Course "Automated Planning: Theory and Practice"
Chapter 06: The Partial Order Causal Link Search Space

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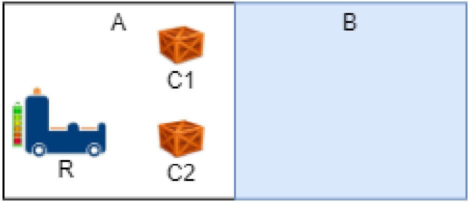
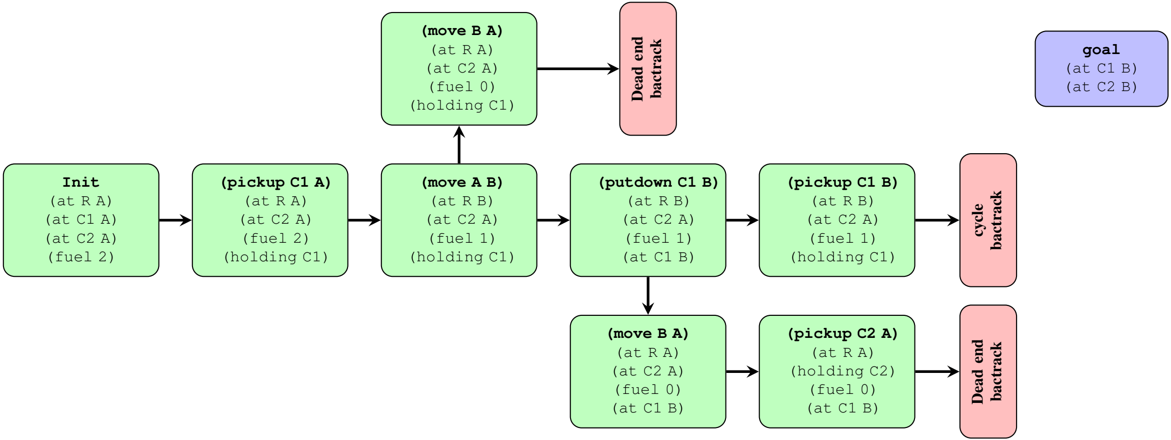
MOTIVATING PROBLEM

- Let's consider a simple planning problem:
  - Two crates `C1`, `C2`, two positions `A`, `B`, and one robot `R`
  - The robot:
    - can `carry` up to two crates
    - can `move` between locations, consuming one unit of fuel
  - Initially crates and robot are at `A`, and the robot has 2 unit of fuel
  - Both crates shall be moved to `B`

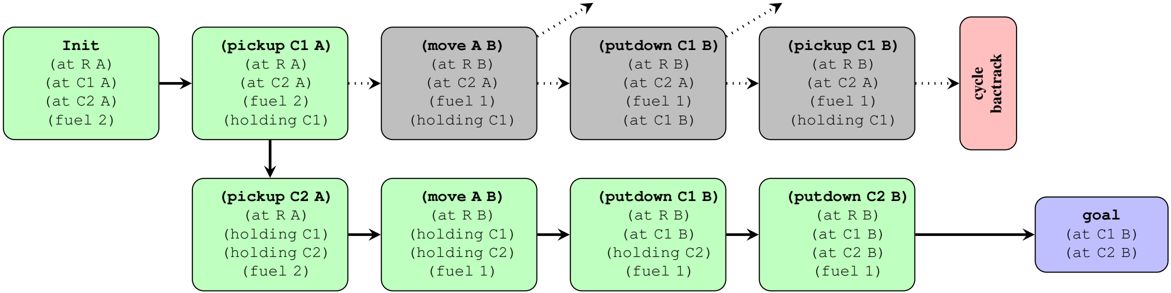


Let's see what forward-chaining planning might do (depending on heuristics)...

Motivating Problem: Forward Search



Motivating Problem: Forward Search



Motivating Problem: Observations

- Most of the actions added before backtracking were useful and necessary

(pickup C1 A) (move A B) (putdown C1 B) ~~(move B A)~~ (pickup C2 A)

- At first, we added them in the wrong order

(pickup C1 A) (move A B) (putdown C1 B) (pickup C2 A)

- Forward and backward planning commit immediately to action order!
  - Puts each action in its final place in the plan!
- State space heuristics must be "smart enough" to tell us:
  - Which actions are useful
  - When to add them in the plan

What if we could "rearrange" actions?

First step: Insertion

- Sequences with arbitrary insertion: Useful?
  - Most of the actions added before backtracking were useful and necessary

    `(pickup C1 A)` `(move A B)` `(putdown C1 B)`

  - Realize you need another one...

    `(pickup C2 A)`

    How to decide which action to *insert*, if not at the end?

  - Make a space...

    `(pickup C1 A)` `(move A B)` `(putdown C1 B)`

    How to decide where to insert it?

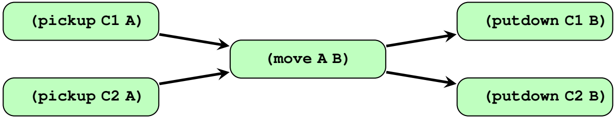
  - ... and place the action there

    `(pickup C1 A)` `(pickup C2 A)` `(move A B)` `(putdown C1 B)`

    How to check that the "old" preconditions remain satisfied?

Second Step: Partial Order

- If we must deal with this complexity:
  - We can "get more from the same price"
- Let's skip sequences completely - a plan could be partially ordered

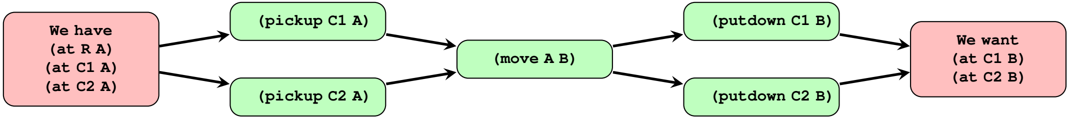


  - A set of actions $A = \{a_1, a_2, a_3, ...\}$
  - A set of precedence constraints $\{a_1 < a_2, a_1 < a_3, ...\}$
    - a_1 must finish before a_2 starts, a_1 must finish before a_3 starts
    - We represent them graphically with solid arrows

How do we generate such plans?

POCL: Introduction

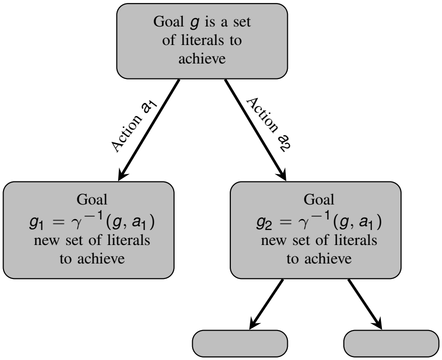
- Partial Order Causal Link (POCL) planning
  - Use a partial order as described before
    - Not when executing the plan
    - Only to delay commitment to action ordering
  - As in backward search:
    - Add useful actions to achieve necessary conditions
    - Keep track of what remains to be achieved
    - Insert actions "at any point" in the plan



More sophisticated "bookkeeping" required!

POCL: Comparison to Backward Search

- Search tree for backward search (as seen earlier)



The goal is a set of literals – simple!

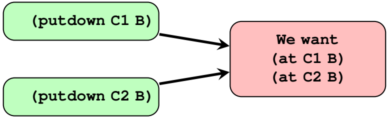
Every step takes you to a new set of literals to achieve

From a search node, you know how to reach the goal using a sequence of actions!

A search node [2] can simply be a goal set!

POCL: Comparison with Backward Search

- In POCL planning there is no sequence – and no clear "before" relation!



The goal is a set of literals – simple!

But no set of literals can describe what must be true before e.g. `(putdown C1, B)` ...

... because we could add a new action "in parallel" ...

... or even between `(putdown C1 B)` and the goal!

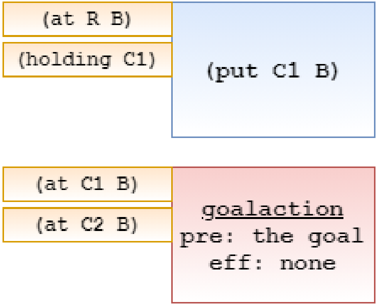
- There are consequences for the POCL plan structure and the node plan structure...

POCL: Conditions, Goal Action

- ... must keep track of individual propositions to be achieved
  - Throughout the plan – not a single state $g_1 = \gamma^{-1}(g, a_1)$
  - May come from preconditions of every action in the plan

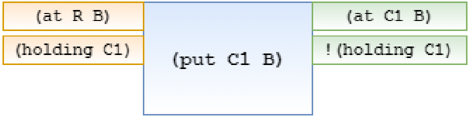
Notation chosen:
Preconditions on the left/top side

  - May come from problem goal as in backward search
    - Trick: Use a uniform representation
    - Add a "fake" goal action to every plan with the goals as preconditions!



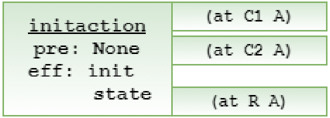
POCL: Effects, Initial Action

- Must keep track of individual propositions that are achieved
    - Throughout the plan - not from a single *relevant* action
    - May come from effects of every action in the plan



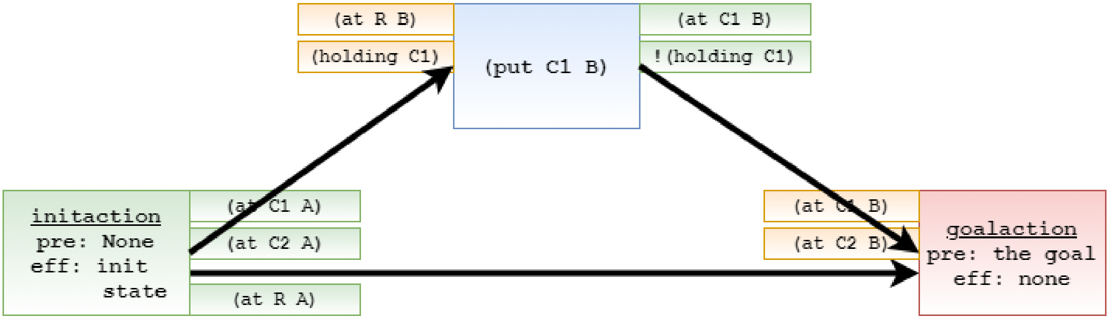
Notation chosen:
Effects on the right/bottom side

- May come from initial state
    - Trick: Use a uniform representation
    - Add a "fake" initial action with the initial state as effect



POCL: Precedence Constraints

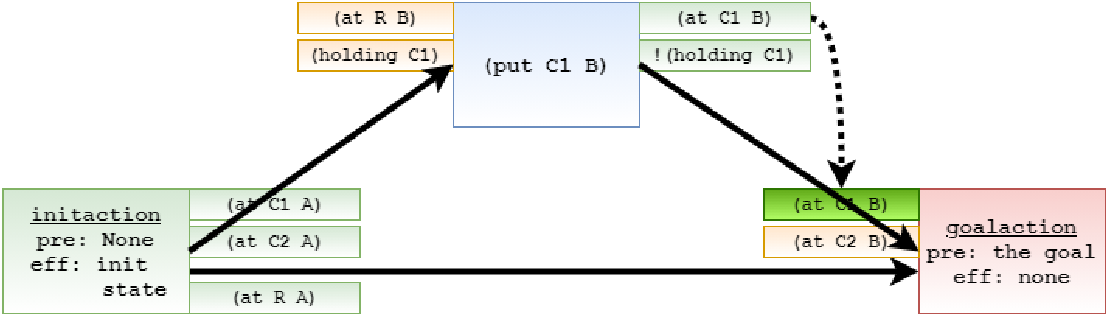
- Plan structure so far



POCL: Causal Links

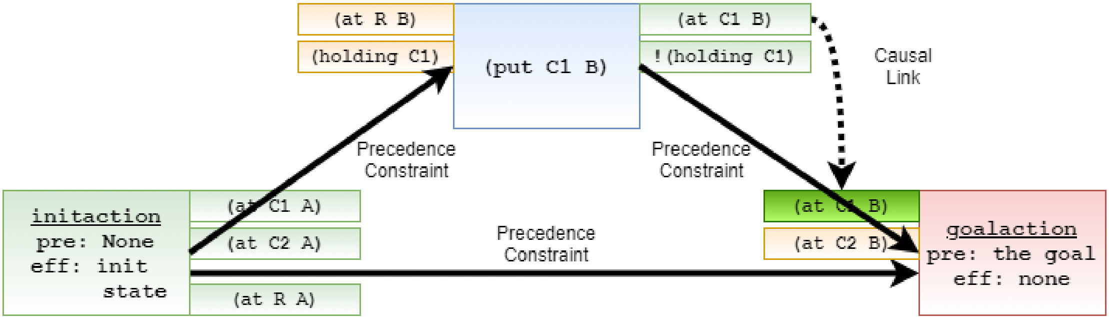
- Let's keep track of which actions achieves which precondition: Causal links

Causal links (dashed):
`(at C1 B)` must remain true between end of `(put C1 B)` and the beginning of `goalaction`.
No one must delete it!
Important for *threat management* (later)



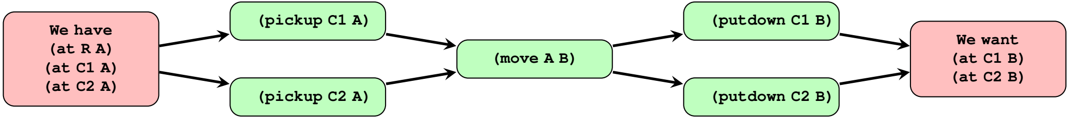
POCL: Partial-Order Plans

- A ground partial-order plan consists of:
  - A set of actions
  - A set of precedence constraints $a \rightarrow b$ (a must precede b)
  - A set of causal links $a \xrightarrow{p} b$ - action a establishes the preconditions p needed by b



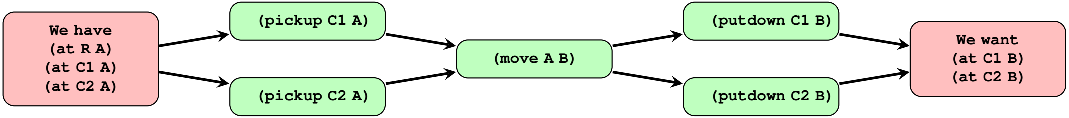
Partial-Order Solutions

- Original motivation: performance
  - A partial-order plan is a solution iff all sequential plans satisfying the ordering are solutions
  - A partial-order plan is a executable iff all sequential plans satisfying the ordering are solutions
    - `(pickup C1 A); (pickup C2 A); (move A B); (putdown C1 B); (putdown C2 B)`
    - `(pickup C2 A); (pickup C1 A); (move A B); (putdown C1 B); (putdown C2 B)`
    - `(pickup C1 A); (pickup C2 A); (move A B); (putdown C2 B); (putdown C1 B)`
    - `(pickup C2 A); (pickup C1 A); (move A B); (putdown C2 B); (putdown C1 B)`



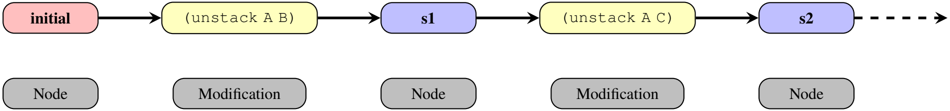
Partial-Order Solutions

- Can be extended to allow concurrent action execution
  - Requires a new formal model!
    - The so far considered transition model *does not define* what happens if `C1` and `C2` are picked up simultaneously

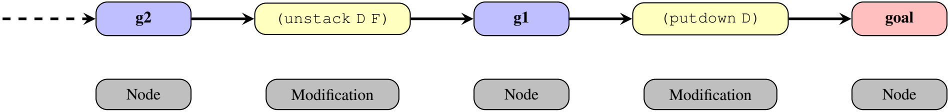


Context: Forward, Backward

- Forward Search: a search node is a "current state"

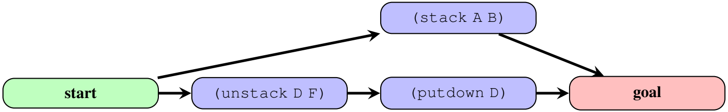


- Backward Search: a search node is a "current goal"



No current state during search!

- With partial-order plans: No "current" state or goal!
  - What's true after `(stack A B)` in example below?
    - Depends on the order in which the other actions are executed!
    - Changes if we insert new actions before `(stack A B)`!

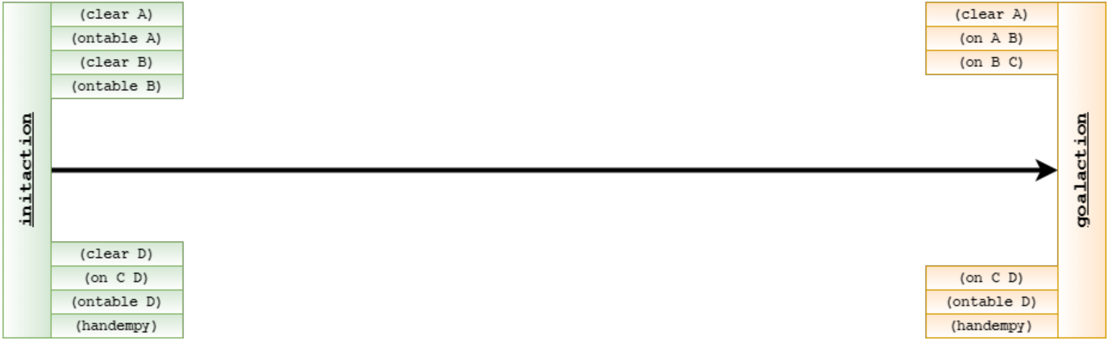


A search node cannot correspond to a state or to a goal!

Search Nodes are Partial Order Plans

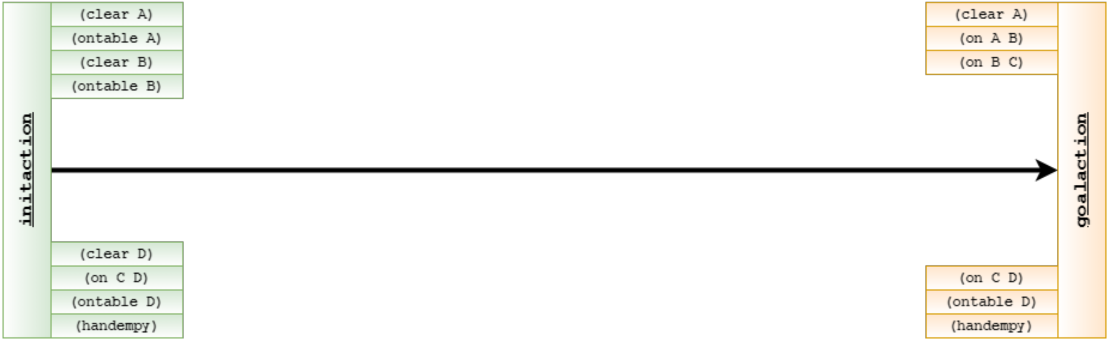
- [1] Each node must contain *more information*: the entire plan!
  - [2] The initial search node contains the initial plan
    - The special initial action and goal action
    - A single precedence constraint

This is one form of "plan-space" planning!



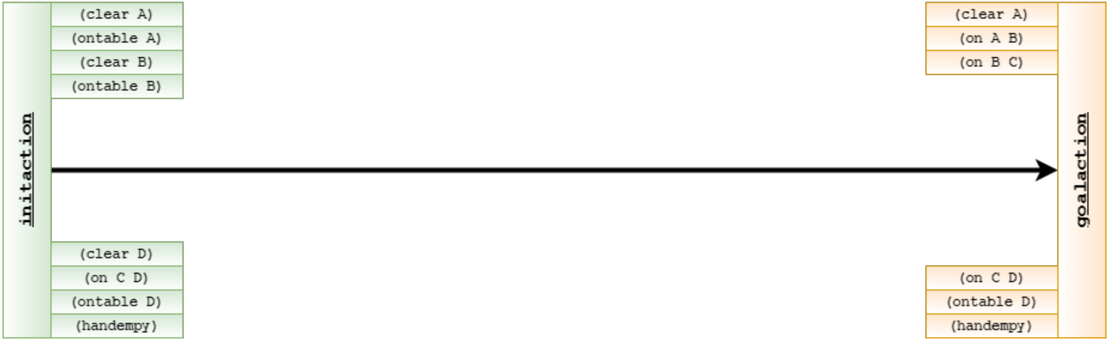
Branching rule

- [3] We need a branching rule!
  - Forward planning: One successor per action applicable is s
  - Backward planning: One successor per action relevant to g
  - POCL: ???



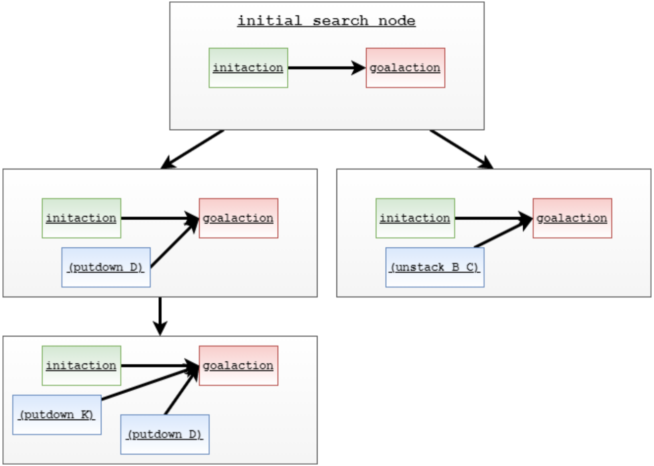
[3] Branching rule

- Identify specific reasons for modifying the plan, called flaws (i.e. todos)
  - 1) Open goal: we have not decided *how* to achieve a precondition (E.g. `(clear A)`)
  - 2) Threat: An action may *interfere* with another
- One successor for each different way of repairing a flaw



Search Space

- [6] Use search strategies, backtracking, heuristics, ... to search this space!



[4] Solution iff there are no flaws
(We will see later how to do it)

[5] Plan extraction: pick any sequential order consistent with the precedence constraints

```
(putdown D); (putdown K)
(putdown K); (putdown D)
```

FLAWS

- Flaw, *noun*:
  - a feature that mars the perfection of something; defect; fault: beauty without flaw; the flaws in our plan.
  - a defect impairing legal soundness or validity.
  - a crack, break, breach, or rent.
- Flaw, in POCL planning:
  - Something we need to take care of to complete the plan
  - Technical definition: An *open goal* or a *threat*

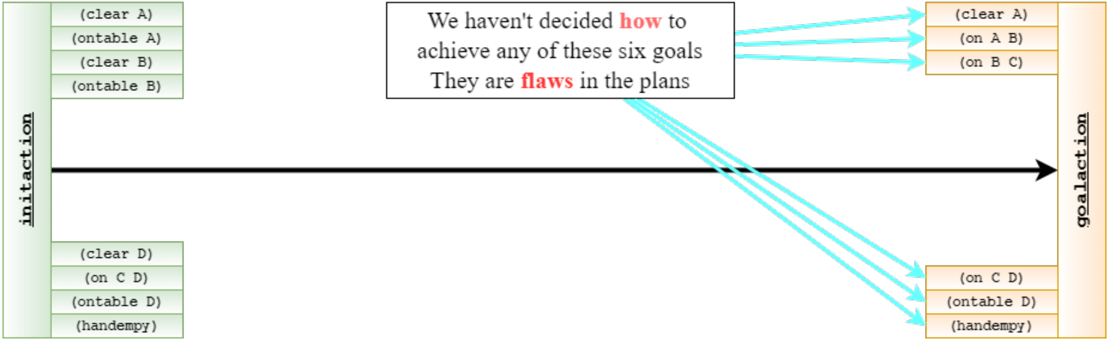
- Not:
  - Something that has "gone wrong"!
  - A problem during planning
  - A mistake in the final solution
  - ...

Flaw types

- Open Goals
- Threats

Flaw Type 1: Open Goals

- An action a has precondition p with no incoming causal link



`(clear A)` is already true in s0, but there is no causal link...
Adding one causal link from s0 means `(clear A)` must never be deleted!
We need other alternatives: delete `(clear A)`, then re-achieve it for `goalaction`..

FLAW TYPE 1: OPEN GOALS

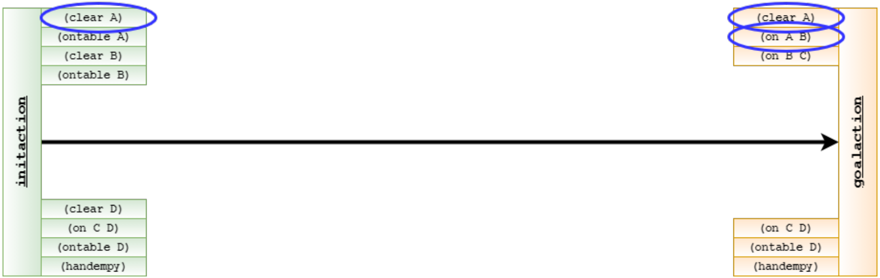
- To resolve an open goal
  - Find an action b that cause p
    - Can be a new action
    - Can be an action already in the plan, if we can make it precede a
  - Add a causal link

Partial order! This was not possible in backward search...

Essential:
Even if there **is already** an action that causes p,
you can still add a **new** action that **also** causes p!

Resolving Open Goals

- We can chose to find support for `(clear A)` 8 successors!
  - From `initaction`; from a new `(unstack B A)`, `(unstack C A)`, or `(unstack D A)`; from a new `(stack A B)`, `(stack A C)`, `(stack A D)`, or `(putdown A)`
- We can chose to find support for `(on A B)` +1 successor
  - Only from a new instance of `(stack A B)`
- ...

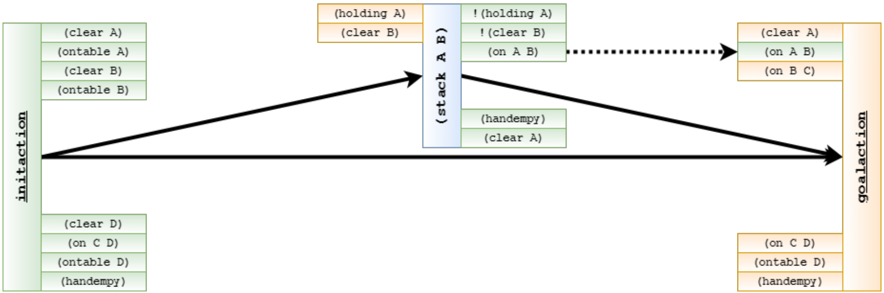


Resolving Open Goals (cont.)

- Suppose we add `(stack A B)` to achieve `(on A B)`
  - Must add a causal link for `(on A B)` (dashed lines)

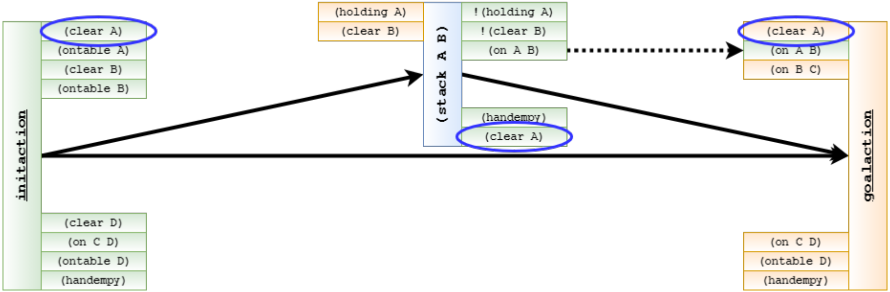
This instance of `(stack A B)` is responsible for achieving `(on A B)` for the `goalaction`

  - Must also add precedence constraints
  - Looks totally ordered: we actually have only one "real" action!



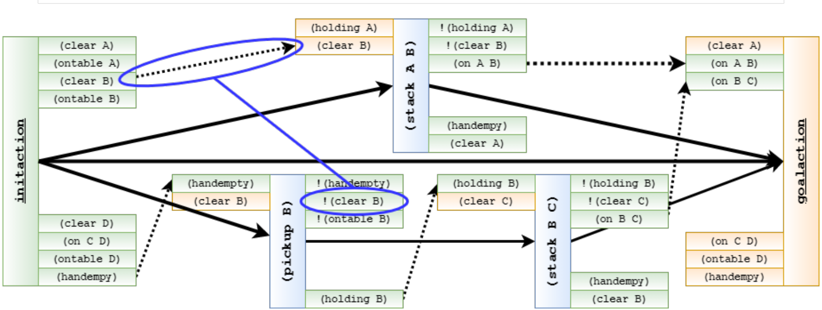
Resolving Open Goals (cont.)

- Now we have 7 open goals
  - We can choose to find support for `(clear A)`:
    - From `initaction`; from the instance of `(stack A B)` just added; from a new instance of `(stack A B)`, `(stack A, C)`, `(stack A D)`, or `(putdown A)`; from a new instance of `(unstack B A)`, `(unstack C A)`, `(unstack D A)`
  - ...



Flaw Type 2: Threats

- A threat against a causal link
  - `initaction` should achieve `(clear B)` for `(stack A B)` - there is a causal link
  - `(pickup B)` deletes `(clear B)`, and may occur between `initaction` and `(stack A B)`
  - We cannot be certain that `(clear B)` still holds when `(stack A B)` starts!



Flaw Type 2: Threats

- A threat against a causal link

time →

Action A1
executes here
makes `(clear B)`
true

Action A2
executes here
requires `(clear B)`

Action A3
unconstrained
may execute here
No problem

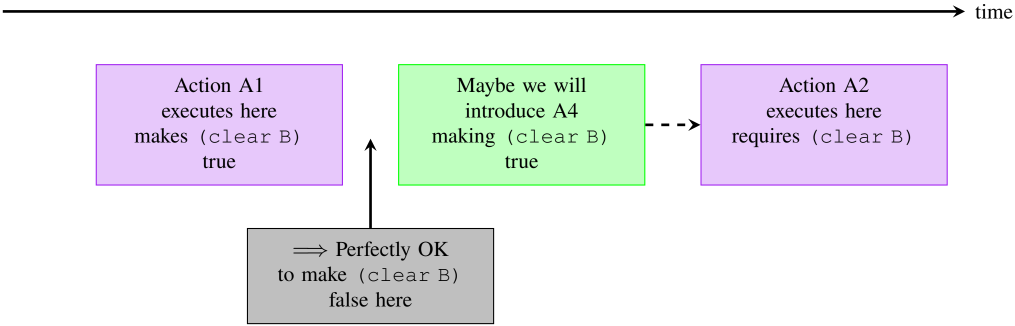
Action A3
unconstrained
may execute here
problem?

Action A3
unconstrained
may execute here
No problem

No! there is no causal link, so no reason to assume `(clear B)` must be preserved from `A1` to `A2`

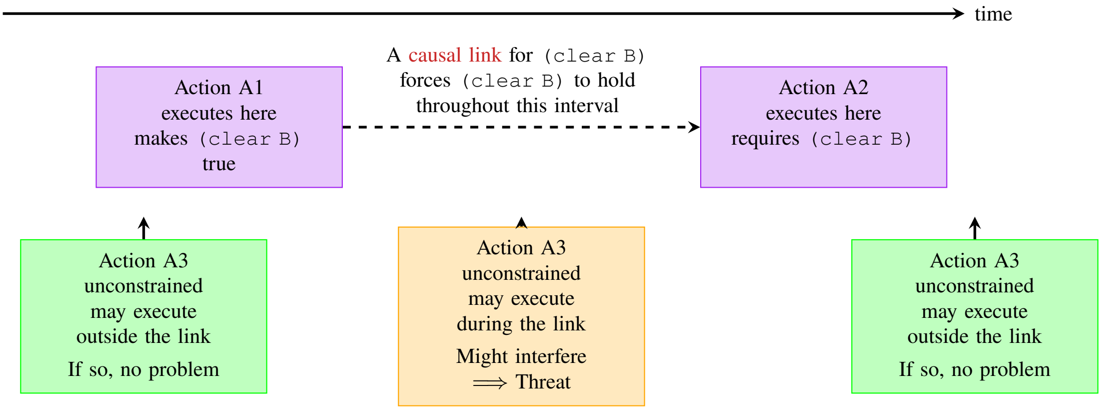
Flaw Type 2: Threats

- Why no threats without causal links?



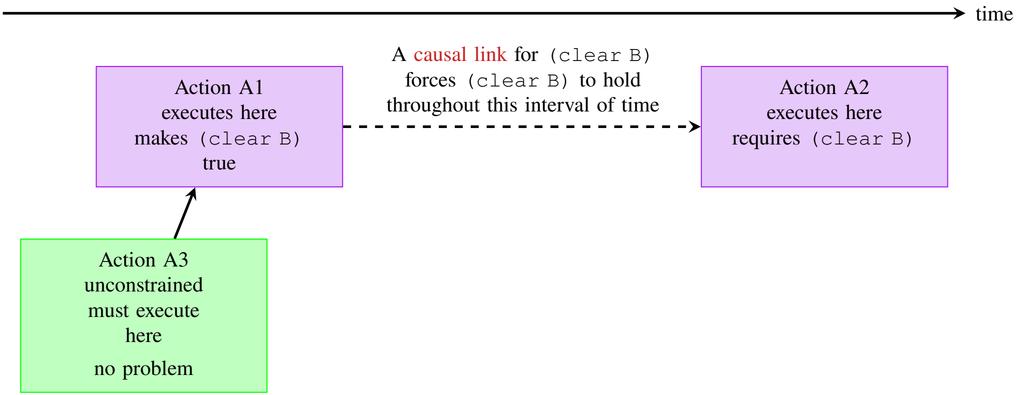
Flaw Type 2: Threats

- But when we have a causal link:

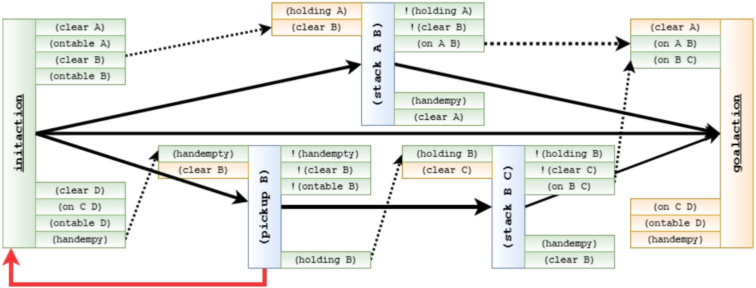


Resolving Threats: Rule 1

- The action that disturbs the causal link is placed before the action that support/achieves the precondition
  - Only possible if the resulting partial order is consistent (acyclic)!



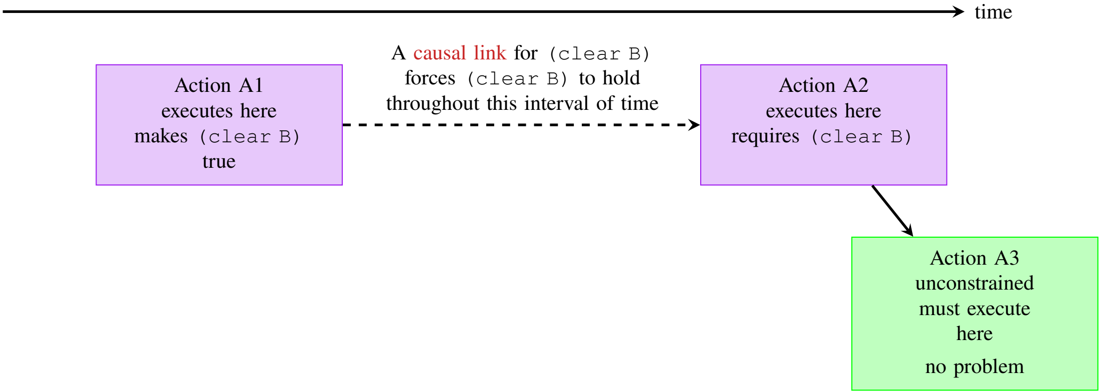
Resolving Threats



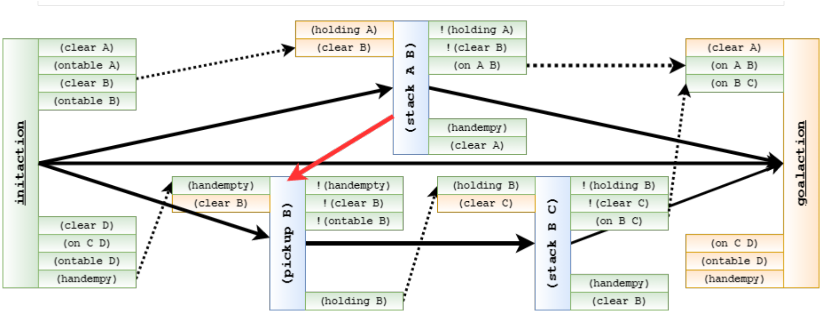
In this case not consistent! (a cycle is created)

Resolving Threats: Rule 2

- The action that disturbs the causal link is placed after the action that requires the precondition
  - Only possible if the the resulting partial order is consistent (acyclic)!

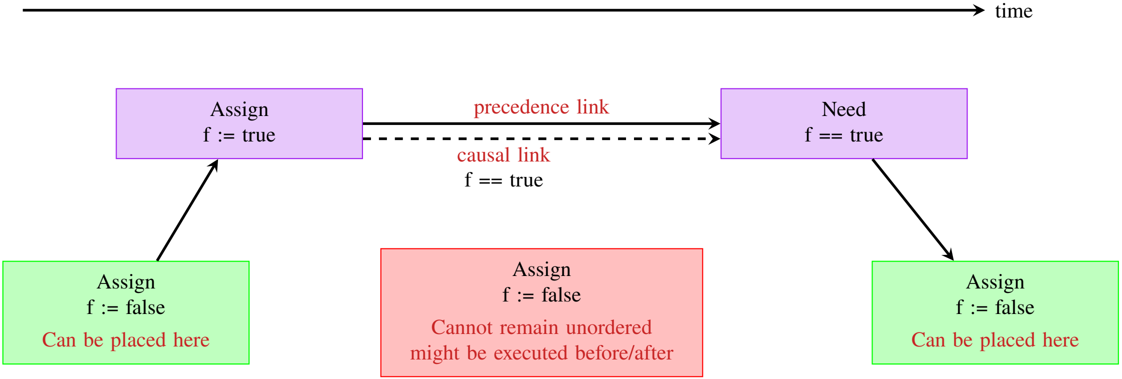


Resolving Threats

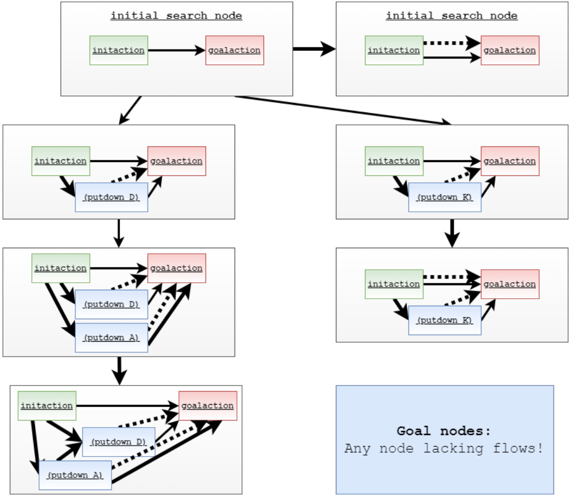


In this case it works! (There are no cycles)

Resolving Threats: Summary



POCL Search Space



Planning as Search

```
function SEARCH(problem)
    initial-node ← MAKE-INITIAL-NODE(problem)              → [2]
    open ← {initial-node}
    while (open ≠ ∅) do
        node ← SEARCH-STRATEGY-REMOVE-FROM(open)           → [6]
        if IS-SOLUTION(node) then                          → [4]
            return EXTRACT-PLAN-FROM(node)                 → [5]
        end if
        for each newnode ∈ SUCCESSORS(node) do             → [3] All ways of resolving some flaw
            open ← open ∪ {newnode}
        end for
    end while
    return Failure                                         → Expanded the entire search space without finding a solution
end function
```

POCL PLANNING: POSSIBLE FORMULATION (SOUND/COMPLETE)

```
function SEARCH(problem)
    initial-node ← MAKE-INITIAL-NODE(problem.init,problem.goal)     → [2]
    open ← {initial-node}
    while (open ≠ ∅) do
        π ← SEARCH-STRATEGY-REMOVE-FROM(open)                        → [6]
        flaws ← OPENGOALS(π) ∪ THREATS(π)
        if flaws = ∅ then                                           → Can prove: π is a solution if there are no remaining flaws
            return π                                                 → [5] Returns a partially ordered solution plan. Any total ordering is a plan achieving the goal!
        end if
        select any flaw φ ∈ flaws                                    → One flaw chosen!
        resolvers ← FINDRSOLVERS(φ,π)                                → May be the empty set
        for each r ∈ resolvers do
            π′ ← REFINE(r, π)                                        → Actually apply the resolver
            open ← open ∪ {π′}                                       → But all resolvers must be tested...
        end for
    end while
    return Failure                                                   → Expanded the entire search space without finding a solution
end function
```

POCL: Successors

We said: "Every flaw leads to successors"

- It is sufficient to try one (any) flaw to resolve!
- Testing other flaw will be redundant!
  - Every flaw has to be resolved
  - Choosing the flaw *later* cannot help us resolve it: all possibilities already exists
  - Chosing the flaw *later* cannot help us resolve some other flaw

select any flaw $\varphi \in$ flaws
resolvers $\leftarrow$ FindRsolvers(φ,π)

Enables the use of heuristics to select flaws and to prioritize open nodes

We must "test" different resolvers

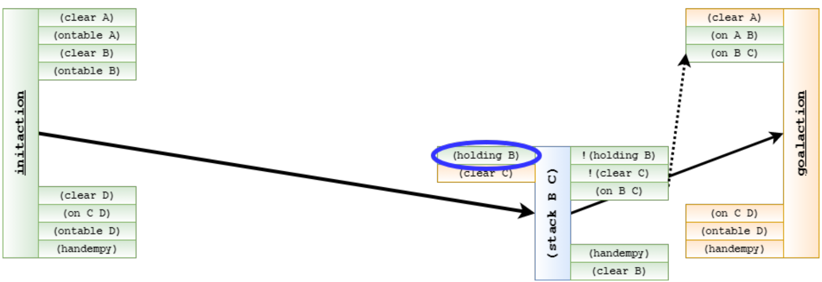
- Choosing one resolver can prevent other problems resolutions
- Open goal: Use action A or action B?
- Threat: Which order to choose?

for each r $\in$ resolvers **do**
  $\pi' \leftarrow$ Refine(r, π)
  open $\leftarrow$ open $\cup$ $\{\pi'\}$
end for

Partial Instantiation

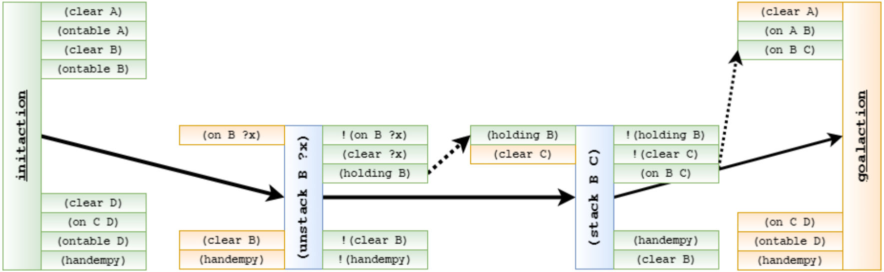
Suppose in the example we want to achieve `(holding B)`

- Ground search generates many alternatives
  - Add `(unstack B A)`, `(unstack B F)`, `(unstack B G)`, ...
  - Add `(pickup B)`
- Lifted search generates two partially instantiated alternatives
  - Add `(unstack B ?x)`
  - Add `(pickup B)`



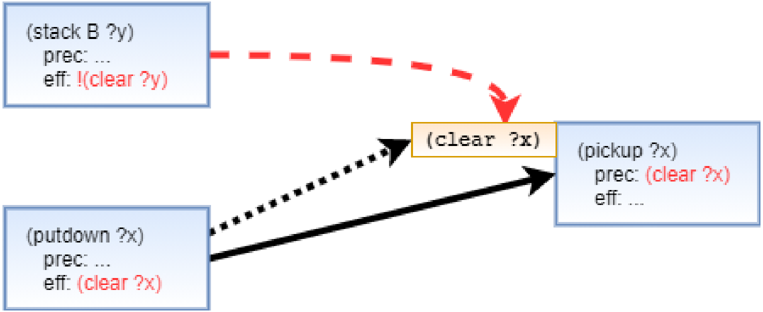
Lifted Partial-Order Plans

- A set of possibly unground actions
- A set of precedence constraints: a must precede b
- A set of causal links: a establishes precondition p needed by b
- A set of binding constraints
  - equality constraints: $v_1 = v_2$ or $v_1 = c$
  - inequality constraints: $v_1 \neq v_2$ or $v_1 \neq c$



Resolving Threats: alternative approach

- For partially uninstantiated actions, we may find potential threats
  - `(stack B ?y)` may threaten the causal link, but only if $?x = ?y$
  - Can be resolved adding a constraint: $?x \neq ?y$

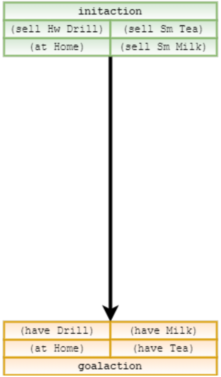


Example

- Taken and adapted from Russell and Norvig [4]
  - **Operator**: `(go ?from ?to)`
    pre: `(at ?from)`
    eff: `(at ?to),¬(at ?from)`
  - **Operator**: `(buy ?product ?store)`
    pre: `(at ?store),(sell ?store ?product)`
    eff: `(have ?product)`
  - **Initial state**
    `(at Home), (sell Hws Drill), (sell Sm Milk), (sell Sm Tea)`
  - **Goal**
    `(at Home), (have Drill), (have Milk), (have Tea)`

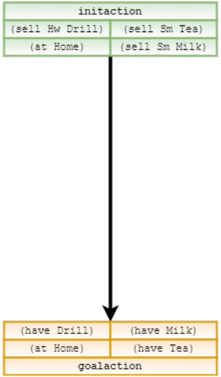
Example (1)

- Initial plan: `initaction`, `goalaction`, and a precedence constraint



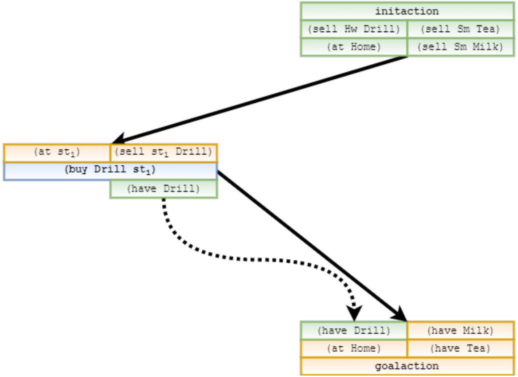
Example (2)

- Four flaws exists: open goals
  - The heuristics suggests to resolve `(have Drill)` first



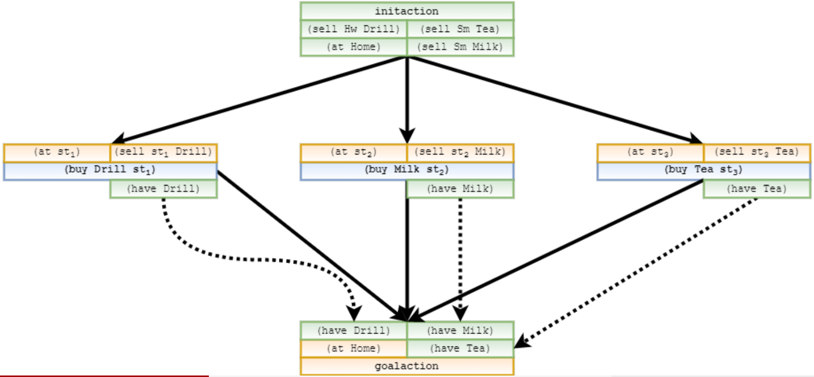
Example (3)

- No action in plan achieves `(have Drill)`, but `(buy ?p ?s)` achieves `(have ?p)`
  - Partially instantiate `(buy Drill ?s)` (ignoring where to buy)



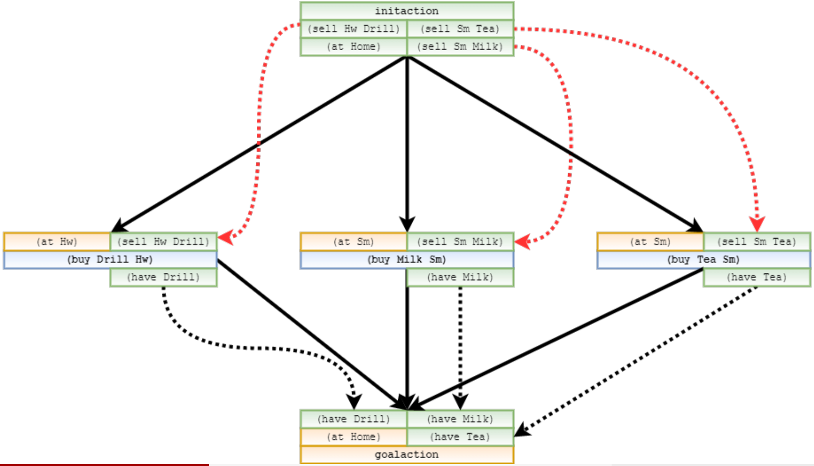
EXAMPLE (4)

- First three refinements: the possible ways to achieve `(have ?p)` preconditions
  - We do not care the order in which to buy things!



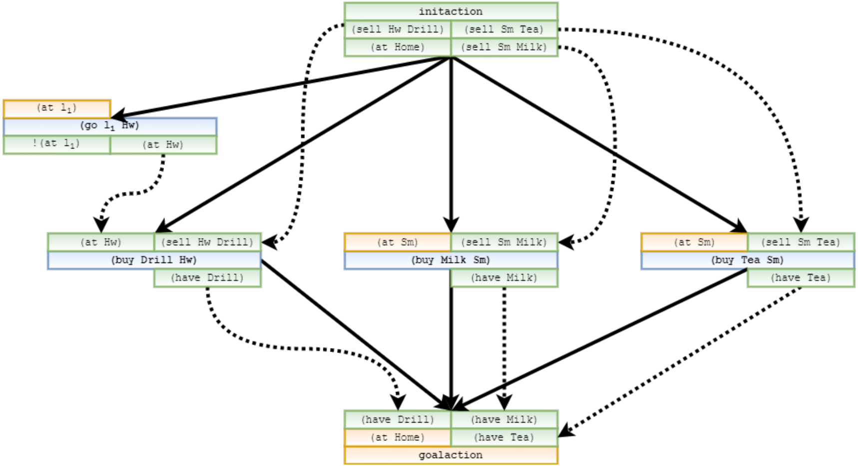
EXAMPLE (5)

- Three more refinements: no action causes `(sell ?p)` - except `initaction`
  - $\Longrightarrow$ use it for support



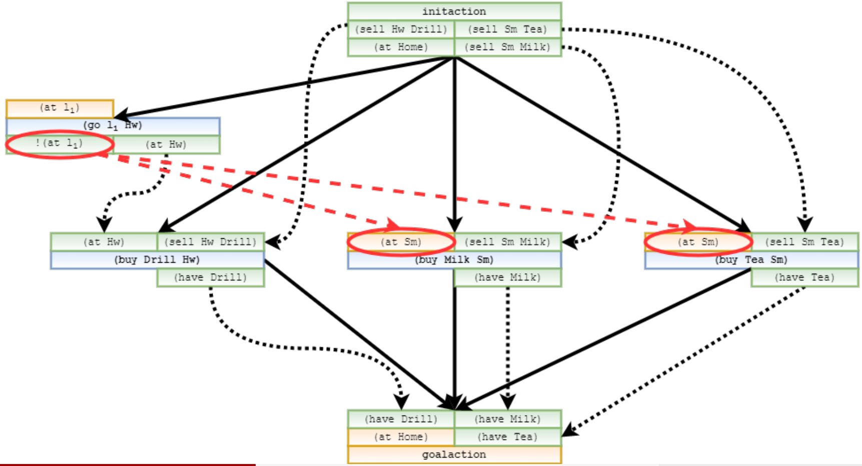
Example (6)

- To establish `(at Hws)`: must go there from somewhere



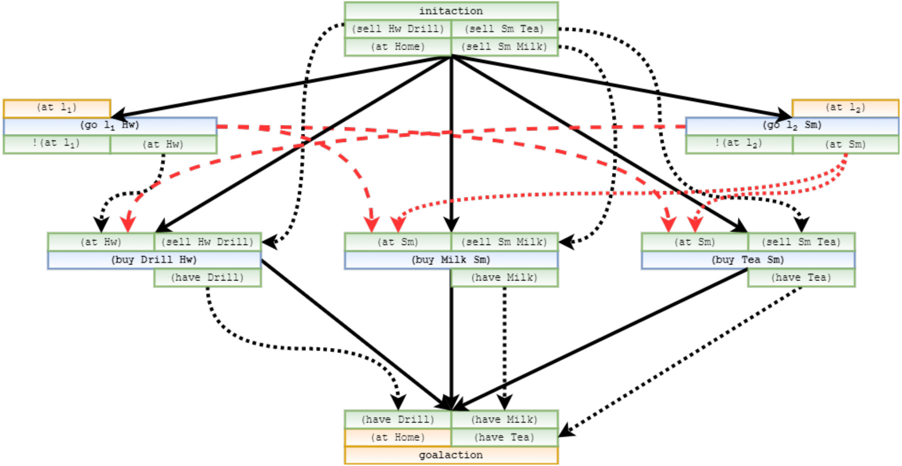
EXAMPLE (7)

- Does $\neg$ `(at` l_1`)` threaten `(at Sm)`?
  - No! Only a causal link to `(at Sm)` can be threatened!



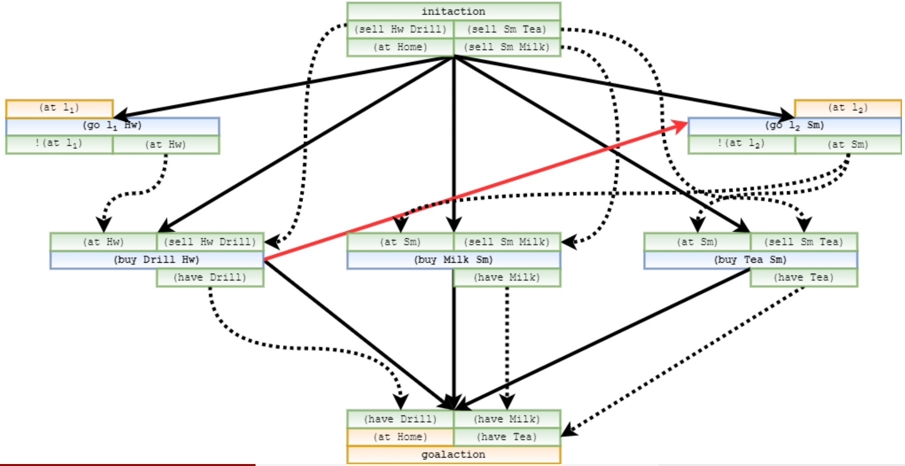
Example (8)

- To establish `(at Sm)`: must go there from somewhere $\Longrightarrow$ mutual threats...
- Let's use same action for both `(at Sm)` $\Longrightarrow$ even more threats – deal with them now or wait!



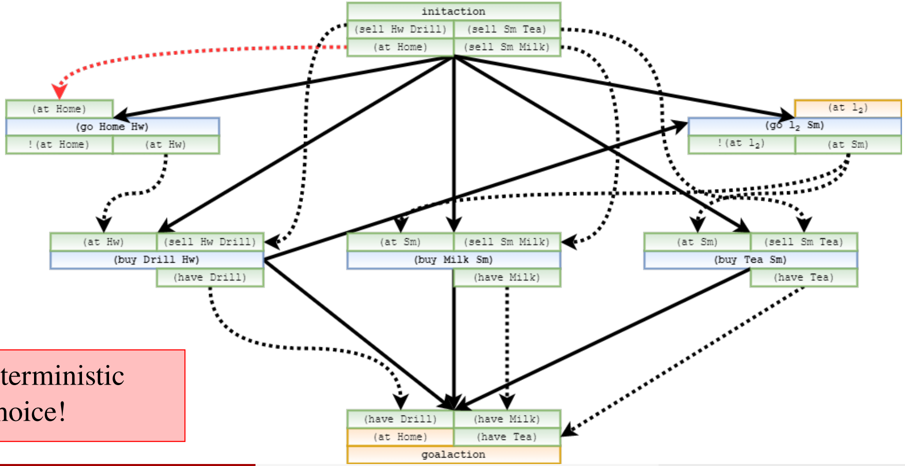
Example (9)

- How to resolve the threat to `(at Hw)`?: Make `(buy Drill)` precede the `(go` l_2 `Sm)`
  - Also happens to resolve the other two threats!



EXAMPLE (10)

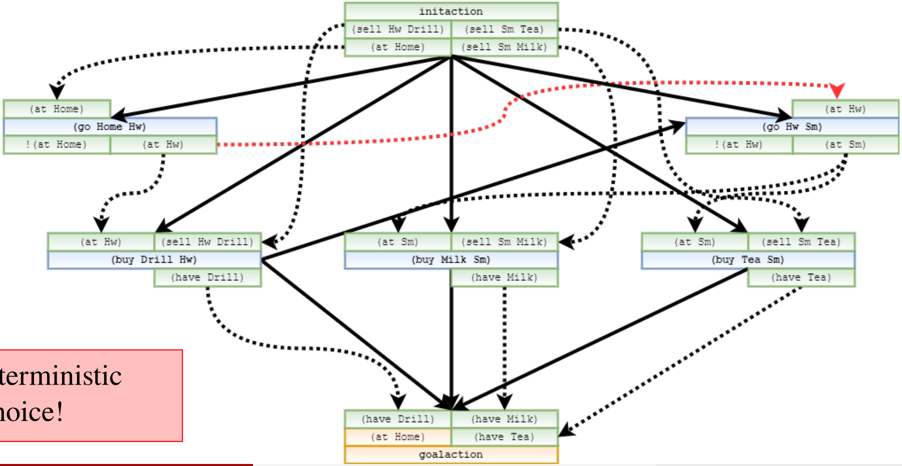
- How to establish `(at` l_1`)`?
    - We do it from `initaction` forcing l_1 = `Home`



Nondeterministic choice!

Example (11)

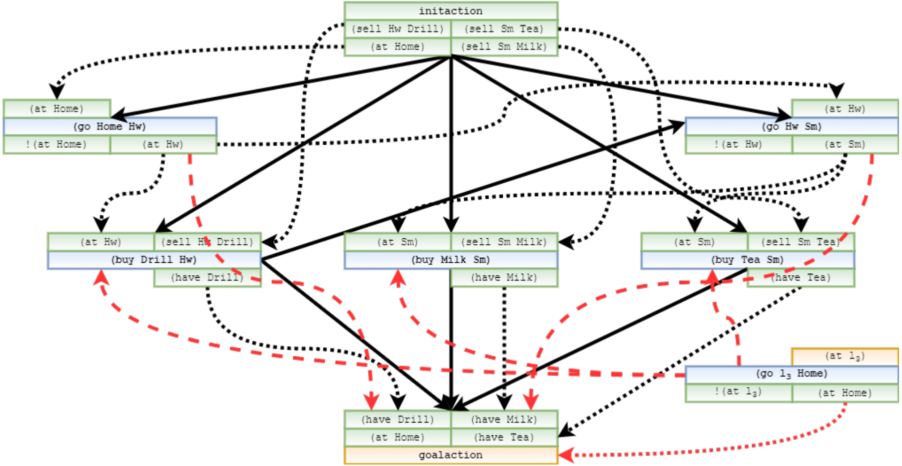
- How to establish `(at` l_2`)`?
  - We do it from `(go Home Hw)` forcing l_2 = `Hw`



Nondeterministic choice!

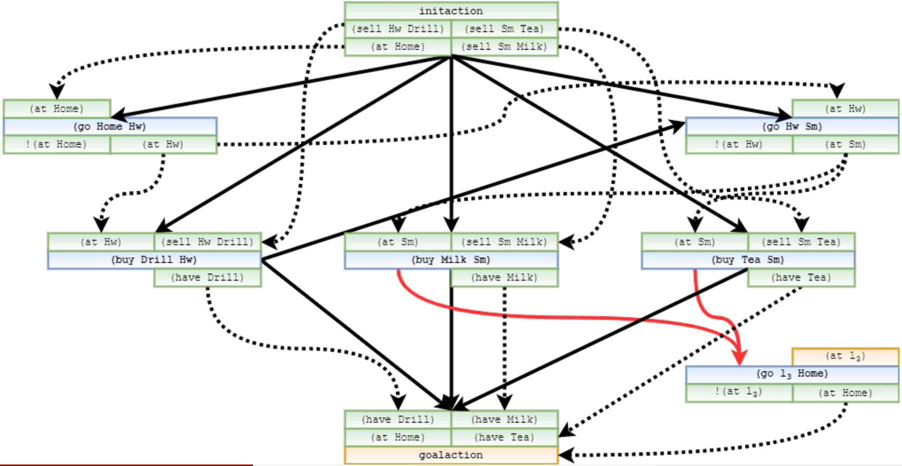
Example (12)

- The only possible way to establish `(at Home)` for `goalaction`
    - Creates several threats



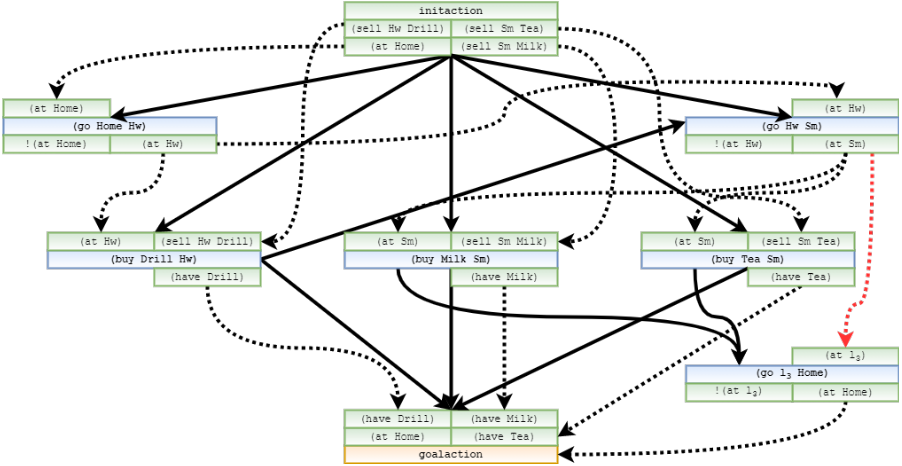
Example (13)

- To remove threats to `(at Sm)` and `(at Hw)`
  - Make `(go Hw Sm)` and `(go Home Hw)` precede `(go` l_3 `Home)`: removes other threats

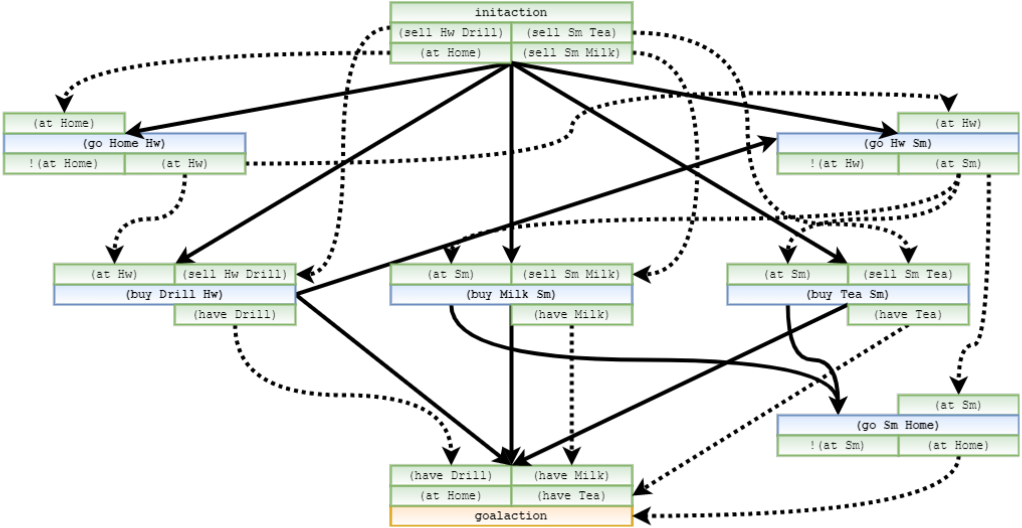


Example (14)

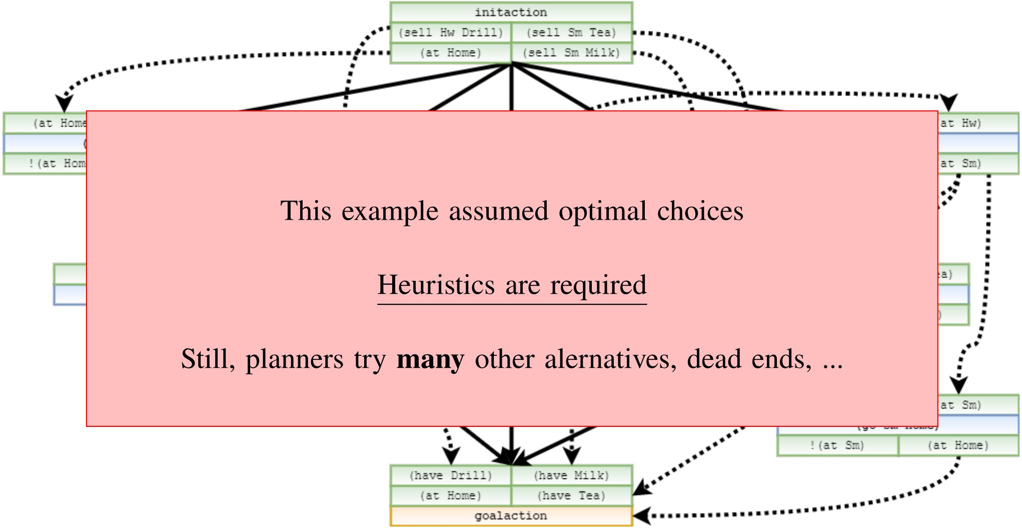
- Establish `(at` l_3`)` with $l_3 =$ `Sm`



Example (15): Final plan



EXAMPLE (16): FINAL PLAN



This example assumed optimal choices

<u>Heuristics are required</u>

Still, planners try **many** other alernatives, dead ends, ...

References I

[1] Hector Geffner and Blai Bonet. *A Concise Introduction to Models and Methods for Automated Planning*. Synthesis Lectures on Artificial Intelligence and Machine Learning. Morgan & Claypool Publishers, 2013. ISBN 9781608459698. doi: 10.2200/S00513ED1V01Y201306AIM022. URL `https://doi.org/10.2200/S00513ED1V01Y201306AIM022`.

[2] Malik Ghallab, Dana S. Nau, and Paolo Traverso. *Automated planning - theory and practice*. Elsevier, 2004. ISBN 978-1-55860-856-6.

[3] Malik Ghallab, Dana S. Nau, and Paolo Traverso. *Automated Planning and Acting*. Cambridge University Press, 2016. ISBN 978-1-107-03727-4. URL `http://www.cambridge.org/de/academic/subjects/computer-science/artificial-intelligence-and-natural-language-processing/automated-planning-and-acting?format=HB`.

[4] Stuart J. Russell and Peter Norvig. *Artificial Intelligence: A Modern Approach (4th Edition)*. Pearson, 2020. ISBN 9780134610993. URL `http://aima.cs.berkeley.edu/`. 48