Planning 1

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Original slides can be found at http://aima.cs.berkeley.edu

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Planning

- The Planning problem
- Planning with State-space search
- Partial-order planning
- Planning graphs
- Planning with propositional logic
- Analysis of planning approaches

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.

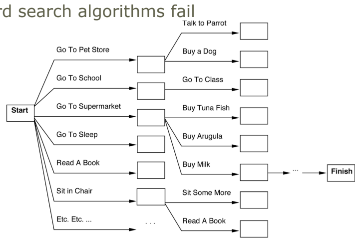
Classical planning environment: fully observable, deterministic, finite, static and discrete.

Assists humans in practical applications
- design and manufacturing
- military operations
- games
- space exploration

Why not standard search?

Consider the task get milk, bananas and a cordless drill

Standard search algorithms fail



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 PDDL

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 ∧ Unknown*
  - FO-literals (grounded and function-free): *At(Plane1, Copenhagen) ∧ At(Plane2, Oslo)*
- 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) ∧ At(P2,SFO) ∧ Plane(P1) ∧ Plane(P2) ∧ Airport(JFK) ∧ Airport(SFO)

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

  With θ *={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 ¬*P* is removed from *s'*

  EFFECT: ¬AT(p,from) ∧ At(p,to):

  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

Expressiveness extension: Planning Domain Description language (PDDL)

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

Standardization *: now (since 2008) in its 3.1 version*

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) ∧ ¬At(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 (PDDL description)

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))

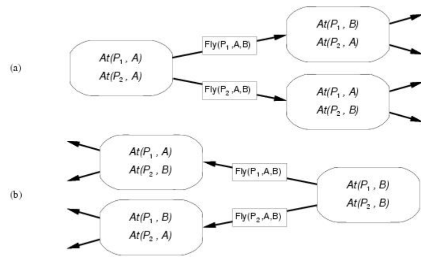
Goal(On(A,B) ∧ On(B,C))

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))*

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.
  - E.g. A*
- 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) ∧ At(C2, B) ∧ … ∧ At(C20, B)*
    - Relevant action for first conjunct: *Unload(C1,p,B)*
    - Works only if pre-conditions are satisfied.
    - Previous state= *In(C1, p) ∧ At(p, B) ∧ At(C2, B) ∧ … ∧ 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 are 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 is 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

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 ∧ LeftShoeOn)

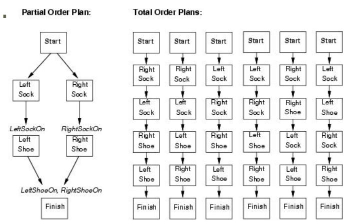
Init()

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(POP)

Any planning algorithm that can place two actions into a plan without which comes first is a PO plan.



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 (A before 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.

Example of final plan

Actions={Rightsock, Rightshoe, Leftsock, Leftshoe, Start, Finish}

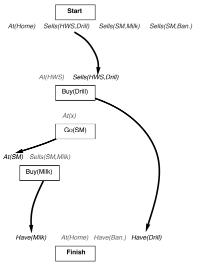
Orderings={Rightsock < Rightshoe; Leftsock < Leftshoe}

Links={Rightsock->Rightsockon -> Rightshoe, Leftsock->Leftsockon-> Leftshoe, Rightshoe->Rightshoeon->Finish, …}

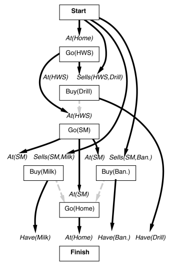
Open preconditions={}

Shopping list example

Shopping list example



Shopping list example



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

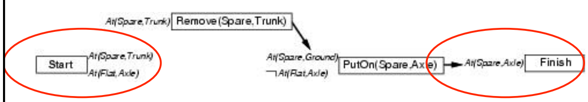
Gradually move from incomplete/vague plans to complete/correct plans

Backtrack if an open condition is unachievable or if a conflict is irresolvable.

Example: Spare tire problem

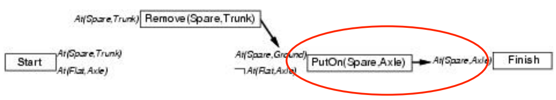
Init(At(Flat, Axle) ∧ At(Spare,trunk))
Goal(At(Spare,Axle))
Action(Remove(Spare,Trunk)
PRECOND: *At(Spare,Trunk)*
EFFECT: *¬At(Spare,Trunk) ∧ At(Spare,Ground))*
Action(Remove(Flat,Axle)
PRECOND: *At(Flat,Axle)*
EFFECT: *¬At(Flat,Axle) ∧ At(Flat,Ground))*
Action(PutOn(Spare,Axle)
PRECOND: *At(Spare,Groundp)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

Solving the problem



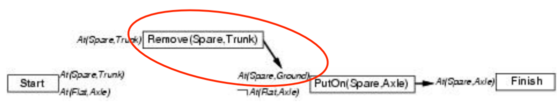
Initial plan: Start with EFFECTS and Finish with PRECOND.

Solving the problem



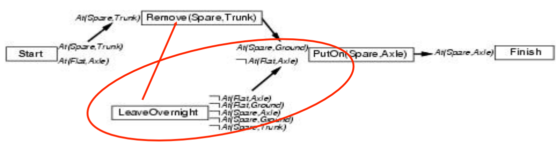
Initial plan: Start with EFFECTS and Finish with PRECOND.
Pick an open precondition: *At(Spare, Axle)*
Only *PutOn(Spare, Axle)* is applicable
Add causal link: $PutOn(Spare,Axle) \xrightarrow{At(Spare,Axle)} Finish$
Add constraint : *PutOn(Spare, Axle) < Finish*

Solving the problem



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

Solving the problem

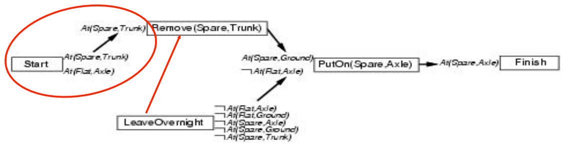


Pick an open precondition: *¬At(Flat, Axle)*
LeaveOverNight is applicable
conflict: *LeaveOverNight* also has the effect ¬ *At(Spare,Ground)*

$$Remove(Spare,Trunk) \xrightarrow{At(Spare,Ground)} PutOn(Spare,Axle)$$

To resolve, add constraint : *LeaveOverNight < Remove(Spare, Trunk)*

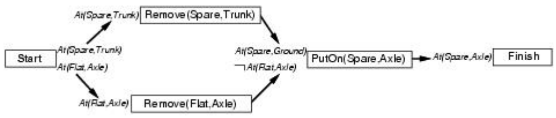
Solving the problem



Pick an open precondition: *At(Spare, 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 constraint.

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 be 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

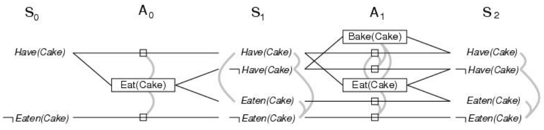
"Could"?
- Records only a restricted subset of possible negative interactions among actions.

They work only for propositional problems.

Example:

Init(Have(Cake))
Goal(Have(Cake) ∧ Eaten(Cake))
Action(Eat(Cake), PRECOND: Have(Cake)
EFFECT: ¬Have(Cake) ∧ Eaten(Cake))
Action(Bake(Cake), PRECOND: ¬ Have(Cake)
EFFECT: Have(Cake))

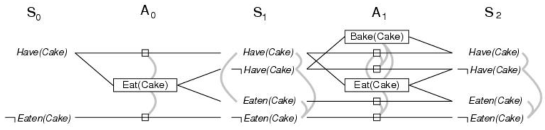
Cake example



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 precond 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

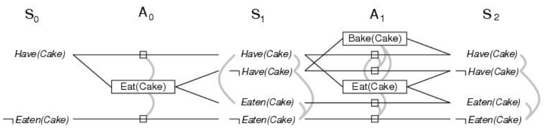
Cake example



Level S1 contains all literals that could result from picking any subset of actions in A0
- Conflicts between literals that can not occur together (as a consequence of the selection action) 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

Cake example



A mutex relation holds between **two actions** when:
- *Inconsistent effects*: one action negates the effect of another.
- *Interference*: one of the effects of one action is the negation of a precondition of the other.
- *Competing needs*: one of the preconditions of one action is mutually exclusive with the precondition of the other.

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.

PG 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).
- Cost of a conjunction of goals? 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

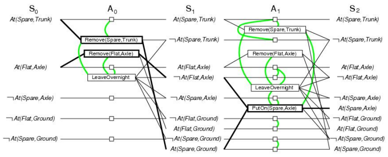
function GRAPHPLAN(*problem*) **return** *solution* or failure
  graph ← INITIAL-PLANNING-GRAPH(*problem*)
  goals ← GOALS[*problem*]
  loop do
    if *goals* all non-mutex in last level of graph **then do**
      solution ← EXTRACT-SOLUTION(*graph, goals,* LENGTH(*graph*))
      if *solution* ≠ failure **then return** *solution*
      else if NO-SOLUTION-POSSIBLE(*graph*) **then return** failure
    graph ← EXPAND-GRAPH(*graph, problem*)

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) ∧ ¬At(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)

GRAPHPLAN example



Initially the plan consist of 5 literals from the initial state and the CWA literals (S0).

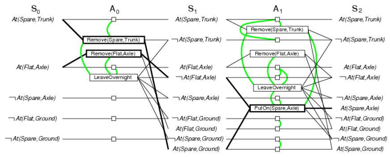
Add actions whose preconditions are satisfied by EXPAND-GRAPH (A0)

Also add persistence actions and mutex relations.

Add the effects at level S1

Repeat until goal is in level Si

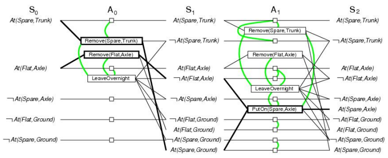
GRAPHPLAN example



EXPAND-GRAPH also looks for mutex relations

- Inconsistent effects
  - E.g. Remove(Spare, Trunk) and LeaveOverNight due to At(Spare,Ground) and **not** At(Spare, Ground)
- Interference
  - E.g. Remove(Flat, Axle) and LeaveOverNight At(Flat, Axle) as PRECOND and **not** At(Flat,Axle) as EFFECT
- Competing needs
  - E.g. PutOn(Spare,Axle) and Remove(Flat, Axle) due to At(Flat.Axle) and **not** At(Flat, Axle)
- Inconsistent support
  - E.g. in S2, At(Spare,Axle) and At(Flat,Axle)

GRAPHPLAN example



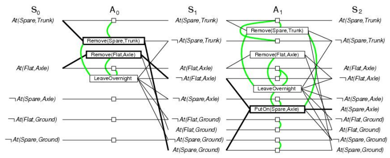
In S2, the goal literals exist and are not mutex with any other

- 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 and literals, every PG will eventually level off !

Planning with propositional logic

Planning can be done by proving theorem in situation calculus.

Here: test the *satisfiability* of a logical sentence:

$$\textit{initial state} \wedge \textit{all possible action descriptions} \wedge \textit{goal}$$

Sentence contains propositions for every action occurrence.

- A model will assign true to the actions that are part of the correct plan and false to the others
- An assignment that corresponds to an incorrect plan will not be a model because of inconsistency with the assertion that the goal is true.
- If the planning is unsolvable the sentence will be unsatisfiable.

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

Planning vs. scheduling

Classical planning:

What to do? In what order?

But not:

How long? When? Using what resources?

Normally:

Plan first, schedule later.

Representation

Job-shop scheduling problem:

- A set of jobs
- Each job is a collection of ACTIONS with some ORDERING CONSTRAINTS
- Each action has a DURATION and a set of RESOURCE CONSTRAINTS

resources may be CONSUMABLE or REUSABLE

Solution:

Start times for all actions, obeying all constraints