Lecture *Hierarchical Planning*

Chapter:
Solving (Non-Hierarchical) Planning Problems via Search

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Overview:

How to Solve Planning Problems?

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- The (relaxed) planning graph as a basis for several heuristics used for planning as heuristic search – both in non-hierarchical and in hierarchical planning.

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- This algorithm will be extended for hierarchical planning.

Pseudo Code

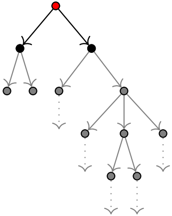
Algorithm: Classical Planning

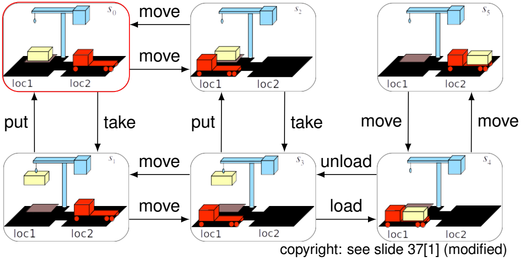
Input: A STRIPS planning problem $\langle V, A, s_I, g \rangle$

Output: A solution $\bar{a}$ or ***fail*** if none exists

$fringe \leftarrow \{(s_I, \varepsilon)\}$
while $fringe \neq \emptyset$ **do**
    $(s, \bar{a}) \leftarrow nodeSelectAndRemove(fringe)$
    if $s \supseteq g$ **then return** $\bar{a}$
    for $a \in A$ **do**
        if $pre(a) \subseteq s$ **then**
            $s' = (s \setminus del(a)) \cup add(a)$
            $fringe \leftarrow fringe \cup \{(s', \bar{a} \circ a)\}$
return ***fail***

Example





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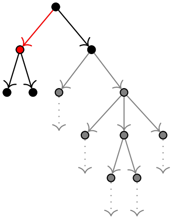

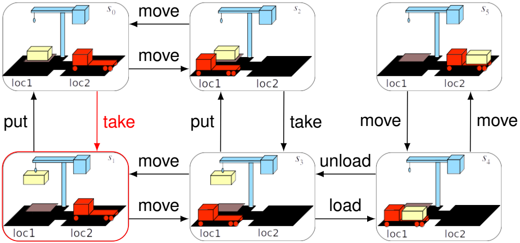

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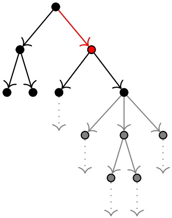

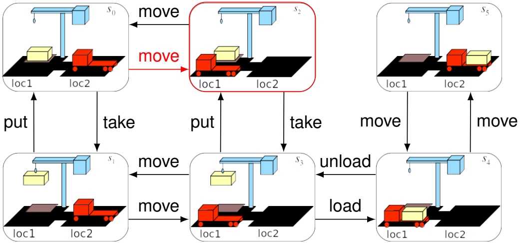

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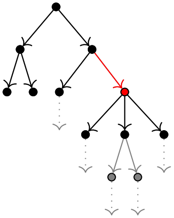

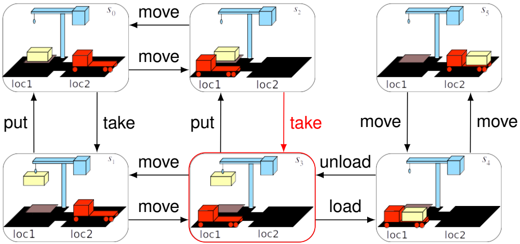

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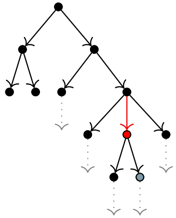

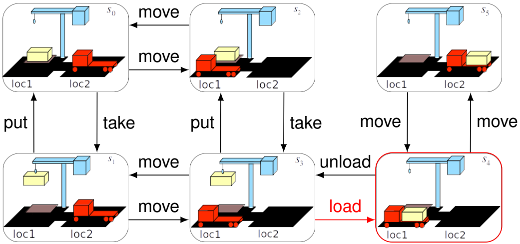

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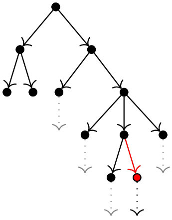

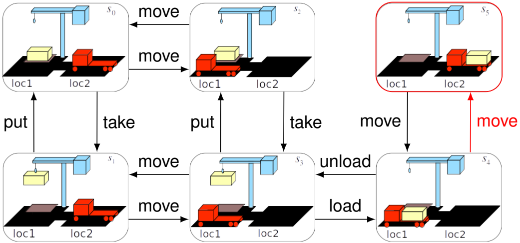

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- For good/low runtimes, there exist various techniques that ensure an efficient implementation:
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  - Only apply actions that change the current state.
  - Test action applicability efficiently, e.g., relying on decision trees. Cf. *Successor Generators* in the work by Malte Helmert. "The Fast Downward Planning System". In: *Journal of Artificial Intelligence Research (JAIR)* 26 (2006), pp. 191–246

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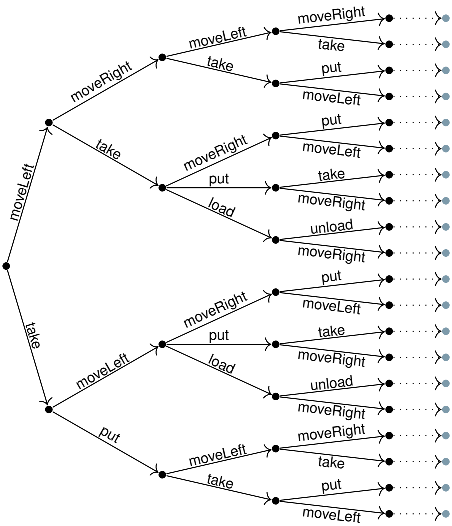
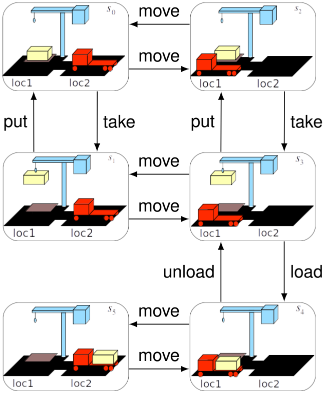
Proof:
Follows from the properties of the underlying search algorithm.

Search-Guidance in Classical Planning





Search-Guidance in Classical Planning, cont'd

Problems with the Search-Guidance:

- High branching factor: usually, many actions are applicable in the current state – resulting in a large search fringes.
- Which state to explore next is decided by heuristics (see later in this chapter).

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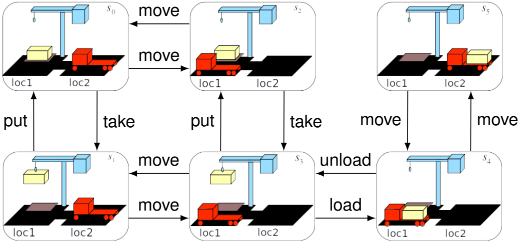

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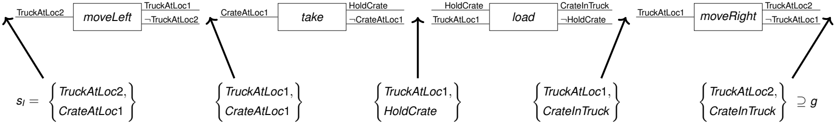
Classical (totally ordered) Solution:



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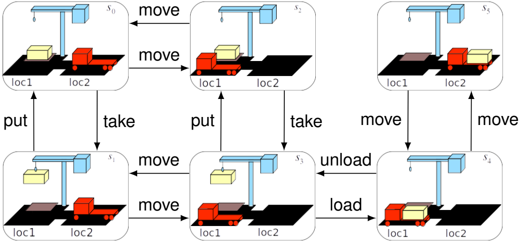

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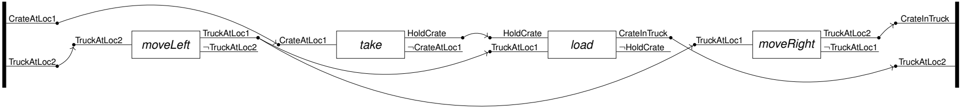

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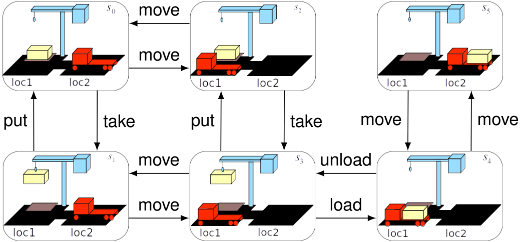

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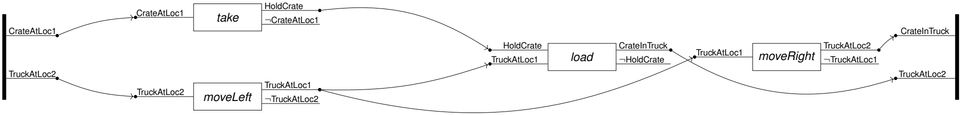
Partially ordered POCL solution:



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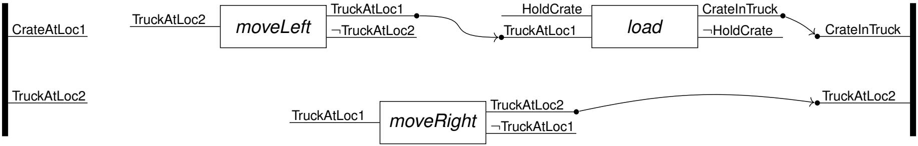
Plan Refinements

Let a search node contain the following partial plan:



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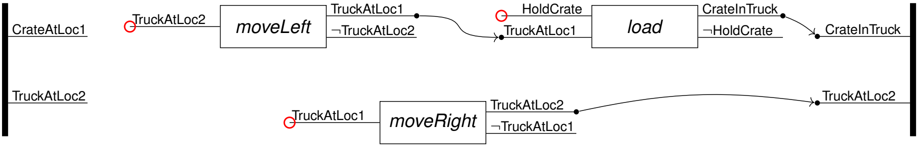

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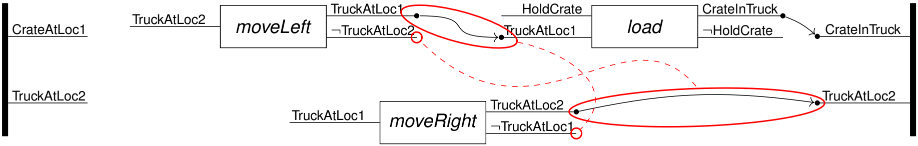

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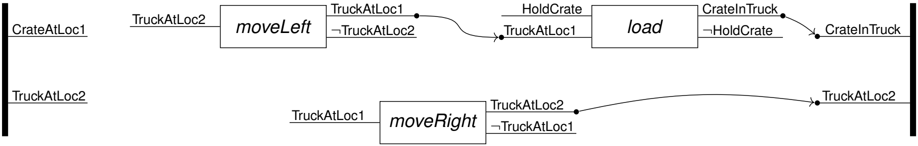

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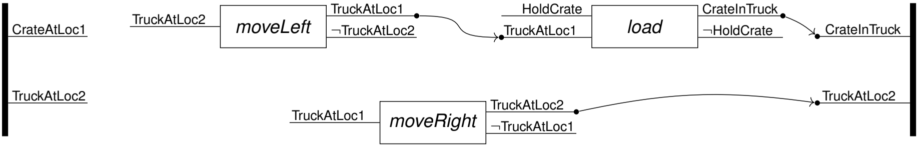

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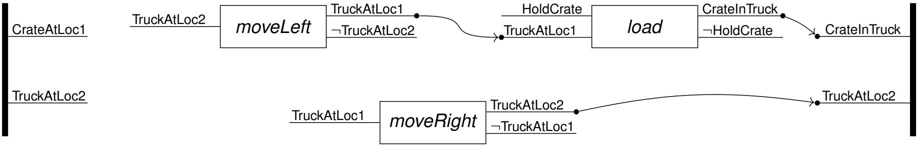

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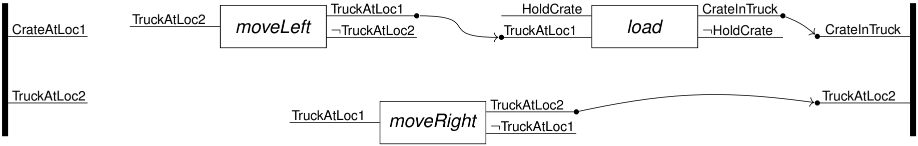

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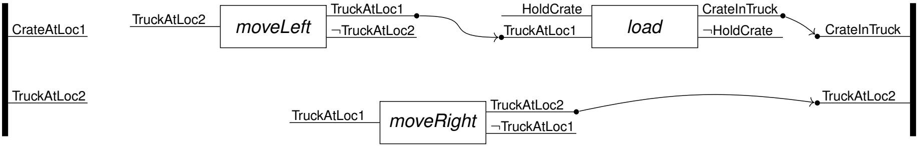

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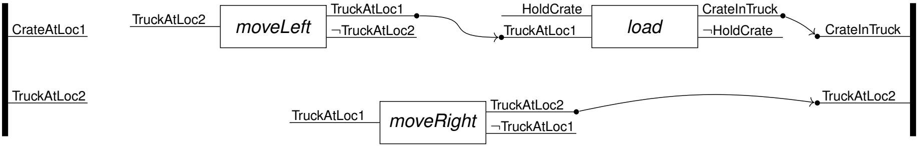
Plan Refinements

Let a search node contain the following partial plan:



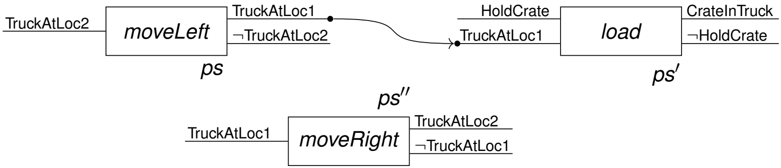
Which refinements exist to fix these flaws?

- Open preconditions:
  - Insert causal links (re-using actions).
  - Insert new actions plus causal links.
- Causal threats:
  - Insert ordering constraints.

→ POCL planning refines search nodes in a *flaw*-directed way: First pick a flaw, then apply all possible modifications.

Resolving Causal Threats

Let $(PS, \prec, CL)$ be a partial plan, $ps, ps' \in PS$ plan steps, and $ps \xrightarrow{\text{TruckAtLoc1}} ps'$ the causal link threatened by $ps'' \in PS$.



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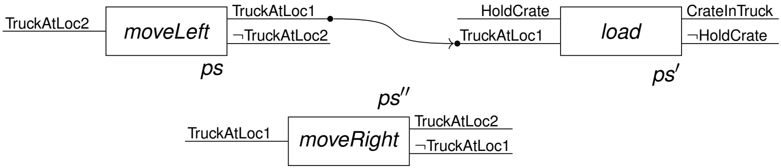

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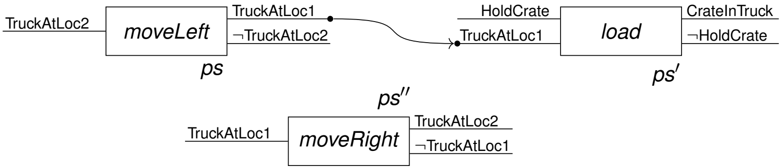

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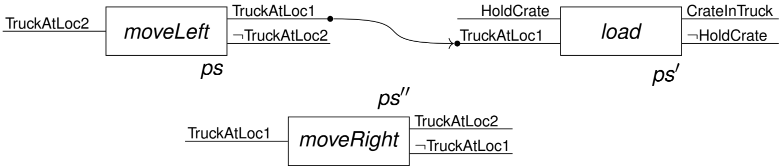

Which plan refinements resolve that causal threat?

- Promotion: order ps'' step *before* ps
- Demotion: order ps'' *behind* ps'

Note:

In case of lifting, we also get another refinement.

Algorithm, Pseudocode

Algorithm: POCL Planning

Input: A POCL planning problem $\langle V, A, P_I \rangle$
Output: A solution plan P or ***fail*** if none exists

$fringe = \{P_I\}$
while $fringe \neq \emptyset$ **do**
  $P := nodeSelectAndRemove(fringe)$
  $F := flawDetection(P)$
  if $F = \emptyset$ **then return** P
  $f := flawSelection(F)$
  $fringe := \{applyModification(m, f) \mid m$ is a modification for f in $P\}$
return *fail*

Note:
POCL planning was originally an alternative algorithm for classical problems, i.e., no initial partial plan was given.

Algorithm, Choice Points

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- *Flaw selection:*
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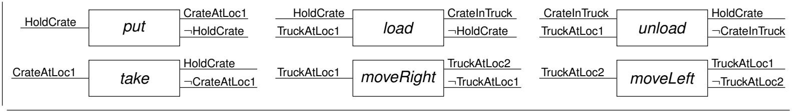
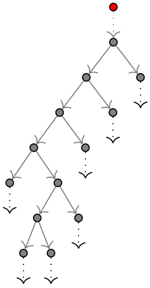
  - How to select a flaw? There are various possibilities, we only cover a few.

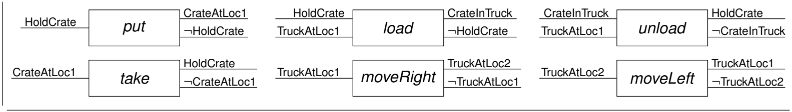
Example

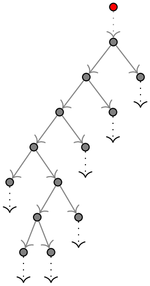




Flaws	**Modifications**
open prec.: CrateInTruck of *goal*	insert *load*
open prec.: TruckAtLoc2 of *goal*	insert *moveRight* insert causal link from *init*

Example





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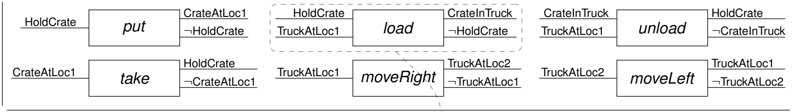

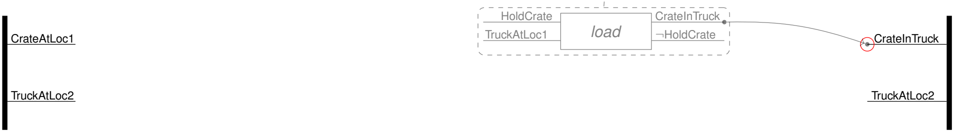

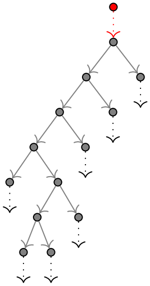

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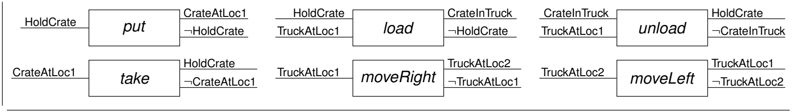

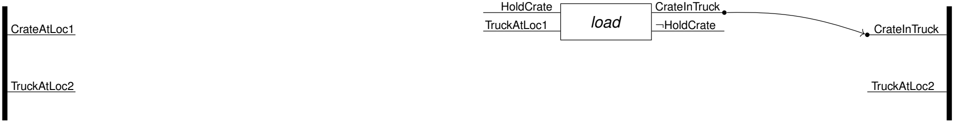

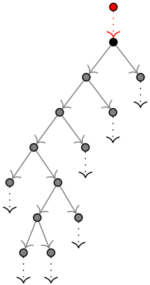

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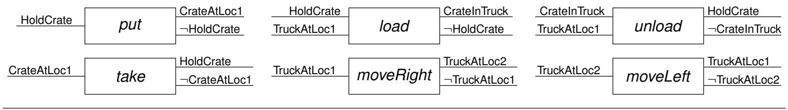

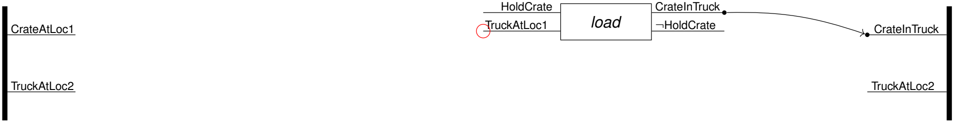

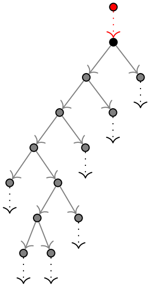

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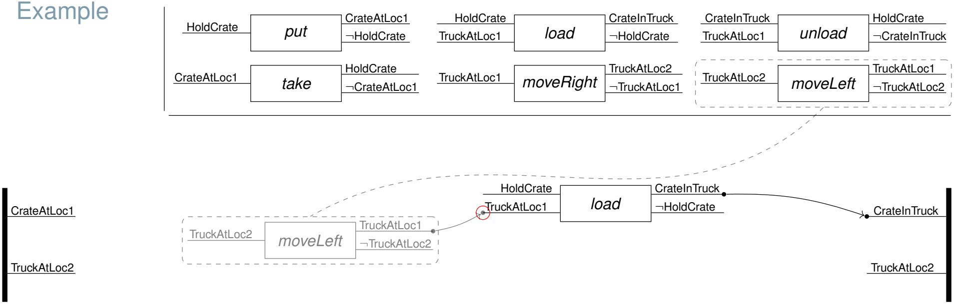

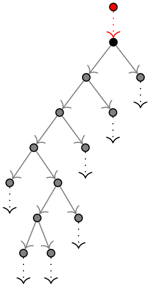

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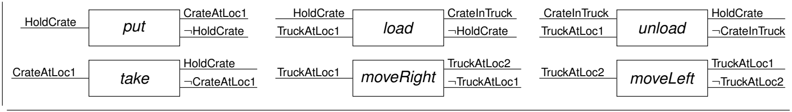

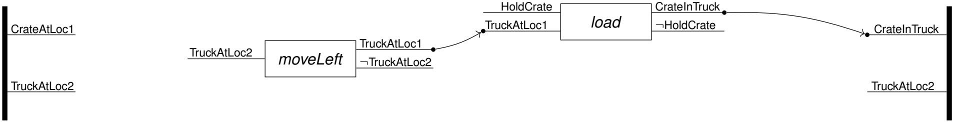

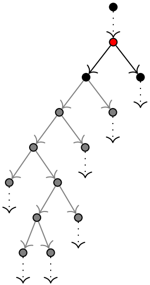

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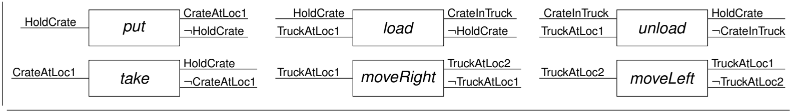

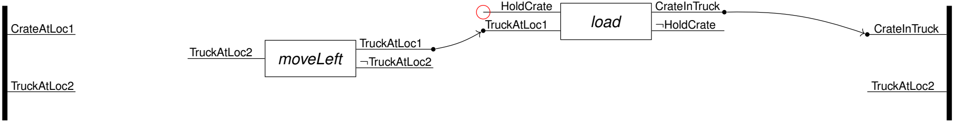

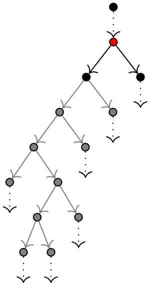

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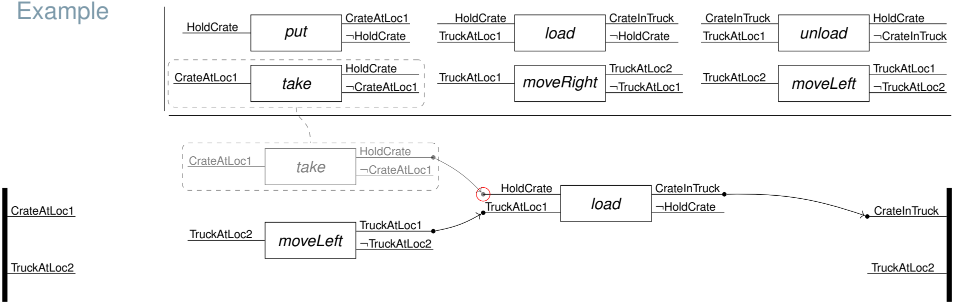

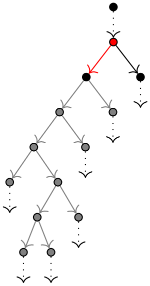

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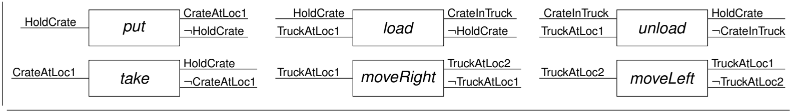

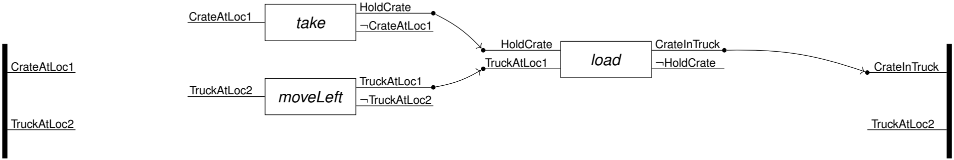

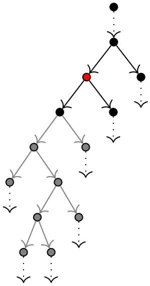

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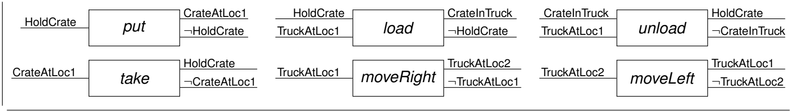

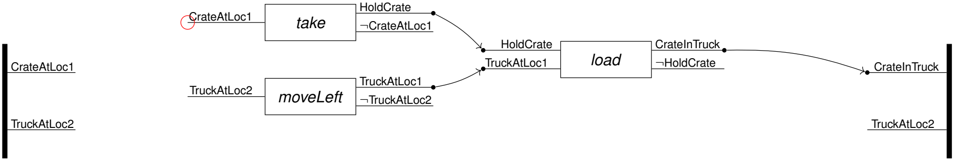

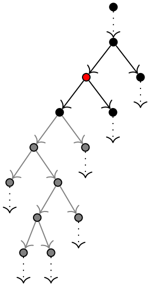

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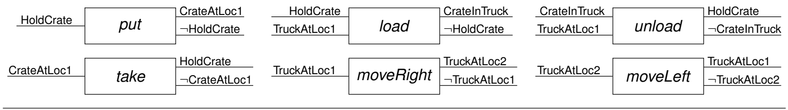

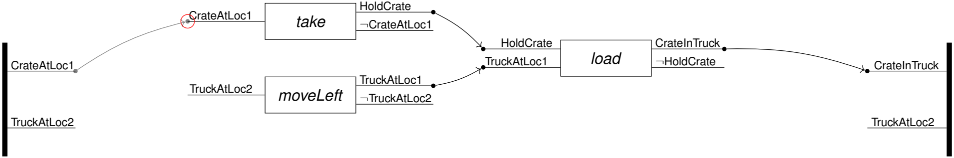

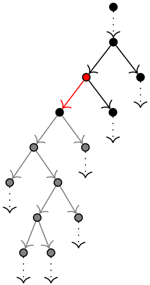

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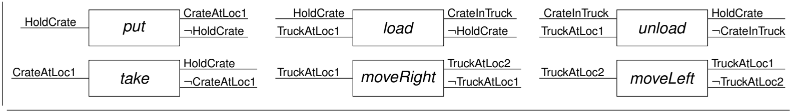

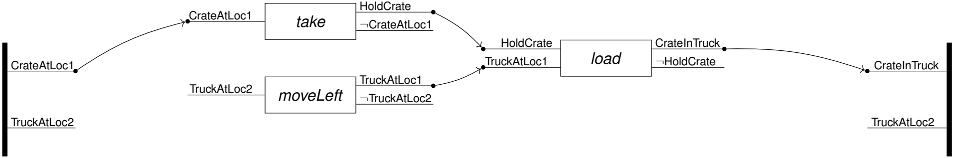

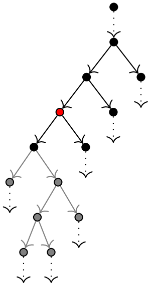

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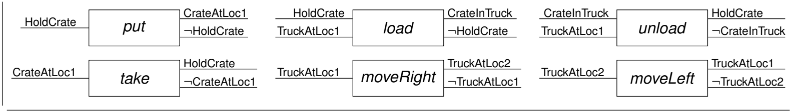

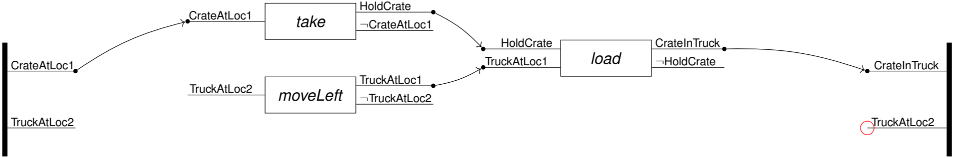

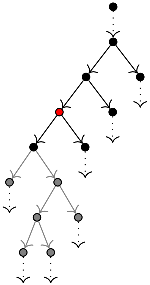

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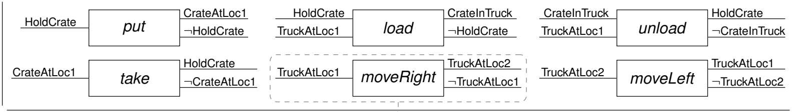

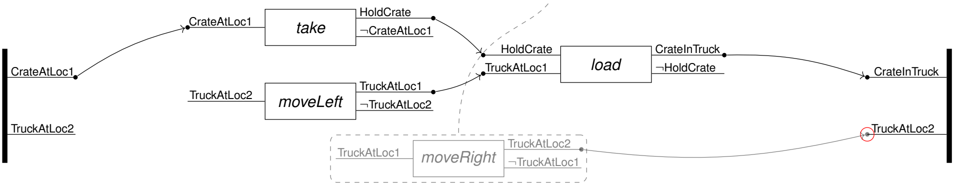

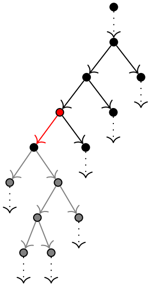

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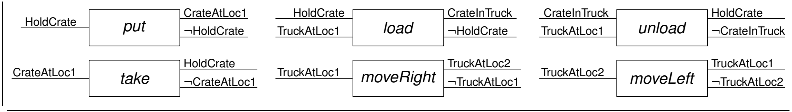
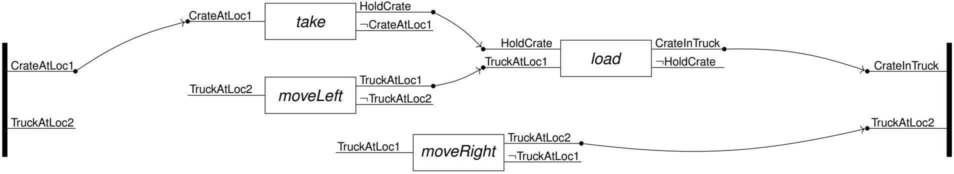
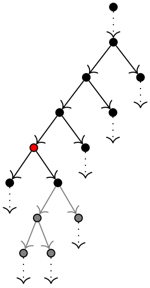
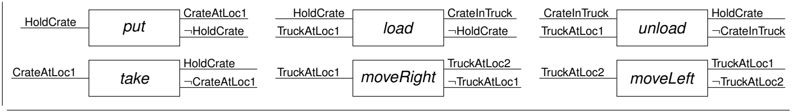


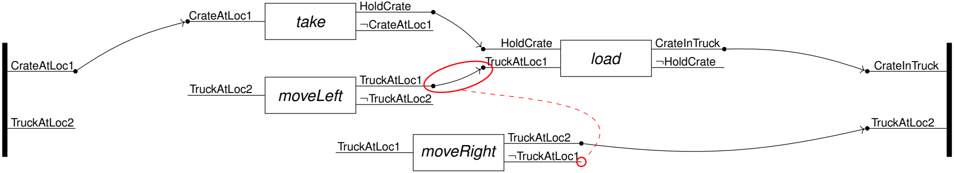


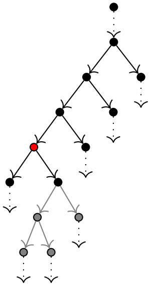


Flaws	**Modifications**
open prec.: TruckAtLoc2 of *moveLeft*	insert causal link from *init* insert *moveRight* insert causal link from *moveRight*
open prec.: TruckAtLoc1 of *moveRight*	insert causal link from *moveLeft* insert *moveLeft*
causal threat: moveLeft $\xrightarrow{\text{TruckAtLoc1}}$ *load* by *moveRight*	promote *moveRight* before *moveLeft* demote *moveRight* after *load*
causal threat: moveRight $\xrightarrow{\text{TruckAtLoc2}}$ *goal* by *moveLeft*	promote *moveLeft* before *moveRight*

Example







Flaws	**Modifications**
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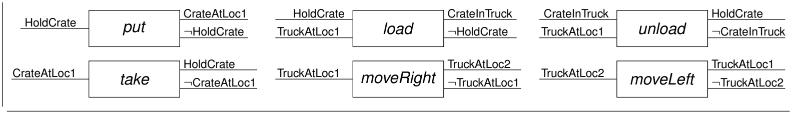
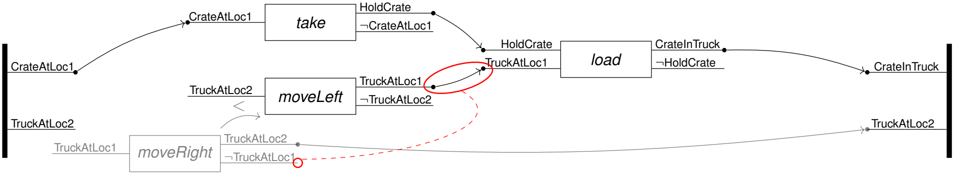
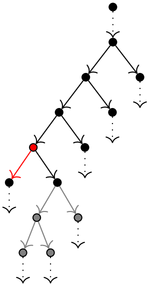
Example







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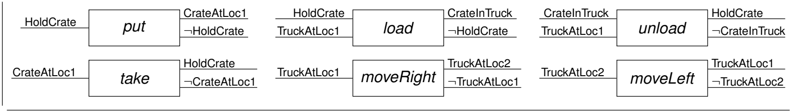

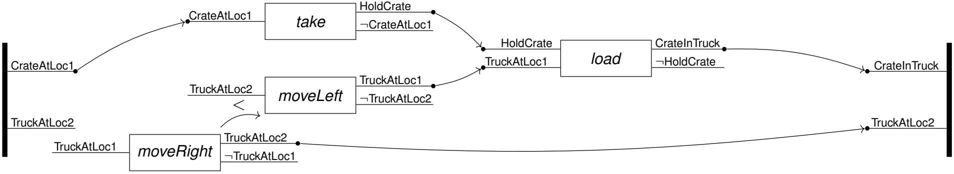

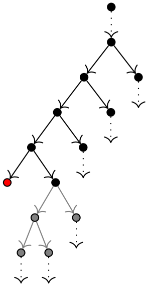

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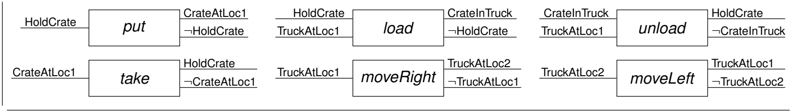

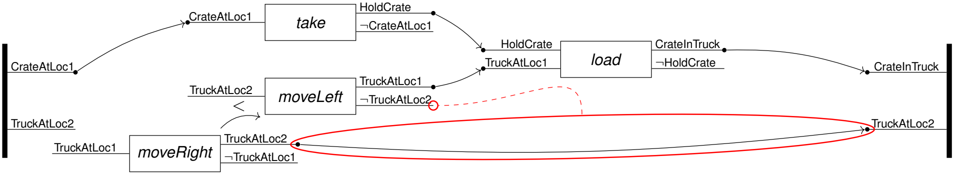

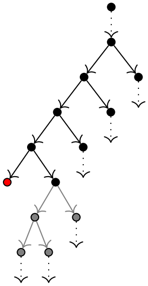

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Discard partial plan due to unresolvable flaw!

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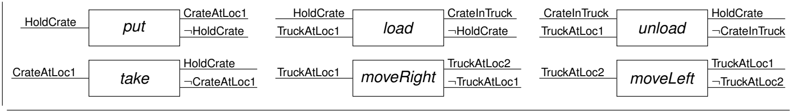

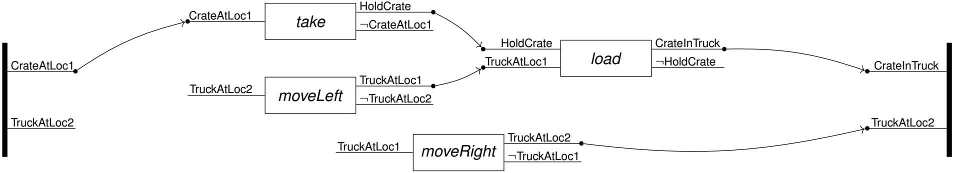

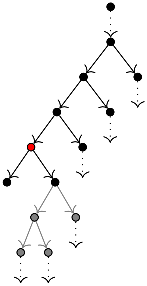

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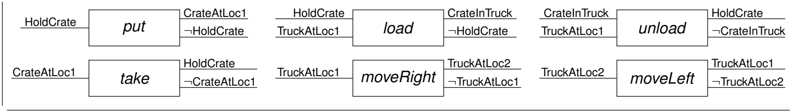

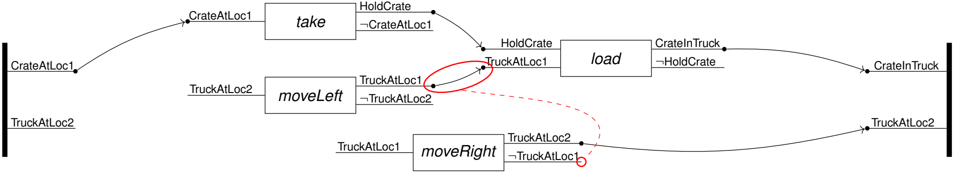

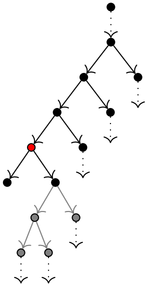

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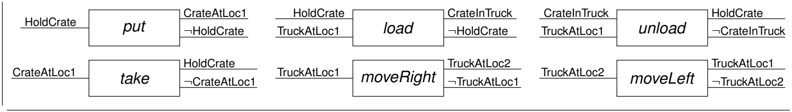

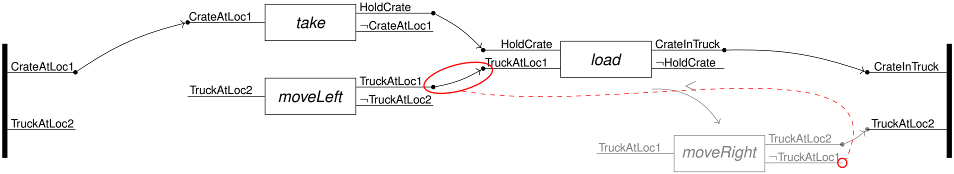

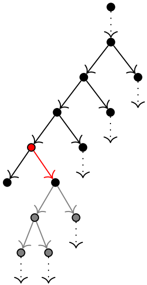

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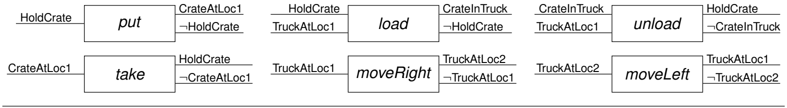

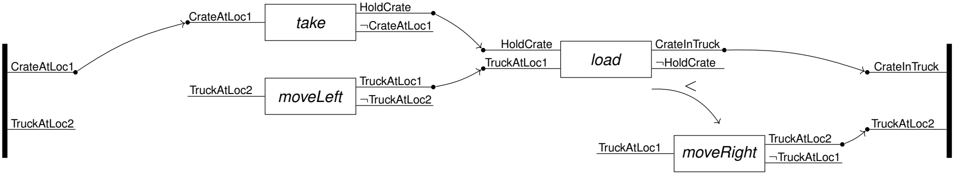

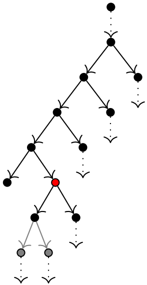

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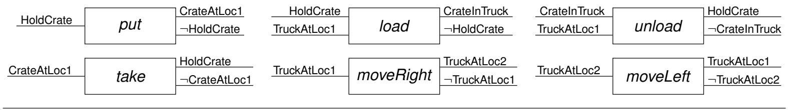

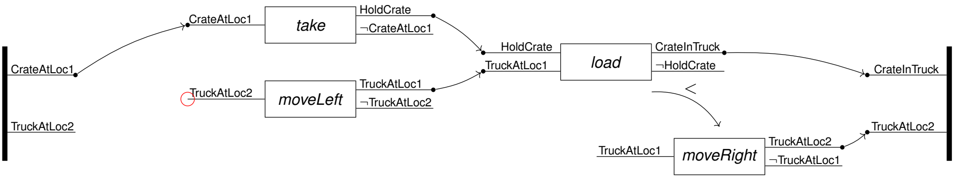

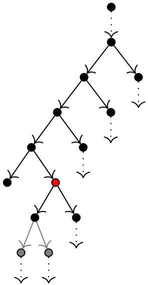

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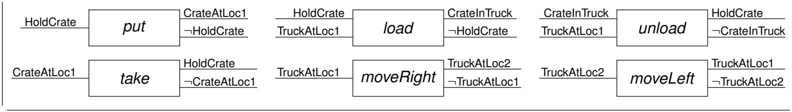

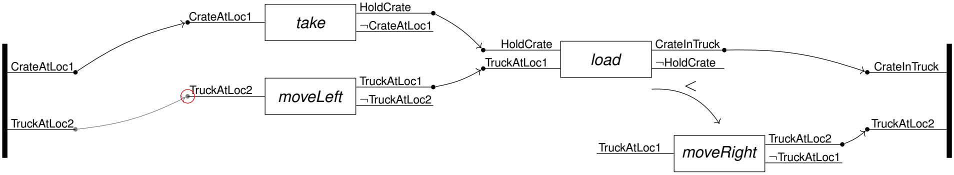

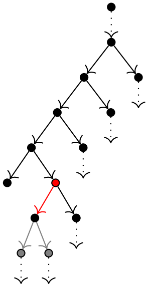

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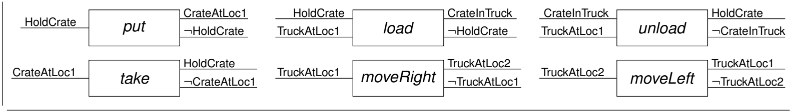

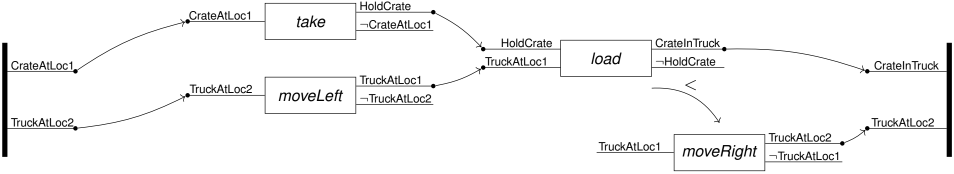

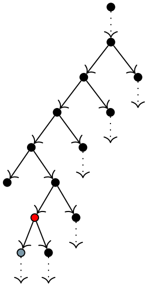

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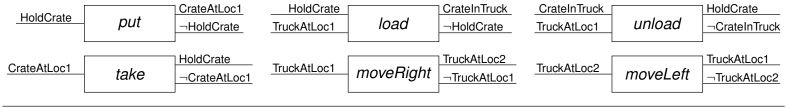

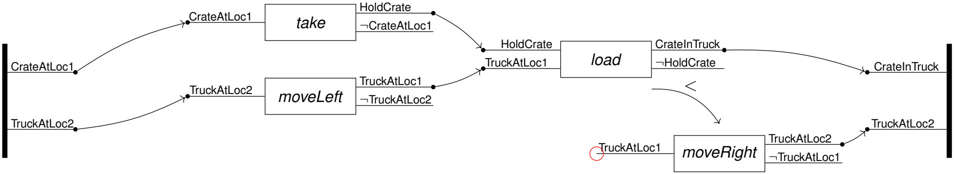

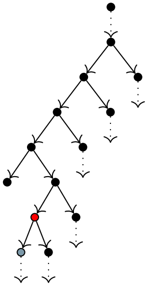

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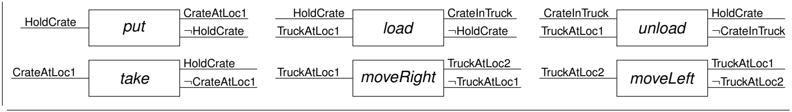

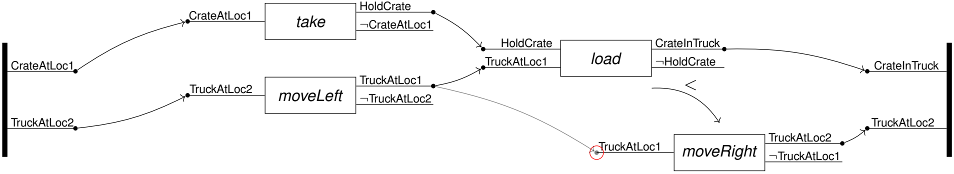

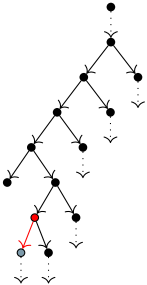

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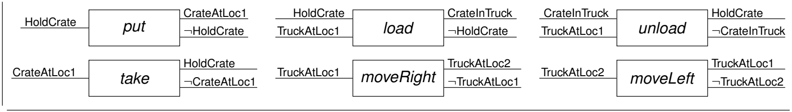

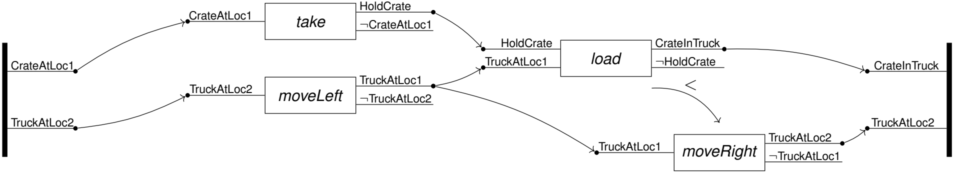

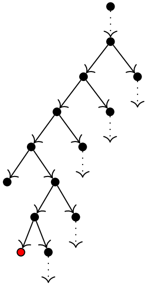

Flaws	Modifications

Since there is no flaw: Return solution plan!

Flaw Selection Strategies

Which flaw to select?

- *For completeness:*
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- *Causal Threats First (CTF):*
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  - → Gives a preference to causal threats: Only deal with link or action insertions after the partial plan has no "internal" issues.
  - → This strategy was part of the well-known POP algorithm by Russell and Norvig's text book *Artificial Intelligence – A Modern Approach* and of the well-known POCL planners SNLP and UCPOP. Here, the *algorithm* resolved all threats before any other flaw (open condition) was selected.

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  - → Nice special case: Fix flaws with just one modification! (This choice can *never* be wrong!)

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- *Left-Most Open Condition First (LMOCF):*
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  - → Search nodes have only one linearization until the chain finally roots in the initial state.

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Some flaw selection strategies:

Flaw selection strategies can be combined/concatenated!

For instance, $\langle CTF, LMOCF, LCFR \rangle$ will:

- First eliminate all causal threats,
- among all non-threat flaws select a left-most open condition,
- and among them some flaw with the fewest modifications.

Flaw Selection Strategies, Literature

There are *many* flaw selection strategies known to the literature. Some pointers:

- Håkan L. S. Younes and Reid G. Simmons. "VHPOP: Versatile heuristic partial order planner". In: *Journal of Artificial Intelligence Research (JAIR)* 20 (2003), pp. 405–430
- Martha E. Pollack et al. "Flaw Selection Strategies For Partial-Order Planning". In: *Journal of Artificial Intelligence Research (JAIR)* 6 (1997), pp. 223–262
- Mike Williamson and Steve Hanks. "Flaw Selection Strategies for Value-Directed Planning". In: *Proc. of the 3rd Int. Conf. on Artificial Intelligence Planning Systems (AIPS 1996)*. AAAI Press, 1996, pp. 237–244

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POCL Planning is sound and complete.

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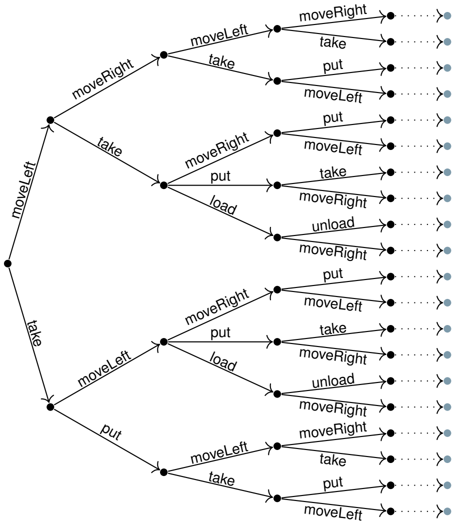
Proof:

Follows from:

- The properties of the underlying search algorithm.
- The fact that for each flaw *all* modifications that could possibly resolve that flaw are branched into the search space.
- The strongest form of completeness does not hold, since only causally relevant actions can be added in POCL planning.

Reminder: Search-Guidance in Classical Planning



Main issue in classical planning:

High branching factor, which usually allows many actions to be applicable in the current state – resulting in a large search fringes. (Dealt with by heuristics).

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Problems with the Search-Guidance:

- Despite smaller branching factor, we still need to decide on which partial plans to work next $\rightarrow$ use heuristics!
- Heuristic design is more complicated here, because there are more constraints to respect (the partial plan rather than just a state).

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- It allows to compare different planning algorithms and to define certain properties.

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- A refinement operator R is called *systematic* if for all $i \neq j$ holds $\langle\langle n_i \rangle\rangle \cap \langle\langle n_j \rangle\rangle = \emptyset$.

Formal Definitions, cont'd

The concept of *planning as refinement search* was formally introduced by:

- Subbarao Kambhampati et al. "Planning as Refinement Search: A Unified Framework for Evaluating Design Tradeoffs in Partial-Order Planning". In: *Artificial Intelligence* 76.1-2 (1995), pp. 167–238
- Subbarao Kambhampati. "Refinement Planning as a Unifying Framework for Plan Synthesis". In: *AI Magazine* 18.2 (1997), pp. 67–98

(The definitions provided here base upon the '95 article.)

Systematicity in Refinement Planning

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- Further reading: Subbarao Kambhampati. "On the Utility of Systematicity: Understanding Tradeoffs between Redundancy and Commitment in Partial-Order Planning". In: *Proc. of the 13th Int. Joint Conf. on Artificial Intelligence (IJCAI 1993)*. Morgan Kaufmann, 1993, pp. 1380–1385

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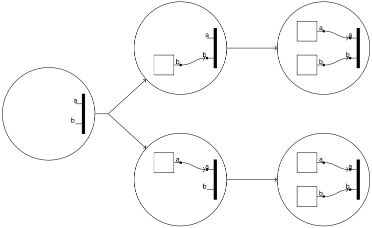
Consider a planning problem with $g = \{a, b\}$ and two actions:

$$A = (\emptyset, \{a\}, \emptyset) \quad B = (\emptyset, \{b\}, \emptyset)$$

The following search space proves that it's not systematic:



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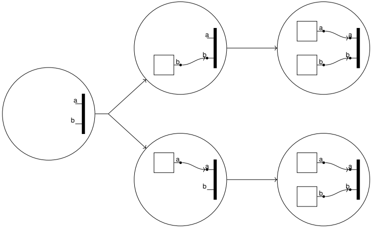

... right? No! The above tree is *not* a (single) POCL search tree: The flaw selection is missing.

A Correct Example

POCL planning ist not systematic.

Consider a planning problem with $g = \{a, b\}$ and three actions:

- $A = (\{c, d\}, \{a\}, \emptyset)$
- $CB = (\emptyset, \{c, b\}, \emptyset)$
- $DB = (\emptyset, \{d, b\}, \emptyset)$

With first resolving the goal precondition *b*, the same set of action sequences (*DB*, *CB*, *A* and *CB*, *DB*, *A*) can be derived in two separate branches.

A Correct Example, cont'd

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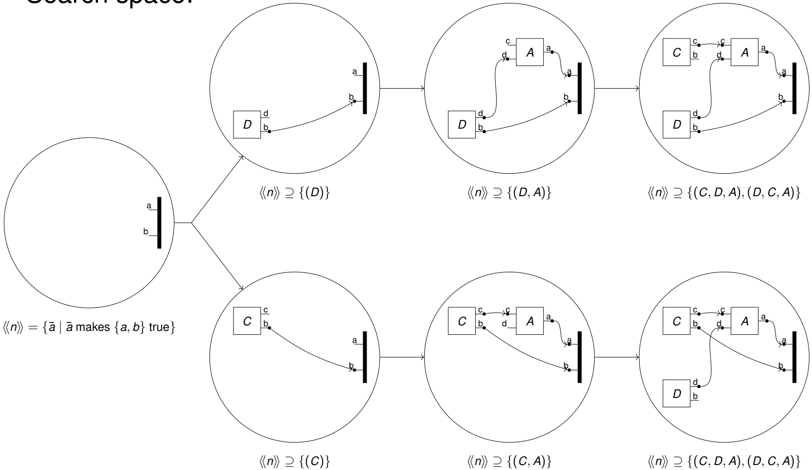
Search space:



Positive Causal Threats

We now extend the set of flaws by a *positive causal threat*.

Definition (Positive Causal Threat)

Let $(PS, \prec, CL)$ be a partial plan. A *positive causal threat* consists of the plan steps $ps, ps' \in PS$, a causal link $ps \xrightarrow{v} ps'$, and the *threatening plan step* $ps'' \in PS$ if and only if

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The modifications to resolve this flaw are analogous to standard causal threats.

Positive Causal Threats, cont'd

Theorem

POCL Planning with positive causal threats is systematic.

Proof:

See David McAllester and David Rosenblitt. "Systematic Nonlinear Planning". In: *Proc. of the 9th National Conf. on Artificial Intelligence (AAAI 1991)*. AAAI Press, 1991, pp. 634–639

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Note that POCL planning is ordinarily done *without* positive causal threats, because it is then usually more efficient (despite being non-systematic).

Influence of Positive Causal Threats, Example

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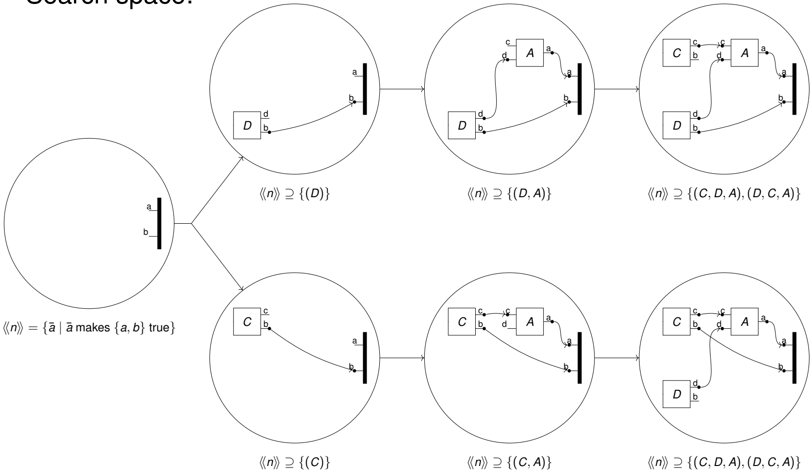

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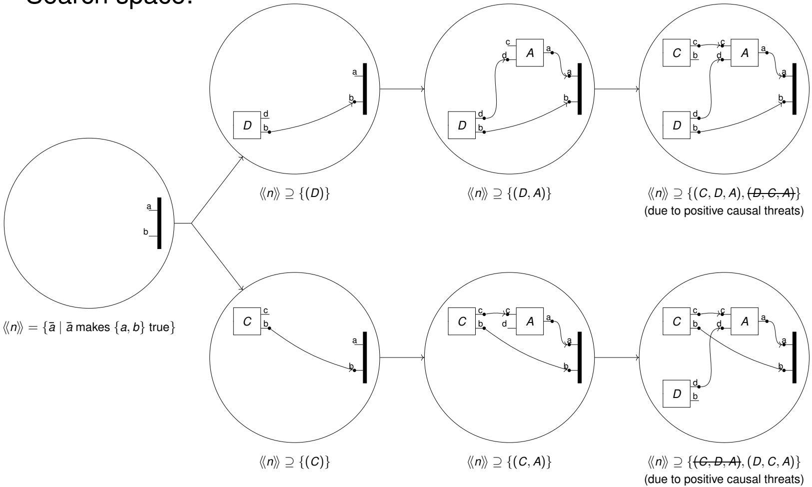

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- In contrast to classical planning, search is a *two-stage* process: In addition to the search node selection, we also select a flaw to work on.
- Refinement search is an algorithm-independent concept to be able to compare different algorithms (e.g., their systematicity).

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Classical Planning:

- pro: State-based search makes development of heuristics relatively “easy”.

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