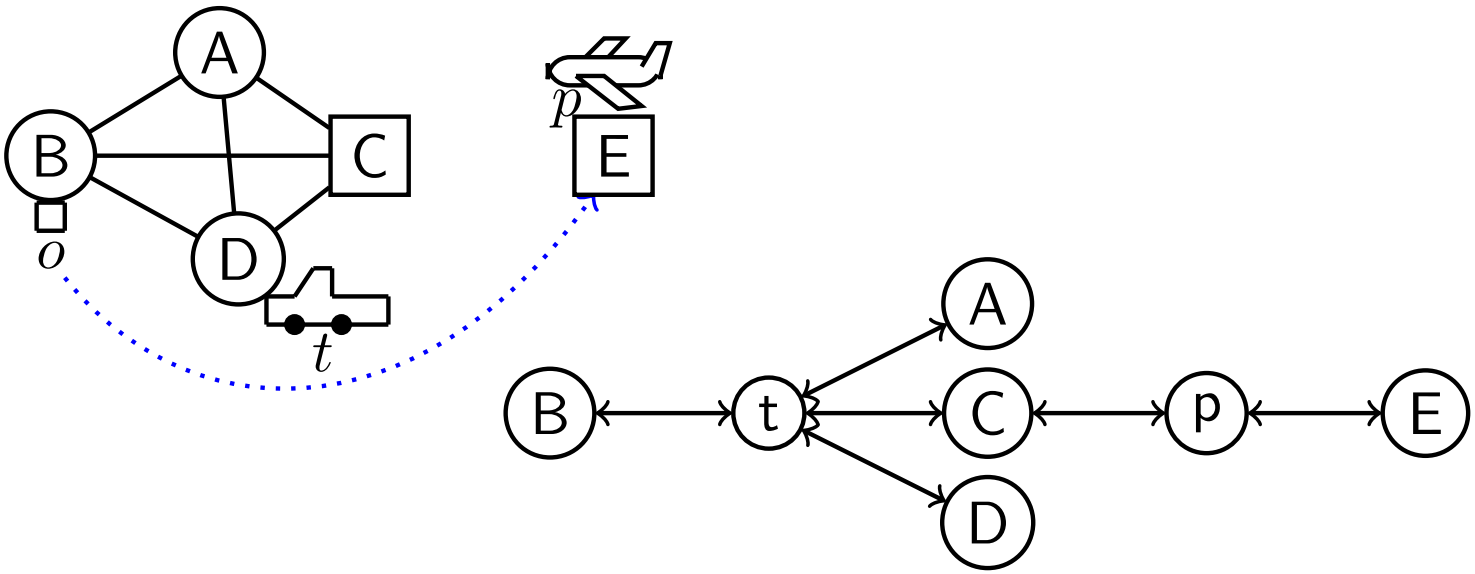
# DTG Example




$DTG_{v_o}$:



# 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 $(v \mapsto d') \rightarrow (v \mapsto d)$

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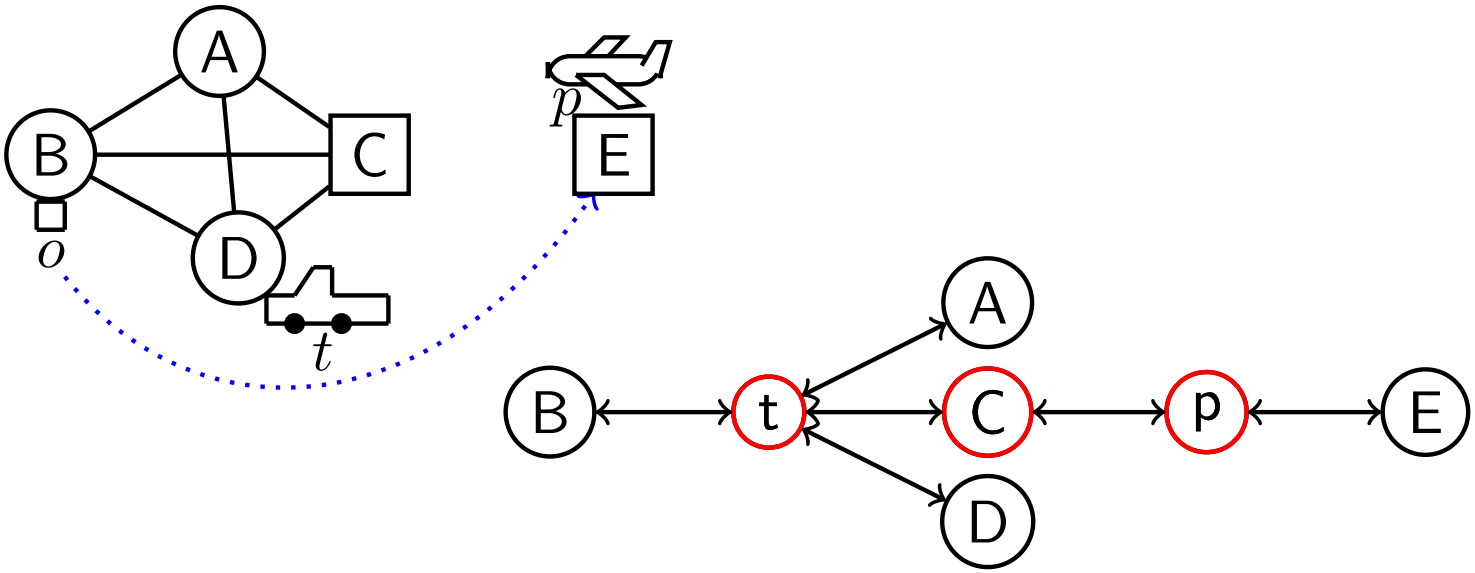
## Abstraction Landmarks

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  - $v \mapsto d$ landmark, and
  - every path from $d_0$ to $d$ passes through $d'$,

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

# Using Landmarks

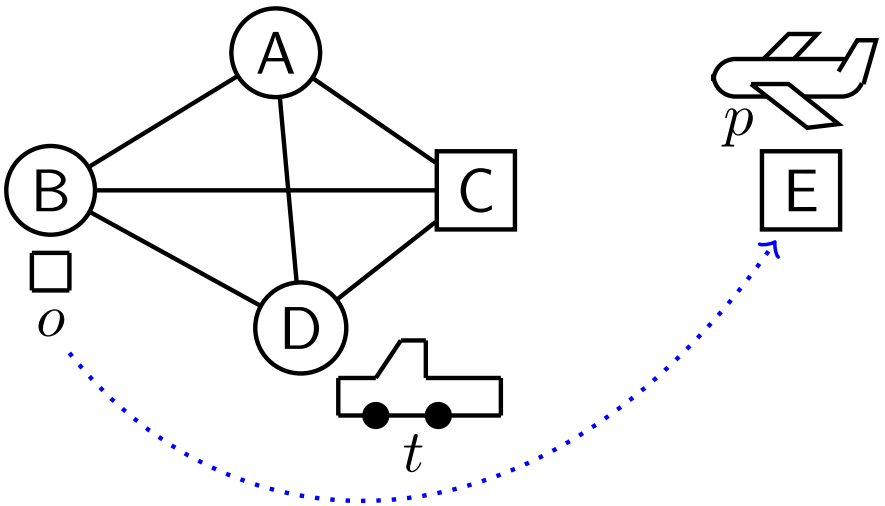
- Some landmarks and orderings can be discovered efficiently
- So what can we do once we have these landmarks?

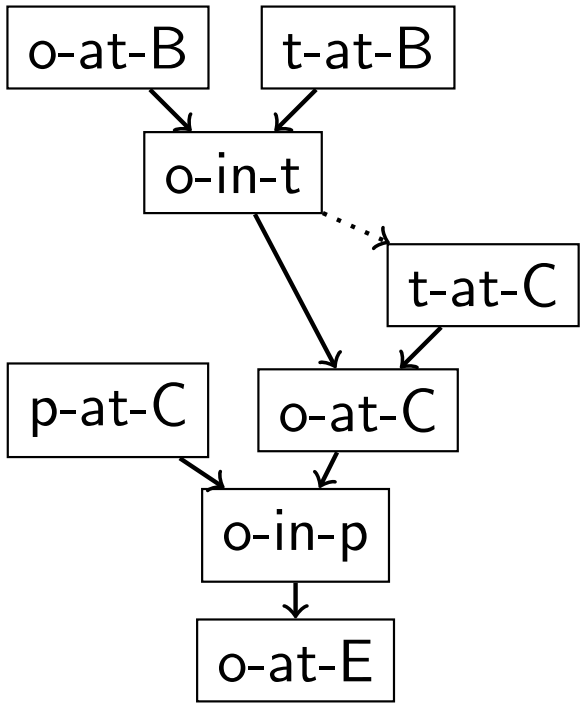
- We assume that landmarks and orderings are discovered in a pre-processing phase, and the same landmark graph is used throughout the planning phase

# 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

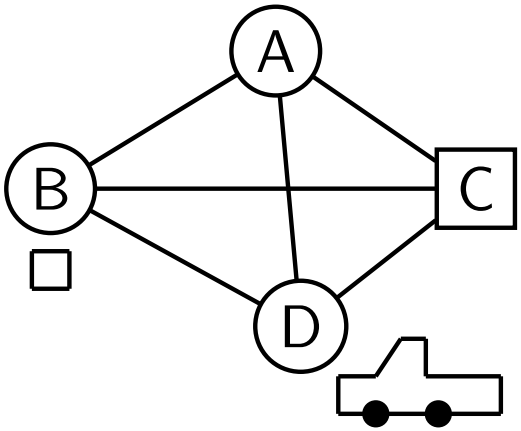
# Using Landmarks as Subgoals - Logistics Example

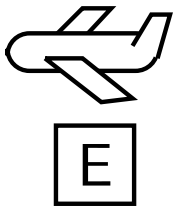


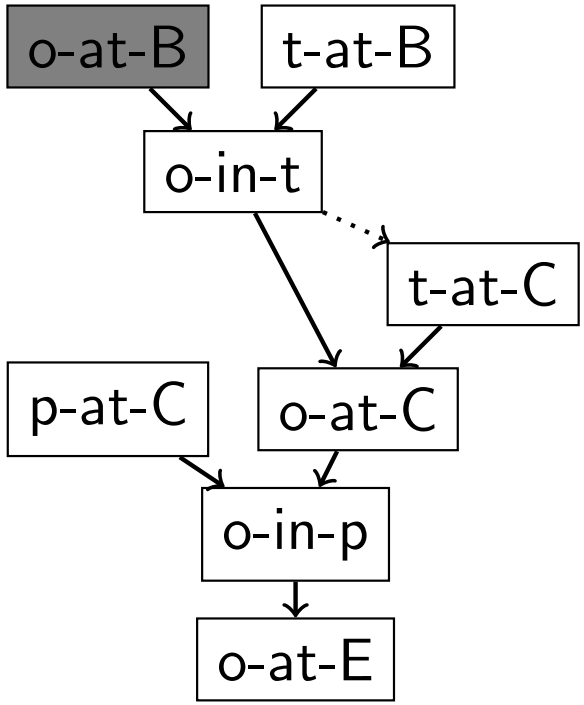




- Partial plan:
- Goal:

# Using Landmarks as Subgoals - Logistics Example

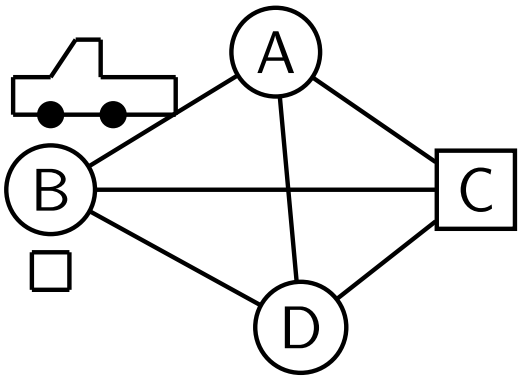


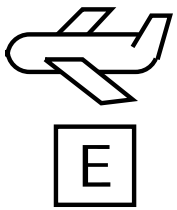



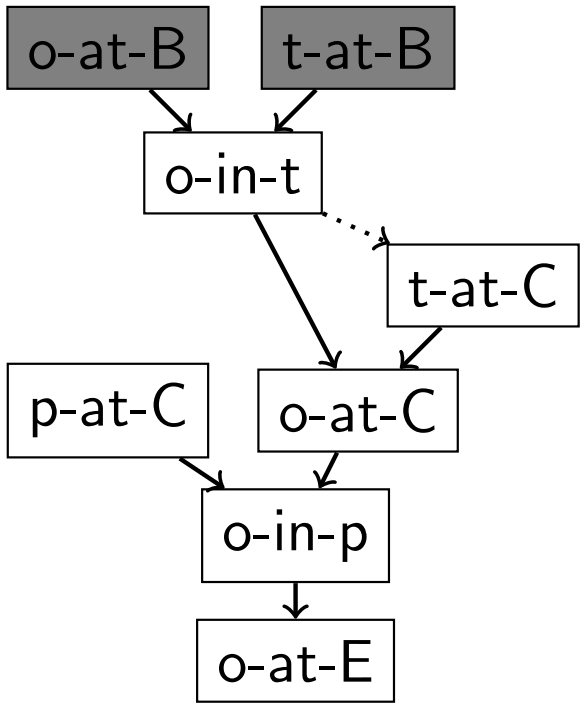




- Partial plan: $\emptyset$
- Goal: t-at-B $\vee$ p-at-C

# Using Landmarks as Subgoals - Logistics Example

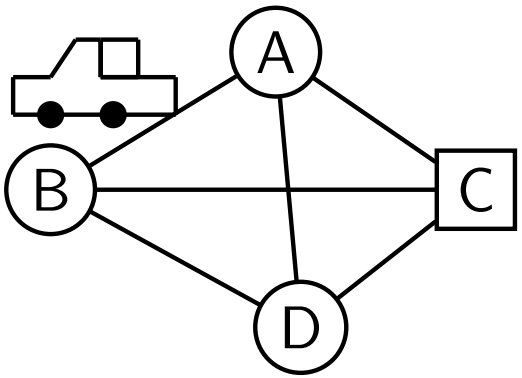


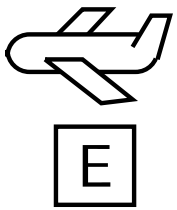



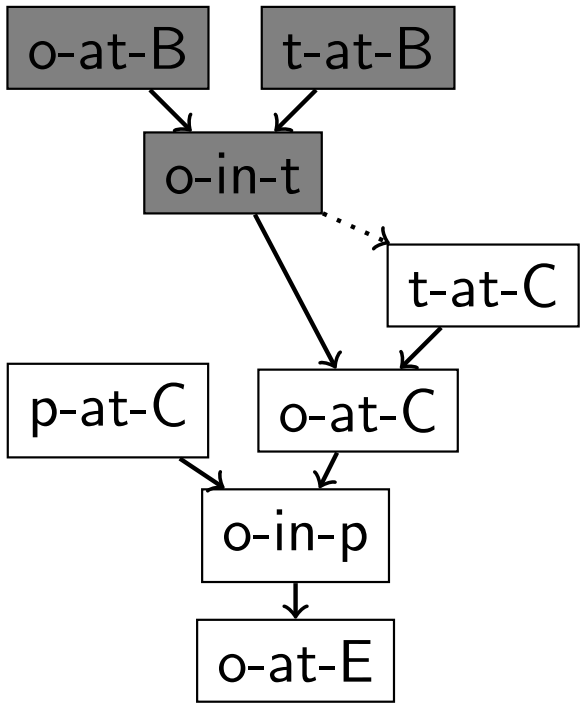




- Partial plan: Drive-t-B
- Goal: o-in-t $\vee$ p-at-C

# Using Landmarks as Subgoals - Logistics Example

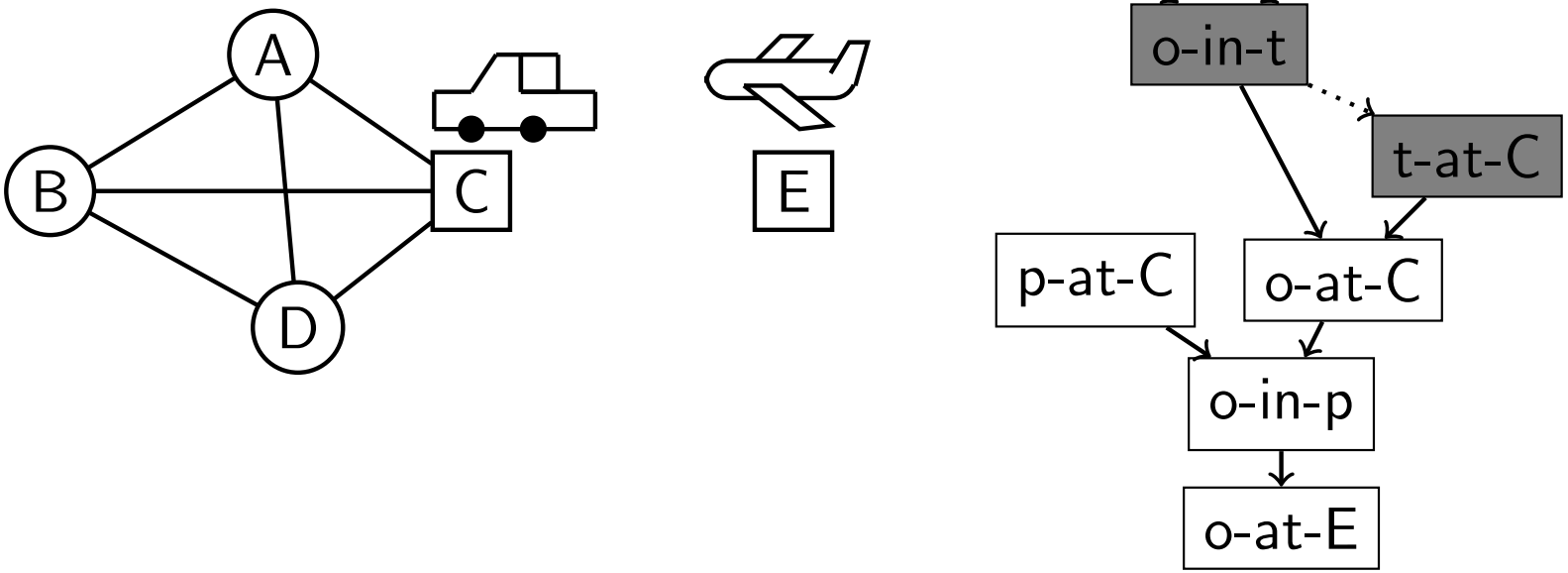


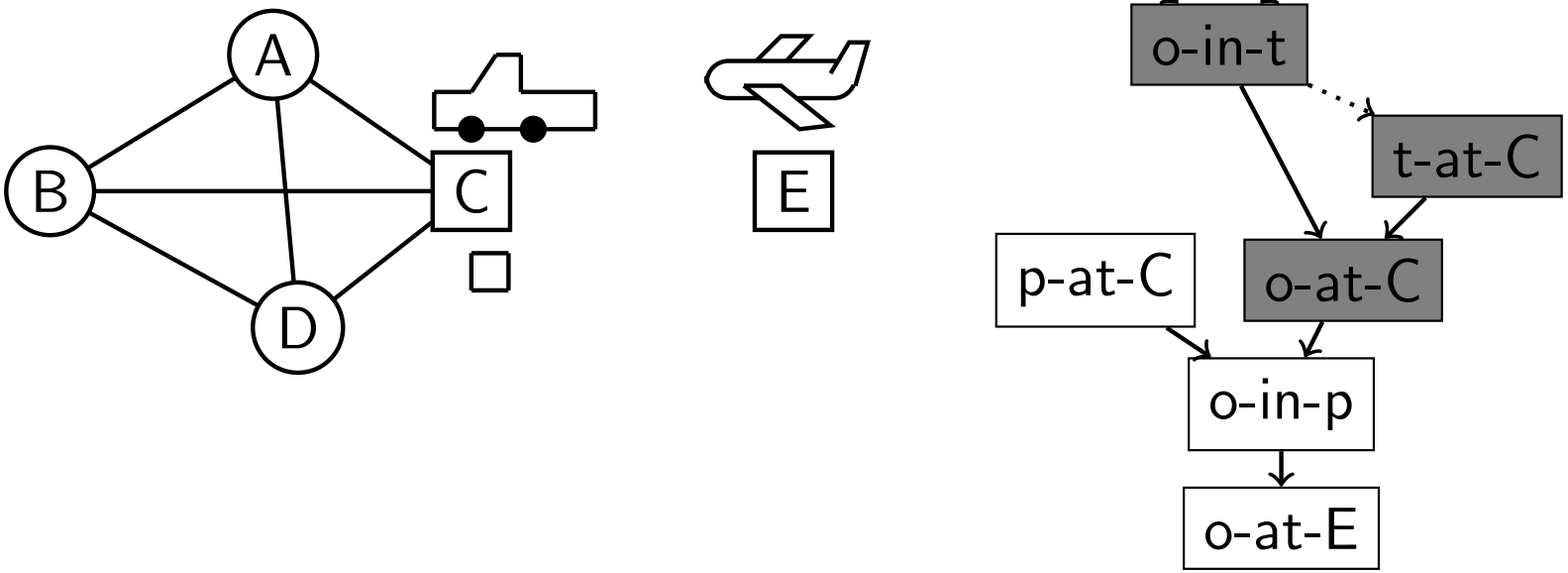

- Partial plan: Drive-t-B, Load-o-B
- Goal: t-at-C $\vee$ p-at-C

# Using Landmarks as Subgoals - Logistics Example



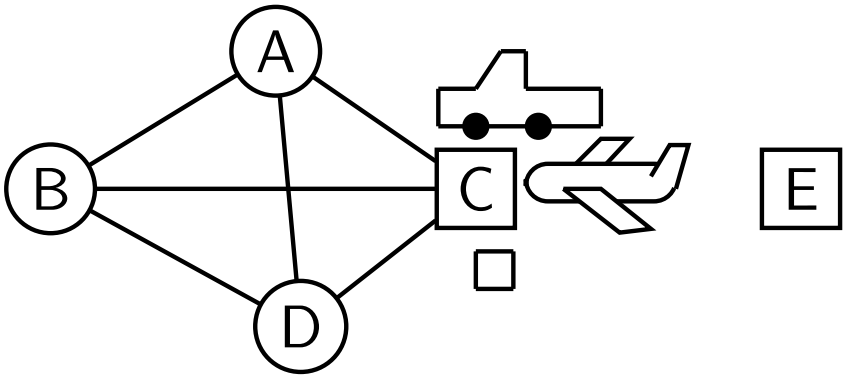

- Partial plan: Drive-t-B, Load-o-B, Drive-t-C
- Goal: o-at-C $\vee$ p-at-C

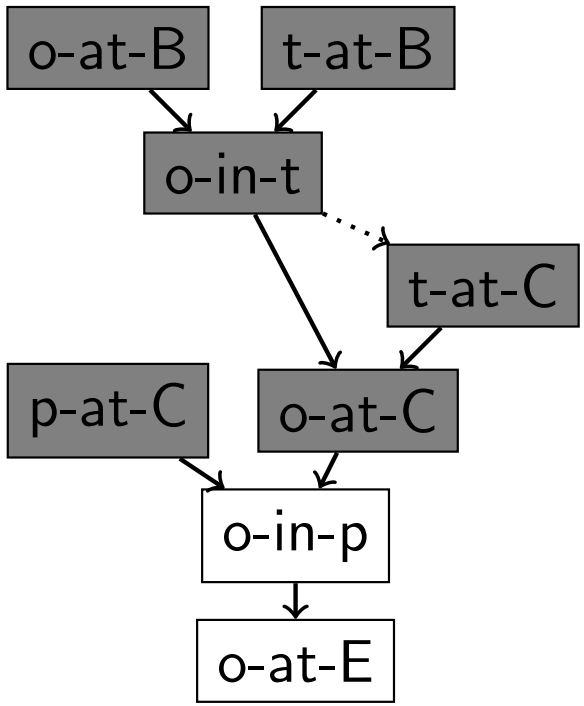
# Using Landmarks as Subgoals - Logistics Example




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

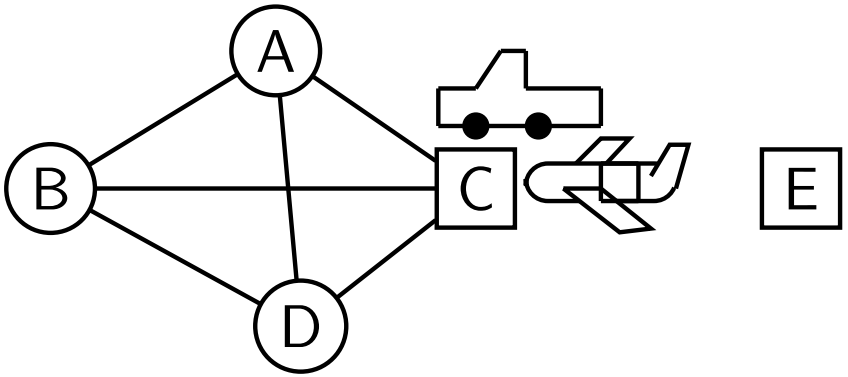
# Using Landmarks as Subgoals - Logistics Example

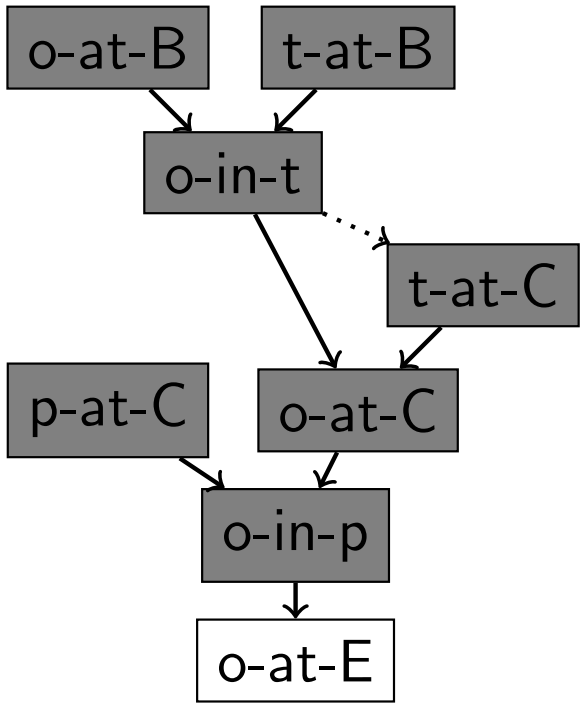



- Partial plan: Drive-t-B, Load-o-B, Drive-t-C, Unload-o-C, Fly-p-C
- Goal: o-in-p

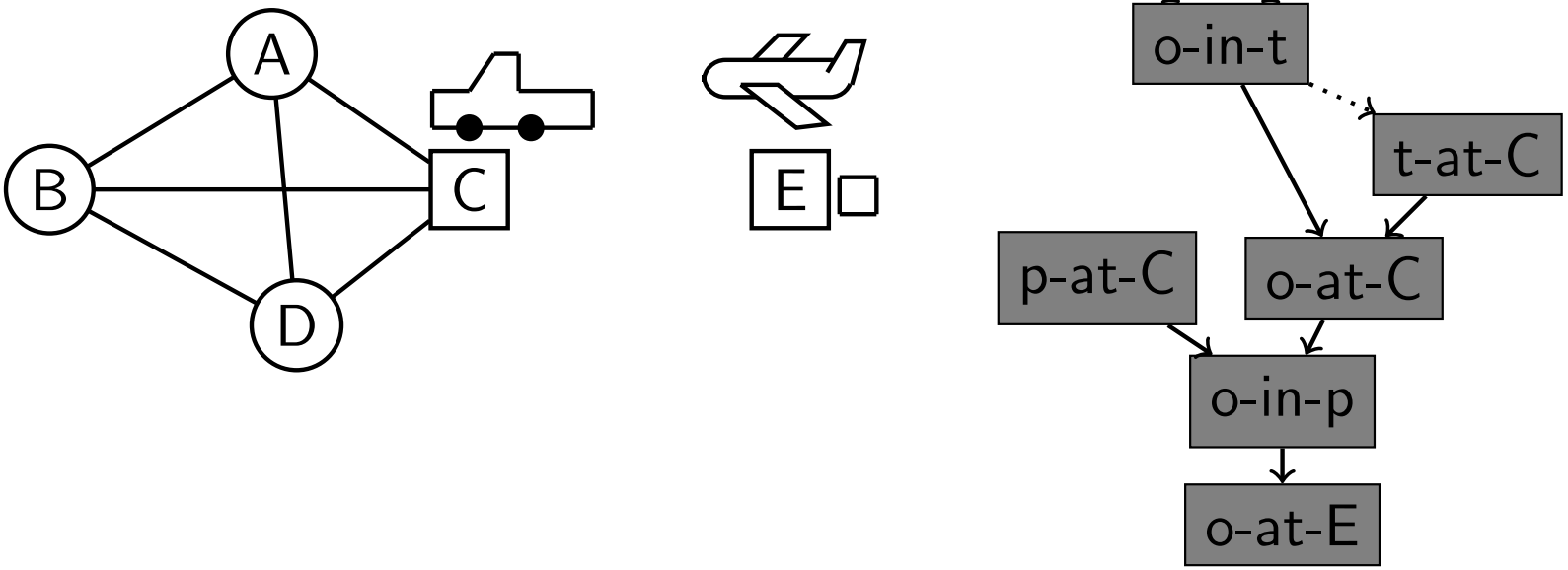
# Using Landmarks as Subgoals - Logistics Example




- 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

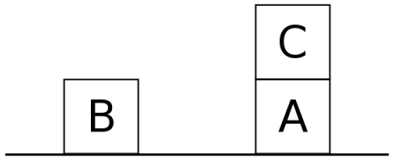



- Partial plan: Drive-t-B, Load-o-B, Drive-t-C, Unload-o-C, Fly-p-C, Load-o-p, Fly-p-E, Unload-o-E
- Goal: $\emptyset$

# Using Landmarks as Subgoals

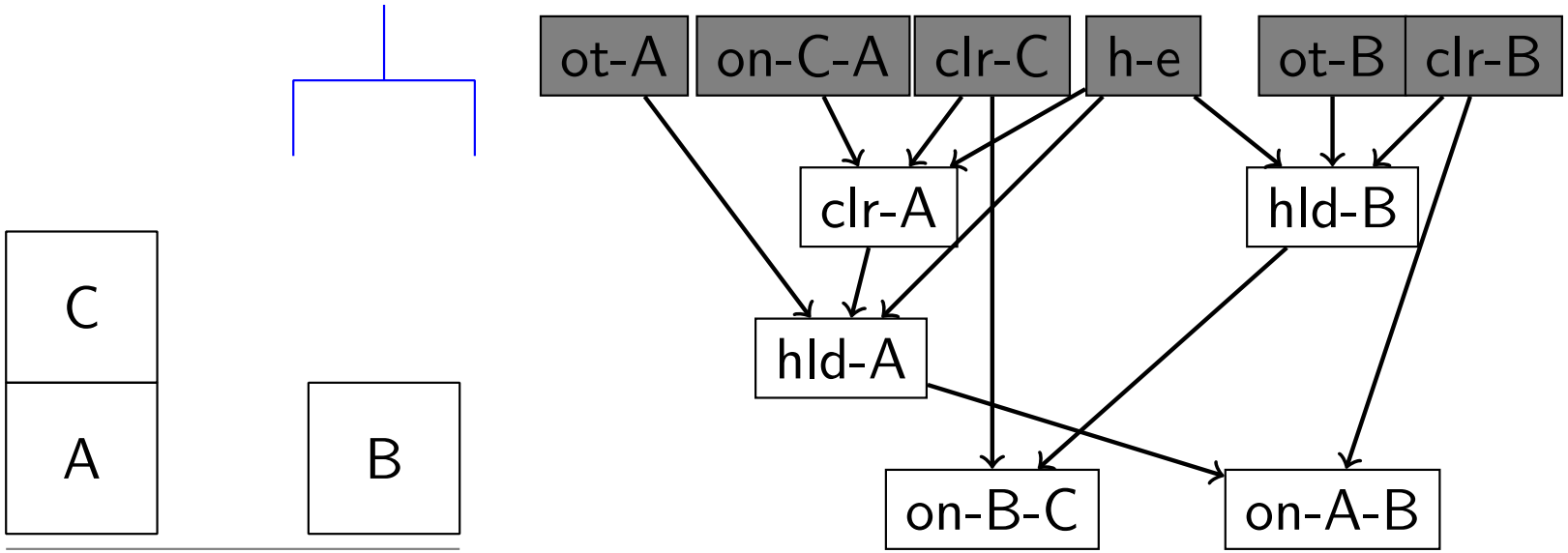
- That was a good example
- Now let's see a bad one

# Using Landmarks as Subgoals - Sussman Example

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

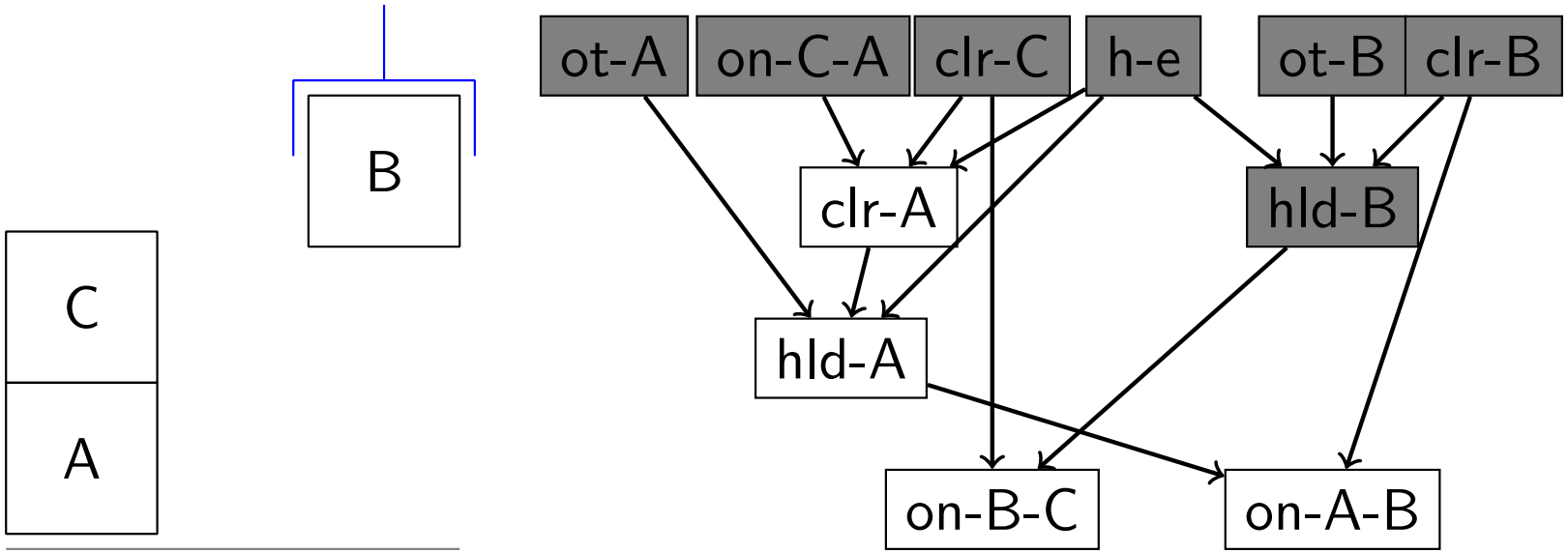
- Goal: *on-A-B*, *on-B-C*

# Using Landmarks as Subgoals - Sussman Example



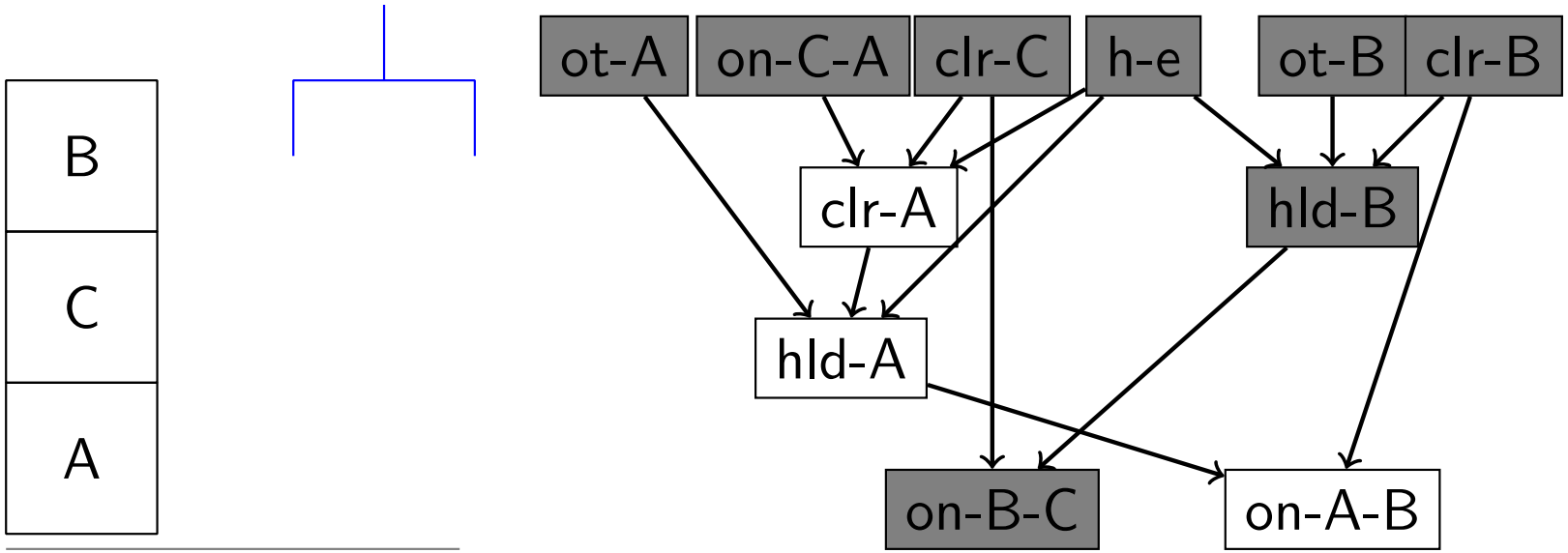

- Partial plan: $\emptyset$
- Goal: clear-A $\vee$ holding-B

# Using Landmarks as Subgoals - Sussman Example



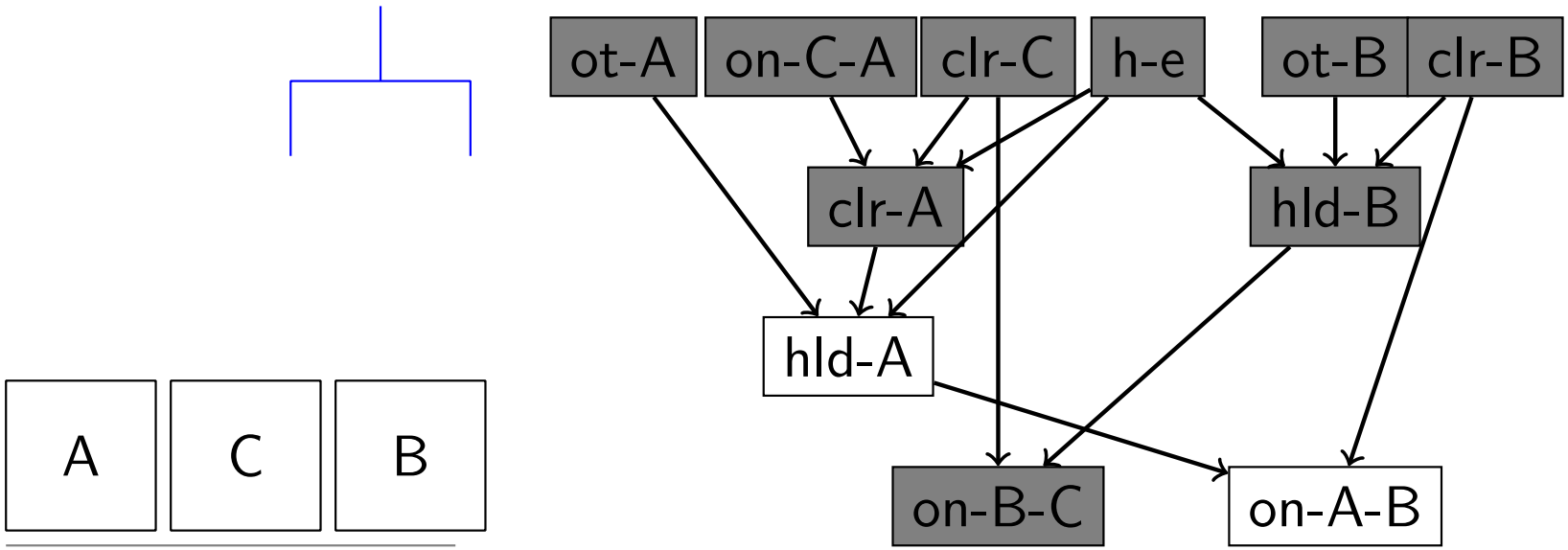

- Partial plan: Pickup-B
- Goal: clear-A $\vee$ on-B-C

# Using Landmarks as Subgoals - Sussman Example



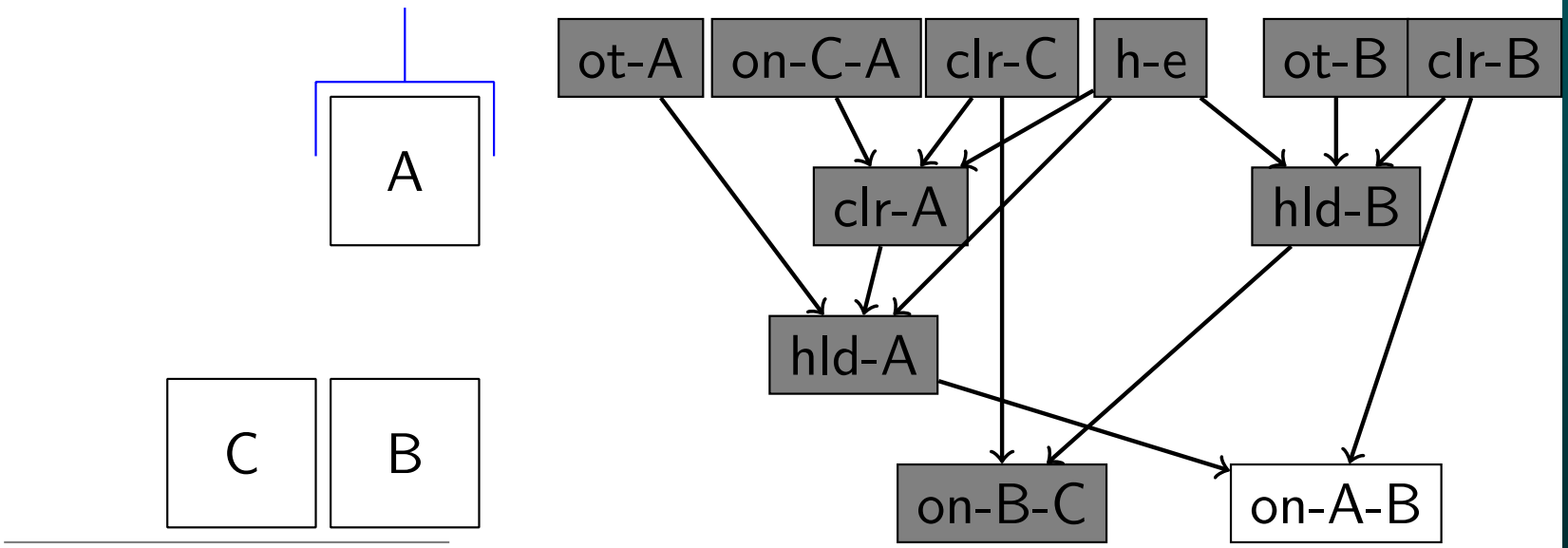

- Partial plan: Pickup-B, Stack-B-C
- Goal: clear-A

# Using Landmarks as Subgoals - Sussman Example



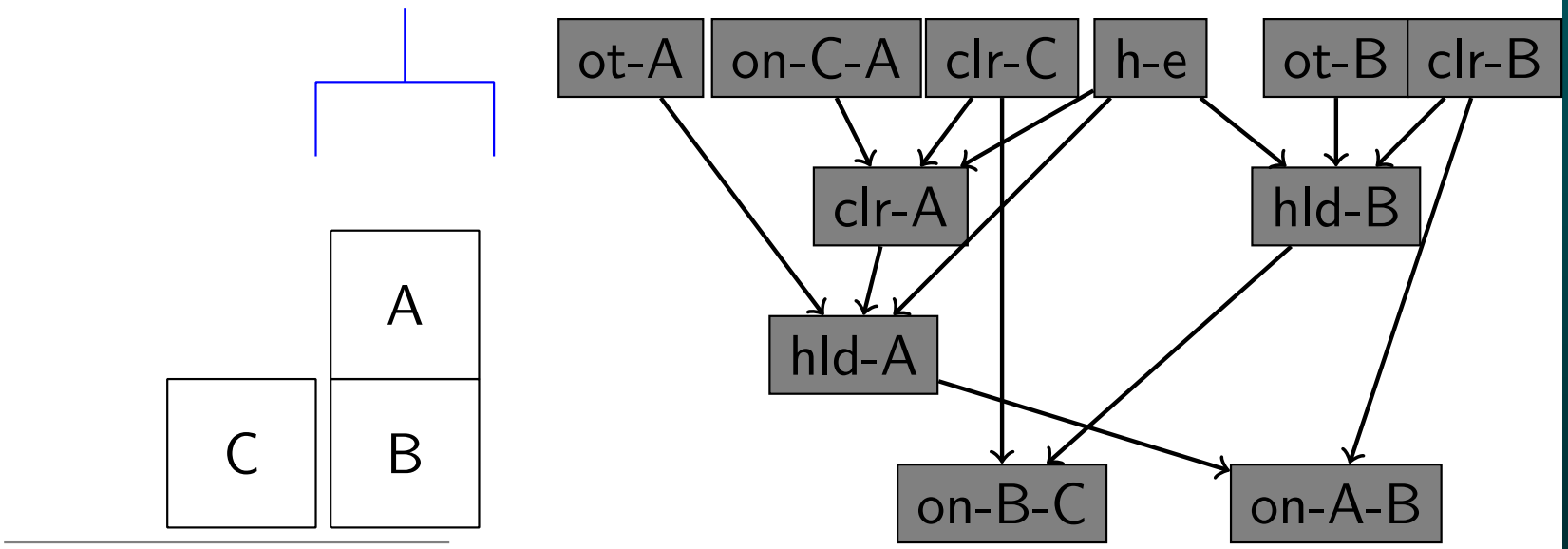

- Partial plan: Pickup-B, Stack-B-C, Unstack-B-C, Putdown-B, Unstack-C-A, Putdown-C
- Goal: holding-A

# Using Landmarks as Subgoals - Sussman Example



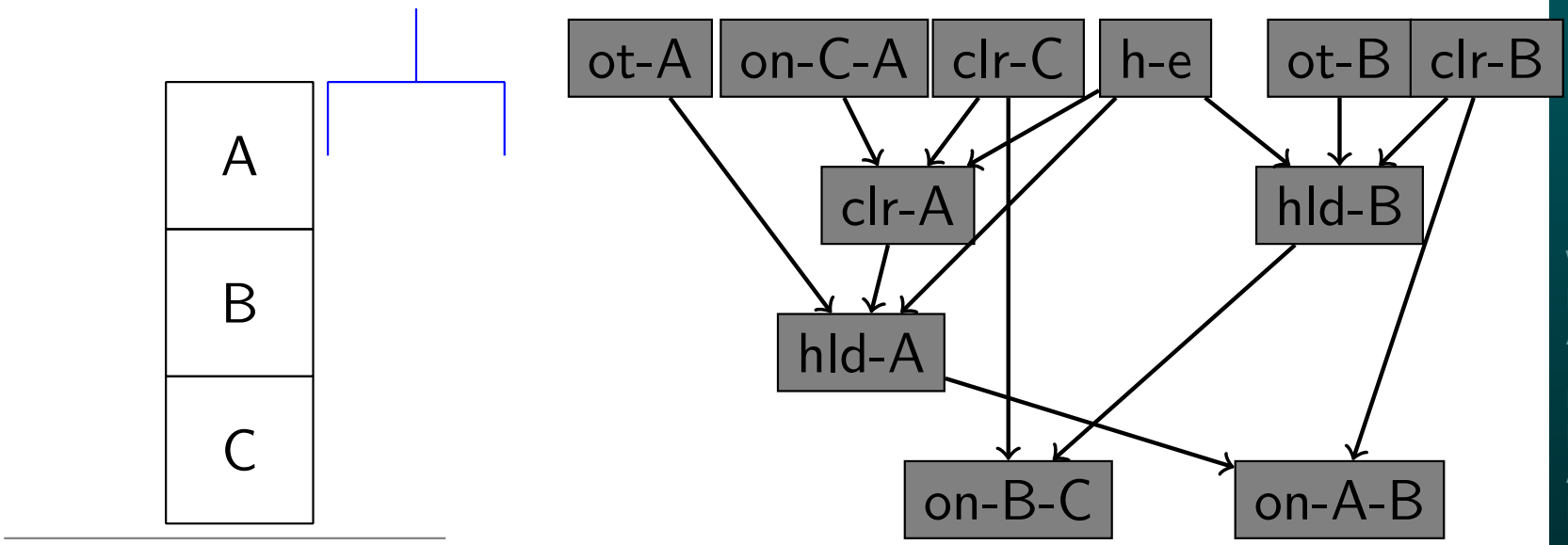

- Partial plan: Pickup-B, Stack-B-C, Unstack-B-C, Putdown-B, Unstack-C-A, Putdown-C, Pickup-A
- Goal: on-A-B

# 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

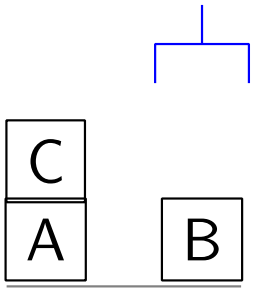
- Pros:
  - Planning is very fast - the base planner needs to plan to a lesser depth
- Cons:
  - Can lead to much longer plans
  - Not complete in the presence of dead-ends

# 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!

# 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 $\pi$ are

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

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

# The Landmark Heuristic

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

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

- $L$ is the set of all (discovered) landmarks
- $\text{Accepted}(s,\pi) \subset L$ is the set of *accepted* landmarks
- $\text{ReqAgain}(s,\pi) \subseteq \text{Accepted}(s,\pi)$ 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 $\pi$ 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

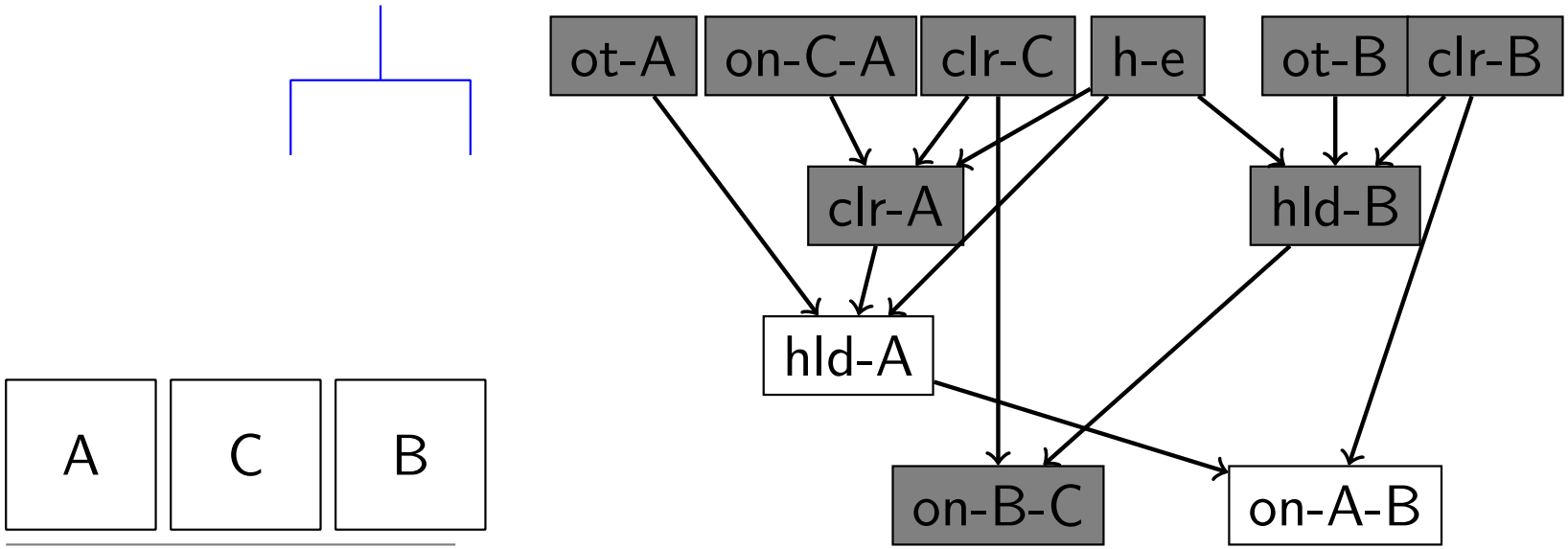
- A landmark $A$ is required again by path $\pi$ in state $s$ if:

  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 that is not accepted

# Accepted and Required Again Landmarks - Example

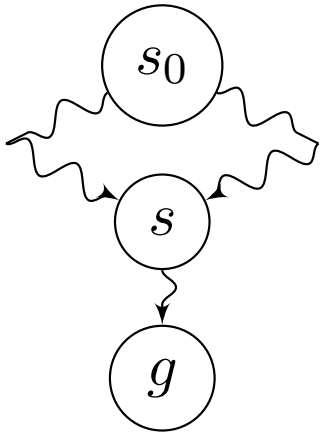
- In the Sussman anomaly, after performing: Pickup-B, Stack-B-C, Unstack-B-C, Putdown-B, Unstack-C-A, Putdown-C




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

# Multi-path Dependence

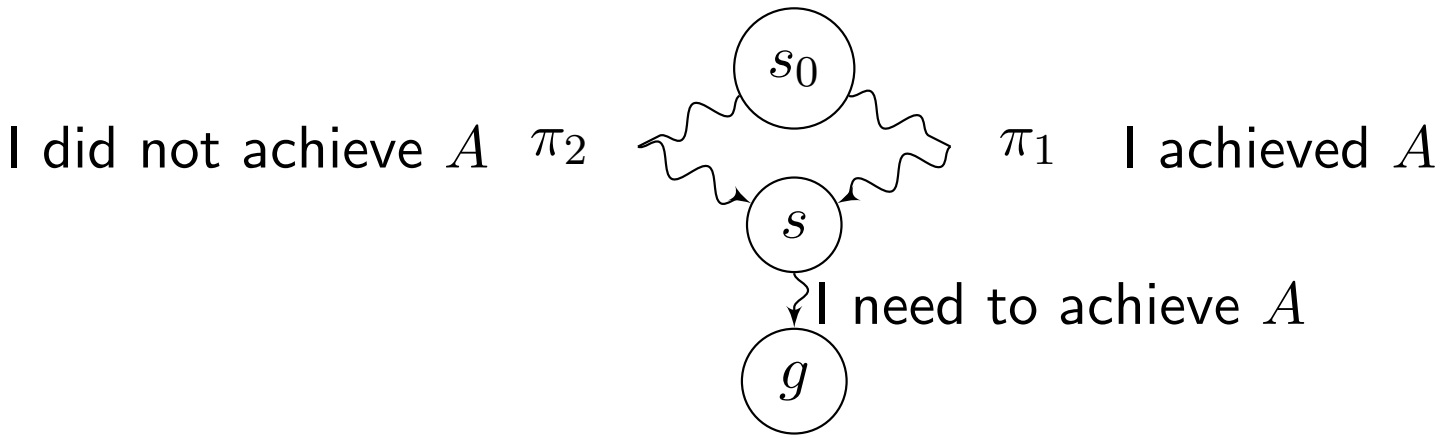
I did not achieve $A$ $\pi_2$




$\pi_1$ I achieved $A$

- Suppose state $s$ was reached by paths $\pi_1, \pi_2$
- Suppose $\pi_1$ achieved landmark $A$ and $\pi_2$ did not
- Conclusion:

# Multi-path Dependence




- Suppose state $s$ was reached by paths $\pi_1, \pi_2$
- Suppose $\pi_1$ achieved landmark $A$ and $\pi_2$ did not
- Conclusion: $A$ needs to be achieved after state $s$
- Proof: $A$ is a landmark, therefore it needs to be true in all valid plans, including valid plans that start with $\pi_2$

# Fusing Data from Multiple Paths

- Suppose $\mathcal{P}$ is a set of paths from $s_0$ to a state $s$. Define

$$L(s, \mathcal{P}) = (L \setminus \text{Accepted}(s, \mathcal{P})) \cup \text{ReqAgain}(s, \mathcal{P})$$

  where
  - $\text{Accepted}(s, \mathcal{P}) = \bigcap_{\pi \in \mathcal{P}} \text{Accepted}(s, \pi)$
  - $\text{ReqAgain}(s, \mathcal{P}) \subseteq \text{Accepted}(s, \mathcal{P})$ is specified as before by $s$ and the various rules
- $L(s, \mathcal{P})$ is the set of landmarks that we know still needs to be achieved after reaching state $s$ via the paths in $\mathcal{P}$

# 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)