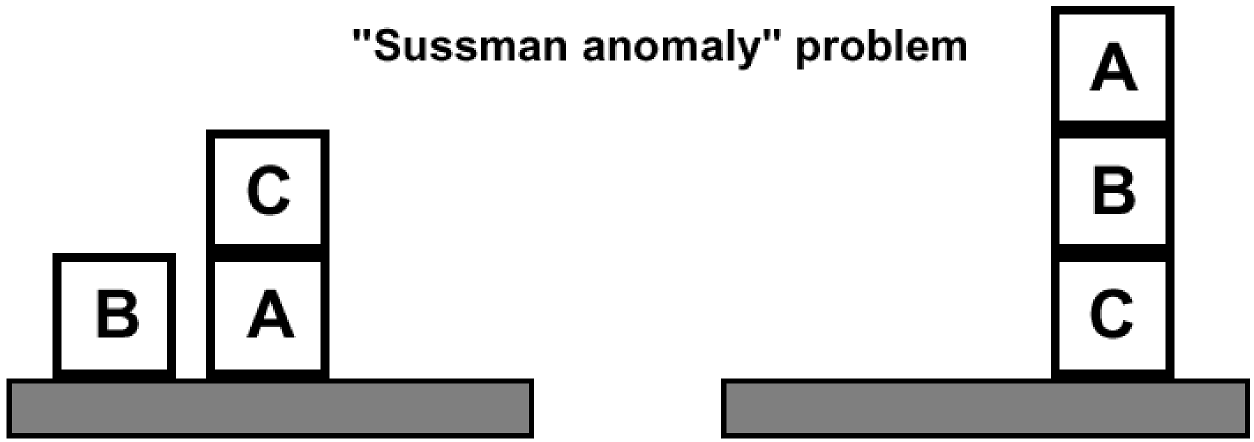
Sussman Anomaly in the block world

"Sussman anomaly" problem



Start State

Goal State

Clear(x) On(x,z) Clear(y)

PutOn(x,y)

~On(x,z) ~Clear(y)
Clear(z) On(x,y)

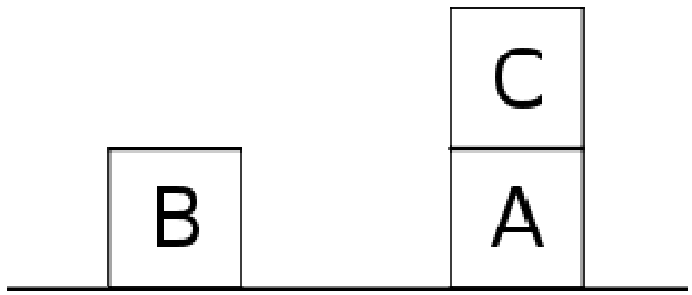
Clear(x) On(x,z)

PutOnTable(x)

~On(x,z) Clear(z) On(x,Table)

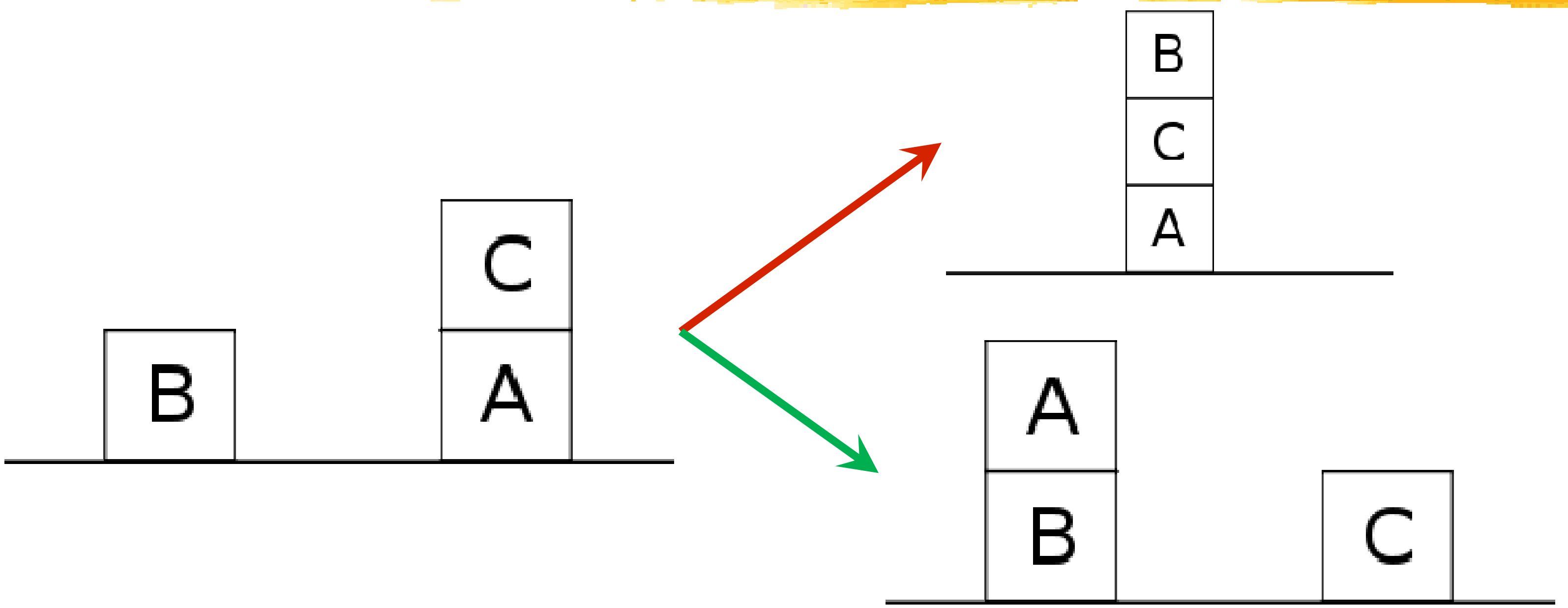
+ several inequality constraints

Sussman Anomaly



- The Sussman Anomaly shows the limitations of non-interleaved planning methods
- Before this was described, people used to do planning by considering different subgoals in SEQUENCE
- The Anomaly will show that naively pursuing one subgoal X after you satisfy the other subgoal Y may not work because steps required to accomplish X might undo things subgoal Y

Sussman Anomaly

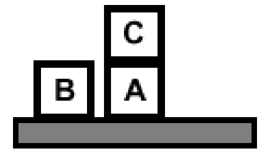


- Final state requires On(A,B) and On(B, C)
- Top diagram tries to focus on subgoal: On(B,C) -- Now trying to put A on top of B cannot be done without undoing On(B, C)
- Bottom diagram tries to focus on subgoal: On(A, B) first; but now trying to put B on top of C would cause On(A,B) to be undone!

Anomaly Illustrates the Need for Interleaved Plans

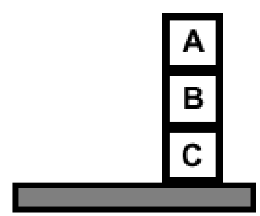
START

On(C,A) On(A,Table) Cl(B) On(B,Table) Cl(C)

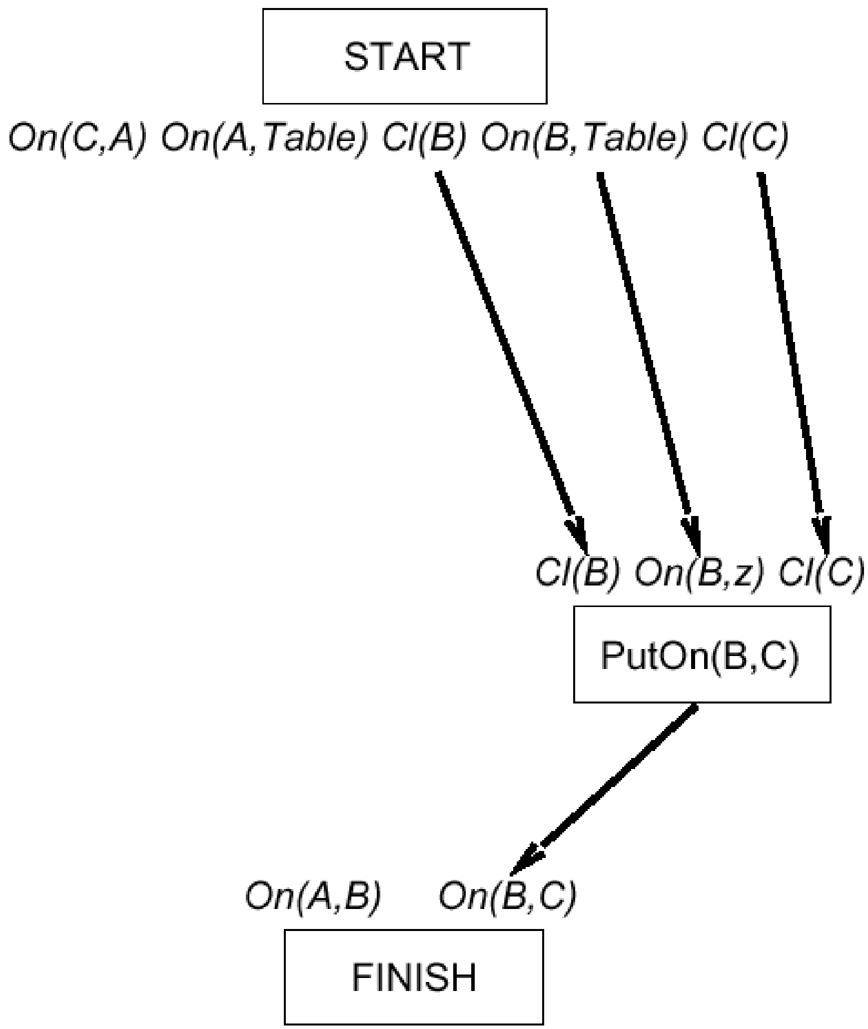


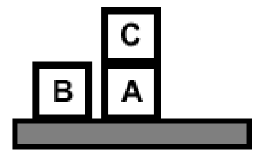
On(A,B) *On(B,C)*

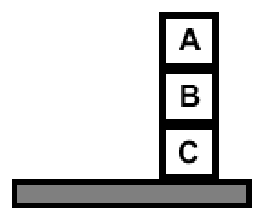
FINISH



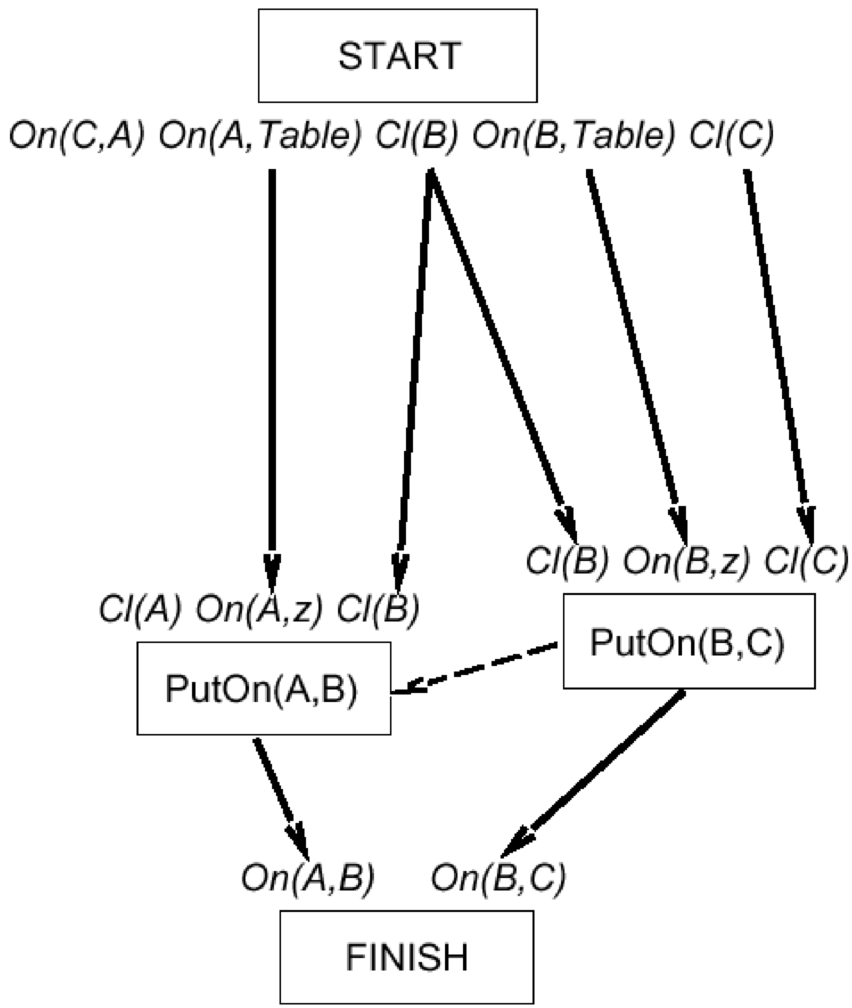
Example: continued

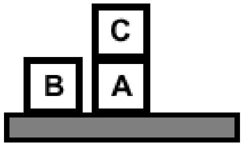




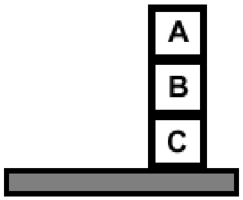


Need to Re-Order Plan Steps Dynamically

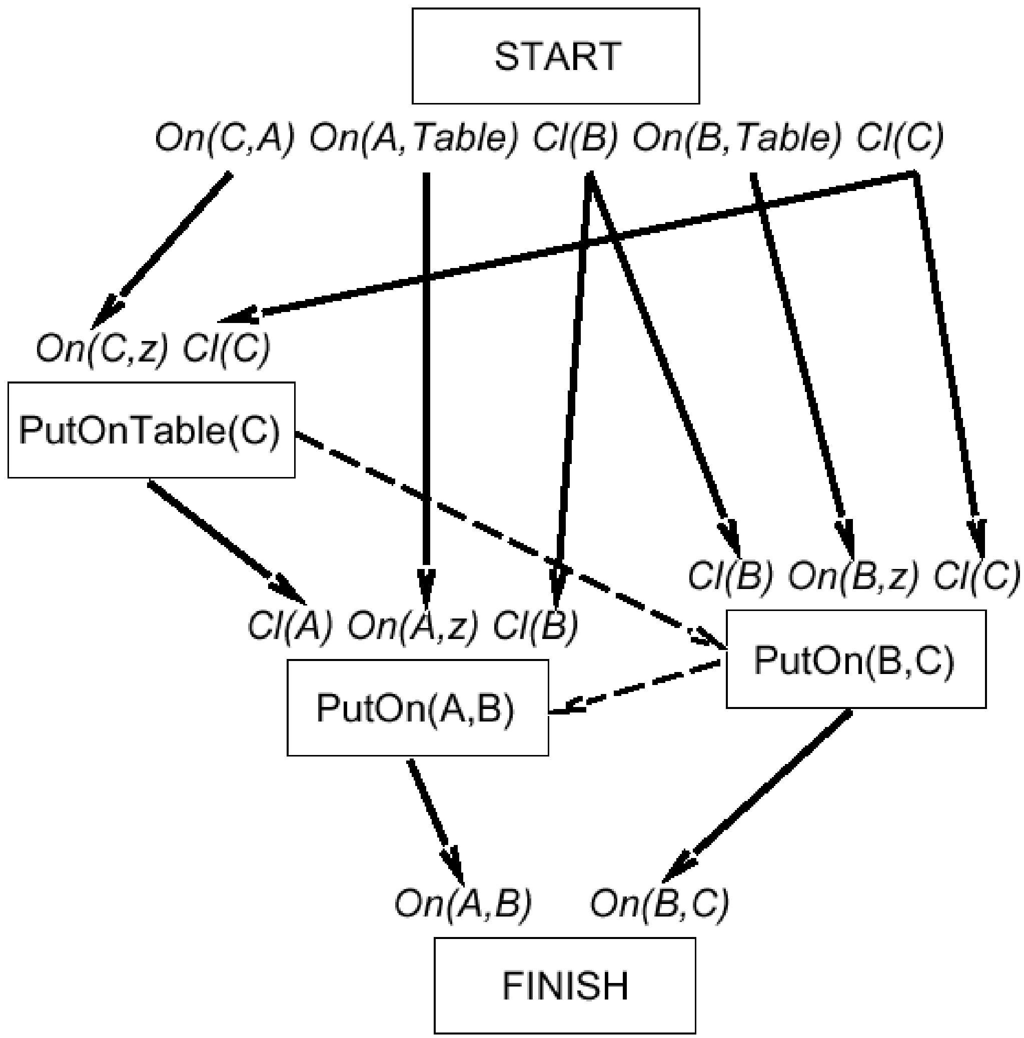


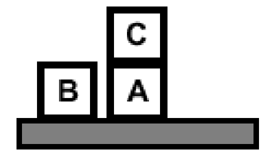


PutOn(A,B) clobbers Cl(B) => order after PutOn(B,C)



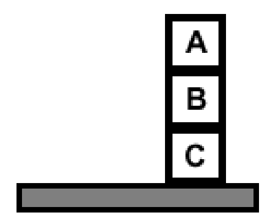
Example (cont.)





PutOn(A,B) clobbers Cl(B) => order after PutOn(B,C)

PutOn(B,C) clobbers Cl(C) => order after PutOnTable(C)



Conclusion from the Blocks Example

- Problem can be solved, BUT not by trying to apply ALL operators to achieve a single goal at a time sequentially – satisfying one goal seems to clobber earlier achieved goals.
- The issue: we are forcing an order on operators when they do not need to be mutually ordered.
- We need an approach that allows INTERLEAVING of steps for multiple goals
- This observation motivates the next planning approach: PARTIAL ORDER PLANNING - to be covered next class…

Partial-order planning

- Progression and regression planning are *totally ordered plan search* forms.
    - They cannot take advantage of problem decomposition.
        - Decisions must be made on how to sequence actions on all the subproblems
- Least commitment strategy:
    - Delay choice during search

Shoe example

Goal(RightShoeOn $\wedge$ LeftShoeOn)

Init()

Action(RightShoe, PRECOND: RightSockOn
EFFECT: RightShoeOn)

Action(RightSock, PRECOND:
EFFECT: RightSockOn)

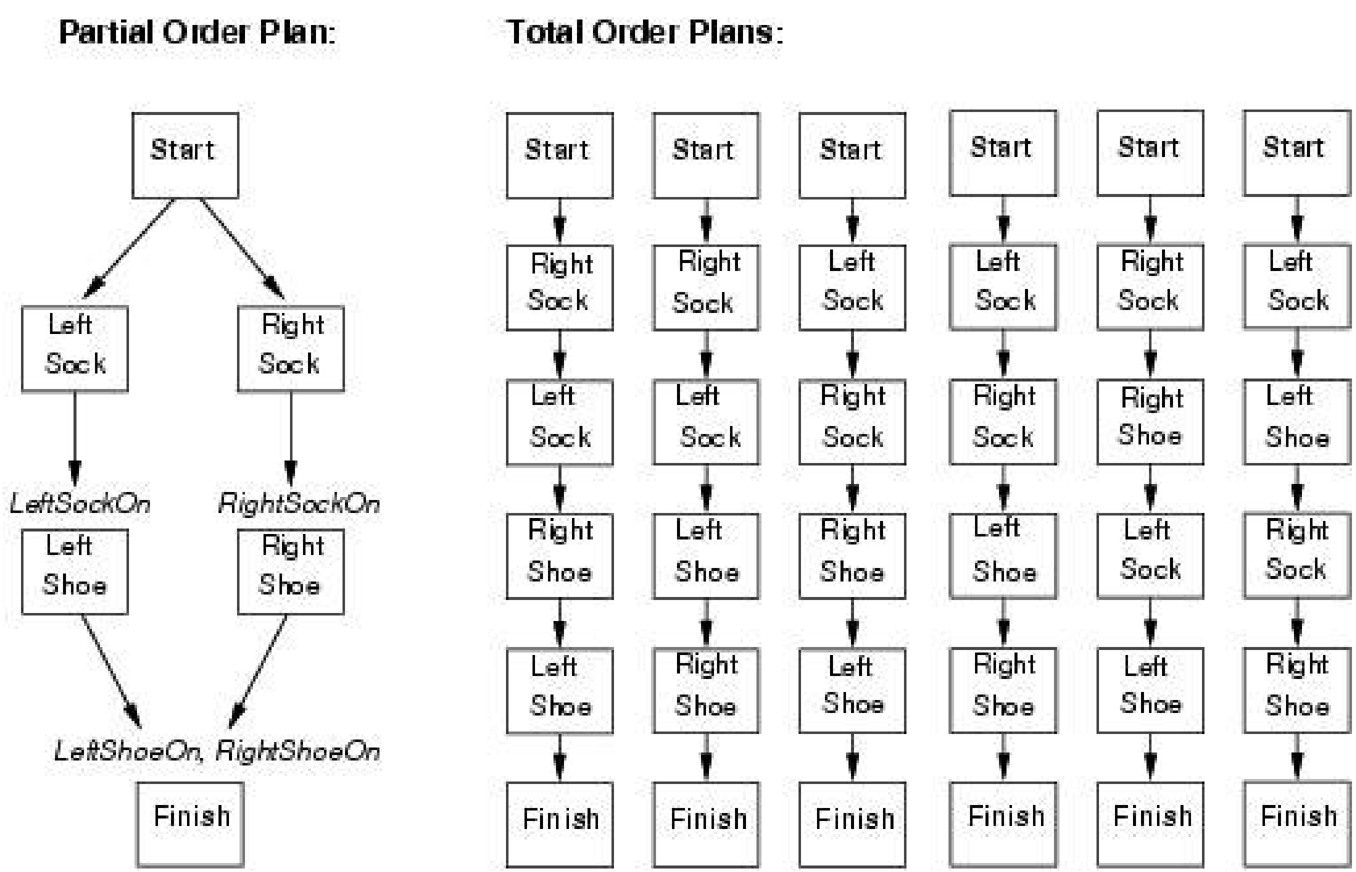
Action(LeftShoe, PRECOND: LeftSockOn
EFFECT: LeftShoeOn)

Action(LeftSock, PRECOND:
EFFECT: LeftSockOn)

Planner: combine two action sequences (1)leftsock, leftshoe (2)rightsock, rightshoe

Partial-order planning

- Any planning algorithm that can place two actions into a plan without commitment about which comes first is a Partial Order Plan



Partial Order Planning as a search problem

- States are (mostly unfinished) plans.
  - The empty plan contains only start and finish actions.
- Each plan has 4 components:
  - A set of actions (steps of the plan)
  - A set of ordering constraints: A < B
    - Cycles represent contradictions.
  - A set of causal links $A \xrightarrow{p} B$
    - The plan may not be extended by adding a new action C that conflicts with the causal link. (if the effect of C is ¬p and if C could come after A and before B)
  - A set of open preconditions.
    - If precondition is not achieved by action in the plan.

POP as a search problem

- A plan is *consistent* iff there are no cycles in the ordering constraints and no conflicts with the causal links.
- A consistent plan with no open preconditions is a *solution*.
- A partial order plan is executed by repeatedly choosing *any* of the possible next actions.
  - This flexibility is a benefit in non-cooperative environments.

Solving POP

- Assume propositional planning problems:
  - The initial plan contains *Start* and *Finish*, the ordering constraint *Start* < *Finish*, no causal links, all the preconditions in *Finish* are open.
  - Successor function :
    - picks one open precondition *p* on an action *B* and
    - generates a successor plan for every possible consistent way of choosing action *A* that achieves *p*.
  - Test goal

Enforcing consistency

- When generating successor plan:
  - The causal link A--p->B and the ordering constraint A < B is added to the plan.
    - If A is new also add start < A and A < B to the plan
  - Resolve conflicts between new causal link and all existing actions
  - Resolve conflicts between action A (if new) and all existing causal links.

Process summary

- Operators on partial plans
  - Add link from existing plan to open precondition.
  - Add a step to fulfill an open condition.
  - Order one step w.r.t another to remove possible conflicts
- Gradually move from incomplete/vague plans to complete/correct plans
- Backtrack if an open condition is unachievable or if a conflict is unresolvable.

Example: Spare tire problem

Init(At(Flat, Axle) $\wedge$ *At(Spare,trunk))*

Goal(At(Spare,Axle))

Action(Remove(Spare,Trunk)

PRECOND: *At(Spare,Trunk)*

EFFECT: $\neg$*At(Spare,Trunk)* $\wedge$ *At(Spare,Ground))*

Action(Remove(Flat,Axle)

PRECOND: *At(Flat,Axle)*

EFFECT: $\neg$*At(Flat,Axle)* $\wedge$ *At(Flat,Ground))*

Action(PutOn(Spare,Axle)

PRECOND: *At(Spare,Groundp)* $\wedge\neg$*At(Flat,Axle)*

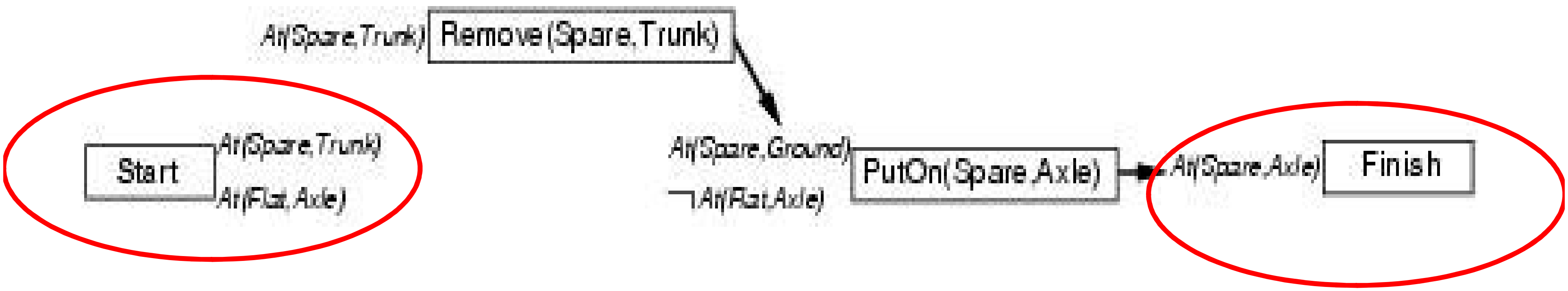
EFFECT: *At(Spare,Axle)* $\wedge$ $\neg$*Ar(Spare,Ground))*

Action(LeaveOvernight

PRECOND:

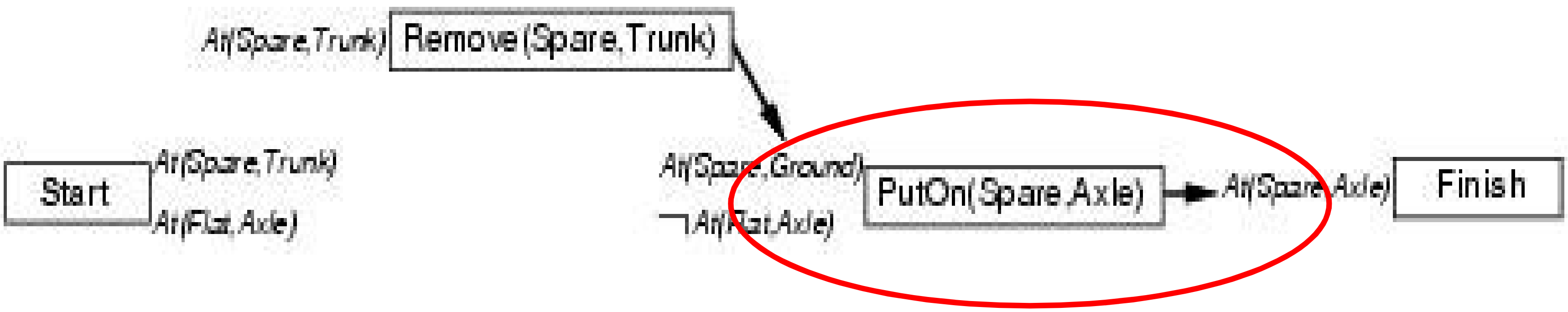
EFFECT: $\neg$ *At(Spare,Ground)* $\wedge$ $\neg$ *At(Spare,Axle)* $\wedge$ $\neg$ *At(Spare,trunk)* $\wedge$ $\neg$ *At(Flat,Ground)* $\wedge$ $\neg$ *At(Flat,Axle))*

Solving the problem



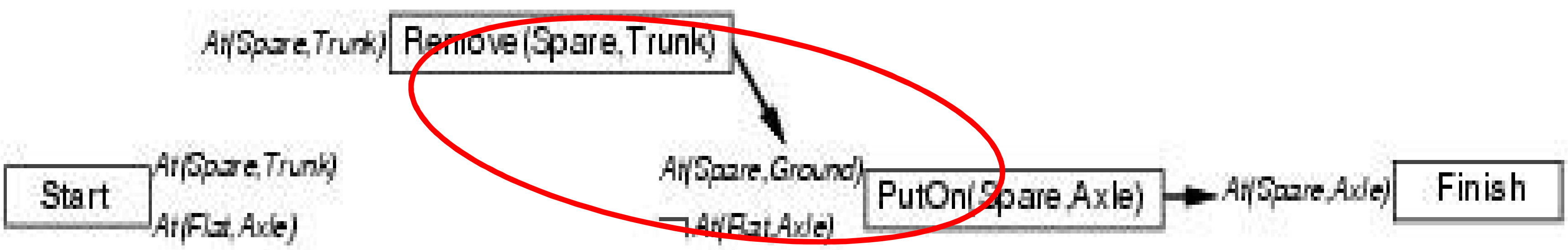
- Intial plan: Start with EFFECTS and Finish with PRECOND.

Solving the problem



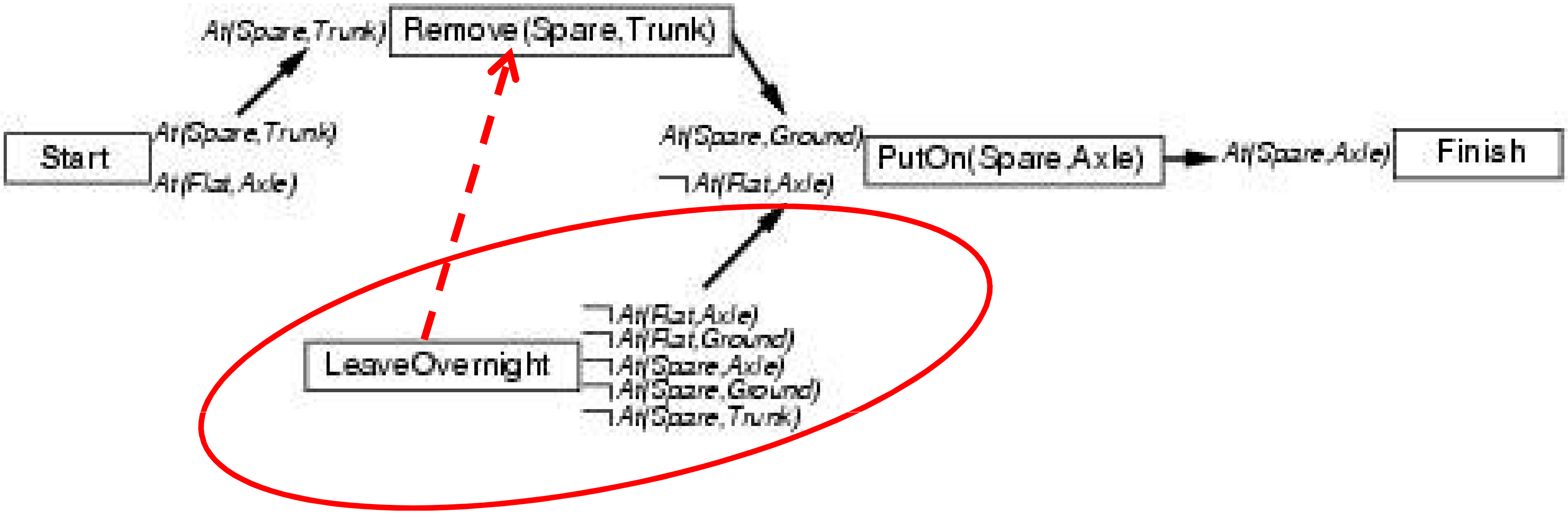
- Intial plan: Start with EFFECTS and Finish with PRECOND.
- Pick an open precondition: *At(Spare, Axle)*
- Only *PutOn(Spare, Axle)* is applicable
- Add causal link: $PutOn(Spare, Axle) \xrightarrow{At(Spare, Axle)} Finish$
- Add constraint : *PutOn(Spare, Axle) < Finish*

Solving the problem



- Pick an open precondition: *At(Spare, Ground)*
- Only *Remove(Spare, Trunk)* is applicable
- Add causal link: $\mathrm{Re}\,move(Spare, Trunk) \xrightarrow{At(Spare, Ground)} PutOn(Spare, Axle)$
- Add constraint : *Remove(Spare, Trunk) < PutOn(Spare,Axle)*

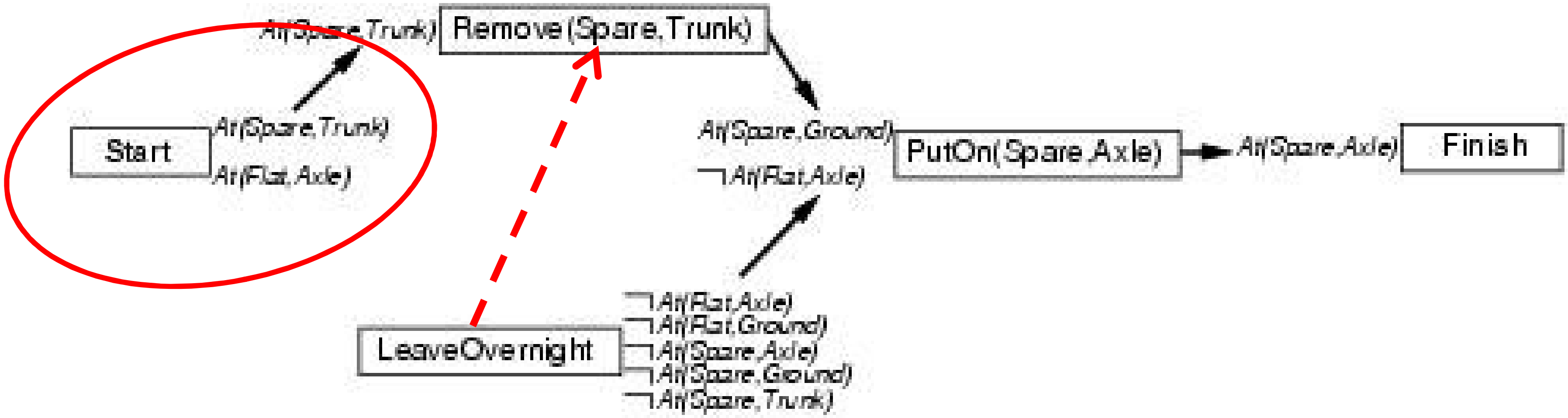
Solving the problem



- Pick an open precondition: *¬ At(Flat, Axle)*
- *LeaveOverNight* is applicable
- conflict: $\mathrm{Re}\,move(Spare, Trunk) \xrightarrow{At(Spare, Ground)} PutOn(Spare, Axle)$

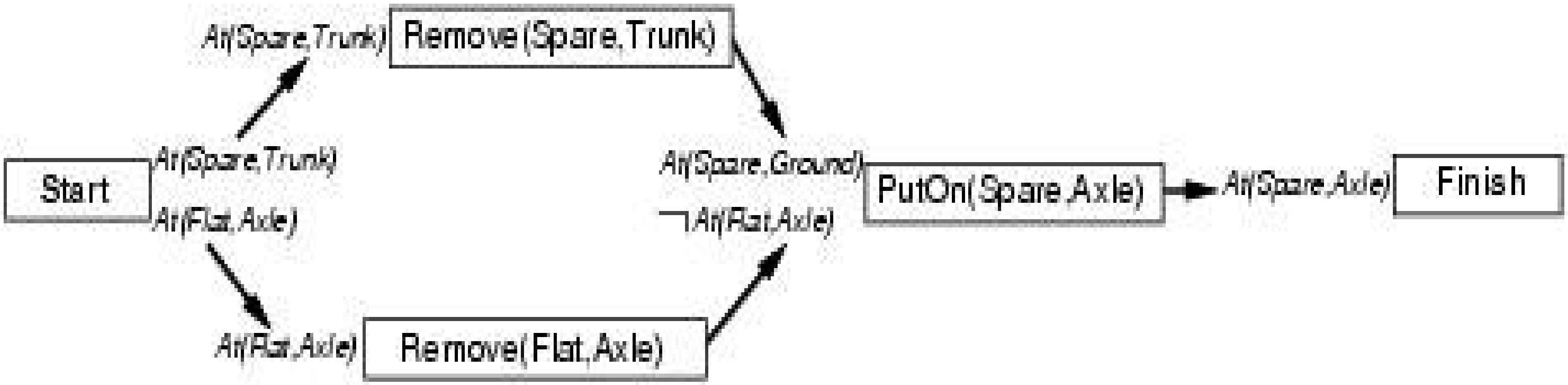
- Because *LeaveOverNight* also makes *¬ At(Spare, Ground)*
- To resolve, add constraint : *LeaveOverNight < Remove(Spare, Trunk)*

Solving the problem



- Pick an open precondition: *At(Spare, Trunk)*
- Only *Start* is applicable
- Add causal link: $Start \xrightarrow{At(Spare,Trunk)} Remove(Spare,Trunk)$
- Conflict: of causal link with effect ¬ *At(Spare,Trunk)* in *LeaveOverNight*
  - *No re-ordering solution possible.*
- Backtrack to a prior move since there is no way to fix this

Solving the problem



- Backtracking step: Remove *LeaveOverNight* and its causal links
- Now try *Remove(Flat, Axle)* as a way to satisfy ¬ *At(Flat, Axle)*
- That one works… and the partial plan can be completed as above

Some details …

- What happens when a **first-order** representation that includes variables is used?
  - Complicates the process of detecting and resolving conflicts.
  - Can be resolved by introducing inequality constraints
- CSP's most-constrained-variable constraint can be used for planning algorithms to select a PRECOND.

Planning graphs

- Used to achieve better heuristic estimates.
  - A solution can also directly extracted using GRAPHPLAN.
- Consists of a sequence of levels that correspond to time steps in the plan.
  - Level 0 is the initial state.
  - Each level consists of a set of literals and a set of actions.
    - *Literals* = all those that *could* be true at that time step, depending upon the actions executed at the preceding time step.
    - *Actions* = all those actions that *could* have their preconditions satisfied at that time step, depending on which of the literals actually hold.

Planning graphs

- "Could"?
  - Records only a restricted subset of possible negative interactions among actions.
- They work only for propositional problems.
- Example:

Init(Have(Cake))

Goal(Have(Cake) $\wedge$ Eaten(Cake))

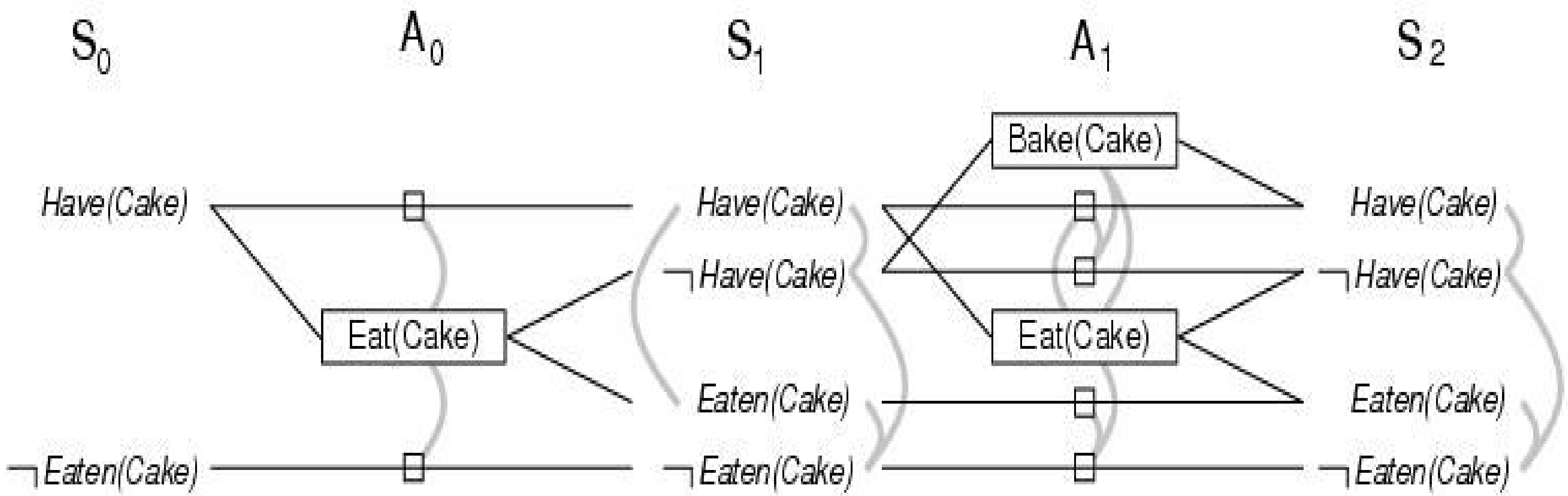
Action(Eat(Cake), PRECOND: Have(Cake)

EFFECT: $\neg$Have(Cake) $\wedge$ Eaten(Cake))

Action(Bake(Cake), PRECOND: $\neg$ Have(Cake)

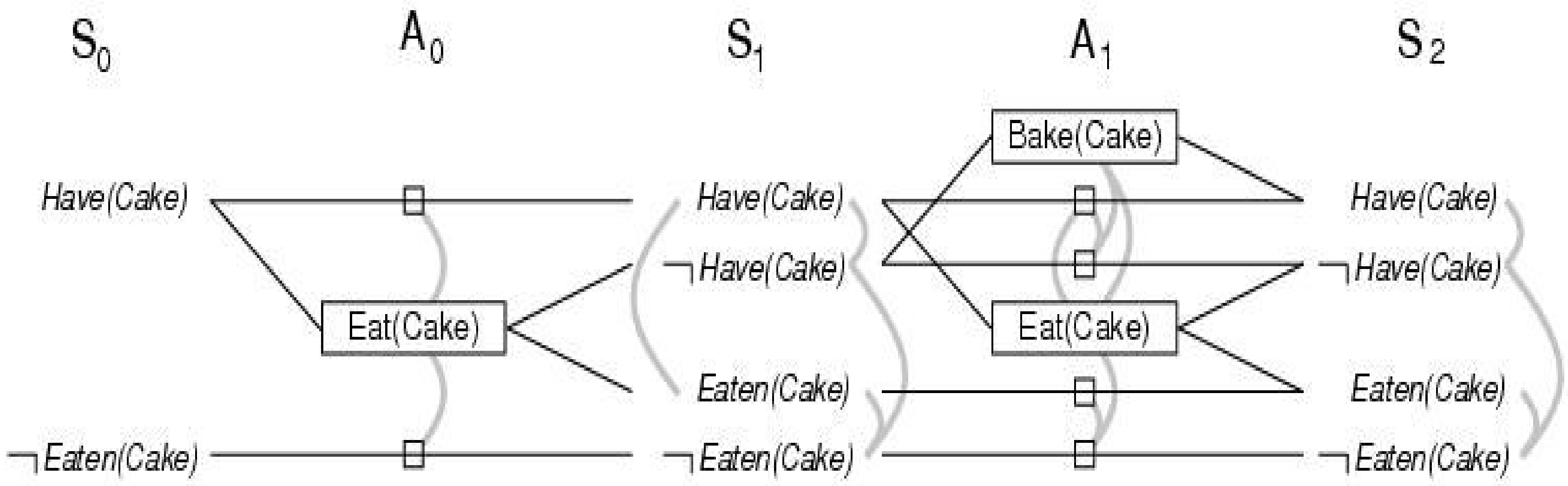
EFFECT: Have(Cake))

Cake example



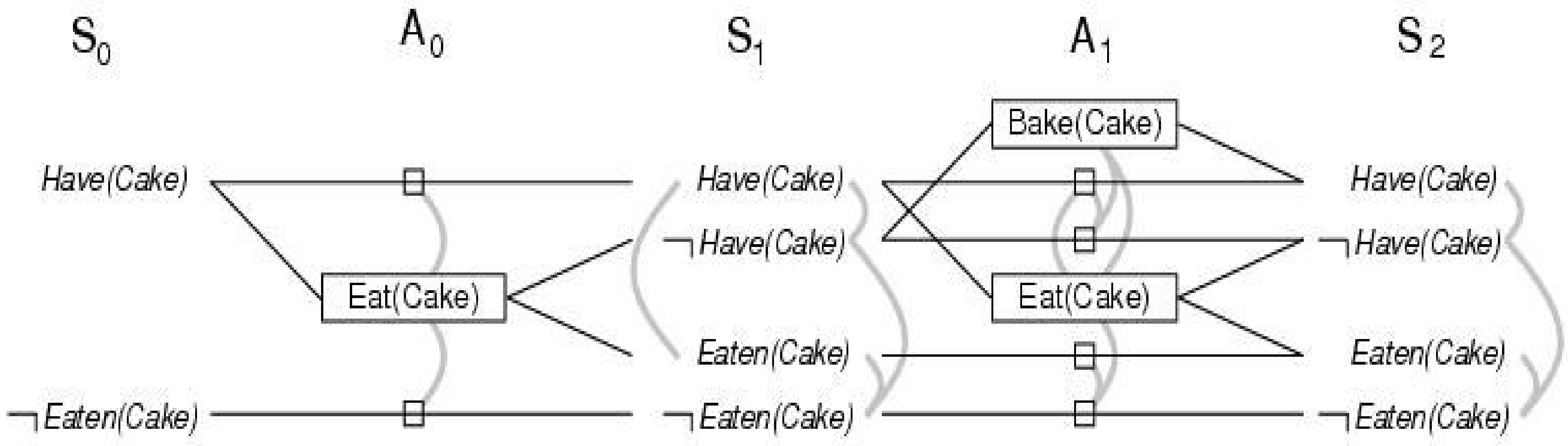
- Start at level S0 and determine action level A0 and next level S1.
  - A0 >> all actions whose preconditions are satisfied in the previous level.
  - Connect precondition and effect of actions S0 --> S1
  - Inaction is represented by persistence actions.
- Level A0 contains the actions that could occur
  - Conflicts between actions are represented by *mutex* links

Cake example



- Level S1 contains all literals that could result from picking any subset of actions in A0
  - Conflicts between literals that cannot occur together are represented by mutex links.
  - S1 defines multiple states and the mutex links are the constraints that define this set of states.
- Continue until two consecutive levels are identical: *leveled off*
  - Or contain the same amount of literals (explanation follows later)

Cake example



- A mutex relation holds between **two actions** when:
  - *Inconsistent effects*: one action negates the effect of another (Have(Cake) and Eat(Cake) for example)
  - *Interference*: one of the effects of one action is the negation of a precondition of the other. Eat(Cake) negates the precondition of Have(Cake) persistence and therefore interferes with it
  - *Competing needs*: one of the preconditions of one action is mutually exclusive with the precondition of the other. For example, Bake(Cake) competes with Eat(Cake) on the Have(Cake) pre condition.
- A mutex relation holds between **two literals** when (*inconsistent support*):
  - If one is the negation of the other OR
  - if each possible action pair that could achieve the literals is mutex.

Plan Graphs and heuristic estimation

- PG's provide information about the problem
  - A literal that does not appear in the final level of the graph cannot be achieved by any plan.
    - Useful for backward search (cost = inf).
  - Level of appearance can be used as cost estimate of achieving any goal literals = *level cost*.
  - Small problem: several actions can occur
    - Restrict to one action using serial PG (add mutex links between every pair of actions, except persistence actions).
  - Max-level, sum-level and set-level heuristics.

PG is a relaxed problem.

The GRAPHPLAN Algorithm

- How to extract a solution directly from the PG

function GRAPHPLAN(*problem*) **return** *solution* or failure

graph ← INITIAL-PLANNING-GRAPH(*problem*)

goals ← GOALS[*problem*]

loop do

if *goals* all non-mutex in last level of graph **then do**

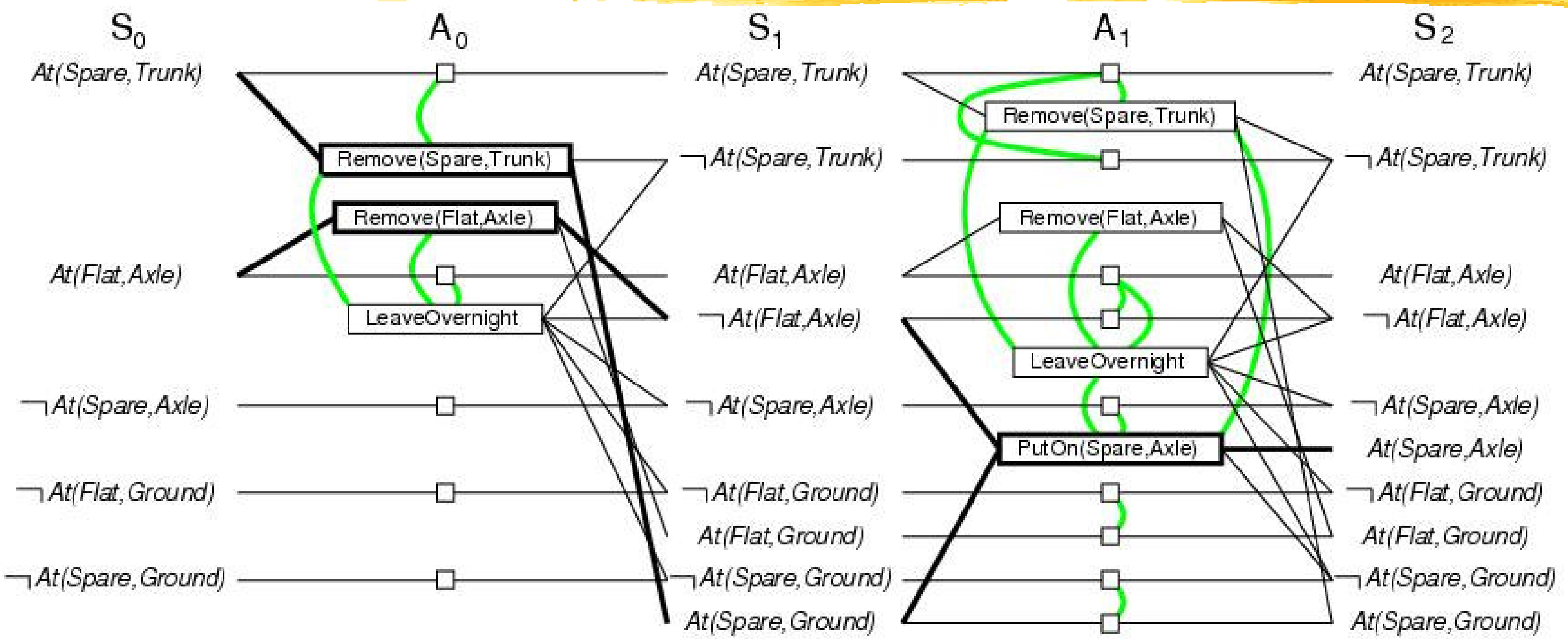
solution ← EXTRACT-SOLUTION(*graph, goals,* LENGTH*(graph)*)

if *solution* ≠ failure **then return** *solution*

else if NO-SOLUTION-POSSIBLE(*graph*) **then return** failure

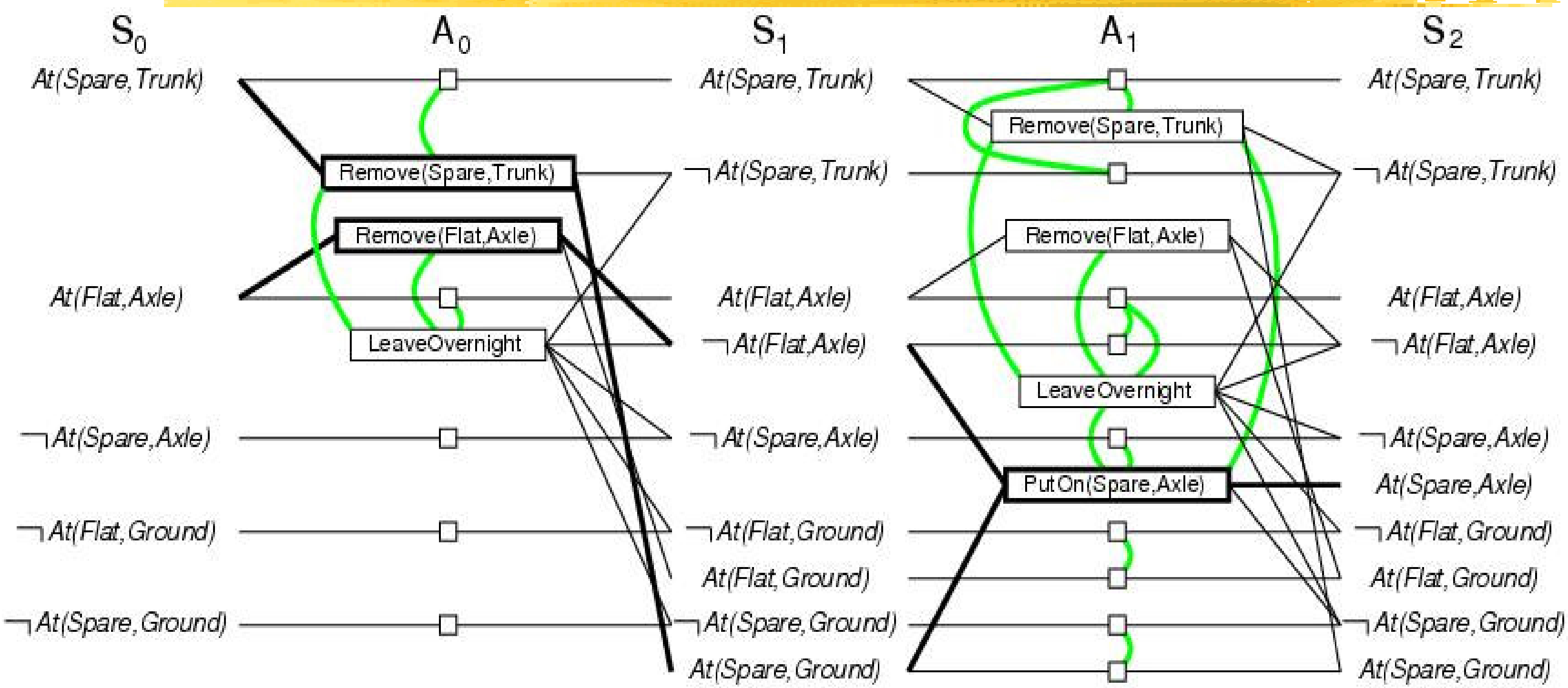
graph ← EXPAND-GRAPH(*graph, problem*)

GRAPHPLAN example



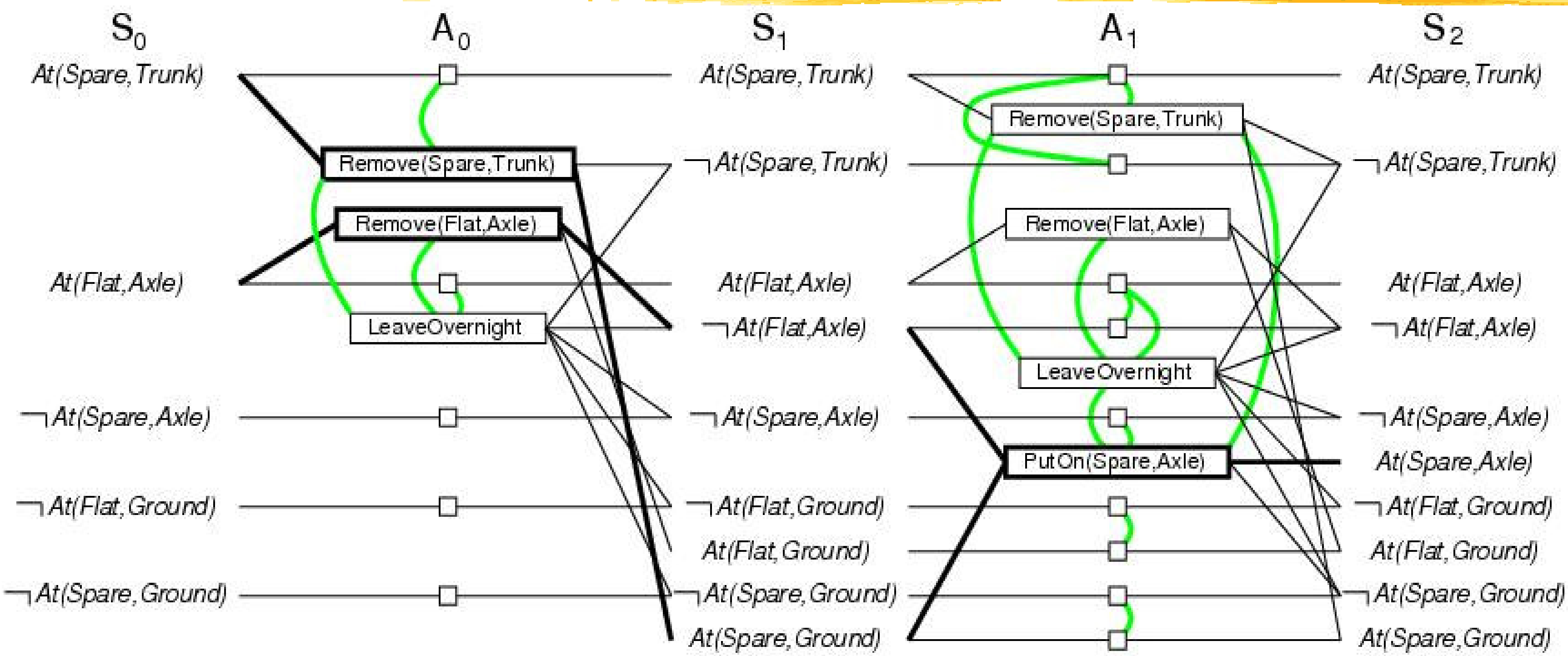
- Initially the plan consist of 5 literals from the initial state and the CWA literals (S0).
- Add actions whose preconditions are satisfied by EXPAND-GRAPH (A0)
- Also add persistence actions and mutex relations.
- Add the effects at level S1
- Repeat until goal state appears in some level

GRAPHPLAN example



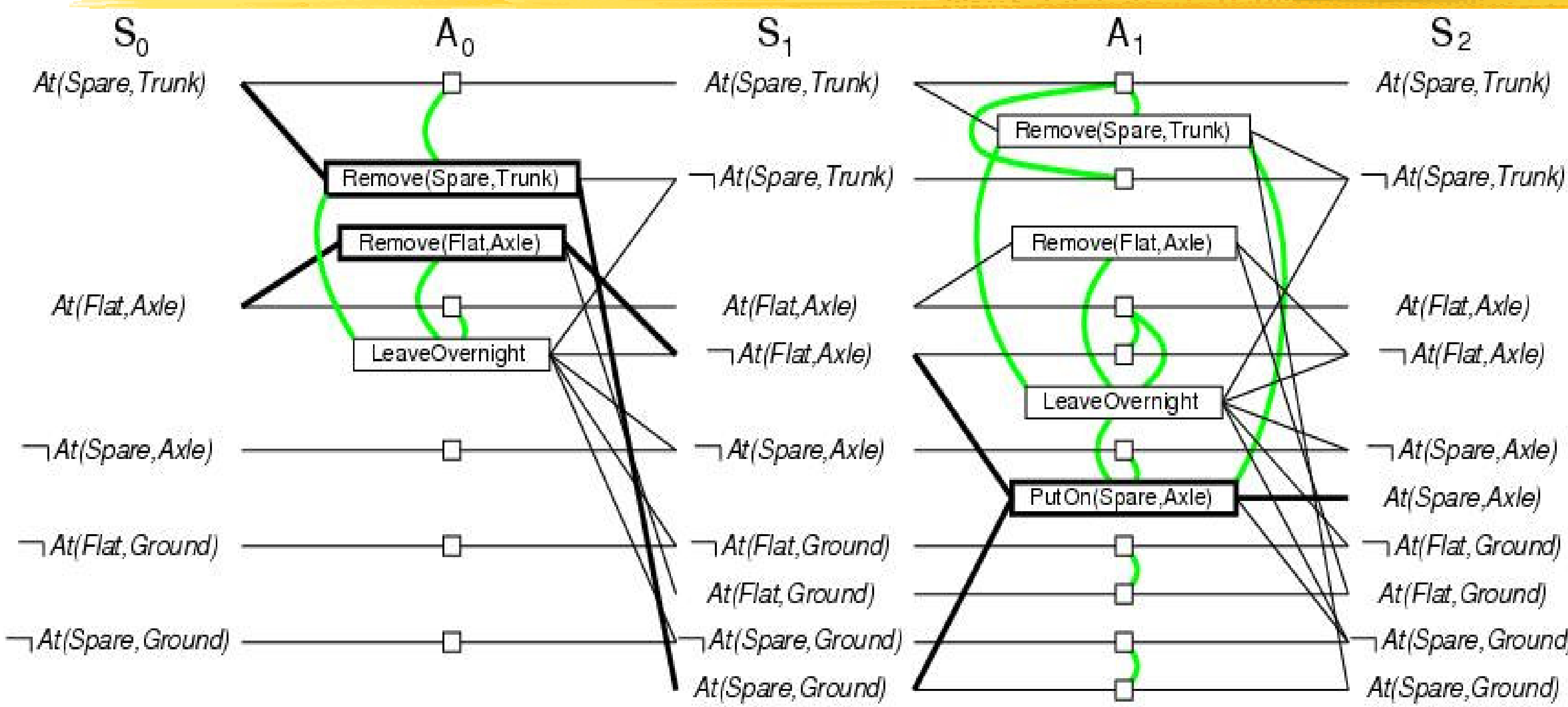
- EXPAND-GRAPH also looks for mutex relations
  - Inconsistent effects
    - E.g. Remove(Spare, Trunk) and LeaveOverNight
  - Interference
    - E.g. Remove(Flat, Axle) and LeaveOverNight
  - Competing needs
    - E.g. PutOn(Spare,Axle) and Remove(Flat, Axle)
  - Inconsistent support
    - E.g. in S2, At(Spare,Axle) and At(Flat,Axle)

GRAPHPLAN example



- In S2, the goal literal exists and is not mutex with any other
  - Solution might exist and EXTRACT-SOLUTION will try to find it
- EXTRACT-SOLUTION can use Boolean CSP to solve the problem or a search process:
  - Initial state = last level of PG and goal goals of planning problem
  - Actions = select any set of non-conflicting actions that cover the goals in the state
  - Goal = reach level S0 such that all goals are satisfied
  - Cost = 1 for each action.

GRAPHPLAN example



- Termination? YES
- PG are monotonically increasing or decreasing:
  - Literals increase monotonically
  - Actions increase monotonically
  - Mutexes decrease monotonically
- Because of these properties and because there is a finite number of actions anc literals, every PG will eventually level off !

Analysis of planning approach

- Planning is an area of great interest within AI
  - Search for solution
  - Constructively prove a existence of solution
- Biggest problem is the combinatorial explosion in states.
- Efficient methods are under research
  - E.g. divide-and-conquer