AI Planning

Artificial Intelligence

Reading

- Required reading
  - Sections 11.1—11.4
- Recommended reading
  - AIMA Section 10.3: Actions, Situations, and Events
  - Chapter 11 entirely

Outline

- Background
  - Situation Calculus
  - Frame, qualification, & ramification problems
- Representation language
- Algorithms

Background

- Focus
  - The focus here is deterministic planning
    - Environment is fully observable
    - Results of actions is deterministic
  - Relaxing the above requires dealing with uncertainty
    - Problem types: sensorless, contingency, exploration
- Planning ‘communities’ in AI
  - Logic-based: Reasoning About Actions & Change
  - Less formal representations: Classical AI Planning
  - Uncertainty (UAI): Graphical Models such as
    - Markov Decision Processes (MDP), Partially Observable MDPs, etc.
- AI Planning is not MRP (Material Requirements Planning)

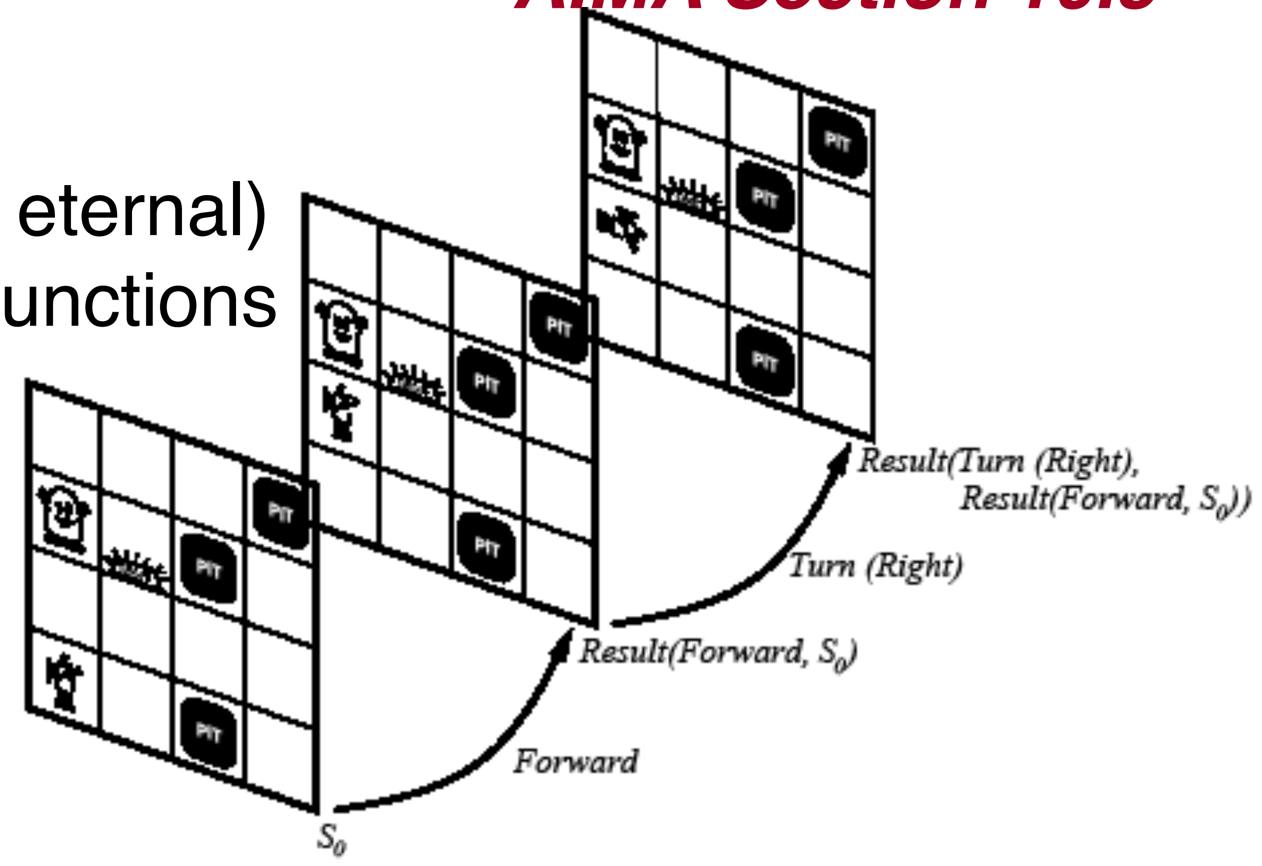
Actions, events, and change

- Planning requires a representation of time
  - to express & reason about sequences of actions
  - to express the effects of actions on the world
- Propositional Logic
  - does not offer a representation for time
  - Each action description needs to be repeated for each step
- Situation Calculus (AIMA Section 10.3)
  - Is based on FOL
  - Each time step is a ‘situation’
  - Allows to represent plans and reason about actions & change

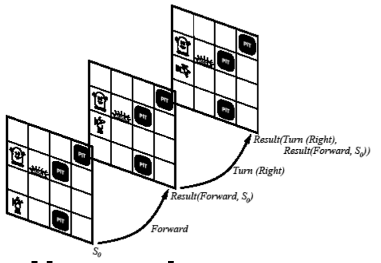
Situation Calculus: Ontology

- Situations
- Fluents
- Atemporal (or eternal) predicates & functions

AIMA Section 10.3



Situation Calculus: Ontology



- Situations
  - Initial state: S_0
  - A function *Result*(*a.s*) gives the situation resulting from applying action *a* in situation *s*
- Fluents
  - Functions & predicates whose truth values can change from one situation to the other
  - Example: $\neg Holding(G_1,S_0)$
- Atemporal (or eternal) predicates and functions
  - Example: $Gold(G_1)$, $LeftLegOf(Wumpus)$

Situation Calculus

- Sequence of actions
  - Result([],s)=s
  - Result([alseq],s)=Result(seq,Result(a,s))
- Projection task
  - Deducing the outcome of a sequence of actions
- Planning task
  - Find a sequence of actions that achieves a desired effect

Example: Wumpus World

- Fluents
  - At(o,p,s), Holding(o,s)
- Agent is in [1,1], gold is in [1,2]
  - At(Agent,[1,1],S_0) ∧ At(G_1,[1,2],S_0)
- In S_0, we also need to have:
  - At(o,x,S_0) ⇔ [(o=Agent) ∧ x=[1,1]] ∨ [(o=G_1) ∧ x=[1,2]]
  - ¬Holding(o,S_0)
  - Gold(G_1) ∧ Adjacent([1,1],[1,2]) ∧ Adjacent([1,2],[1,1])
- The query is:
  - ∃ seq At(G_1,[1,1],Result(seq,S_0))
- The answer is
  - At(G1,[1,1],Result(Go([1,1],[1,2]),Grab(G_1),Go([1,2],[1,1]),S_0))

Importance of Situation Calculus

- Historical note
  - Situation Calculus was the first attempt to formalizing planning in FOL
  - Other formalisms include Event Calculus
  - The area of using logic for planning is informally called in the literature “Reasoning About Action & Change”
- Highlighted three important problems
  1. Frame problem
  2. Qualification problem
  3. Ramification problem

‘Famous’ Problems

- Frame problem
  - Representing all things that stay the same from one situation to the next
  - Inferential and representational
- Qualification problem
  - Defining the circumstances under which an action is guaranteed to work
  - Example: what if the gold is slippery or nailed down, etc.
- Ramification problem
  - Proliferation of implicit consequences of actions as actions may have secondary consequences
  - Examples: How about the dust on the gold?

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- Background
  - Situation Calculus
  - Frame, qualification, & ramification problems
- **Representation language**
- Algorithms

Planning Languages

- Languages must represent..
  - States
  - Goals
  - Actions
- Languages must be
  - Expressive for ease of representation
  - Flexible for manipulation by algorithms

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 (ground 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
    - *Poor* $\wedge$ *Unknown* $\wedge$ *At(P2, Tahiti)*
  - 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 positive literals)
  - Effect (conj of function-free literals and P is True and not P is false)
  - Add-list vs delete-list in Effect

State Representation

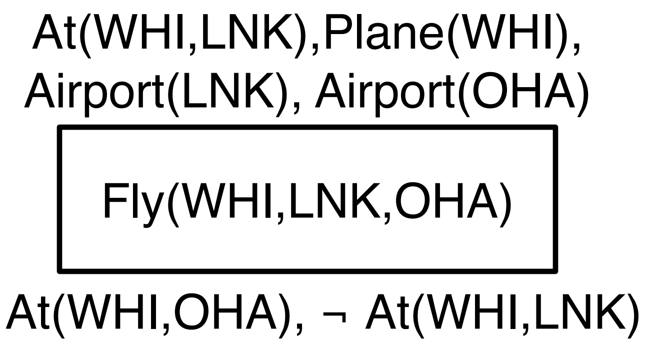
- A state is represented with a conjunction of positive literals
- Using
  - Logical Propositions: *Poor* ∧ *Unknown*
  - FOL literals: *At(Plane1,OMA)* ∧ *At(Plan2,JFK)*
- FOL literals must be ground & function-free
  - Not allowed: *At(x,y)* or *At(Father(Fred),Sydney)*
- Closed World Assumption
  - What is not stated are assumed false

Goal Representation

- Goal is a <u>partially</u> specified state
- A proposition satisfies a goal if it contains all the atoms of the goal and possibly others..
  - Example: Rich ∧ Famous ∧ Miserable satisfies the goal Rich ∧ Famous

Action Representation

- Action Schema
  - Action name
  - Preconditions
  - Effects



- Example

  Action(Fly(p,from,to),
  PRECOND: At(p,from) ∧ Plane(p) ∧ Airport(from) ∧ Airport(to)
  EFFECT: ¬At(p,from) ∧ At(p,to))

- Sometimes, Effects are split into ADD list and DELETE list

Applying an Action

- Find a substitution list θ for the variables
  - of all the precondition literals
  - with (a subset of) the literals in the current state description
- Apply the substitution to the propositions in the effect list
- Add the result to the current state description to generate the new state
- Example:
  - Current state: At(P1,JFK) ∧ At(P2,SFO) ∧ Plane(P1) ∧ Plane(P2) ∧ Airport(JFK) ∧ Airport(SFO)
  - It satisfies the precondition with θ={p/P1,from/JFK, to/SFO)
  - Thus the action Fly(P1,JFK,SFO) is applicable
  - The new current state is: At(P1,SFO) ∧ At(P2,SFO) ∧ Plane(P1) ∧ Plane(P2) ∧ Airport(JFK) ∧ Airport(SFO)

Languages for Planning Problems

- STRIPS
  - Stanford Research Institute Problem Solver
  - Historically important
- ADL
  - Action Description Languages
  - See Table 11.1 for STRIPS versus ADL
- PDDL
  - Planning Domain Definition Language
  - Revised & enhanced for the needs of the International Planning Competition
  - Currently version 3.1

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 extention: Action Description language (ADL)

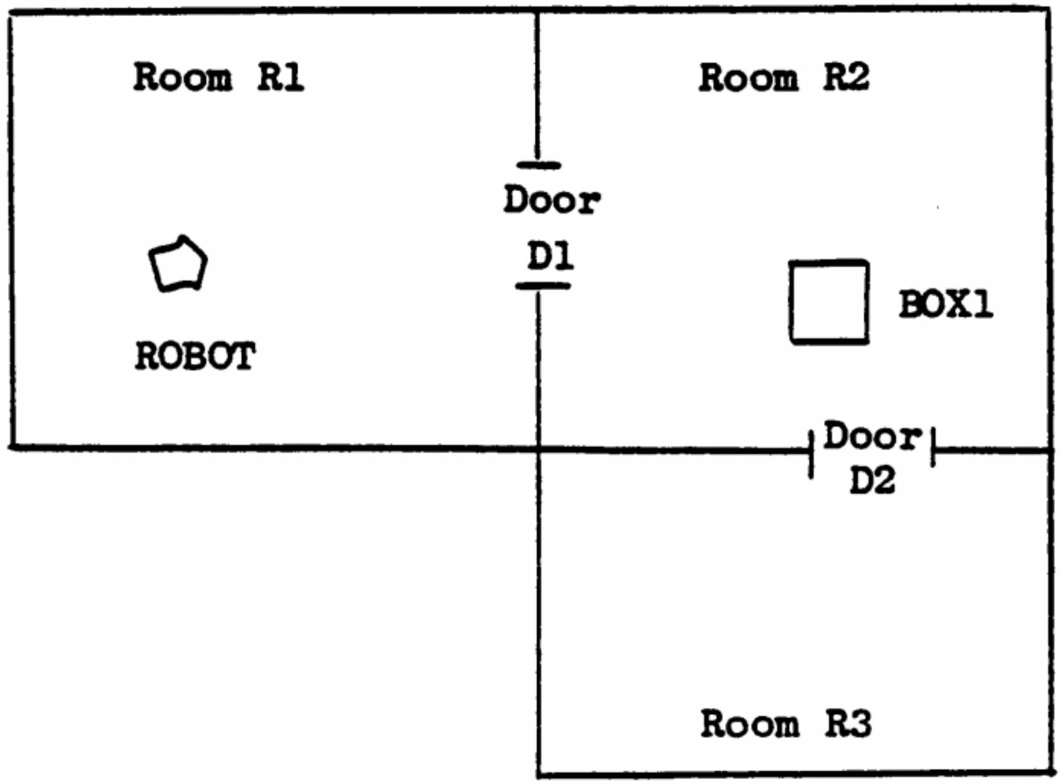
  Action(Fly(p:Plane, from: Airport, to: Airport),

  PRECOND: $At(p,from) \wedge (from \neq to)$

  EFFECT: $\neg At(p,from) \wedge At(p,to)$)

- Standardization : Planning domain definition language (PDDL)

STRIPS



STRIPS - Box in the Room Example

//Initial state:
INROOM(ROBOT, R1) ∧ CONNECTS(D1, R1, R2) ∧ CONNECTS(D2, R2, R3) ∧ BOX(BOX1), INROOM(BOX1, R2)

//Goal:
BOX(BOX1) ∧ INROOM(BOX1, R1)

//Actions:
GOTHRU(d, r1, r2) //Robot goes from room r1 to room r2, through door d
Preconditions: INROOM(ROBOT, r1) ∧ CONNECTS(d, r1, r2)
Postconditions: NOT INROOM(ROBOT, r1) ∧ INROOM(ROBOT, r2)

PUSHTHRU(b, d, r1, r2) //Robot pushes box b through door d from room r1 to room r2
Preconditions: INROOM(b, r1) ∧ INROOM(ROBOT, r1) ∧ CONNECTS(d, r1, r2)
Postconditions: NOT INROOM(ROBOT, r1) ∧ NOT INROOM (b, r1) ∧ INROOM(ROBOT, r2) ∧ INROOM(b, r2)

Here is the solution (sequence of actions to achieve the goal, while starting from initial state) for described example:

1. GOTHRU(D1,R1,R2)
2. PUSHTHRU(BOX1,D1,R2,R1).

Example: Air Cargo

- See Figure 11.2
- Initial state
- Goal State
- Actions: Load, Unload, Fly

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

- See Figure 11.3
- Initial State
- Goal State
- Actions:
  - *Remove(Spare,Trunk), Remove(Flat, Axle)*
  - *PutOn(Spare,Axle)*
  - *LeaveOvernight*
- Note
  - the negated precondition ¬*At(Flat,Axle)* not allowed in STRIPS.
  - Could be easily replaced with *Clear(Axle)*, adding one more predicate to the language

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,Ground) ∧¬At(Flat,Axle)*
EFFECT: *At(Spare,Axle) ∧ ¬At(Spare,Ground))*
Action(LeaveOvernight
PRECOND:
EFFECT: *¬ At(Spare,Ground) ∧ ¬ At(Spare,Axle) ∧ ¬ At(Spare,trunk) ∧ ¬ At(Flat,Ground) ∧ ¬ At(Flat,Axle))*

STRIPS?

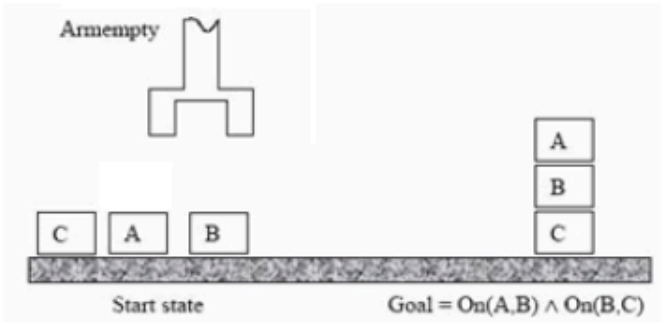
Example: Blocks World

- See Fig 11.4
- Initial state
- Goal
- Actions:
  - *Move*(b,x,y)
  - *MoveToTable*(b,x)

Example: Blocks world

Init(On(A, Table) ∧ On(B,Table) ∧ On(C,Table) ∧ Block(A) ∧ Block(B) ∧ Block(C)
∧ Clear(A) ∧ Clear(B) ∧ Clear(C))

Goal(On(A,B) ∧ On(B,C))



Action(Move(b,x,y)

PRECOND: *On(b,x) ∧ Clear(b) ∧ Clear(y)*
∧ Block(b) ∧ (b≠x) ∧ (b≠y) ∧ (x≠y)

EFFECT: *On(b,y) ∧ Clear(x) ∧ ¬ On(b,x) ∧ ¬ Clear(y))*

Action(MoveToTable(b,x)

PRECOND: *On(b,x) ∧ Clear(b) ∧ Block(b) ∧ (b≠x)*

EFFECT: *On(b,Table) ∧ Clear(x) ∧ ¬ On(b,x))*

Spurious actions: Move(B,C,C)

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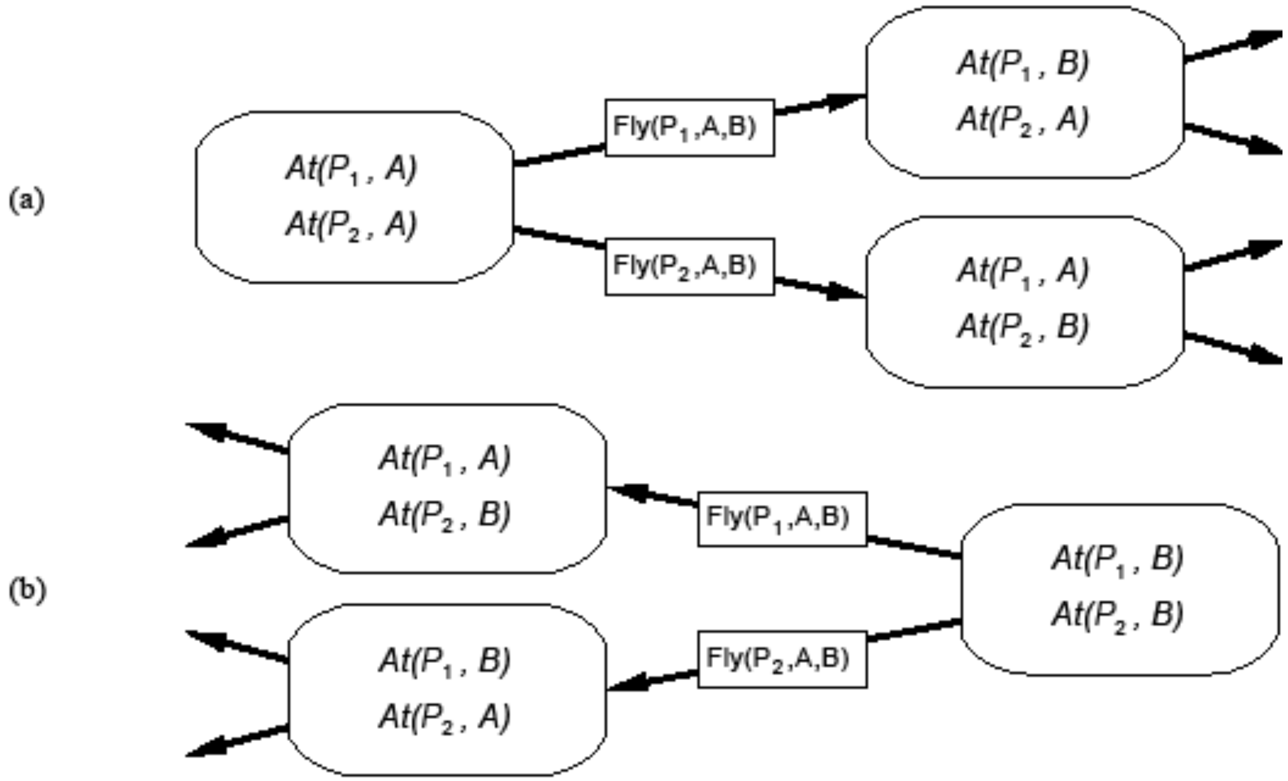
- **Planning Algorithms**
  - **State-Space Search**
  - Partial-Order Planning (POP)
  - Planning Graphs (GRAPHPLAN)
  - SAT Planners

State-Space Search (1)

- Search the space of states (first chapters)
  - Initial state, goal test, step cost, etc.
  - Actions are the transitions between state
- Actions are invertible (why?)
  - Move forward from the initial state: Forward State-Space Search or <u>Progression Planning</u>
  - Move backward from goal state: Backward State-Space Search or <u>Regression Planning</u>

State-Space Search (2)

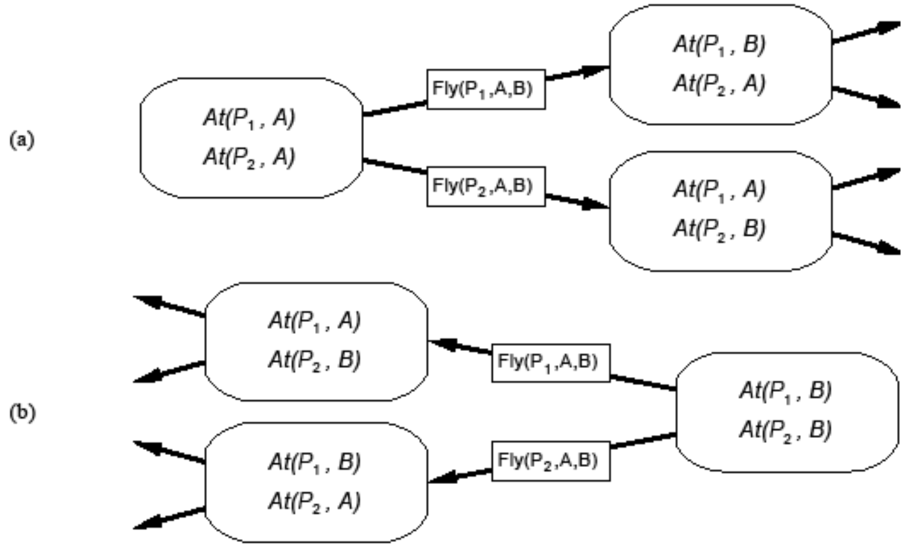


State-Space Search (3)

- Remember that the language has no functions symbols
- Thus number of states is finite
- And we can use any complete search algorithm (e.g., A*)
  - We need an admissible heuristic
  - The solution is a path, a sequence of actions: total-order planning
- Problem: Space and time complexity
  - STRIPS-style planning is PSPACE-complete unless actions have
    - only positive preconditions and
    - only one literal effect

SRIPS in State-Space Search

- STRIPS representation makes it easy to focus on 'relevant' propositions and
  - Work backward from goal (using EFFECTS)
  - Work forward from initial state (using PRECONDITIONS)
  - Facilitating bidirectional search



Relevant Action

- An action is relevant
  - In Progression planning when its preconditions match a subset of the current state
  - In Regression planning, when its effects match a subset of the current goal state

Consistent Action

- The purpose of applying an action is to ‘achieves a desired literal’
- We should be careful that the action does not undo a desired literal (as a side effect)
- A consistent action is an action that does not undo a desired literal

Backward State-Space Search

- Given
  - A goal *G* description
  - An action *A* that is relevant and consistent
- Generate a predecessor state where
  - Positive effects (literals) of *A* in *G* are deleted
  - Precondition literals of *A* are added unless they already appear
  - Substituting any variables in A's effects to match literals in G
  - Substituting any variables in A's preconditions to match substitutions in A's effects
- Repeat until predecessor description matches initial state

Heuristic to Speed up Search

- We can use A*, but we need an admissible heuristic
  1. Divide-and-conquer: sub-goal independence assumption
  - Problem relaxation by removing
  2. … all preconditions
  3. … all preconditions <u>and</u> negative effects
  4. … negative effects only: Empty-Delete-List

1. Subgoal Independence Assumption

- The cost of solving a conjunction of subgoals is the sum of the costs of solving each subgoal independently
- Optimistic
  - Where subplans interact negatively
  - Example: one action in a subplan delete goal achieved by an action in another subplan
- Pessimistic (not admissible)
  - Redundant actions in subplans can be replaced by a single action in merged plan

2. Problem Relaxation: Removing Preconditions

- Remove preconditions from action descriptions
  - All actions are applicable
  - Every literal in the goal is achievable in one step
- Number of steps to achieve the conjunction of literals in the goal is equal to the number of unsatisfied literals
- Alert
  - Some actions may achieve several literals
  - Some action may remove the effect of another action

3. Remove Preconditions & Negative Effects

- Considers only positive interactions among actions to achieve multiple subgoals
- The minimum number of actions required is the sum of the union of the actions' positive effects that satisfy the goal
- The problem is reduced to a set cover problem, which is NP-hard
  - Approximation by a greedy algorithm cannot guarantee an admissible heuristic

4. Removing Negative Effects (Only)

- Remove all negative effects of actions (no action may destroy the effects of another)
- Known as the Empty-Delete-List heuristic
- Requires running a simple planning algorithm
- Quick & effective
- Usable in progression or regression planning

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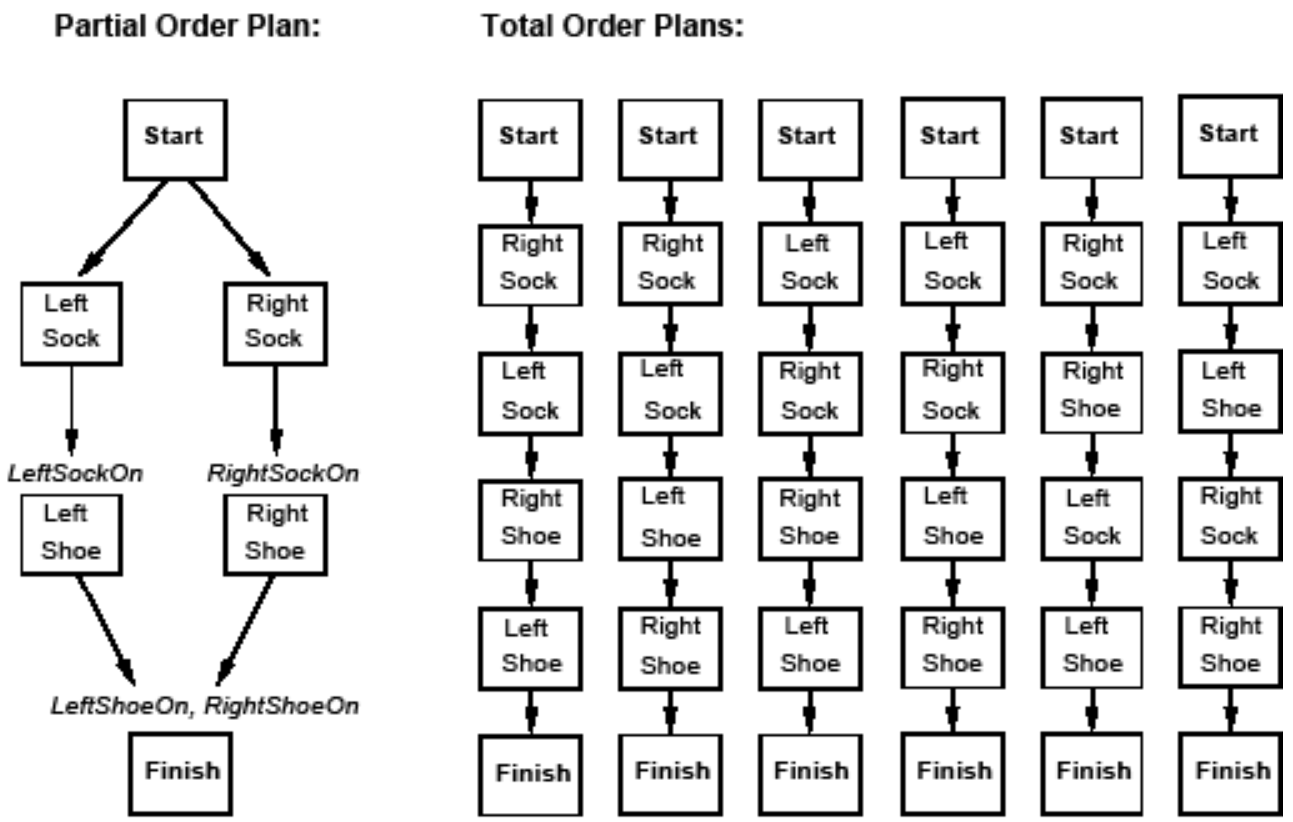
  - **Partial-Order Planning (POP)**
  - Planning Graphs (GRAPHPLAN)
  - SAT Planners

Partial Order Planning (POP)

- State-space search
  - Yields totally ordered plans (linear plans)
- POP
  - Works on subproblems independently, then combines subplans
  - Example
    - Goal(RightShoeOn ∧ LeftShoeOn)
    - Init()
    - *Action*(RightShoe, PRECOND: RightSockOn, EFFECT: RightShoeOn)
    - *Action*(RightSock, EFFECT: RightSockOn)
    - *Action*(LeftShoe, PRECOND: LeftSockOn, EFFECT: LeftShoeOn)
    - *Action*(LeftSock, EFFECT: LeftSockOn)

POP Example & its linearization



Components of a Plan

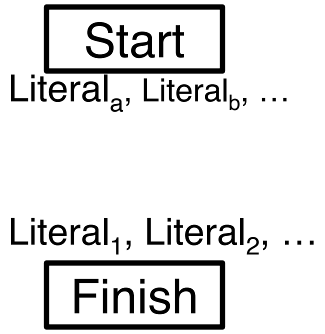
1. A set of actions
2. A set of ordering constraints
   - A ⍰⍰B reads "A before B" but not necessarily immediately before B
   - Alert: caution to cycles A ⍰⍰B and B ⍰⍰A
3. A set of causal links (protection intervals) between actions
   - A $\xrightarrow{p}$ B reads "A achieves *p* for B" and p must remain true from the time A is applied to the time B is applied
   - Example "RightSock $\xrightarrow{\textit{RightSockOn}}$ RightShoe
4. A set of open preconditions
   - Planners work to reduce the set of open preconditions to the empty set w/o introducing contradictions

Consistent Plan (POP)

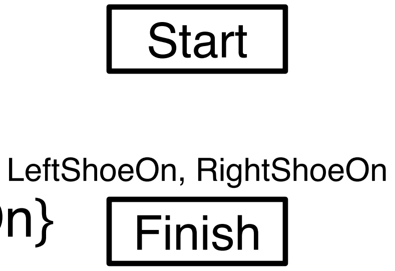
- Consistent plan is a plan that has
  - No cycle in the ordering constraints
  - No conflicts with the causal links
- Solution
  - Is a consistent plan with no open preconditions
- To solve a conflict between a causal link $A \xrightarrow{p} B$ and an action C (that clobbers, threatens the causal link), we force C to occur outside the "protection interval" by adding
  - the constraint C ⍰⍰A (demoting C) or
  - the constraint B ⍰⍰C (promoting C)

Setting up the PoP

- Add dummy states
  - Start
    - Has no preconditions
    - Its effects are the literals of the initial state
  - Finish
    - Its preconditions are the literals of the goal state
    - Has no effects


Start
Literal_a, Literal_b, …
Literal_1, Literal_2, …
Finish

- Initial Plan:
  - Actions: {Start, Finish}
  - Ordering constraints: {Start $\boxed{?}\boxed{?}$Finish}
  - Causal links: {}
  - Open Preconditions: {LeftShoeOn,RightShoeOn}

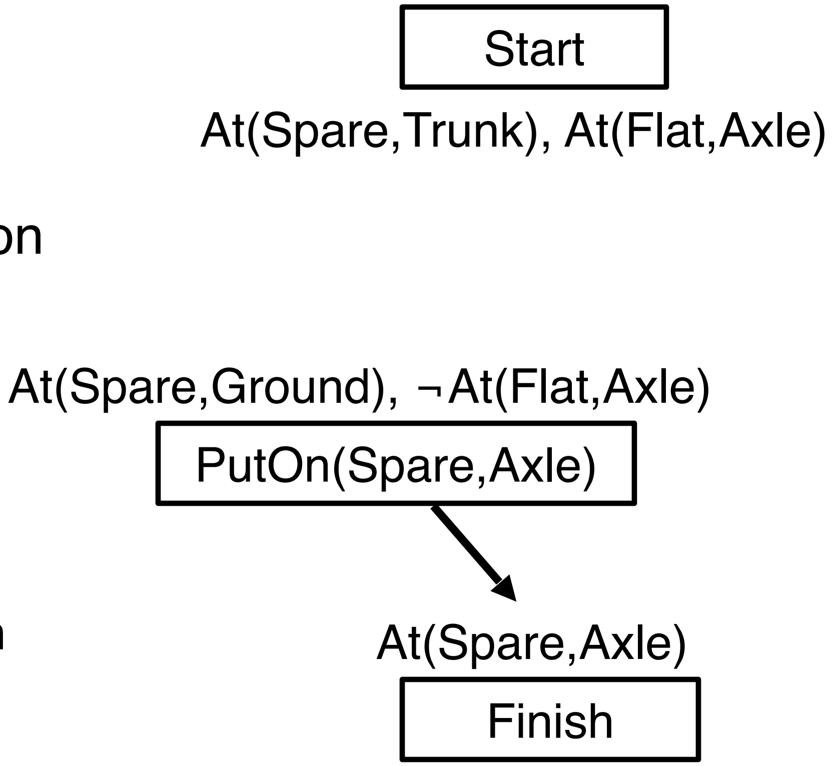


POP as a Search Problem

- The successor function arbitrarily picks one open precondition *p* on an action B
- For every possible consistent action A that achieves *p*
  - It generates a successor plan adding the causal link $A \xrightarrow{p} B$ and the ordering constraint A $\boxed{?}\boxed{?}$B
  - If A was not in the plan, it adds Start $\boxed{?}\boxed{?}$A and A $\boxed{?}\boxed{?}$Finish
  - It resolves all conflicts between
    - the new causal link and all existing actions
    - between A and all existing causal links
  - Then it adds the successor states for combination of resolved conflicts
- It repeats until no open precondition exists

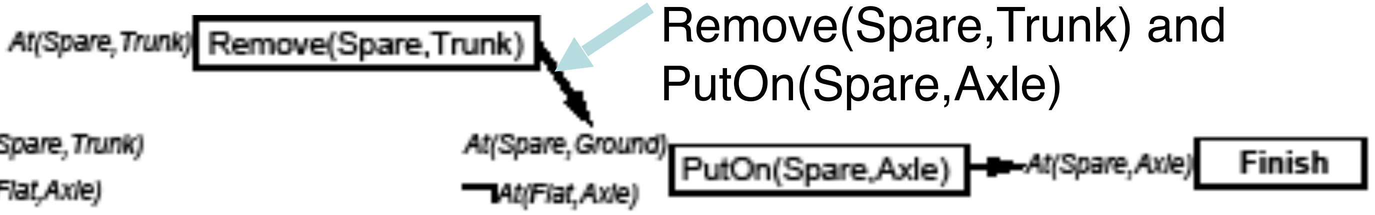
Example of POP: Flat tire problem

- See problem description in Fig 11.7 page 391


Start
At(Spare,Trunk), At(Flat,Axle)
At(Spare,Ground), ¬At(Flat,Axle)
PutOn(Spare,Axle)
At(Spare,Axle)
Finish

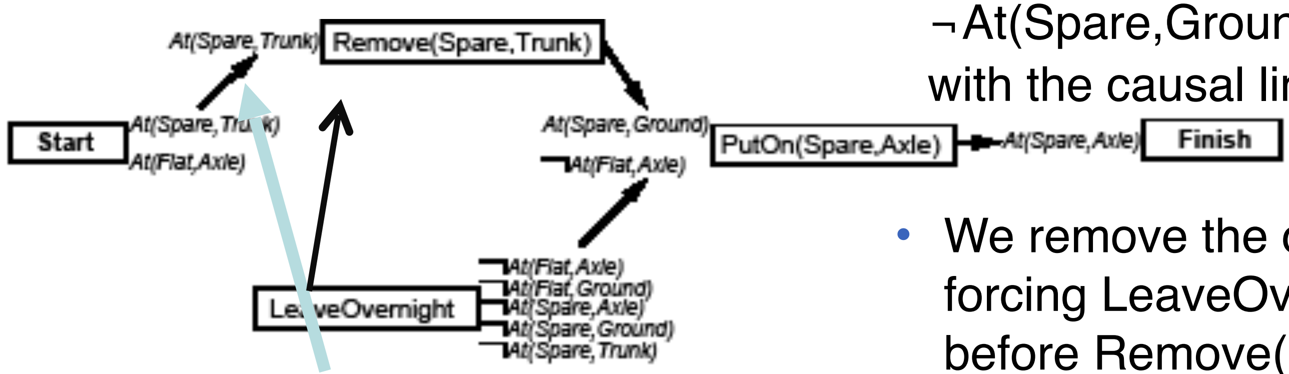
- Only one open precondition
- Only 1 applicable action

- Pick up At(Spare,Ground)
- Choose only applicable action Remove(Spare,Trunk)



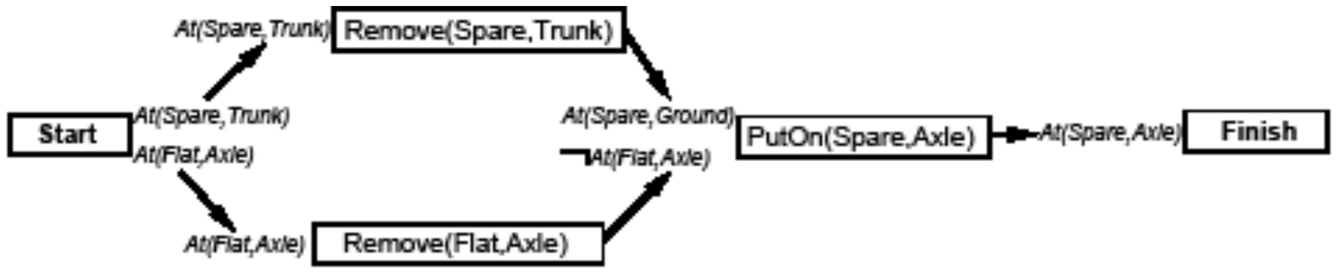
Add causal link between Remove(Spare,Trunk) and PutOn(Spare,Axle)

- Pick up ¬At(Flat,Axle)
- There are 2 applicable actions: LeaveOvernight and Remove(Flat,Axle)
- Choose LeaveOvernight



- LeaveOvernight has effect ¬At(Spare,Ground), which conflicts with the causal link
- We remove the conflict by forcing LeaveOvernight to occur before Remove(Spare,Trunk)

- Conflicts with effects of Remove(Spare,Trunk)
- The only way to resolve the conflict is to undo LeaveOvernightuse the action Remove(Flat,Axle)



- This time, we choose Remove(Flat,Axle)
- Pick up At(Spare,Trunk) and choose Start to achieve it
- Pick up At(Flat,Axle) and choose Start to achieve it.
- We now have a complete consistent partially ordered plan

POP Algorithm (1)

- Backtrack when fails to resolve a threat or find an operator
- Causal links
  - Recognize when to abandon a doomed plan without wasting time expanding irrelevant part of the plan
  - allow early pruning of inconsistent combination of actions
- When actions include variables, we need to find appropriate substitutions
  - Typically we try to delay commitments to instantiating a variable until we have no other choice (least commitment)
- POP is sound, complete, and systematic (no repetition)

POP Algorithm (2)

- Decomposes the problem (advantage)
- But does not represent states explicitly: it is hard to design heuristic to estimate distance from goal
  - Example: Number of open preconditions – those that match the effects of the start node. Not perfect (same problems as before)
- A heuristic can be used to choose which plan to refine (which precondition to pick-up):
  - Choose the most-constrained precondition, the one satisfied by the least number of actions. Like in CSPs!
  - When no action satisfies a precondition, backtrack!
  - When only one action satisfies a precondition, pick up the precondiction.

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  - SAT Planners

Planning Graph

- Is special data structure used for
  1. Deriving better heuristic estimates
  2. Extract a solution to the planning problem: GRAPHPLAN algorithm
- Is a sequence $\langle S_0, A_0, S_1, A_1, \ldots, S_i \rangle$ of levels
  - Alternating state levels & action levels
  - Levels correspond to time stamps
  - Starting at initial state
  - State level is a set of (propositional) literals
    - All those literals that could be true at that level
  - Action level is a set of (propositionalized) actions
    - All those actions whose preconditions appear in the state level (ignoring all negative interactions, etc.)
- Propositionalization may yield combinatorial explosition in the presence of a large number of objects

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Focus

- Building the Planning Graph
- Using it for Heuristic Estimation
- Using it for generating the plan

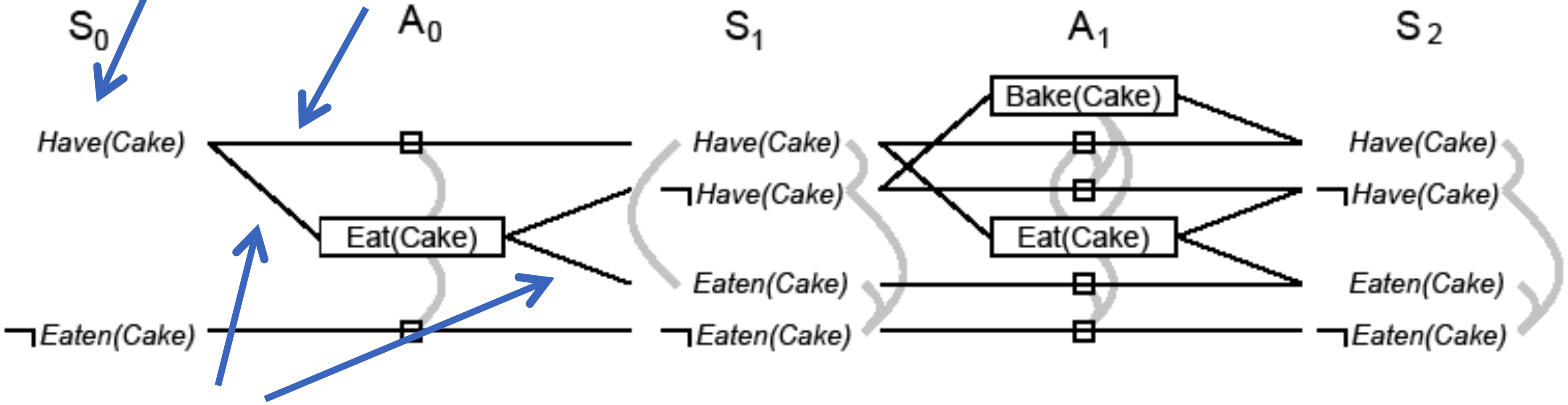
Example of a Planning Graph (1)

Init(Have(Cake))
Goal(Have(Cake)∧Eaten(Cake))

Action(Eat(Cake)
  Precond: Have(Cake)
  Effect: ¬Have(Cake)∧Eaten(Cake))
  Action(Bake(Cake)
  Precond: ¬Have(Cake)
  Effect: Have(Cake))

Propositions true at the initial state

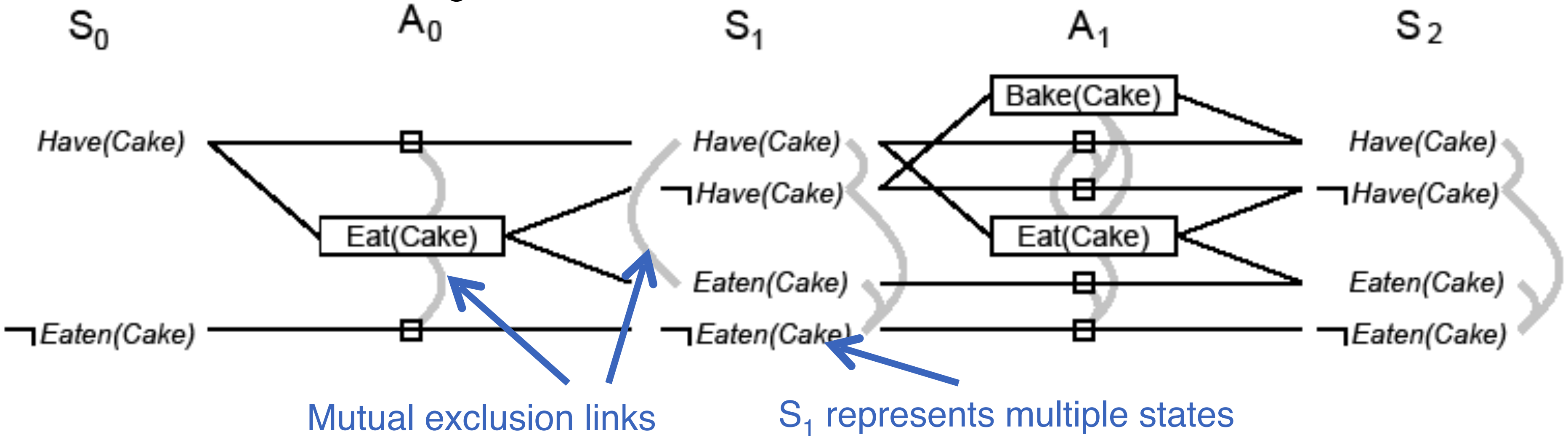
Persistence Actions (noop)



Action is connected to its preconds & effects

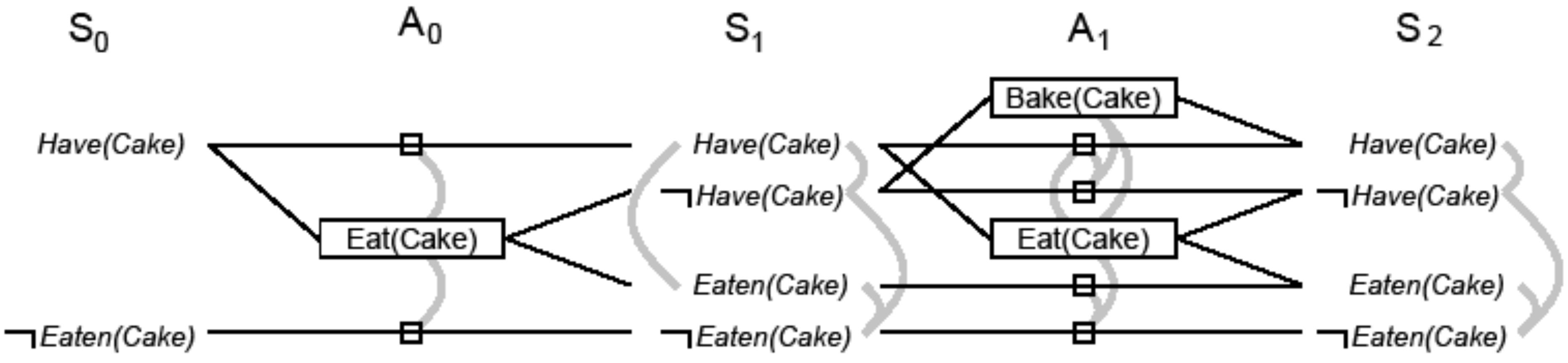
Example of a Planning Graph (2)

- At each state level, list all literals that may hold at that level
- At each action level, list all noops & all actions whose preconditions may hold at previous levels
- Repeat until plan 'levels off,' no new literals appears ($S_i=S_{i+1}$)
- Building the Planning Graph is a polynomial process
- Add (binary) mutual exclusion (mutex) links between conflicting actions and between conflicting literals



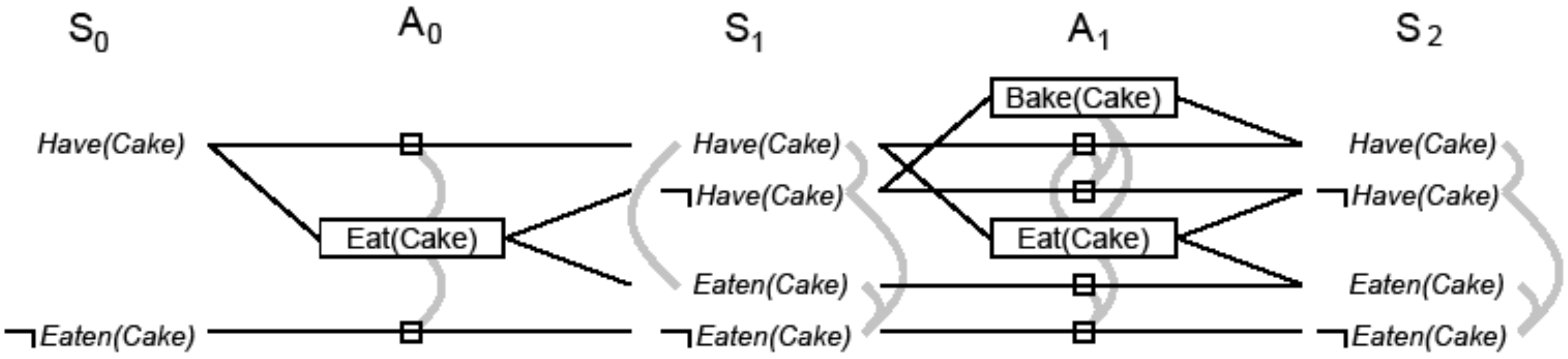
Mutex Links between Actions

1. **Inconsistent effects**: one action negates an effect of another
   - Eat(Cake) & noop of Have(Cake) disagree on effect Have(Cake)
2. **Interference**: An action effect negates the precondition of another
   - Eat(Cake) negates precondition of the noop of Have(Cake):
3. **Competing needs**: A precondition on an action is mutex with the precondition of another
   - Bake(Cake) & Eat(Cake): compete on Have(Cake) precondition



Mutex Links between Literals

1. Two literals are negation of each other
2. **Inconsistent support**: Each pair of actions that can achieve the two literals is mutex. Examples:
   - In S1, Have(Cake) & Eaten(Cake) are mutex
   - In S2, they are not because Bake(Cake) & the noop of Eaten(Cake) are not mutex



Focus

- Building the Planning Graph
- **Using it for Heuristic Estimation**
  - Planning graph as a relaxation of original problem
  - Easy to build (compute)
- Using it for generating the plan

Planning Graph for Heuristic Estimation

- A literal that does not appear in the final level cannot be achieved by any plan
  - State-space search: Any state containing an unachievable literal has cost h(n)=∝
  - POP: Any plan with an unachievable open condition has cost h(n)=∝
- The estimate cost of any goal literal is the first level at which it appears
  - Estimate is admissible for individual literals
  - Estimate can be improved by serializing the graph (serial planning graph: one action per level) by adding mutex between all actions in a given level
- The estimate of a conjunction of goal literals
  - Three heuristics: max level, level sum, set level

Estimate of Conjunction of Goal Literals

- Max-level
  - The largest level of a literal in the conjunction
  - Admissible, not very accurate
- Level sum
  - Under subgoal independence assumption, sums the level costs of the literals
  - Inadmissible, works well for largely decomposable problems
- Set level
  - Finds the level at which all literals appear w/o any pair of them being mutex
  - Dominates max-level, works extremely well on problems where there is a great deal of interaction among subplans

Focus

- Building the Planning Graph
- Using it for Heuristic Estimation
- **Using it for generating the plan**
  - GraphPlan algorithm [Blum & Furst, 95]

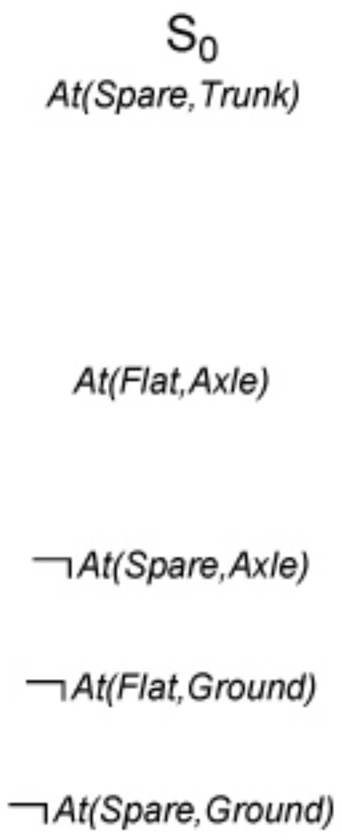
GRAPHPLAN algorithm

```
GRAPHPLAN(problem) returns solution or failure
graph ← INITIALPLANNINGGRAPH(problem)
goals ← GOALS[problem]
loop do
    if goals all non-mutex in last level of graph then do
        solution ← EXTRACTSOLUTION(graph,goals,LENGTH(graph))
        if solution ≠ failure then return solution
        else if  NOSOLUTIONPOSSIBLE(graph) then return failure
    graph ← EXPANDGRAPH (graph,problem)
```

- Two main stages
  1. Extract solution
  2. Expand the graph

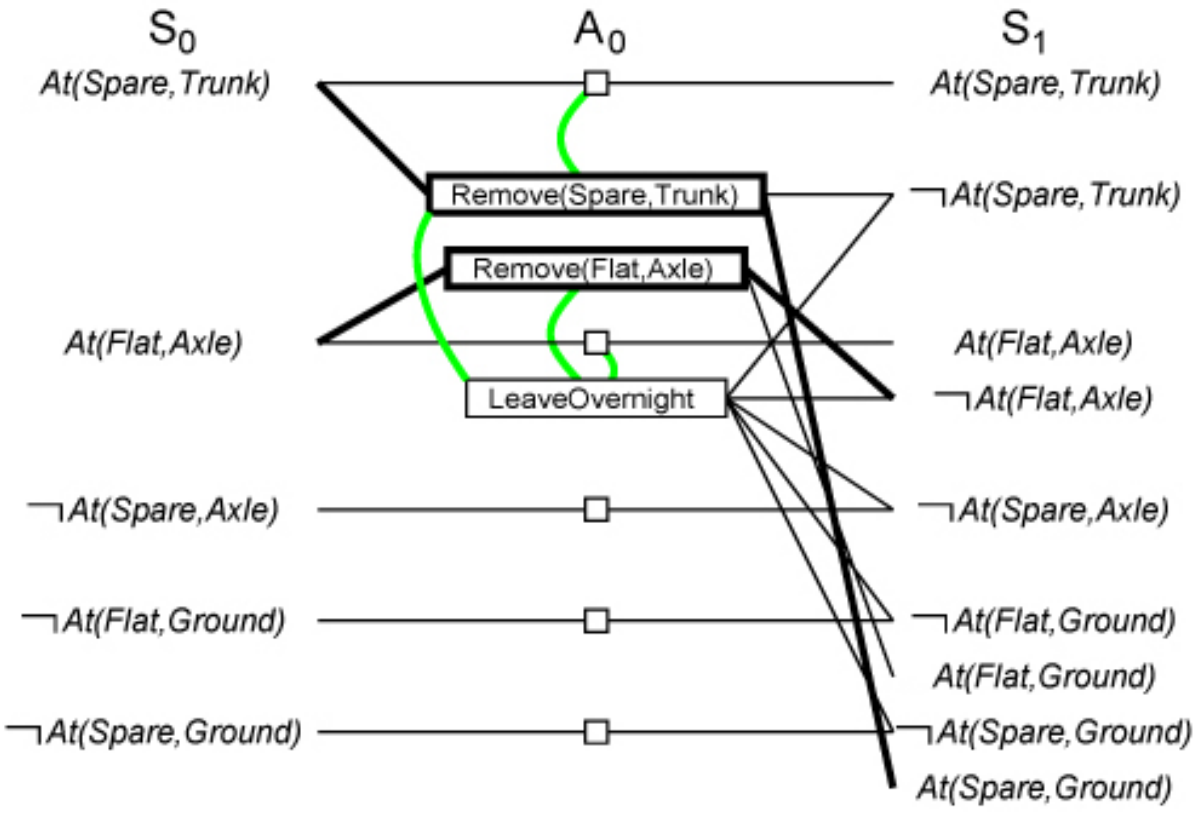
Example of GRAPHPLAN Execution (1)

- At(Spare,Axle) is not in S_0
- No need to extract solution
- Expand the plan



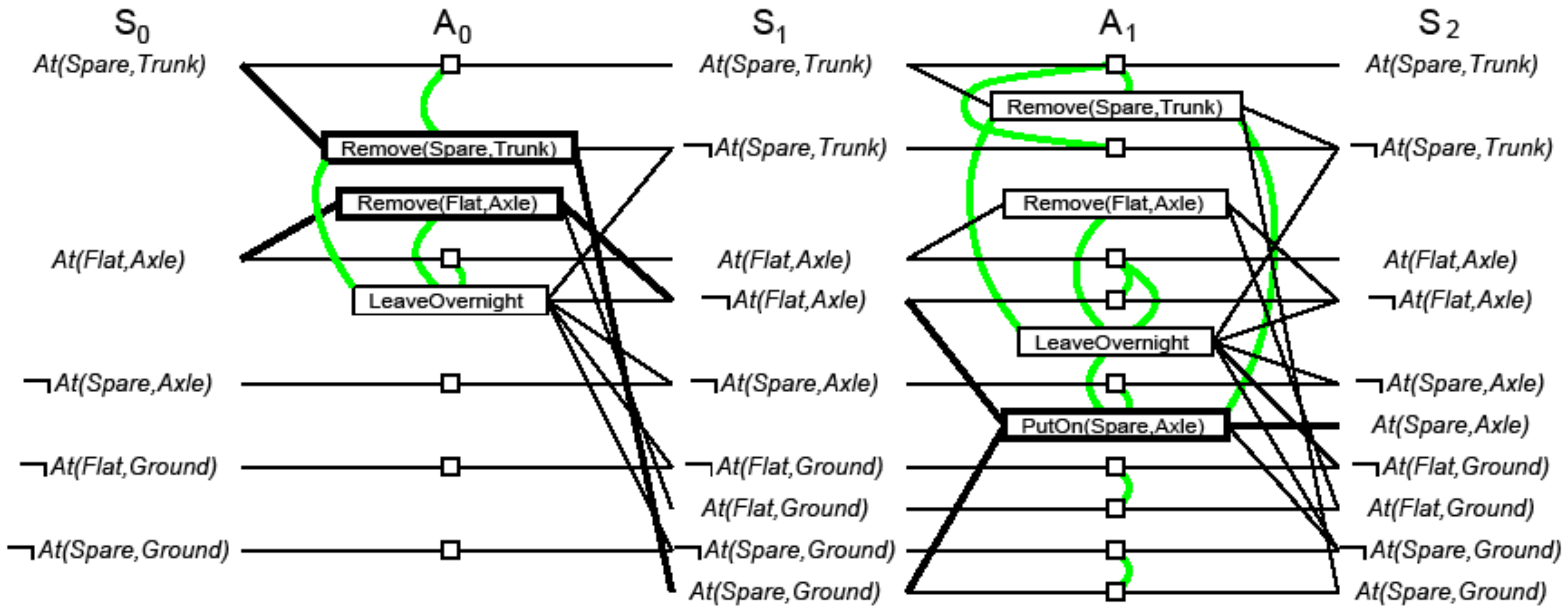
Example of GRAPHPLAN Execution (2)

- Three actions are applicable
- 3 actions and 5 noops are added
- Mutex links are added
- At(Spare,Axle) still not in S_1
- Plan is expanded



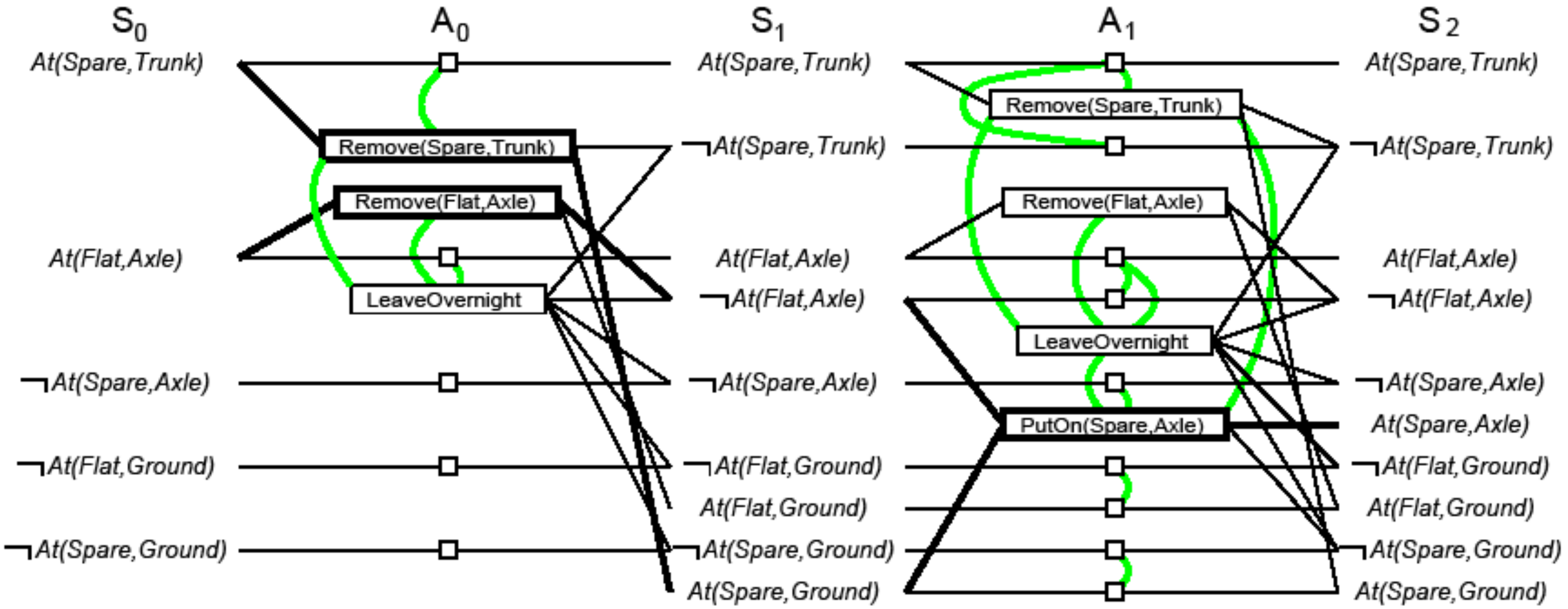
Example of GRAPHPLAN Execution (3)

- Illustrates well mutex links: inconsistent effects, interference, competing needs, inconsistent support



Solution Extraction (Backward)

1. Solve a Boolean CSP: Variables are actions, domains are {0=out of plan, 1=in plan), constraints are mutex
2. Search problem from last level backward



Backtrack Search for Solution Extraction

- Starting at the highest fact level
  - Each goal is put in a goal list for the current fact layer
  - Search iterates thru each fact in the goal list trying to find an action to support it which is not mutex with any other chosen action
  - When an action is chosen, its preconditions are added to the goal list of the lower level
  - When all facts in the goal list of the current level have a consistent assignment of actions, the search moves to the next level
- Search backtracks to the previous level when it fails to assign an action to each fact in the goal list at a given level
- Search succeeds when the first level is reached.

Termination of GRAPHPLAN

- GRAPHPLAN is guaranteed to terminate
  - Literal increase monotonically
  - Actions increase monotonically
  - Mutexes decrease monotinically
- A solution is guaranteed not to exist when
  - The graph levels off with all goals present & non-mutex, and
  - EXTRACTSOLUTION fails to find solution

Optimality of GRAPHPLAN

- The plans generated by GRAPHPLAN
  - Are optimal in the number of steps needed to execute the plan
  - Not necessarily optimal in the number of actions in the plan (GRAPHPLAN produces partially ordered plans)

Outline

- Background
  - Situation Calculus
  - Frame, qualification, & ramification problems
- Representation language
- Planning Algorithms
  - State-Space Search
  - Partial-Order Planning (POP)
  - Planning Graphs (GRAPHPLAN)
  - SAT Planners