Course "Automated Planning: Theory and Practice"
Chapter 11: Landmarks Heuristics

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Landmarks

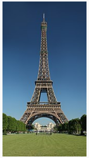
"a geographic feature used by explorers and others
to find their way back or through an area"

A landmark is a recognizable natural or artificial feature used for navigation, a feature that stands out from its near environment and is often visible from long distances. [12]

Natural

https://it.wikipedia.org/wiki/Cervino

Artificial



https://it.wikipedia.org/wiki/Torre_Eiffel

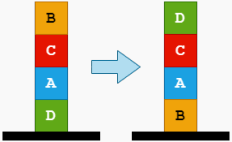
Landmarks in planning

- Something you must achieve or use in every solution to a problem instance!

Assume we are considering a state s...

Fact Landmarks for s

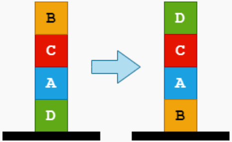
- A fact that must be true at some point in every solution starting from s



`(clear A), (holding C), (clear B), ...`

Formula Landmarks for s

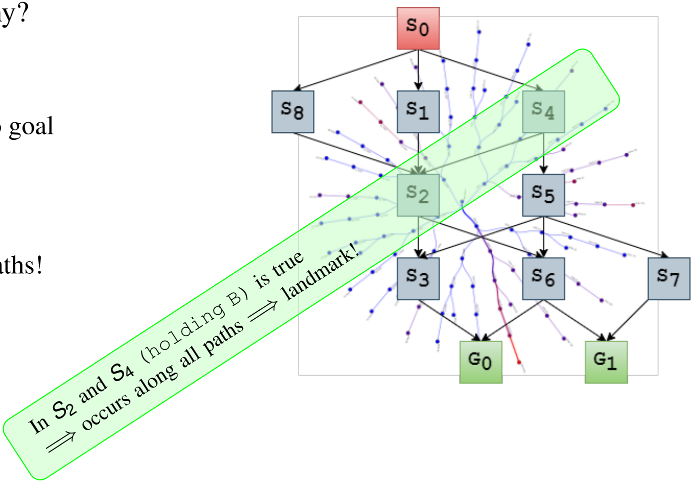
- A formula that must be true at some point in every solution starting from s



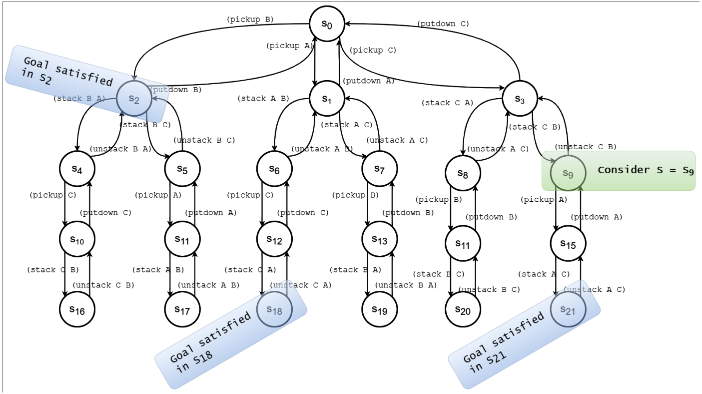
`((clear A)` $\wedge$ `(handempty))` $\vee$ `(clear A) ...`

Landmarks in planning (cont.)

- Facts and formulas, not states! Why?
  - Usually many paths lead from s to goal states!
  - Few states are shared among all paths!
  - Many facts occur along all paths!
    - $\Longrightarrow$ Landmarks!



Landmarks in planning (cont.)



- Is there a landmark state s_{lm} we must pass to reach some goal from s_9?
- No! But we may have to pass different states satisfying the same fact f_{lm}!

Landmarks in planning: Misunderstandings

- Not "we must reach (pass through) the landmark state"!
- Instead "we must reach some state that satisfies the fact/formula landmark"!

- A landmark fact is not "a fact that is true in every solution"!
- A solution is a plan! Facts are true in states!
- A landmark fact is "a fact that is true in some state along every path from the initial state to any goal state"!

- Not "a landmark fact is a state that ...
- A fact is not a state!
  A state consists of many facts!

- Can you be "close" to a landmark?
- You can be in a state s that is close to another state s' satisfying the landmark.
- Problem: How to know?
  - Distance is "number of edges" or "cost of reaching", not $\Delta x / \Delta y$. And the graph may not even be expanded yet!

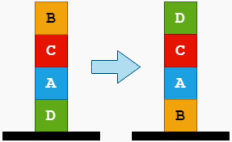
Landmarks in Planning (cont.)

- Something you must pass *by/through* in *every solution* to a specific planning problem

Assume we are considering a state s...

Fact Landmarks for s

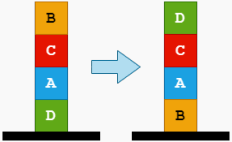
- A fact that must be true at some point in every solution starting from s



`(clear A), (holding C), (clear B), ...`

Action Landmarks for s

- An action that must be used in every solution starting from s



`(unstack B C) (putdown B) (stack D C)`

- ... so the effects of action landmarks are *fact landmarks* and so are their *preconds*

  (except those facts that are already true in s)

Landmarks in Planning (cont.)

- Generalization
  - Disjunctive action landmark $\{ a_1, a_2, a_3 \}$ for state s
    - Every solution starting in state s and reaching a goal must use *at least one* of these actions

Finding Landmarks: General Technique

Current planning problem P

Initial state does not include atom A

Modified planning problem P'

Removed *all actions that add atom* A

If this problem P' is unsolvable ...

Test:
Delete relaxation of P' is unsolvable
or $h_m(s_0) = \infty$, or...
$\Longrightarrow$ P' is unsolvable

... then every solution to P
must use one of the removed actions

$\Longrightarrow$ Action set is a disj.act.landmark

$\Longrightarrow$ Atom A is a fact landmark

- Unsolvable when removing a set of actions
  $\Longrightarrow$ some action in the set must be used $\Longrightarrow$ disjunctive action landmark

Finding Landmarks: General Technique (cont.)

- This is a very general technique
- It is applicable to *any* planning problem, *any* atom!

- General techniques tend to be widely applicable but slow!

Verifying Landmarks

- How difficult is to verify that an action is an action landmark, in the general case?
  - Suppose we can determine if any STRIPS problem P has a solution.
  - We add to the problem a new action:
```
(:action cheat
   :parameters ()
   :precondition ()
   :effect (<goal-formula>))
```
  - If `(cheat)` is an action landmark, then it is *needed* in order to solve the problem $\Longrightarrow$ the original problem was *unsolvable*
- $\Longrightarrow$ As difficult as solving the planning problem (PSPACE-complete) Porteous et al. [15]

Verifying Landmarks (cont.)

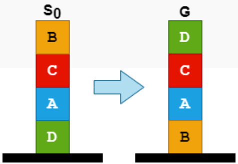
- How difficult is to verify that a fact is a fact landmark, in the general case?
  - Suppose we can determine if any STRIPS problem P has a solution.
  - We add a new fact `(cheated)` (false in the initial state)
  - We add to the problem a new action:

```
(:action cheat
   :parameters ()
   :precondition ()
   :effect (and (cheated) <goal-formula>))
```

  - If `(cheated)` is a fact landmark, then `(cheat)` was necessary $\Longrightarrow$ the original problem was *unsolvable*
- $\Longrightarrow$ Again, as difficult as solving the planning problem Porteous et al. [15]

But of course there are special cases...

FINDING LANDMARKS: MEANS-ENDS ANALYSIS



- Discover landmarks using means-ends analysis

Unachieved goal facts are (obviously) fact landmarks: `(clear D)`, `(on D C)`, `(on A B)`

fact-landmarks $\leftarrow G \setminus s$

Suppose `(on D C)` is a landmark, `(on D C)` is not true in the current state s
$\Longrightarrow$ we must *cause* `(on D C)` with an action
$\Longrightarrow$ compute *achievers* = { `(stack D C)` }

do {
  for each $p \in$ fact-landmarks {
    // Create *disjunctive* action landmark
    achievers $\leftarrow \{a \in A | p \in eff(a)\}$

All achievers require these candidates = { `(holding D)`, `(handempty)`, `(clear C)`,...}

candidates $\leftarrow \bigcap_{a \in achievers} pre(a)$

`(handempty)` is already true, but new = { `(holding D)`, `(clear C)`,...} are *not*!

new $\leftarrow$ candidates $\setminus s$
fact-landmarks $\leftarrow$ fact-landmarks $\cup$ new

May be we can find more landmarks related to achieving *those*!

  }
} **until** no more fact-landmarks found

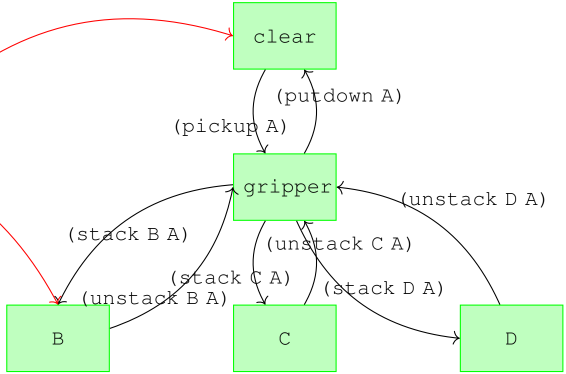
Finding Landmarks: Actions, Backward

- Effects of disjunctive action landmarks:
  - All shared effects must also take place regardless of the "chosen" action, similarly to shared *preconditions* on previous slide
  - Given a disjunctive action landmark, every fact in $\cap_{a \in landmark}\{eff(a)\} \setminus s$ is a fact landmark for s

Finding Landmarks: Domain Transition Graphs

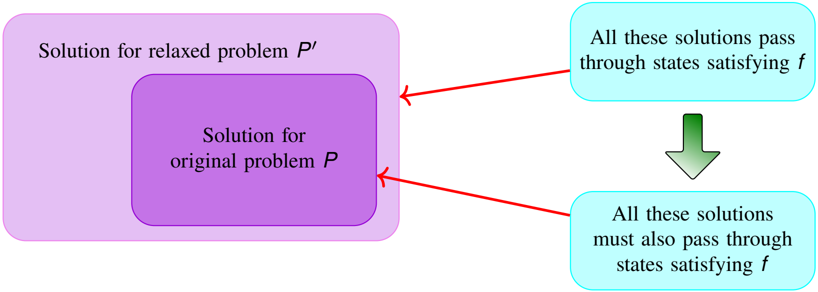
- A directed graph for a state variable x whose vertex corresponds to possible values the state variable can take (i.e. its domain D_x), and there is an arc (v, v') between two possible values v, v' if there is an action o such that $v \in \mathit{eff}^-(o)$ and $v' \in \mathit{eff}^+(o)$.

- Use of the DTG
  - Current state: `aboveA = clear`
  - In goal: `aboveA = B`
- Then `aboveA = gripper` is a fact landmark...
  - ... and `(pickup A)` + `(stack B A)` are action landmarks



Landmarks and Relaxation

- Assume a problem P, and a relaxed problem P'
  - Suppose f is a fact landmark for P'



  - Then f is a fact landmark for the original problem as well!!
  - Similar for action landmarks, etc..

Finding Landmarks: ...

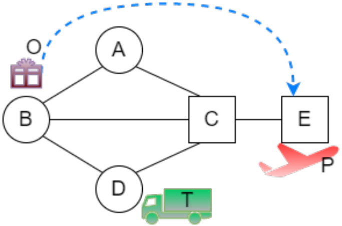
- Many other techniques exists...
  - It is beyond the scope of the course
  - Possible reference: Hoffmann et al. [8], Richter et al. [16], Zhu and Givan [17], Gregory et al. [7], Keyder et al. [11], Karpas and Domshlak [9], Domshlak et al. [2], Domshlak et al. [3], Mirkis and Domshlak [14]

Landmark Ordering

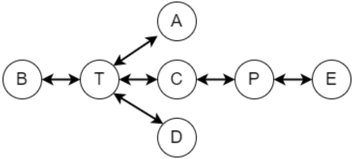
- Landmarks can be (partially) ordered according to the order in which they must be achieved
- Sometimes we can find or approximate necessary orderings
  - We must achieve `(holding A)` then `(holding B)` ...
- Some landmarks and orderings can be discovered automatically

Landmark Ordering: Example Problem [10]

- Domain:
  - Truck T transports object O with road network A/B/C/D
  - Airplane P transports object O between airports C/E
- Goal
  - Object at E



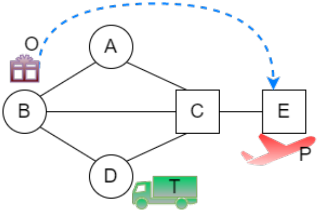
- Domain transition graph for `location-of-object`:

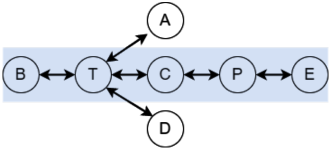


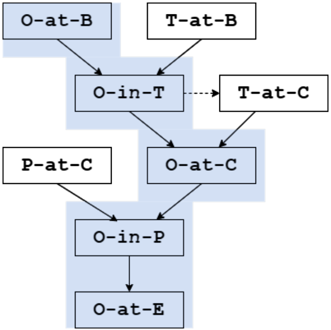
- Note: Every edge in the road network corresponds to a path through T in the DTG!

Landmark Ordering: Inference Karpas and Richter [10]

- One way of inferring the order of landmarks:
  - Directly from the DTG!







Landmark Ordering: Types of Landmark Orderings

- Two kind of landmark ordering
  - 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

Landmark Ordering: 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 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: $A \rightarrow_n B \Rightarrow A \rightarrow_{gn} B \Rightarrow A \rightarrow B$

Encoding in LTL with past operators (Lichtenstein et al. [13])

- $\overline{A} \rightarrow \overline{B}$, iff $\overline{A}$ true some time before $\overline{B}$ i.e., $\overline{B} \rightarrow \mathbf{Y}\,\mathbf{O}\,\overline{A}$ which means that given a path π, $\pi, i \models \overline{B} \rightarrow \mathbf{Y}\,\mathbf{O}\,\overline{A}$ that is if $\overline{B}$ holds at time instant i, then there shall be a $j < i$ such that $\overline{A}$ holds.
- $\overline{A} \rightarrow_n \overline{B}$, iff $\overline{A}$ always true one step before $\overline{B}$ becomes true, i.e., $(\overline{B} \wedge \mathbf{Y}\,\neg\overline{B}) \rightarrow \mathbf{Y}\,\mathbf{H}\,\overline{A}$ which means that given a path π, $\pi, i \models (\overline{B} \wedge \mathbf{Y}\,\neg\overline{B}) \rightarrow \mathbf{Y}\,\mathbf{H}\,\overline{A}$ that is if $\overline{B}$ holds at time instant i and $\neg\overline{B}$ holds at $i-1$ ($\overline{B}$ becomes true), then at $\forall j \leq i-1$ $\overline{A}$ holds.
- $\overline{A} \rightarrow_{gn} \overline{B}$, iff $\overline{A}$ true one step before $\overline{B}$ becomes true for the first time, i.e., $(\overline{B} \wedge \mathbf{Y}\,\mathbf{H}\,\neg\overline{B}) \rightarrow \mathbf{Y}\,\overline{A}$ which means that given a path π, $\pi, i \models (\overline{B} \wedge \mathbf{Y}\,\mathbf{H}\,\neg\overline{B}) \rightarrow \mathbf{Y}\,\overline{A}$, that is if at time i $\overline{B}$ holds and all $j < i$ are such that $\neg\overline{B}$ holds ($\overline{B}$ becomes true for the first time), then at step $j = i-1$ $\overline{A}$ holds.

From the above considerations it is easy to see: $A \rightarrow_n B \Rightarrow A \rightarrow_{gn} B \Rightarrow A \rightarrow B$

The used past temporal operators are $\mathbf{Y}$ = Yesterday, $\mathbf{H}$ = Historically, $\mathbf{O}$ = Once in the past, they are the past correspondence of $\mathbf{X}$ = in the next step, $\mathbf{G}$ = Globally, and $\mathbf{F}$ = Eventually. See Lichtenstein et al. [13] for details on LTL with past operators!

Landmark Ordering: Reasonable Landmark 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

$$B \rightsquigarrow \neg B \rightsquigarrow A \rightsquigarrow B \Rightarrow A \rightarrow_r B$$

- 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

Landmark Ordering: Complexity

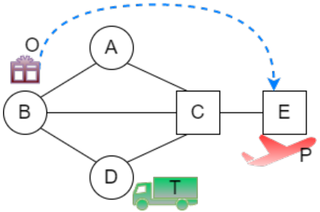
- Everything is PSPACE-complete
- Deciding if a given fact is a landmark is PSPACE-complete
  - Proof Sketch: it's the same as deciding if the problem without actions that achieve this fact is unsolvable
- Deciding if there is a natural / necessary / greedy-necessary / reasonable ordering between two landmarks is PSPACE-complete

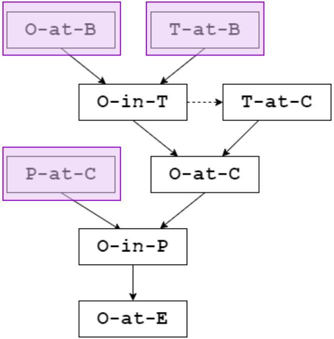
Ordered Landmarks as Subgoals

- 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

Ordered Landmarks as Subgoals (cont.)

- Try to plan for each landmark separately in the inferred order

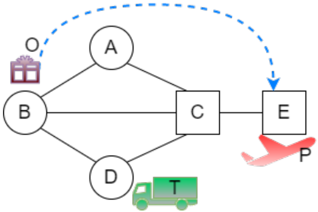


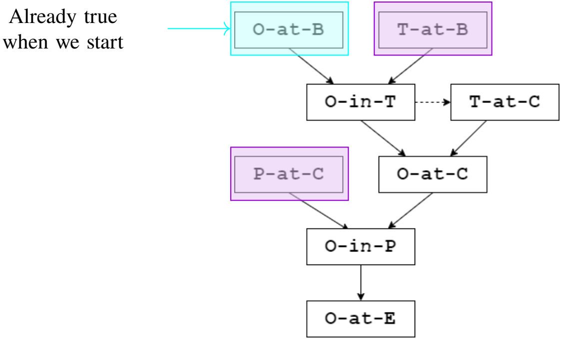


- Three landmarks could be "first" (all predecessors achieved)
- Current goal: O-at-B $\vee$ T-at-B $\vee$ P-at-C (disjunctive)!

Ordered Landmarks as Subgoals (cont.)

- Try to plan for each landmark separately in the inferred order

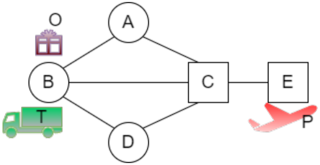




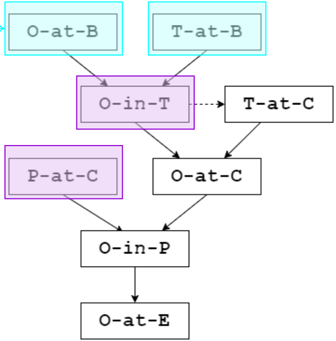
- Two landmarks could be "first" (all predecessors achieved)
- Current goal: `T-at-B` ∨ `P-at-C` (disjunctive)!

Ordered Landmarks as Subgoals (cont.)

- Suppose we begin by achieving `T-at-B`: simple planning problem, results in a single action – `(drive T B)`



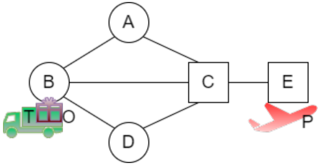
Already true when we start

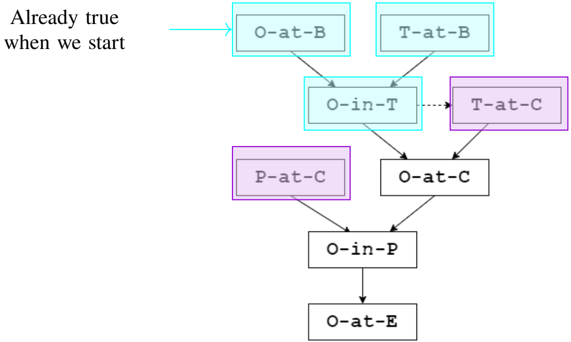


- Current goal: `O-in-T` ∨ `P-at-C`

Ordered Landmarks as Subgoals (cont.)

- Suppose we continue by achieving `O-at-B`: simple planning problem, results in a single action – `(load-truck O T B)`

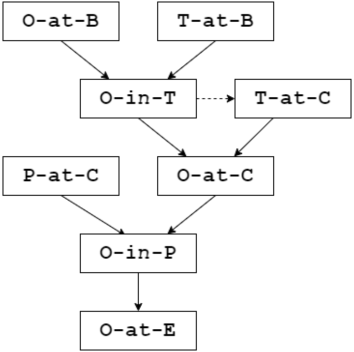




- Current goal: `P-at-C` $\vee$ `T-at-C`

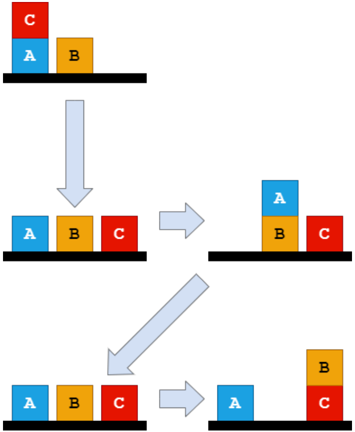
Landmarks as Subgoals (cont.)

- Sometimes very helpful, but:
  - There are still choices to be made - backtrack points!
  - Optimizing one part of the overall goal at a time:
    - Can't see the whole picture
    - Can miss opportunities:
      Cheapest solution here $\Longrightarrow$ more expressive solution later!
    - Can be incomplete:
      Cheapest solution here $\Longrightarrow$ impossible to solve later!



The Problem with Separating Subgoals

- The Sussman Anomaly (Gerald Sussman)
  - Goal: `(on A B), (on B C)`
  - Now: `(on C A), (clear C), (clear B), (ontable A), (ontable B)`
- Idea: Achieve one at a time!
  - First, plan only for `(on A B)`
  - Then, plan only for `(on B C)`
- Achieve first subgoal `(on A B)`
  - `(unstack C A), (putdown C), (pickup A), (stack A B)`
- Achieve second subgoal `(on B C)`
  - `(unstack A B), (putdown A), (pickup B), (stack B C)` $\Longrightarrow$ original goal destroyed!

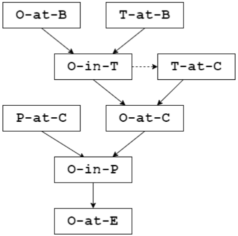


Using Landmarks as Subgoals - Pros and Cons

- 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

Landmark Heuristics

- The LAMA state space planner counts landmarks:
  - Landmarks that need to be achieved after reaching state s through action sequence π
  - $L(s, \pi) =$



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

All discovered landmarks, minus those that are *accepted* as achieved (have become true after predecessors are achieved!)

Plus those we can show will have to be *re-achieved*

(Example: Landmarks that were reached, are no longer true, but are required by the goal)

- $h(s) = |L(s, \pi)|$
- Not admissible: One action may achieve multiple landmarks!

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

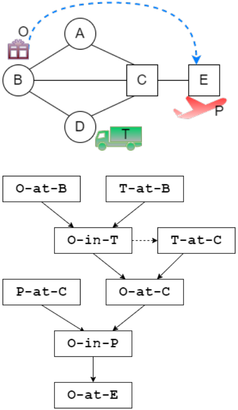
- A landmark A is required again by path π in state s if:
  - false-goal A is false in s and is a goal, or
  - open-prerequisite A is false in s and is a greedy-necessary predecessor of some landmark B that is not accepted
- It's also possible to use approach described in Buffet and Hoffmann [1]
  - 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

Landmark Heuristics (cont.)

- To achieve admissible heuristic estimates:
  - Idea: The cost of each action is *divided* across the landmarks it achieves

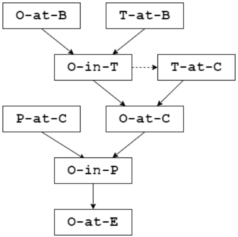
- Simplified example
  - Suppose there is a `goto-and-pick` action of cost 10, that achieves both `T-at-B` and `O-in-T`
  - Suppose *no other action* can achieve these landmarks
  - One can then let (for example) $cost(\texttt{T-at-B}) = 3$ and $cost(\texttt{O-in-T}) = 7$

- The sum of the cost of remaining landmarks is then an admissible heuristic
  - Must decide how to split costs across landmarks
  - Optimal split can be computed polinomially, but it is still expensive



Landmarks: Modified Problem

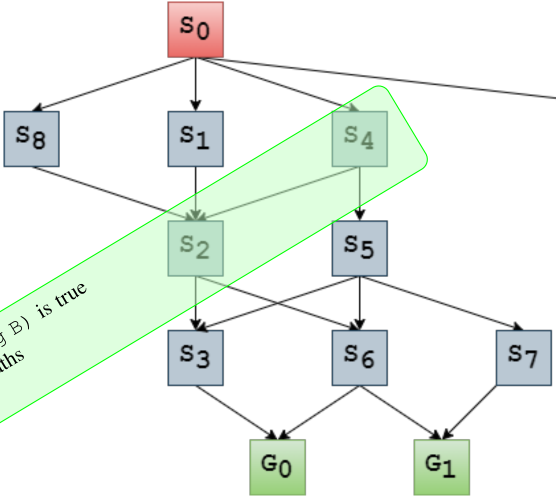
- Landmarks are, in essence, implicit goals
  - We can make these explicit by reformulating the planning problem
- Landmarks as a basis for a modified planning problem Domshlak et al. [2]
  - Add new facts "`achieved=landmark-n`"
    - Example: `object-has-been-in-plane`
  - An action achieving a landmark makes the corresponding facts true
    - `(load object plane)` $\Longrightarrow$ `object-has-been-in-plane` := `true`
  - The goal requires all such facts to be true!
    - `(:goal object-has-been-in-plane ...)`
  - $\Longrightarrow$ Any *other* heuristic can be applied to the modified problem!
    - $h_{PDB}(s)$ - pattern databases: What is the cost of achieving `object-has-been-in-plane`?



Why Modifying 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 et al. [2]
  - 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 (discussed later).

Landmarks: More Misunderstandings



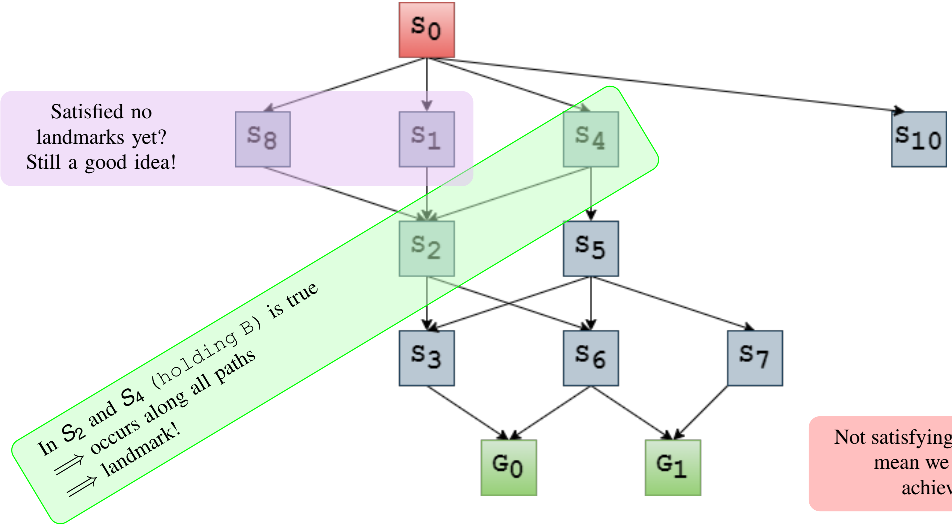
In S_2 and S_4 `(holding B)` is true
$\implies$ occurs along all paths
$\implies$ landmark!

Also happens to satisfy `(holding B)`

Might still be a bad idea!

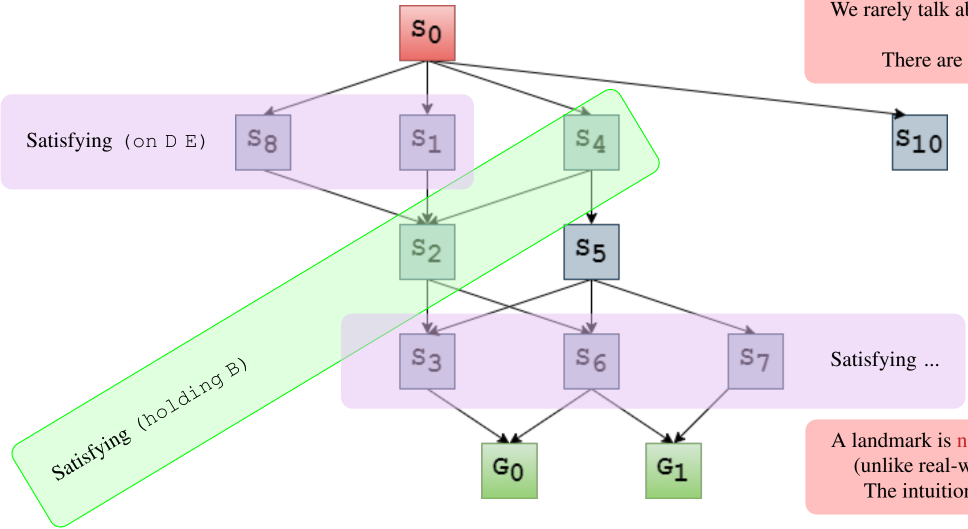
Satisfying a landmark does not mean we must be close to achieving the goal!

Landmarks: More Misunderstandings (cont.)



Not satisfying a landmark does not mean we can't be close to achieving the goal!

Landmarks: More Misunderstandings (cont.)



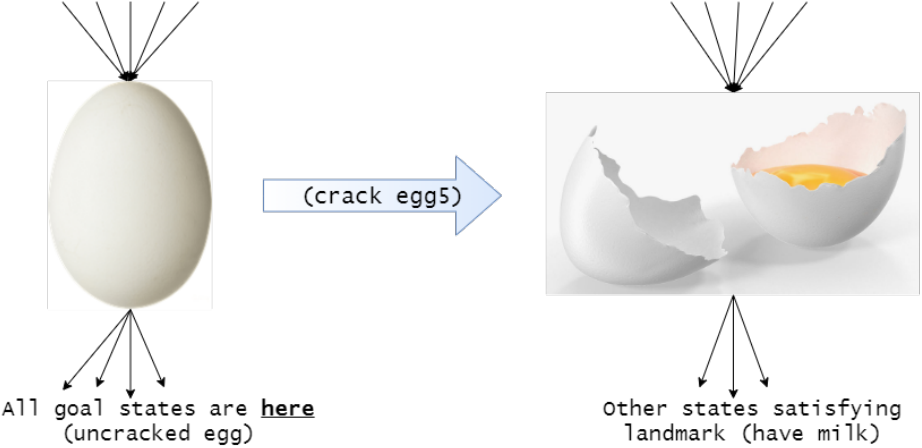
We rarely talk about "the" landmark

There are often many ...

A landmark is not a unique location (unlike real-world landmarks): The intuition breaks down...

Landmarks: Ideas that Don't Work

"If I reach a state satisfying a landmark, I won't have to backtrack"!



Landmarks: Commented references

- Hoffmann et al. [8]: Introduces landmarks and the backchaining generation method.
- Richter et al. [16]: Describes the DTG method for finding landmarks and the landmark heuristic used by LAMA.
- Zhu and Givan [17]: Describes the method for finding the complete set of causal delete-relaxation landmarks in polynomial time.
- Gregory et al. [7]: Further methods for finding disjunctive landmarks.
- Keyder et al. [11]: Conjunctive landmarks (not discussed here); explains how to approximate greedy-necessary orderings in Zhu & Givan's landmark discovery method.
- Karpas and Domshlak [9]: Describes the admissible landmark heuristic and multi-path dependence.
- Domshlak et al. [2] and Domshlak et al. [3]: Describes how to compile landmarks into a planning problem and use them with abstraction heuristics.
- Mirkis and Domshlak [14]: Describe a framework for exploiting such landmarks in heuristic-search for over subscription planning.

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