INF5390 - Kunstig intelligens

Agents That Plan

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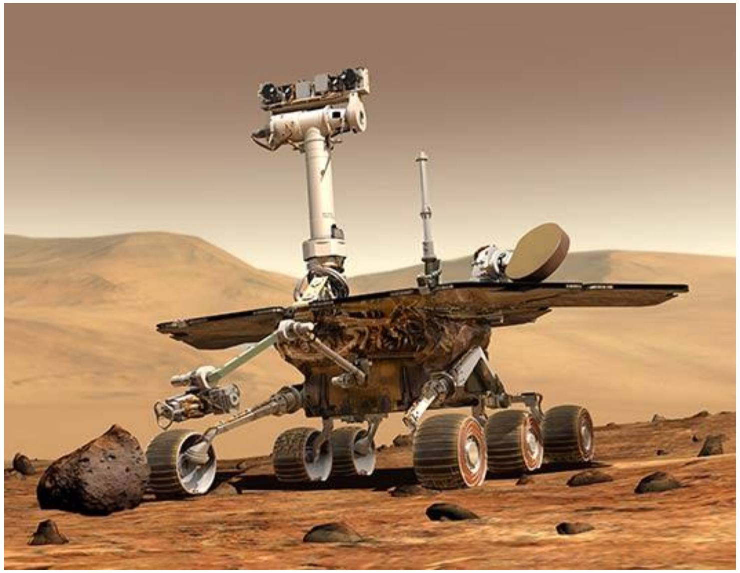
Outline

- Planning agents
- Plan representation
- State-space search
- Planning graphs
- GRAPHPLAN algorithm
- Partial-order planning
- Summary

AIMA Chapter 10: Classical Planning

What is planning?

Planning is a type of **problem solving**
in which the agent uses
beliefs about **actions** and their **consequences**
to find a **solution plan**,
where a plan is
a **sequence of actions**
that leads
from an **initial state**
to a **goal state**



Previously described approaches

- Planning by search (INF5390-03)
  - Atomic representations of states
  - Very large number of possible actions
  - Needs good domain heuristics to bound search space
- Planning by logical reasoning (INF5390-04)
  - Hybrid agent can use domain-independent heuristics
  - But relies on propositional inference (no variables)
  - Model size rises sharply with problem complexity
- Neither of these approaches scale directly to industrially significant problems

Factored plan representation

- *Factored* representation of:
  - Initial state
  - Available actions in a state
  - Results of applying actions
  - Goal tests
- Representation language PDDL
  - Planning Domain Definition Language
  - Developed from early AI planners, e.g. STRIPS, pioneering robot work at Stanford in early 1970ies
- Used for *classical planning*
  - Environment is observable, deterministic, finite, static, and discrete

Representation of states and goals

- *States* are represented by conjunctions of function-free ground literals in first-order logic
- Example: $At(Plane_1, Melbourne) \wedge At(Plane_2, Sydney)$
- Closed-world assumption: Any condition not mentioned in a state is assumed to be false
- Goal state - a partially specified state, *satisfied* by any state that contains the goal conditions
- Example goal: $At(Plane_2, Tahiti)$

Representation of actions

- An *action schema* has three components
  - √ *Action* description: Name and parameters (universally quantified variables)
  - √ *Precondition*: Conjunction of positive literals stating what must be true before action application
  - √ *Effect*: Conjunction of positive or negative literals stating how situation changes with operator application
- Example
  - √ ***Action****(Fly(p, from, to),*
    PRECOND: *At*(*p, from*) $\wedge$ *Plane(p)* $\wedge$
    Airport(from) $\wedge$ *Airport(to),*
    EFFECT: $\neg$ *At*(*p, from*) $\wedge$ *At(p, to))*

How are planning actions applied?

- Actions are *applicable* in states that satisfy its preconditions (by binding variables)
  - State: $At(P_1, JFK) \wedge At(P_2, SFO) \wedge Plane(P_1) \wedge Plane(P_2) \wedge Airport(JFK) \wedge Airport(SFO)$
  - Precondition: $At(p, from) \wedge Plane(p) \wedge Airport(from) \wedge Airport(to)$
  - Binding: $\{p/P_1, from/JFK, to/SFO\}$
- State after executing action is same as before, except positive effects added (*add list*) and negative deleted (*delete list*)
  - New state: $At(P_1, SFO) \wedge At(P_2, SFO) \wedge Plane(P_1) \wedge Plane(P_2) \wedge Airport(JFK) \wedge Airport(SFO)$

Planning solution

- The planned actions that will take the agent from the initial state to the goal state
- Simple version:
  - √ *An action sequence*, such that when executed from the initial state, results in a final state that satisfies the goal
- More complex cases:
  - √ *Partially ordered set of actions*, such that every action sequence that respects the partial order is a solution

Example - Air cargo planning in PDDL

- ***Init***(*At(C1, SFO)* $\wedge$ *At(C2, JFK)* $\wedge$ *At(P1, SFO)* $\wedge$ *At(P2, JFK)* $\wedge$ *Cargo(C1)* $\wedge$ *Cargo(C2)* $\wedge$ *Plane(P1)* $\wedge$ *Plane(P2)* $\wedge$ *Airport(JFK)* $\wedge$ *Airport(SFO))*
- ***Goal***(*At(C1, JFK)* $\wedge$ *At(C2, SFO))*
- ***Action***(*Load(c, p, a)*,
  PRECOND: *At(c, a)* $\wedge$ *At(p, a)* $\wedge$ *Cargo(c)* $\wedge$ *Plane(p)* $\wedge$ *Airport(a)*,
  EFFECT: $\neg$ *At(c, a)* $\wedge$ *In(c, p))*
- ***Action***(*Unload(c, p, a)*,
  PRECOND: *In(c, p)* $\wedge$ *At(p, a)* $\wedge$ *Cargo(c)* $\wedge$ *Plane(p)* $\wedge$ *Airport(a)*,
  EFFECT: *At(c, a)* $\wedge$ $\neg$ *In(c, p))*
- ***Action***(*Fly(p, from, to)*,
  PRECOND: *At(p, from)* $\wedge$ *Plane(p)* $\wedge$ *Airport(from)* $\wedge$ *Airport(to)*,
  EFFECT: $\neg$ *At(p, from)* $\wedge$ *At(p, to))*

Example – Air cargo solution

- From initial state
  - √ ***Init***(*At(C1, SFO)* ∧ *At(C2, JFK)* ∧ *At(P1, SFO)* ∧ *At(P2, JFK)* ∧ *Cargo(C1)* ∧ *Cargo(C2)* ∧ *Plane(P1)* ∧ *Plane(P2)* ∧ *Airport(JFK)* ∧ *Airport(SFO)*)
- To goal state:
  - √ ***Goal***(*At(C1, JFK)* ∧ *At(C2, SFO)*)
- Solution – a sequence of actions:
  - √ [*Load(C1, P1, SFO), Fly(P1, SFO, JFK), Unload(C1, P1, JFK), Load(C2, P2, JFK), Fly(P2, JFK, SFO), Unload(C2, P2, SFO)*]

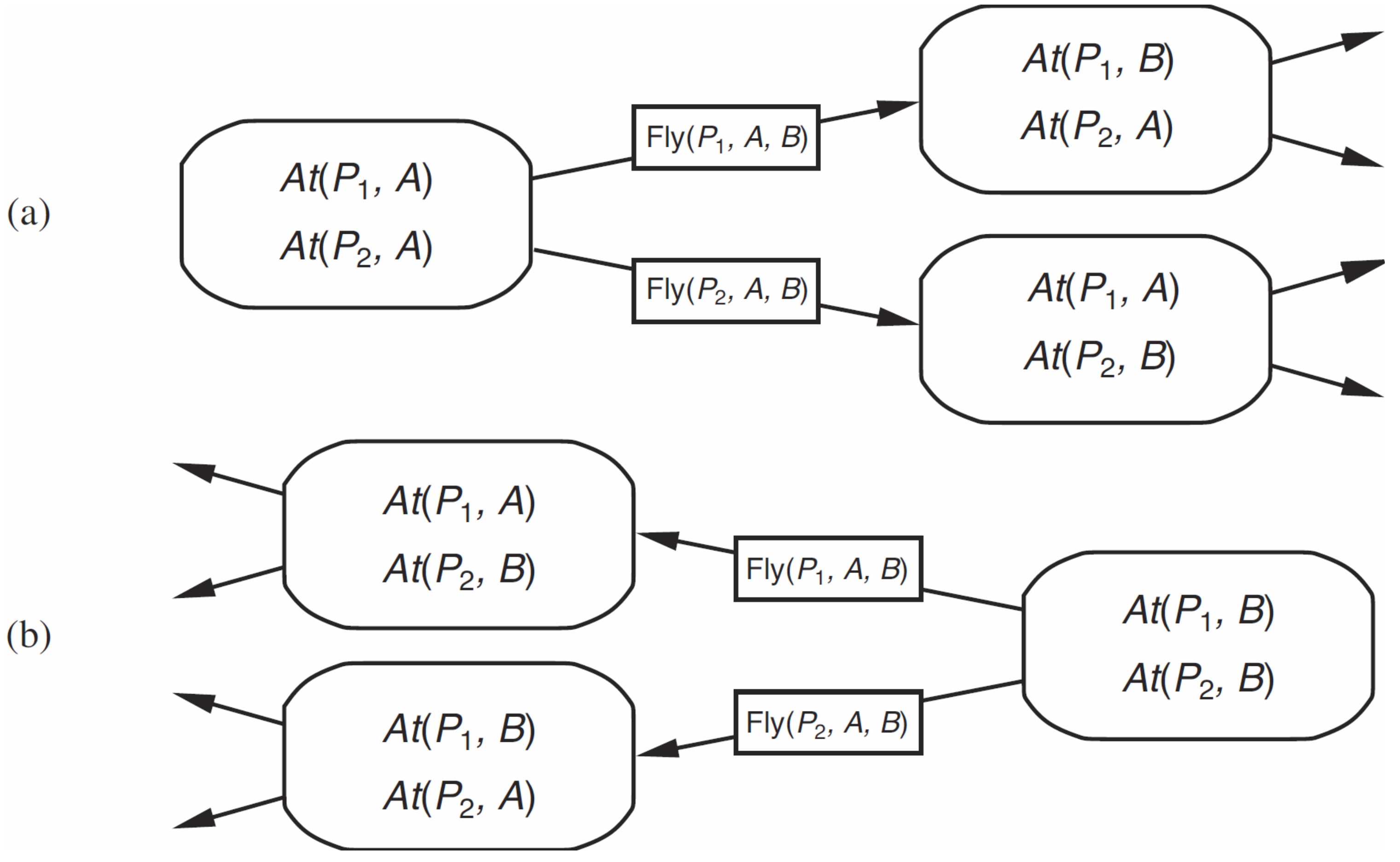
- How can the planner generate the plan?

Current popular planning approaches

- Forward state-space search with strong heuristics
- Planning graphs and GRAPHPLAN algorithm
- Partial order planning in plan space
- Planning as Boolean satisfiability (SAT)
- Planning as first-order deduction
- Planning as constraint-satisfaction

- We will consider the three first ones

Forward and backward state search



Forward state-space search

- *Progression* planning:
  - Start in initial state
  - Apply actions whose preconditions are satisfied
  - Generate successor states by adding/deleting literals
  - Check if successor state satisfies goal test
- Can be highly inefficient
  - All actions are applied, even when irrelevant
  - Large branching factor (many possible actions)
- Heuristics to guide search are required!

Backward state-space search

- *Regression* planning:
  - √ Start in goal state
  - √ Apply actions that are relevant and consistent
    - Relevant: The action can lead to the goal (adds goal literal)
    - Consistent: The action does not undo (delete) a goal literal
  - √ Create predecessor states
  - √ Continue until initial state is satisfied
- More efficient, but still requires heuristics
- State-space searches can only produce linear plans

Heuristics for planning

- Neither forward nor backward search is efficient without a good heuristic, which has to be *admissible* (i.e. optimistic)
- Possible heuristics include:
  - *Adding more edges* to the search graph, thereby making it easier to find a solution path, e.g. ignore pre-conditions or ignore delete lists
  - *Create state abstractions*, many-to-one mapping from ground states to abstract ones, solve problem in the abstract space, and map down to ground again
- Heuristics generate estimates h(s) for remaining cost of a state that can be used by e.g. A*

Planning graphs

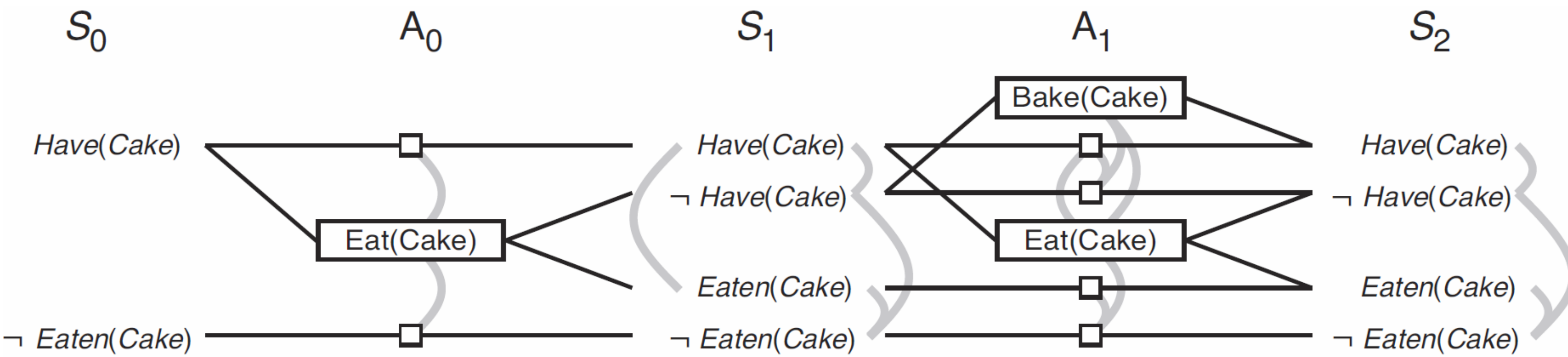
- A *planning graph* is a special data structure that can be used as a heuristic in search algorithms or directly in an algorithm that generates a solution plan
- Directed graph organized into one *level* for each time step of plan, where a level contains all literals that *may* be true at that step. Literals may be mutually exclusive (*mutex* links)
- Works only for propositional planning problems (no variables), but action schemas with variables may be converted to this form

Example planning problem

- Goal: “Have cake and eat cake too”

- ***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))*

Planning graph for the example



- Alternating state and action layers
- Real and «persistence» actions (small rectangles)
- Mutex links (grey arcs) btw. incompatible states
- Graph *levels off* at S_2 (states repeat themselves)

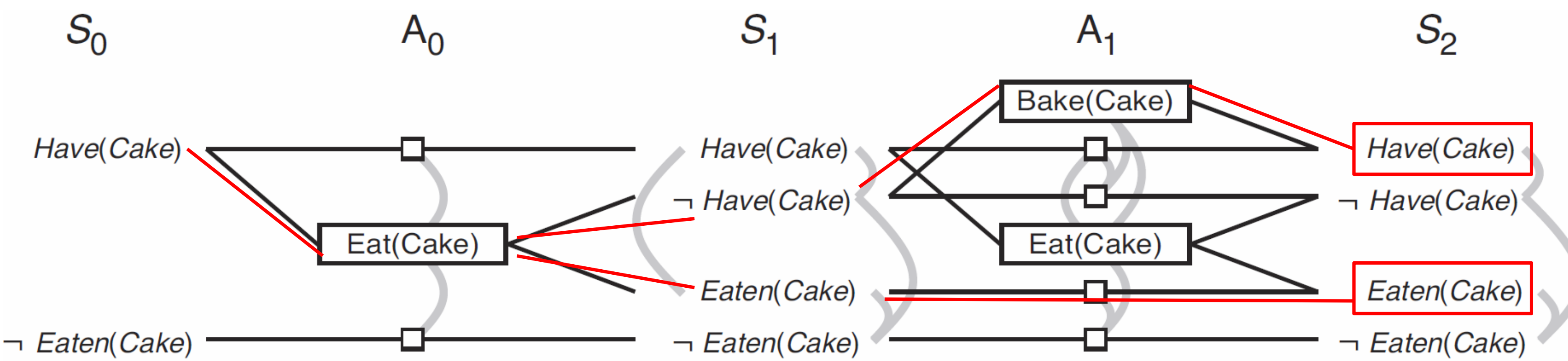
Mutex links (mutual exclusion)

- Between two actions:
  - √ *Inconsistent effects* – one action negates an effect of the other (e.g. *Eat(Cake)* and persistent *Have(Cake)*)
  - √ *Interference* – an effect of one action negates a pre-condition of the other (e.g. *Eat(Cake)* and *Have(Cake)*)
  - √ *Competing needs* – a pre-condition of one action negates a pre-condition of the other (e.g. *Eat(Cake)* and *Bake(Cake)*)
- Between two states (literals):
  - √ One literal is the negation of the other
  - √ Each possible pair of actions that could achieve the two literals is mutually exclusive

The GRAPHPLAN algorithm

- Uses a planning graph to extract a solution to a planning problem
- Repeatedly
  - √ Extend planning graph by one level
  - √ If all goal literals are included non-*mutex* in level
    - Try to extract solution that does not violate any *mutex* links, by following links backward in graph
    - Return solution if successful extraction
  - √ If the graph has leveled off then report failure
- Creating planning graph is only of polynomial complexity, but plan extraction is exponential

Extracting a solution

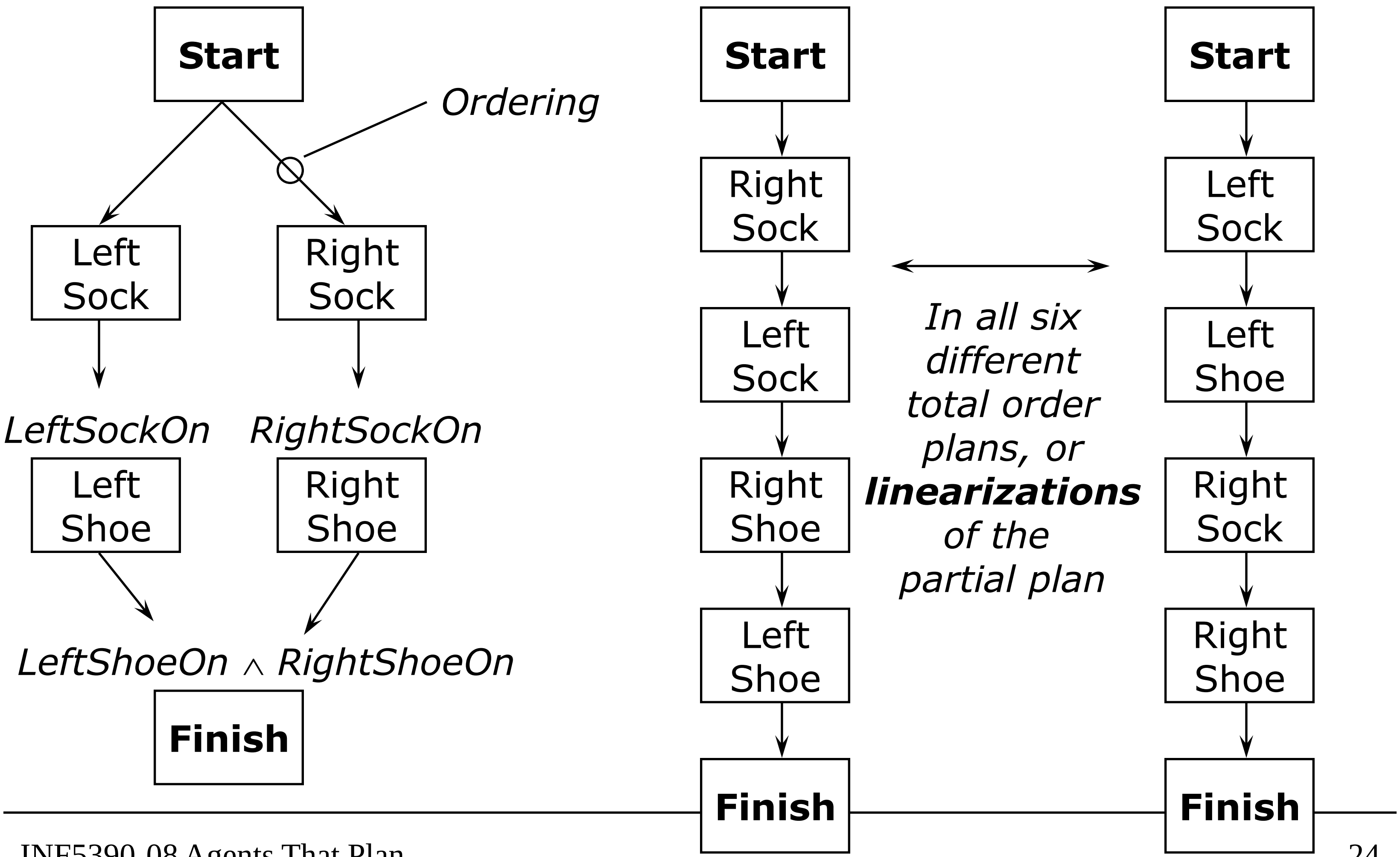


- The goal is *Have(Cake)* ∧ Eaten(Cake)
- Both goal literals non-mutex in S_2
- *Bake(Cake)* and *Eaten(Cake)* non-mutex in A_1
- ¬ *Have(Cake)* and *Eaten(Cake)* non-mutex in S_1
- *Eat(Cake)* non-mutex in A_0
- *Have(Cake)* in S_0 is initial state

Partial order planning in plan space

- Each node in the search space corresponds to a (partial) plan
- Search starts with empty plan that is expanded progressively until complete plan is found
- Search operators work in plan space, e.g. *add step, add ordering*, etc.
- The solution is the final plan, the path to it is irrelevant
- Can create *partially ordered plans*

Example - Partial and total order plans

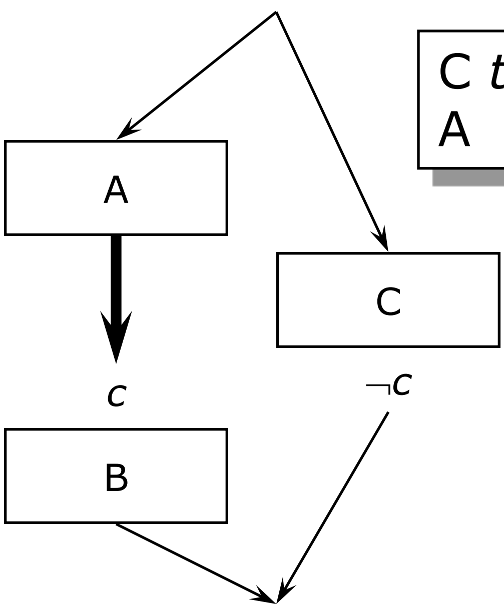


Partial-order plan representation

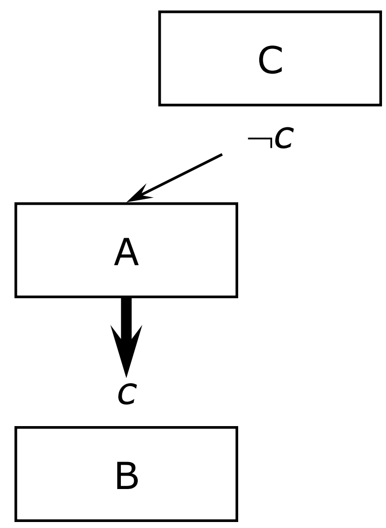
- A set of *steps*, where each step is an *action* (taken from action set of planning problem)
- Initial empty plan contains just *Start* (no precondition, initial state as effect) and *Finish* (goal as precondition, no effects)
- A set of step *ordering constraints* of the form $A < B$ ("*A* before *B*"): A must be executed before B
- A set of *causal links* $A \xrightarrow{c} B$, "*A* achieves *c* for *B*": the purpose of *A* is to achieve precondition *c* for *B;* no action is allowed between *A* and *B* that negates *c*
- Set of *open preconditions*, not achieved by any action yet. The planner must reduce this set to empty set

Protected causal links

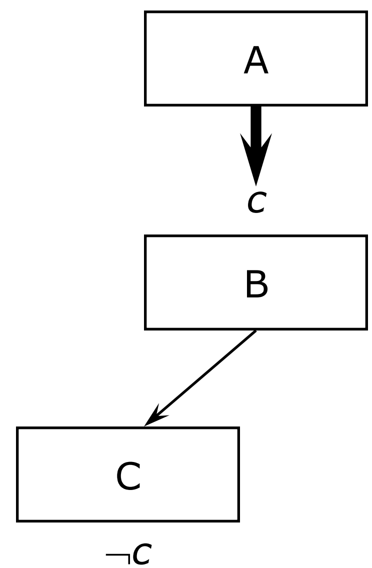
- Causal links in a partial plan are *protected* by ensuring that *threats* (steps that might delete the protected condition) are *ordered* to come *before* or *after* the protected link



C *threatens* $A \xrightarrow{c} B$



C ordered to come before A



C ordered to come after B

POP – Partial Order Planning

- Start with initial plan
  - Contains *Start* and *Finish* steps
  - All preconditions of *Finish* (goals) as open preconditions
  - The ordering constraint *Start* < *Finish,* no causal links
- Repeatedly
  - Pick arbitrarily one open precondition *c* on an action *B*
  - Generate a successor plan for every consistent way of choosing an action *A* that achieves *c*
  - Stop when a solution has been found, i.e. when there are no open preconditions for any action
- Successful solution plan
  - Complete and consistent plan the agent can execute
  - May be partial, agent may choose arbitrary linearization

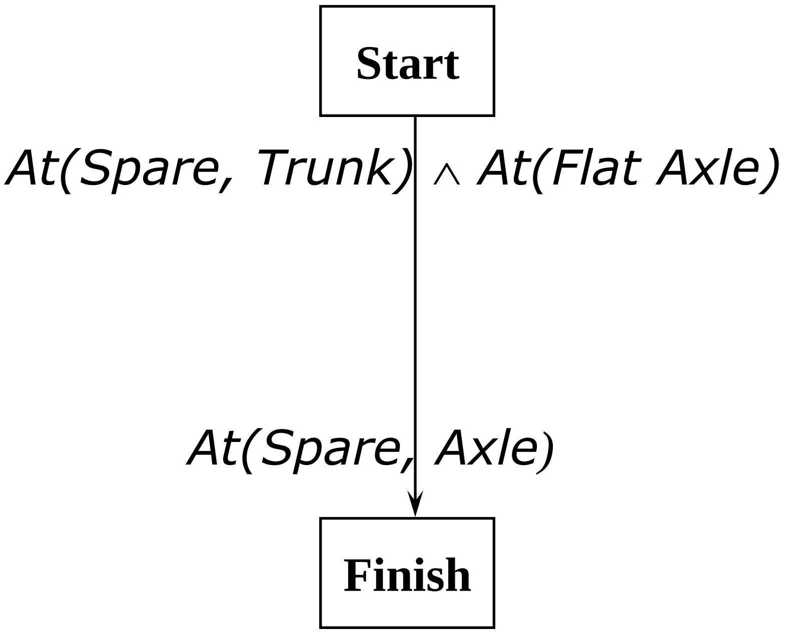
Example – Change tire

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

Uses ADL language, extends STRIPS

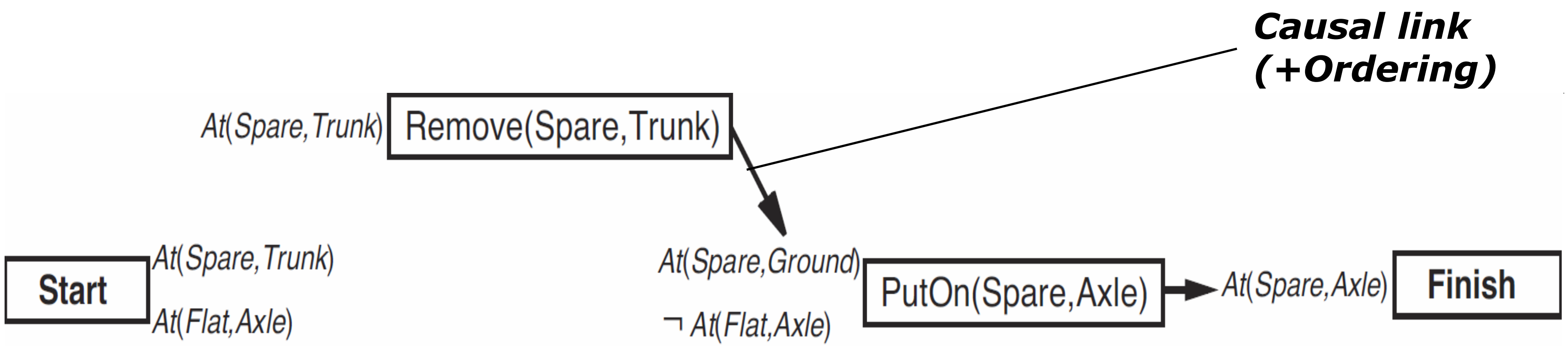
Tire (1) - Initial plan

- For each planning iteration, one step will be added. If this leads to an inconsistent state, the planner will backtrack
- The planner will only consider steps that serve to achieve a precondition that has not yet been achieved



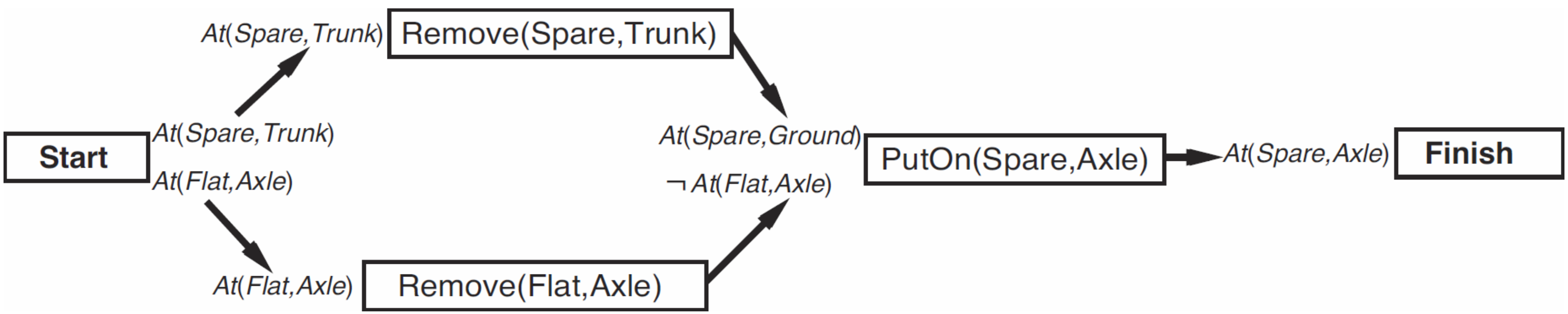
Tire (2) - Achieving open preconditions

- Start by selecting *PutOn* action that achieves *Finish*
- Select *At(Spare, Ground)* precondition of *PutOn*, and choose *Remove(Spare, Trunk)* action
- The planner will *protect* the causal links by not inserting new steps that violate achievements



Tire (3) – Finishing the plan

- Planner selects to achieve ¬*At(Flat, Axle)* precondition of *PutOn* by *Remove(Flat, Axle)*
- Final two preconditions are satisfied by *Start*



Summary

- Planning agents produce *plans* - sequences of actions - that contribute to reaching goals
- Planning systems operate on *explicit representation* of states, actions, goals, and plans
- *PDDL* (Planning Domain Definition Language) describes *action schemas* in terms of *precondition* and *effects*
- *State-space planning* operates on situations, searches in forward or backward direction, and produces fully ordered plans

Summary (cont.)

- A *planning graph* is a data structure that can constructed efficiently and be used to extract solution plans (GRAPHPLAN algorithm)
- *Plan-space planning* (POP algorithm) operates on plans, starting with a minimal plan and extending it until a solution is found, and can create partially ordered plans
- Planning is a very active AI field, where techniques are evolving rapidly, and no consensus on best approach exists yet