Chapter 11: Planning

- The Planning problem
- Planning with State-space search
- Partial-order planning

What is Planning

- Generate sequences of actions to perform tasks and achieve objectives.
  - ***States, actions and goals***
- Search for solution over abstract space of plans.
- Assists humans in practical applications
  - ***design and manufacturing***
  - ***military operations***
  - ***games***
  - ***space exploration***

Difficulty of real world problems

- Assume a problem-solving agent using some search method …
  - ***Which actions are relevant?***
    - Exhaustive search vs. backward search
  - ***What is a good heuristic functions?***
    - Good estimate of the cost of the state?
    - Problem-dependent vs, -independent
  - ***How to decompose the problem?***
    - Most real-world problems are ***nearly*** decomposable.

Planning language

- What is a good language?
  - ***Expressive enough to describe a wide variety of problems.***
  - ***Restrictive enough to allow efficient algorithms to operate on it.***
  - ***Planning algorithm should be able to take advantage of the logical structure of the problem.***
- STRIPS and ADL

General language features

- Representation of states
  - ***Decompose the world in logical conditions and represent a state as a conjunction of positive literals.***
    - Propositional literals: $Poor \wedge Unknown$
    - FO-literals (grounded and function-free): $At(Plane1, Melbourne) \wedge At(Plane2, Sydney)$
  - ***Closed world assumption***
- Representation of goals
  - ***Partially specified state and represented as a conjunction of positive ground literals***
  - ***A goal is satisfied if the state contains all literals in goal.***

General language features

- Representations of actions
  - ***Action = PRECOND + EFFECT***

    Action(Fly(p,from, to),

    PRECOND: At(p,from) ∧ Plane(p) ∧ Airport(from) ∧ Airport(to)

    EFFECT: ¬AT(p,from) ∧ At(p,to))

  = action schema (p, from, to need to be instantiated)
    - Action name and parameter list
    - Precondition (conj. of function-free literals)
    - Effect (conj of function-free literals and P is True and not P is false)
  - ***Add-list vs delete-list in Effect***

Language semantics?

- How do actions affect states?
  - ***An action is applicable in any state that satisfies the precondition.***
  - ***For FO action schema applicability involves a substitution θ for the variables in the PRECOND.***

    $At(P1,JFK) \wedge At(P2,SFO) \wedge Plane(P1) \wedge Plane(P2) \wedge Airport(JFK) \wedge Airport(SFO)$

    Satisfies : $At(p,from) \wedge Plane(p) \wedge Airport(from) \wedge Airport(to)$

    With $\theta = \{p/P1, from/JFK, to/SFO\}$

    Thus the action is applicable.

Language semantics?

- The result of executing action a in state s is the state s'
  - ***s' is same as s except***
    - Any positive literal *P* in the effect of *a* is added to *s'*
    - Any negative literal $\neg P$ is removed from *s'*

At(P1,SFO) ∧ At(P2,SFO) ∧ Plane(P1) ∧ Plane(P2) ∧ Airport(JFK) ∧ Airport(SFO)

  - ***STRIPS assumption: (avoids representational frame problem)***

every literal NOT in the effect remains unchanged

Expressiveness and extensions

- STRIPS is simplified
  - ***Important limit: function-free literals***
  - ***Allows for propositional representation***
- Function symbols lead to infinitely many states and actions
- Recent extension:Action Description language (ADL)

Action(Fly(p:Plane, from: Airport, to: Airport),
PRECOND: At(p,from) $\wedge$ *(from* $\neq$ *to)*
EFFECT: $\neg$*At(p,from)* $\wedge$ *At(p,to))*

Standardization *: Planning domain definition language (PDDL)*

Example: air cargo transport

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))

Goal(At(C1,JFK) ∧ At(C2,SFO))

Action(Load(c,p,a)

PRECOND: *At(c,a) ∧At(p,a) ∧Cargo(c) ∧Plane(p) ∧Airport(a)*

EFFECT: ¬*At(c,a) ∧In(c,p))*

Action(Unload(c,p,a)

PRECOND: *In(c,p) ∧At(p,a) ∧Cargo(c) ∧Plane(p) ∧Airport(a)*

EFFECT: *At(c,a) ∧ ¬In(c,p))*

Action(Fly(p,from,to)

PRECOND: *At(p,from) ∧Plane(p) ∧Airport(from) ∧Airport(to)*

EFFECT: ¬ *At(p,from) ∧ At(p,to))*

[Load(C1,P1,SFO), Fly(P1,SFO,JFK), Load(C2,P2,JFK), Fly(P2,JFK,SFO)]

Example: Spare tire problem

Init(At(Flat, Axle) ∧ At(Spare,trunk))
Goal(At(Spare,Axle))
Action(Remove(Spare,Trunk)
PRECOND: *At(Spare,Trunk)*
EFFECT: ¬*At(Spare,Trunk) ∧ At(Spare,Ground))*
Action(Remove(Flat,Axle)
PRECOND: *At(Flat,Axle)*
EFFECT: ¬*At(Flat,Axle) ∧ At(Flat,Ground))*
Action(PutOn(Spare,Axle)
PRECOND: *At(Spare,Groundp) ∧¬At(Flat,Axle)*
EFFECT: *At(Spare,Axle) ∧ ¬Ar(Spare,Ground))*
Action(LeaveOvernight
PRECOND:
EFFECT: ¬ *At(Spare,Ground) ∧ ¬ At(Spare,Axle) ∧ ¬ At(Spare,trunk) ∧ ¬ At(Flat,Ground) ∧ ¬ At(Flat,Axle))*

This example goes beyond STRIPS: negative literal in pre-condition (ADL description)

Example: Blocks world

Init(On(A, Table) $\wedge$ *On(B,Table)* $\wedge$ *On(C,Table)* $\wedge$ *Block(A)* $\wedge$ *Block(B)* $\wedge$ *Block(C)* $\wedge$ *Clear(A)* $\wedge$ *Clear(B)* $\wedge$ *Clear(C))*

Goal(On(A,B) $\wedge$ *On(B,C))*

Action(Move(b,x,y)

PRECOND: *On(b,x)* $\wedge$ *Clear(b)* $\wedge$ *Clear(y)* $\wedge$ *Block(b)* $\wedge$ $(b \neq x)$ $\wedge$ $(b \neq y)$ $\wedge$ $(x \neq y)$

EFFECT: *On(b,y)* $\wedge$ *Clear(x)* $\wedge$ $\neg$ *On(b,x)* $\wedge$ $\neg$ *Clear(y))*

Action(MoveToTable(b,x)

PRECOND: *On(b,x)* $\wedge$ *Clear(b)* $\wedge$ *Block(b)* $\wedge$ $(b \neq x)$

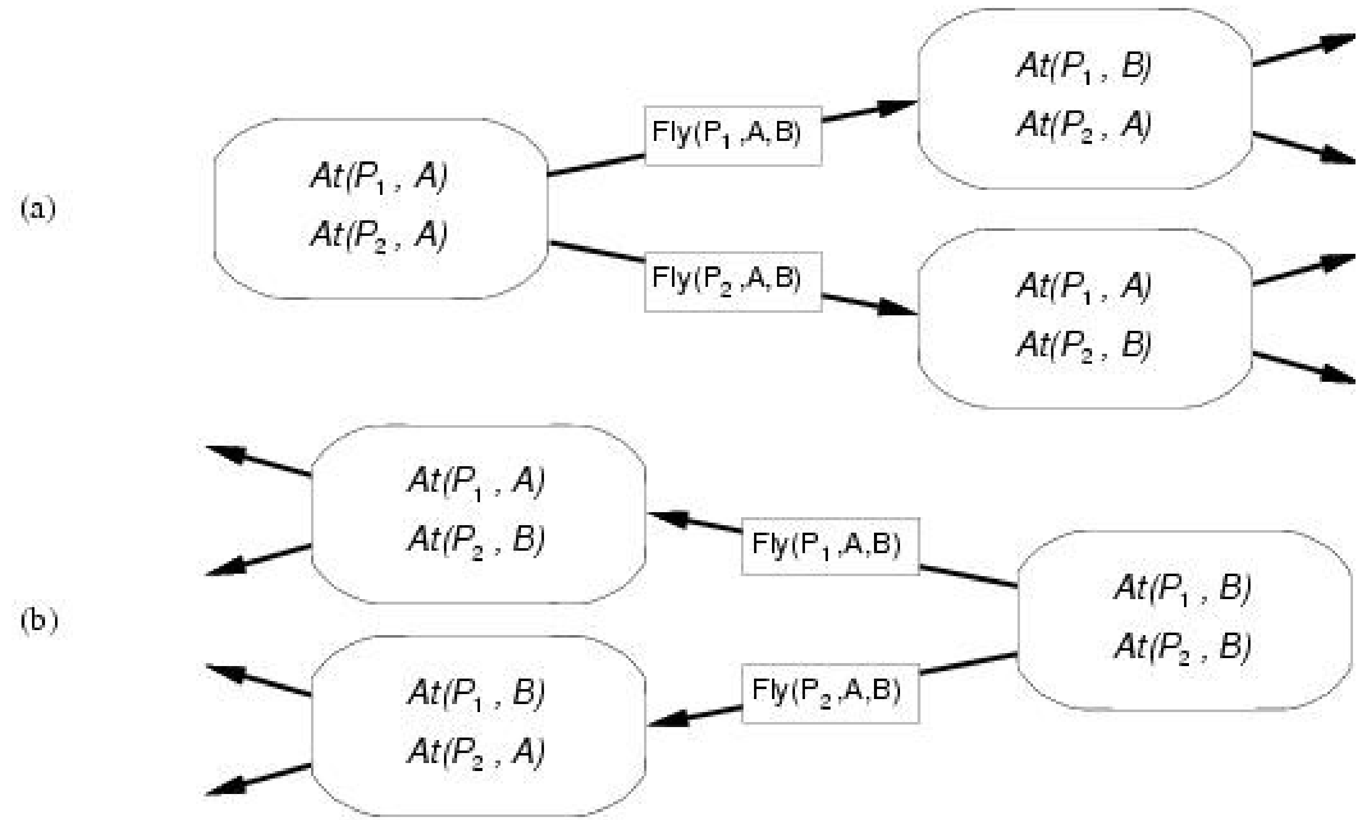
EFFECT: *On(b,Table)* $\wedge$ *Clear(x)* $\wedge$ $\neg$ *On(b,x))*

Spurious actions are possible: Move(B,C,C)

Planning with state-space search

- Both forward and backward search possible
- Progression planners
  - ***forward state-space search***
  - ***Consider the effect of all possible actions in a given state***
- Regression planners
  - ***backward state-space search***
  - ***To achieve a goal, what must have been true in the previous state.***

Progression and regression



Progression algorithm

- Formulation as state-space search problem:
  - ***Initial state = initial state of the planning problem***
    - Literals not appearing are false
  - ***Actions = those whose preconditions are satisfied***
    - Add positive effects, delete negative
  - ***Goal test = does the state satisfy the goal***
  - ***Step cost = each action costs 1***
- No functions … any graph search that is complete is a complete planning algorithm.
- Inefficient: (1) irrelevant action problem (2) good heuristic required for efficient search

Regression algorithm

- How to determine predecessors?
  - ***What are the states from which applying a given action leads to the goal?***

    Goal state = $At(C1, B) \wedge At(C2, B) \wedge \ldots \wedge At(C20, B)$

    Relevant action for first conjunct: *Unload(C1,p,B)*

    Works only if pre-conditions are satisfied.

    Previous state= $In(C1, p) \wedge At(p, B) \wedge At(C2, B) \wedge \ldots \wedge At(C20, B)$

    Subgoal At(C1,B) should not be present in this state.
- Actions must not undo desired literals (consistent)
- Main advantage: only relevant actions are considered.
  - ***Often much lower branching factor than forward search.***

Regression algorithm

- General process for predecessor construction
  - ***Give a goal description G***
  - ***Let A be an action that is relevant and consistent***
  - ***The predecessors is as follows:***
    - Any positive effects of A that appear in G are deleted.
    - Each precondition literal of A is added , unless it already appears.
- Any standard search algorithm can be added to perform the search.
- Termination when predecessor satisfied by initial state.
  - ***In FO case, satisfaction might require a substitution.***

Heuristics for state-space search

- Neither progression or regression are very efficient without a good heuristic.
  - ***How many actions are needed to achieve the goal?***
  - ***Exact solution is NP hard, find a good estimate***
- Two approaches to find admissible heuristic:
  - ***The optimal solution to the relaxed problem.***
    - Remove all preconditions from actions
  - ***The subgoal independence assumption:***

    The cost of solving a conjunction of subgoals is approximated by the sum of the costs of solving the subproblems independently.

Partial-Order Planning (POP)

- 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***

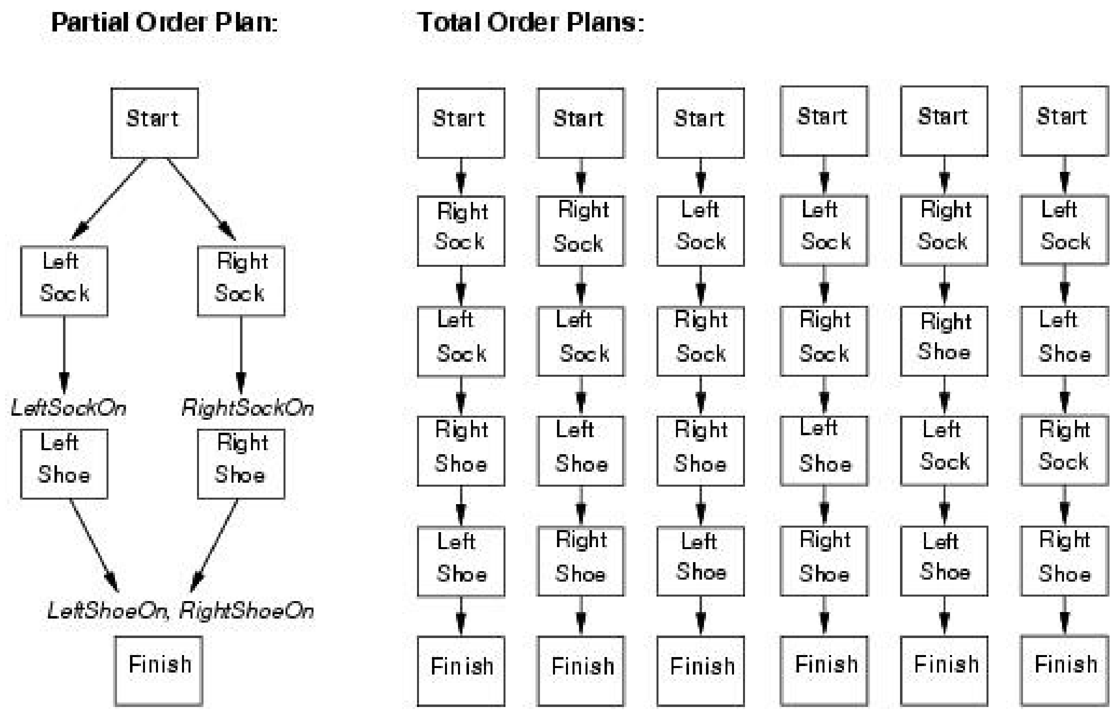
Shoe example

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 which comes first is a POP.



POP 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 constraing 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: ¬*At(Spare,Trunk)* $\wedge$ *At(Spare,Ground))*

Action(Remove(Flat,Axle)

PRECOND: *At(Flat,Axle)*

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

Action(PutOn(Spare,Axle)

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

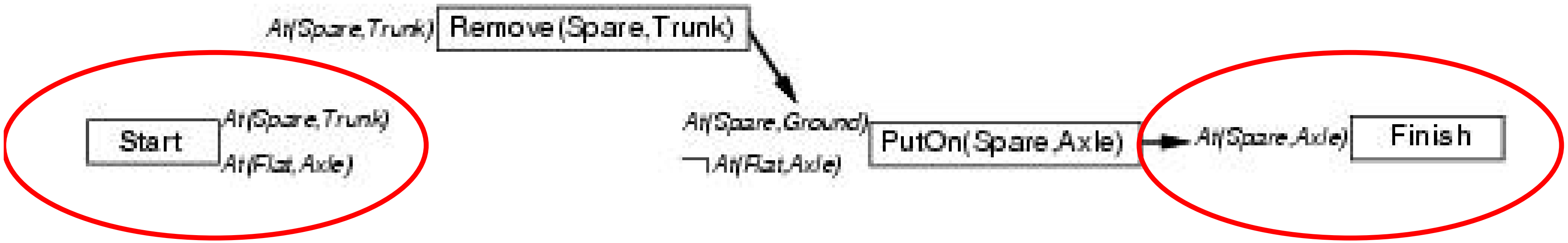
EFFECT: *At(Spare,Axle)* $\wedge$ ¬*Ar(Spare,Ground))*

Action(LeaveOvernight

PRECOND:

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

Solving the problem

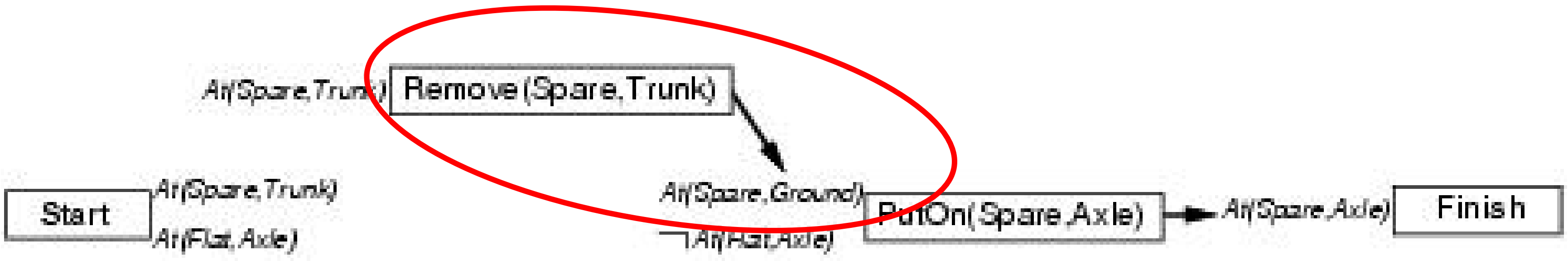


- Intial plan: Start with EFFECTS and Finish with PRECOND.

Solving the problem

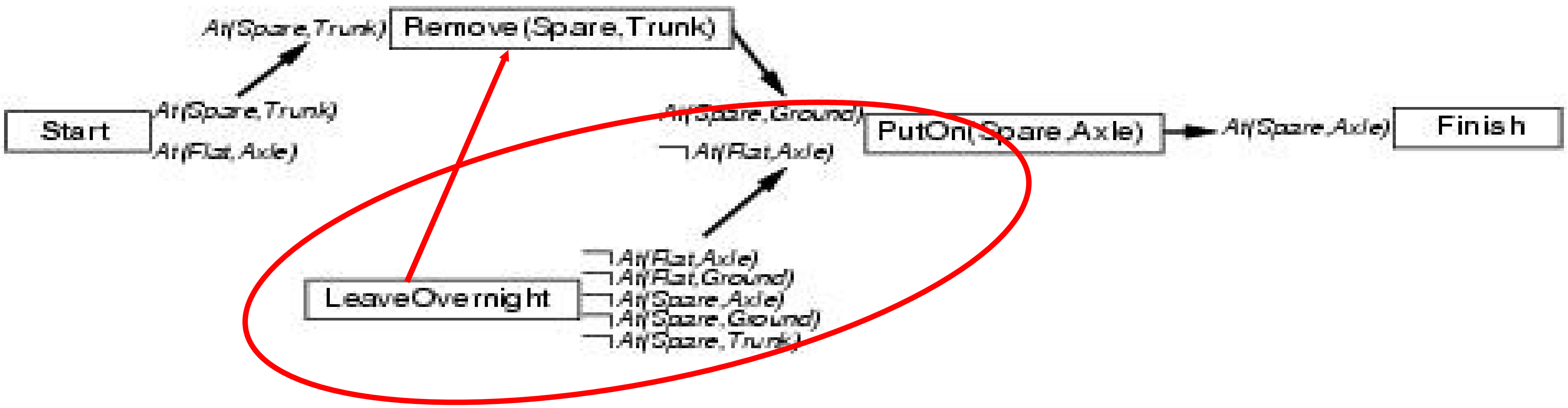
- Intial plan: Start with EFFECTS and Finish with PRECOND.
- Pick an open precondition: *At(Spare, Axle)*
- Only *PutOn(Spare, Axle)* is applicable
- Add causal link: $PutOn(Spare, Axle) \xrightarrow{At(Spare,Axle)} Finish$
- Add constraint : *PutOn(Spare, Axle) < Finish*

Solving the problem



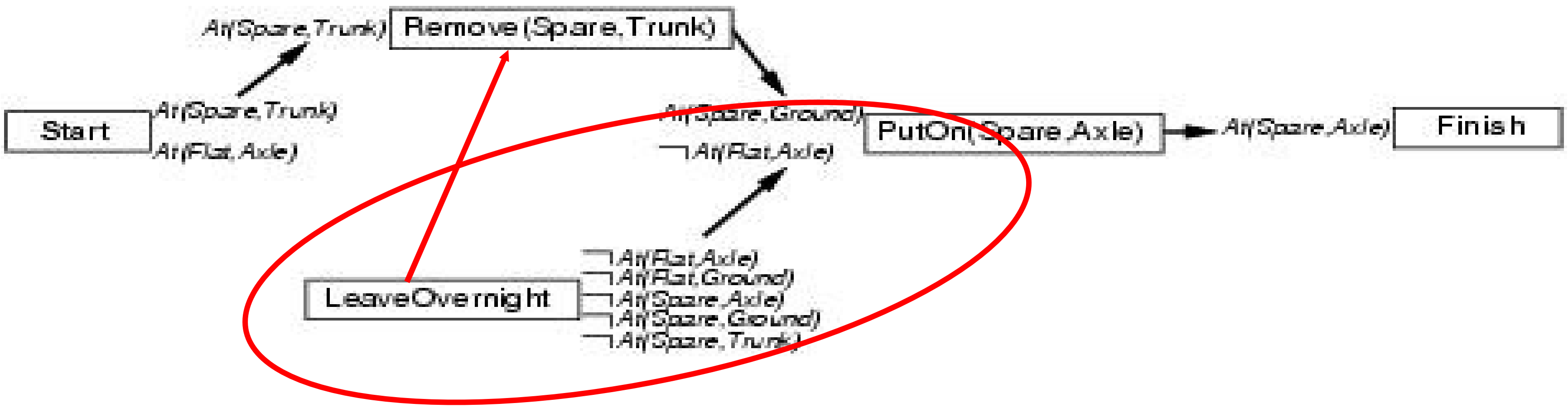
- Pick an open precondition: *At(Spare, Ground)*
- Only *Remove(Spare, Trunk)* is applicable
- Add causal link: $\text{Re}\,move(Spare,Trunk) \xrightarrow{At(Spare,Ground)} PutOn(Spare,Axle)$
- Add constraint : *Remove(Spare, Trunk) < PutOn(Spare,Axle)*

Solving the problem



- Pick an open precondition: *At(Spare, Ground)*
- *LeaveOverNight* is applicable
- conflict: $Remove(Spare,Trunk) \xrightarrow{At(Spare,Ground)} PutOn(Spare,Axle)$
- To resolve, add constraint : *LeaveOverNight* < *Remove(Spare, Trunk)*

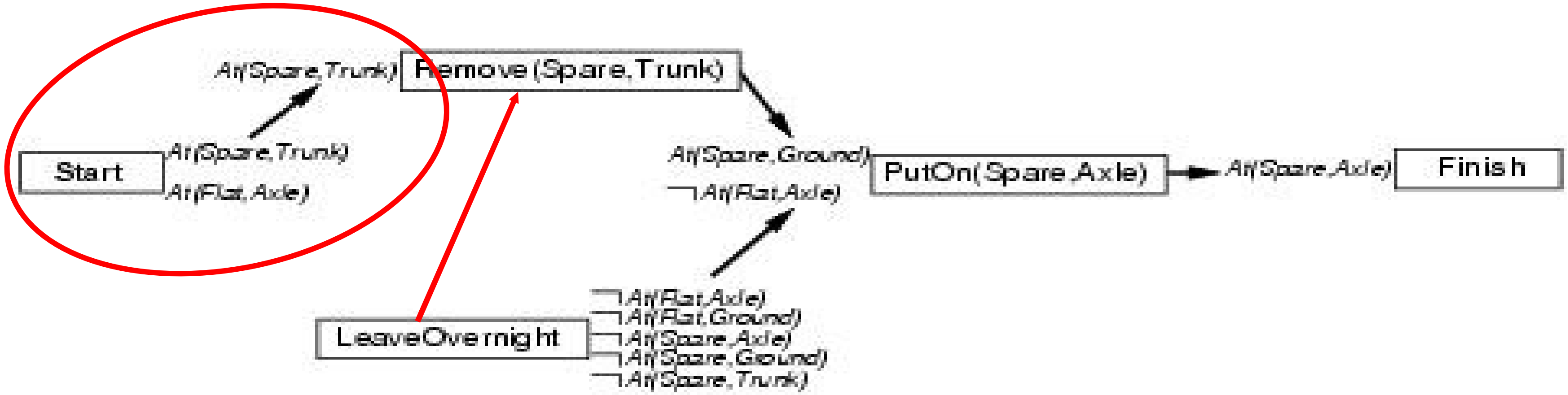
Solving the problem



- Pick an open precondition: *At(Spare, Ground)*
- *LeaveOverNight* is applicable
- conflict: $Remove(Spare,Trunk) \xrightarrow{At(Spare,Ground)} PutOn(Spare,Axle)$
- To resolve, add constraint : *LeaveOverNight* < *Remove(Spare, Trunk)*
- Add causal link:

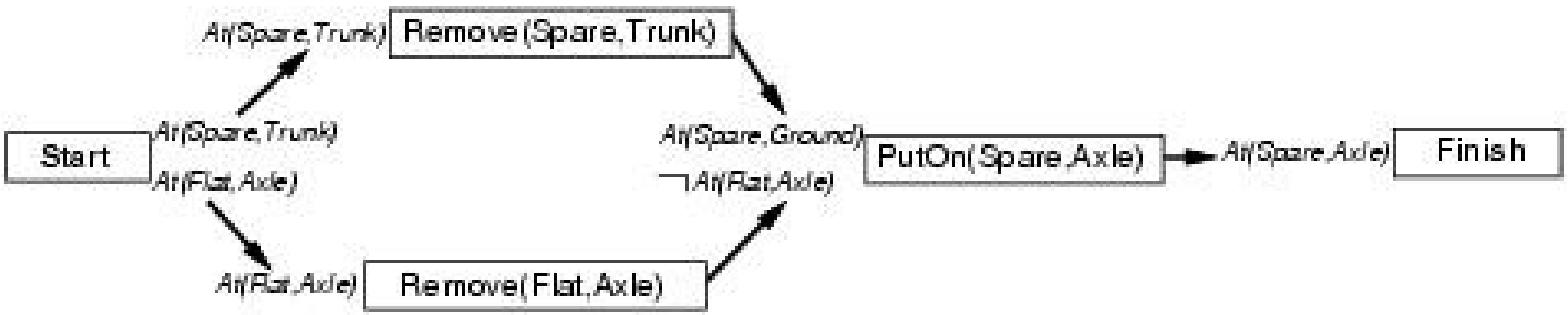
$$LeaveOverNight \xrightarrow{\neg At(Spare,Ground)} PutOn(Spare,Axle)$$

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

Solving the problem



- Remove *LeaveOverNight*, *Remove(Spare, Trunk)* and causal links
- Repeat step with Remove(Spare,Trunk)
- Add also RemoveFlatAxle and finish

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 constrainst.***
- CSP's most-constrained-variable constraint can be used for planning algorithms to select a PRECOND.

Conclusion

- 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***