Hierarchical Planning: Limits, Extensions, and Model Repair

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18 December 2025

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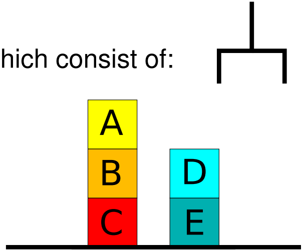
Planning Formalism

Classical Planning

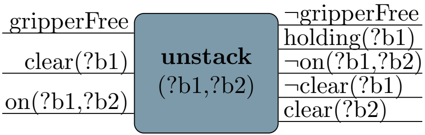
Let's start with *classical planning problems*, which consist of:

- All existing state variables V.
- An initial state $s_I \in 2^V$.
- A set of available actions A.
- A goal description $g \subseteq V$.



→ Find an action sequence (i.e., a *plan*) that transforms s_I into g.

For example, one of the available actions is:


gripperFree

clear(?b1)

on(?b1,?b2)

unstack (?b1,?b2)

¬gripperFree

holding(?b1)

¬on(?b1,?b2)

¬clear(?b1)

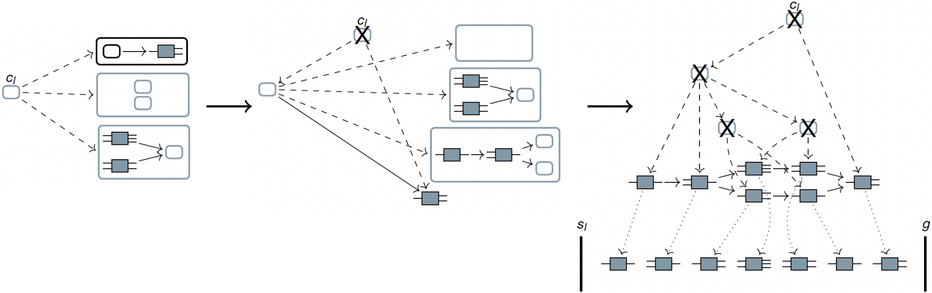
clear(?b2)

- For an action to be executable, all preconditions must hold.
- Actions change states by adding or deleting their effects.

Hierarchical Task Network (HTN) Planning

In HTN Planning,

- we do not (only) plan for state-based variables; instead,
- we have initial *compound* tasks that need to be refined
  for which the model contains “methods”, the refinement rules.
- The solution is an executable, primitive task network (refinement).



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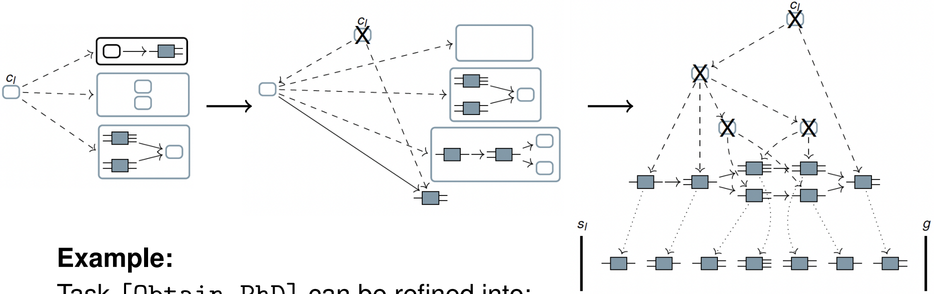
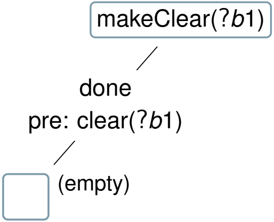


Example:

Task `[Obtain PhD]` can be refined into:
`[Do Research]` → `[Write Thesis]` → `[Defend Thesis]`

HTN Planning by Example (Special Case: Totally Ordered)

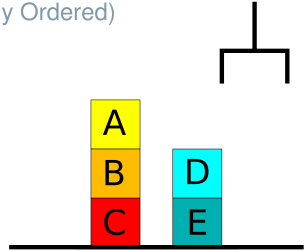


makeClear(?b1)

done

pre: clear(?b1)

(empty)



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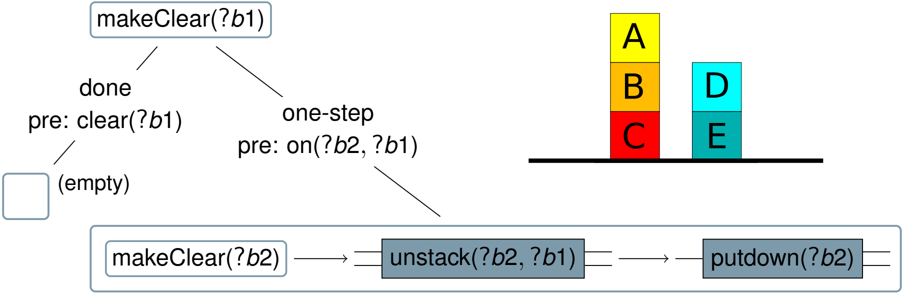

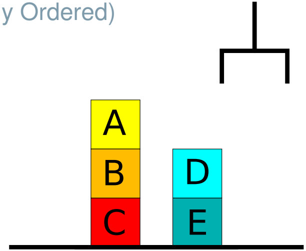

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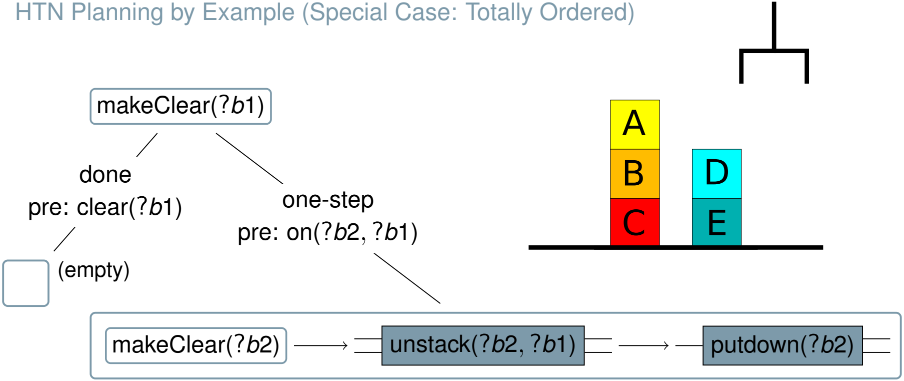

makeClear(C)

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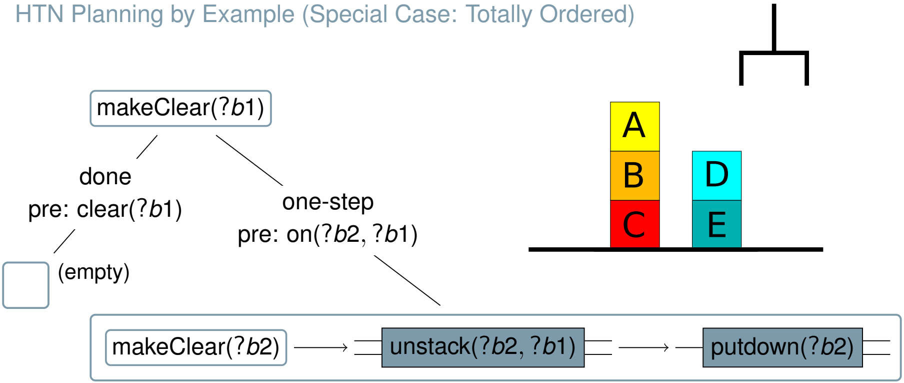

makeClear(C)

~~makeClear(C)~~ makeClear(B) unstack(B,C) putdown(B)

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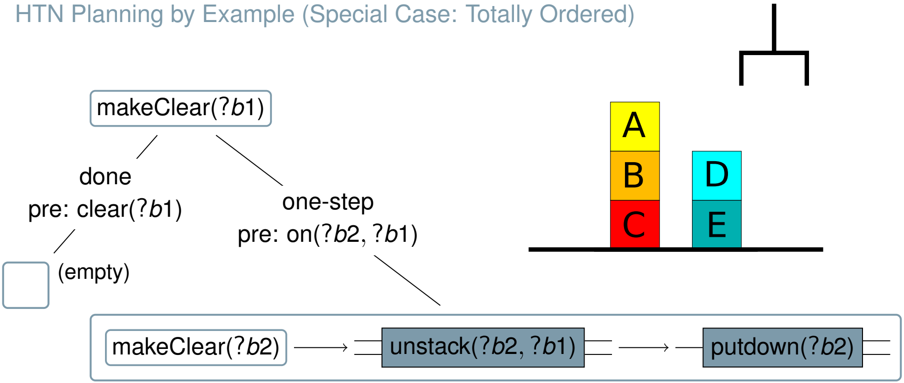

makeClear(?b1)

done
pre: clear(?b1)

(empty)

one-step
pre: on(?b2, ?b1)

makeClear(?b2) → unstack(?b2, ?b1) → putdown(?b2)

makeClear(C)

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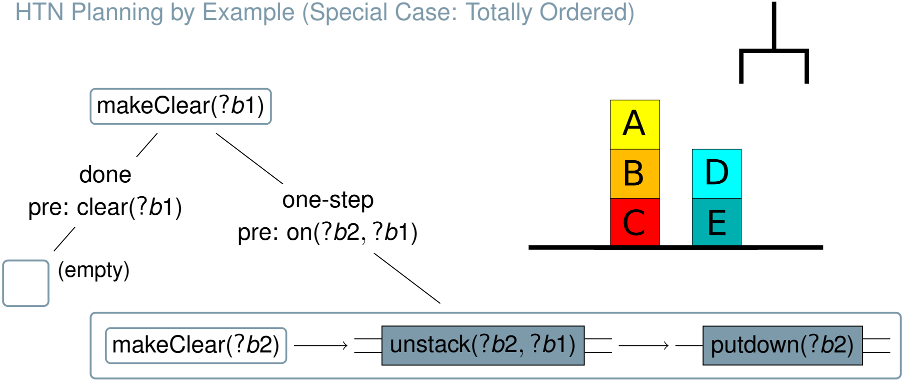

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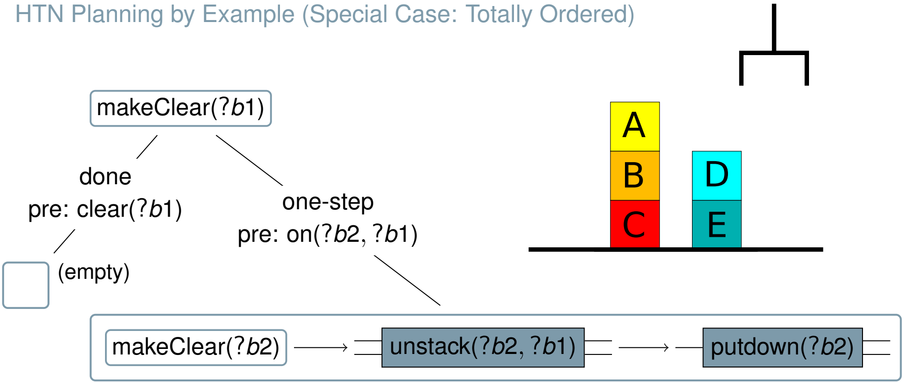

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Note that in this model, we don’t need the predicates *gripperFree* and *holding(?b)* – since their “logic” is encoded into the task hierarchy.

Recap: What is HTN Planning?

Let’s provide a more theoretical (but “cleaner”) viewpoint.

- Let $\mathcal{P}$ be an HTN problem and let’s define:
  - $\mathit{Sol}_{\mathit{classic}}(\mathcal{P}) = \{\bar{a} \mid \bar{a} \in \mathit{sol}(\mathcal{P}')$, where $\mathcal{P}'$ is the induced classical problem $\}$, where $\mathit{sol}(\cdot)$ is the solution set of its classical planning problem

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→ $Sol(\mathcal{P}) = Sol_{classic}(\mathcal{P}) \cap Sol_{hierarchical}(\mathcal{P})$.

This observation gives a new/simplified view on HTN planning:

HTN planning = classical planning + grammar to filter solutions

Outline

Research Expertise and Interests

My Research Directions:

(1) Algorithm and heuristic design (solve problems quickly)

(2) Computational Complexity Analyses

times (cross product)

(a) Solving (mostly hierarchical) planning problems

(b) Repairing flawed (both classical and hierarchical) models

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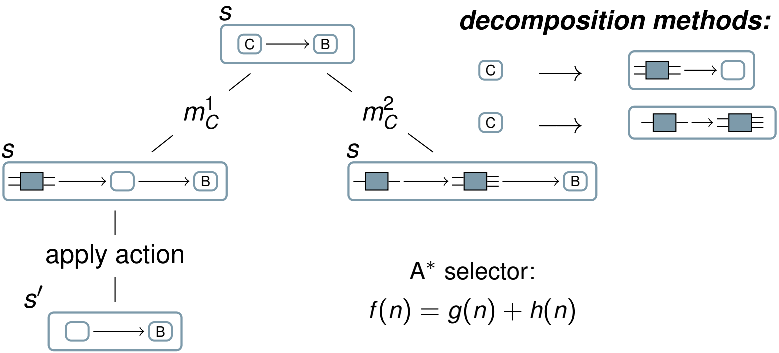
Today / Talk Outline:

- What's HTN planning? (Check!)
- Solving HTN problems via A* search.
- Extension of HTNs to uncertainty.
- Model Repair: some overview.

Progression Search to Solve HTN Problems

HTN Progression Search via A^*

- **node selection:** Select a node with minimal f value.
  - g: cost incurred so far (number of progressed/applied actions)
  - h: estimate of number of actions to still be applied
- **node expansion:**
  - primitive? Progress it! (Update the state.)
  - compound? Apply all its decomposition methods!
- **solution:** The action sequences encoded in the search path.

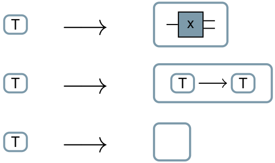


A^* selector:

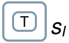
$$f(n) = g(n) + h(n)$$

A^* is Incomplete: We have infinitely many nodes with perfect f-value!

decomposition methods:



$g(n_0) = 0$, $h^*(n_0) = 1$



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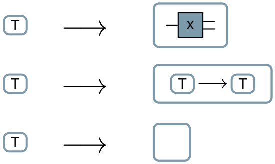

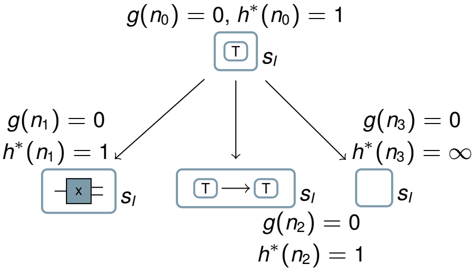

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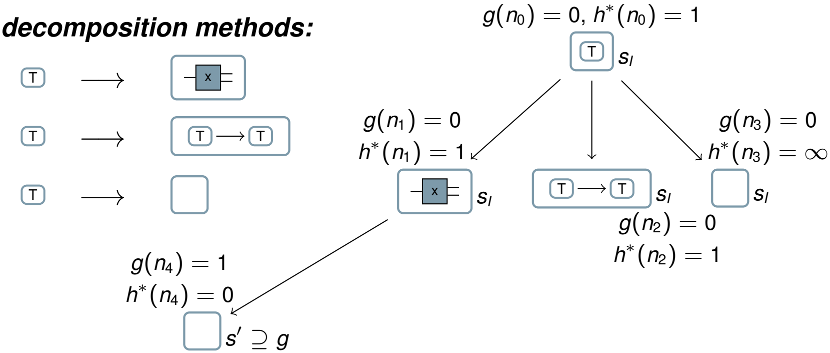

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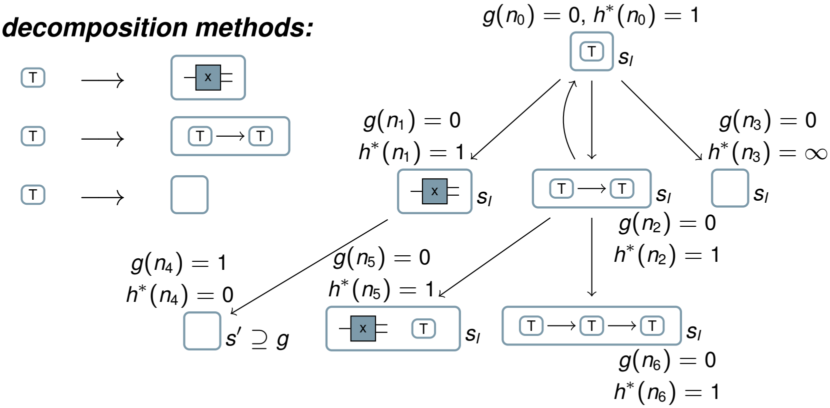

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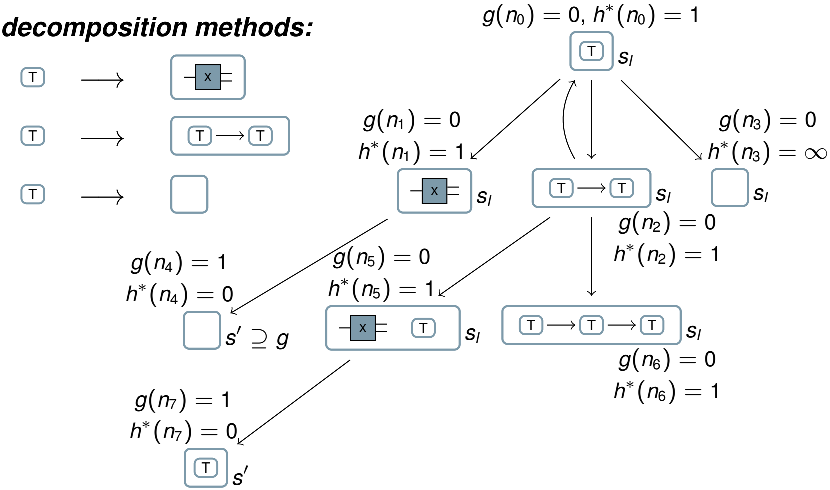

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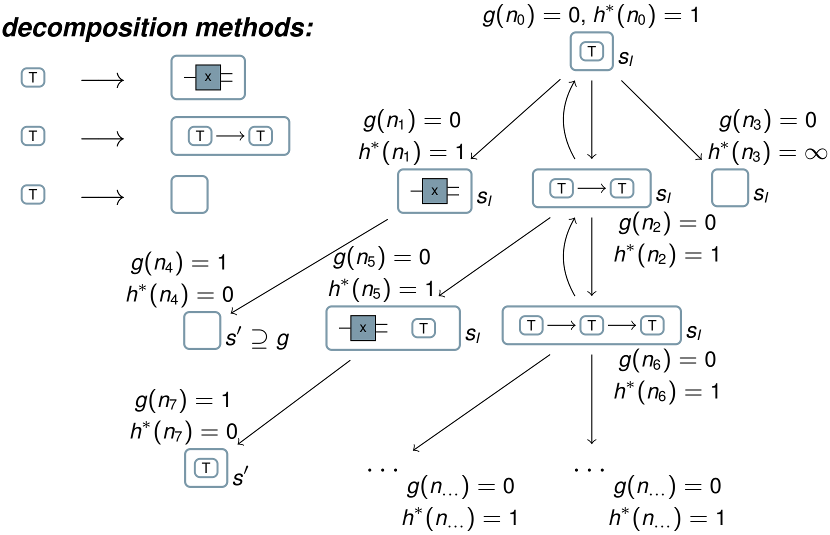

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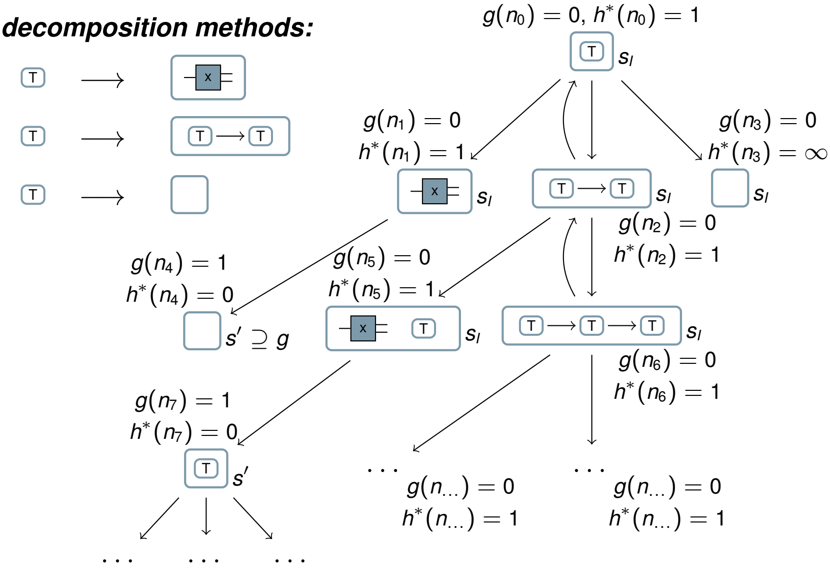

Key Messages

So, what about progression search?

- Progression search is a state-of-the-art approach.
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What about other algorithms?

- There's also planning as SAT: **see tomorrow's PhD defense!**
- Currently, that is the only approach that guarantees termination!

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FOND HTN Planning

Deterministic vs. Non-Deterministic HTN Planning

The solution criteria of HTN planning so far, informally:

Given an initial compound task,

- find a refinement task network (according to methods/rules),
- such that it does possess an executable action linearization.

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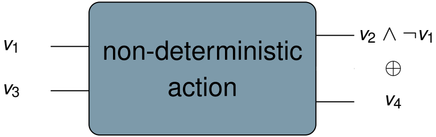

Two pairs of effects:

- **Either** add v_2 and delete v_1,
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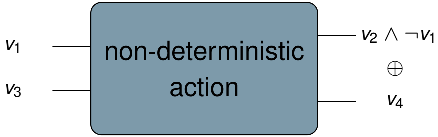

v_1

v_3

non-deterministic action

$v_2 \wedge \neg v_1$

$\oplus$

v_4

Two pairs of effects:

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New solution criteria:

- Find a refinement task network (as before!),
- such that *we can execute it no matter what happens*.

Different Solution Concepts

We developed two main categories of solution concepts:

1. Solutions are still (partially ordered) task networks (we called them fixed-method policies)
   - without likelihoods; plans “have to work”, ICAPS’21
   - with probability distribution, KR’25

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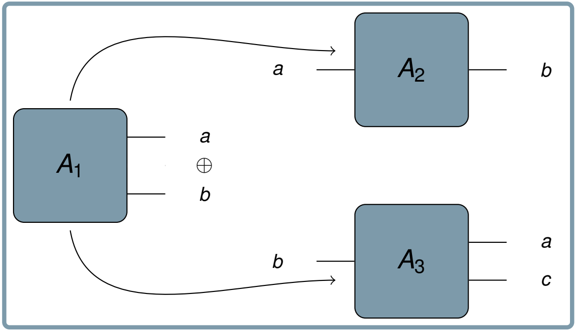
We now give short examples, current developments, and some interesting properties for each!

Fixed-Method Solutions: Strong Solutions

Assume we found this plan:



(To turn the empty initial state into one that makes c true.)

Does it do its job?

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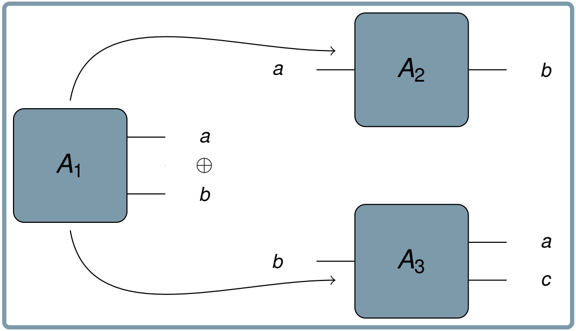

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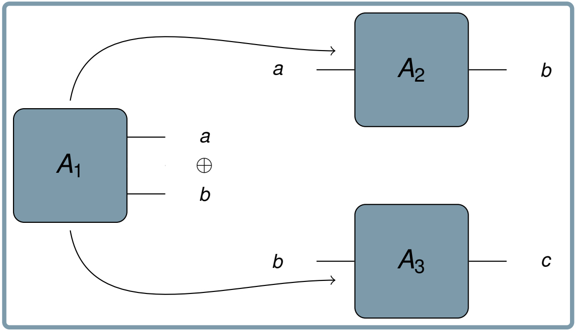
Does it do its job? **Yes!** *With a policy:*

- If A_1 produces a, then execute A_2 next (and then A_3)
- If A_1 produces b, then execute A_3 next (and then A_2)

Fixed-Method Solutions: Weak Solutions

Assume we found *this* plan:



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What about now?

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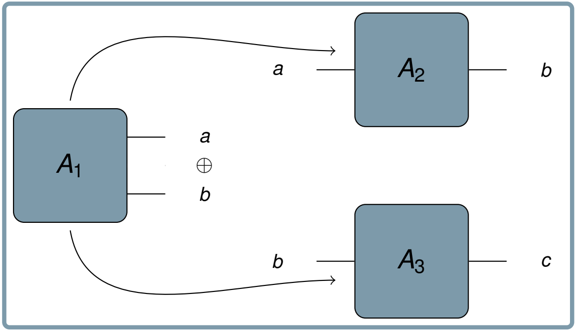

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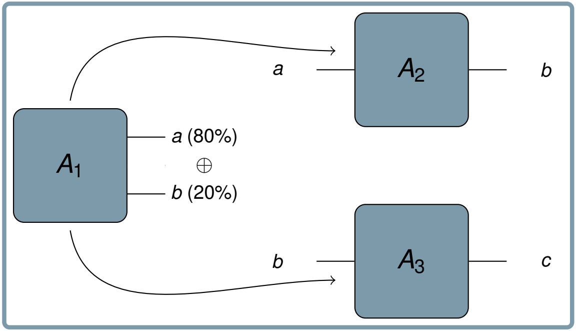
What about now? *Kinda.* But only one branch succeeds:

- If A_1 produces a, then execute A_2 next (and then A_3)
- If A_1 produces b, A_2 can't be executed, but must! :(

Fixed-Method Solutions: What if we have effect likelihoods?

Assume we found *this* plan:



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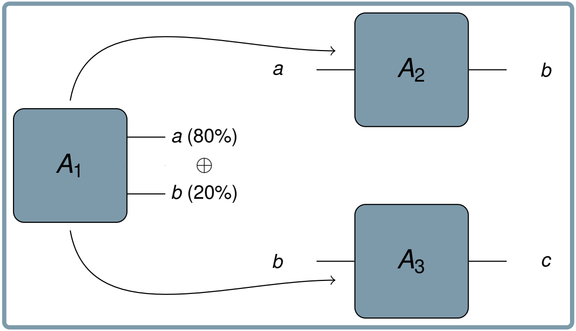

(To turn the empty initial state into one that makes c true.)

What about now? *Yes,* and we can quantify its success probability:

- It succeeds with 80% likelihood (and fails with 20%).
- Thus, we can ask for a plan that succeeds with $\mathbb{P} \geq p$

Fixed-Method Solutions: Overview

Trivia / work so far:

- For non-deterministic effects:
  - Formalism and complexity results (“plan existence”), ICAPS’21
  - Sadly, *no planner exists yet!*
- Extension to effect likelihoods:
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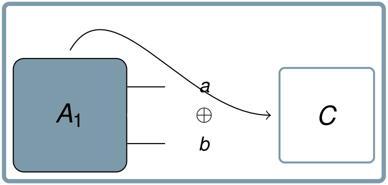
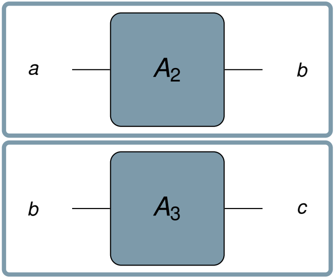
  - Because solutions are fixed sets of actions!
  - Prevents solutions such as *“(re)submit paper until accepted”* :(
  - Formalism with likelihoods remains undecidable even under *significant restrictions*: total order + tail-recursiveness

Method-based Solutions: Limitations of Fixed-method Solutions

Initial task network:



Decomposition methods for C:



Is there a fixed-method solution?

Method-based Solutions: Limitations of Fixed-method Solutions

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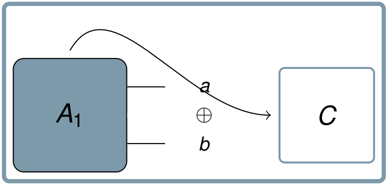
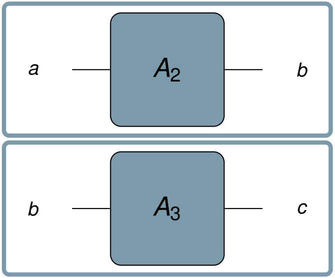


Decomposition methods for C:



Is there a fixed-method solution?

- No, because no single primitive plan always works!
- But there is if we can delay the method choice!

→ Solution definition is a policy $\pi : s, tn \mapsto [a \text{ or } (c, m)]$

Method-based Solutions: Overview

Trivia / work so far:

- For non-deterministic effects:
  - Formalism and complexity results (“plan existence”), ICAPS’22
  - One planner, grounder, and heuristics, IJCAI’24
- Extension to effect likelihoods:
  - Nothing, yet

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Some pro’s and con’s:

- **Pro:** We finally can: *“(re)submit until accepted”*! :)
  That’s since a policy can recursively re-invoke a compound task.

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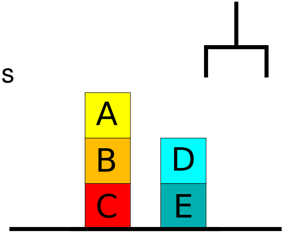
Some pro’s and con’s:

- **Pro:** We finally can: *“(re)submit until accepted”*! :)
  That’s since a policy can recursively re-invoke a compound task.
- **Con:** Computationally even harder than fixed-method ones.

Modeling Support

Blocksworld Revisited



We want automated support in creating actions (and their interactions) like the one below:

Warm-up: ***Is the action correctly modeled?***

```
(:action unstack
   :parameters (?b1 ?b2 - block)
   :precondition (and (gripperFree)
                      (on ?b1 ?b2) (clear ?b1))
   :effect (and (not (gripperFree)) (holding ?b1)
                (not (on ?b1 ?b2)) (not (clear ?b1))
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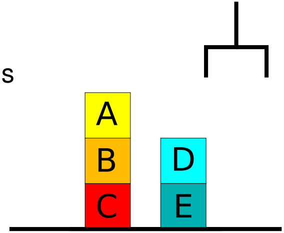

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Yes! We had that exact action on slide 1! :)

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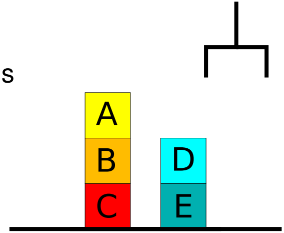

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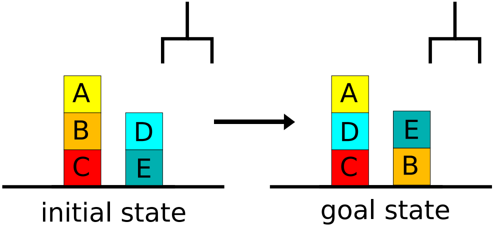
Yes! We had that exact action on slide 1! :) Though one can argue: Did we forget to demand ?b1≠?b2? (Not required here.)

Patient Zero

How about this situation? Is it modeled correctly?



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(define (problem blocksworld-prob)
  (:domain blocksworld)
  (:init (clear A) (on A B) (on B C) (onTable C)
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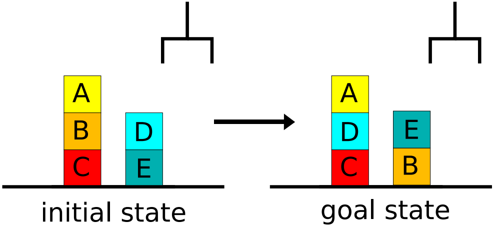

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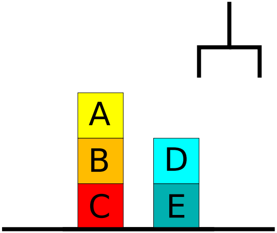
No! The gripper being initially empty is missing!

Okay, modeling is hard, so...

How do provide modeling support?

So far, our proposal was to provide a set of test plans:

- Some are supposed to be solutions (but might not), *whitelist plans*
- others should not be solutions (but might). *blacklist plans*



Example:

- "unstack(A,B) putdown(A) unstack(B,C) putdown(B) is executable"
- "unstack(A,B) putdown(A) unstack(B,C) unstack(D,E) is *not* executable"

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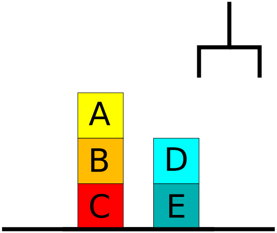

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What's a (good) repair?

- A set of precondition or effect additions or removals.
- Minimal number of repairs, or getting assessed by LLMs.

Overview

Trivia / work so far:

- Complexity investigations:
  - for classical planning (i.e., change preconditions/effects): almost always NP-complete (IJCAI 2021)
  - for HTN planning (i.e., add/delete actions to/from methods) also almost always NP-complete (IJCAI 2021); complexity for black + whitelist plans: [NP-hard,in Σ_2^p] (AAAI'23)

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    - Ideas how to integrate with LLMs (HAXP workshop 2025)
- (My, and all(?)) Repair algorithms for HTN planning:
  - Compilation into another HTN problem (SoCS 2024)
  - Just ask an LLM to repair the problem (AAAI 2026)

Summary

Research Expertise and Interests

My Research Directions:

(1) Algorithm and heuristic design (solve problems quickly)

(2) Computational Complexity Analyses

times (cross product)

(a) Solving (mostly hierarchical) planning problems

(b) Repairing flawed (both classical and hierarchical) models

Today / Talk Outline:

- What's HTN planning? (Check!)
- Solving HTN problems via A* search.
- Extension of HTNs to uncertainty.
- Model Repair: some overview.

Thank you
for listening!