Artificial Intelligence 1: Planning

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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

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) ∧ 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

Recent extension:Action Description language (ADL)

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

  PRECOND: At(p,from) ∧ (from ≠ to)

  EFFECT: ¬At(p,from) ∧ 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) ∧ ¬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)

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))*

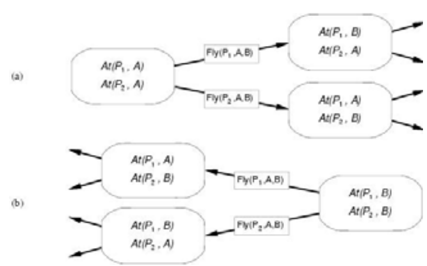
Spurious actions are possible: Move(B,C,C)

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.
- 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 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

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

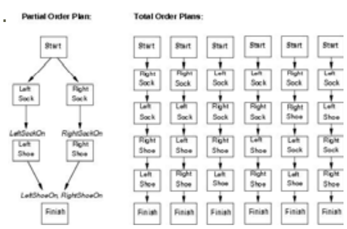
Shoe example

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={}

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

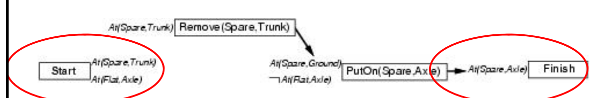
Gradually move from incomplete/vague plans to complete/correct plans

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

Example: Spare tire problem

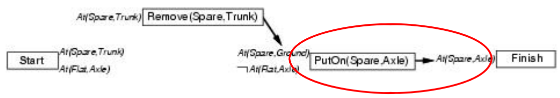
Init(At(Flat, Axle) ∧ At(Spare,trunk))
Goal(At(Spare,Axle))
Action(Remove(Spare,Trunk)
  PRECOND: *At(Spare,Trunk)*
  EFFECT: *¬At(Spare,Trunk) ∧ At(Spare,Ground))*
Action(Remove(Flat,Axle)
  PRECOND: *At(Flat,Axle)*
  EFFECT: *¬At(Flat,Axle) ∧ At(Flat,Ground))*
Action(PutOn(Spare,Axle)
  PRECOND: *At(Spare,Groundp)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

Solving the problem



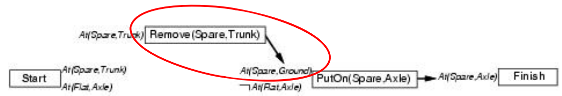
Initial plan: Start with EFFECTS and Finish with PRECOND.

Solving the problem



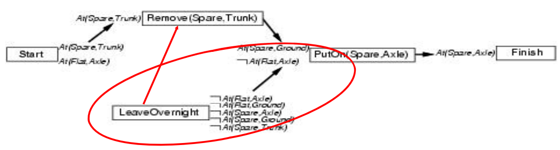
Initial plan: Start with EFFECTS and Finish with PRECOND.
Pick an open precondition: *At(Spare, Axle)*
Only *PutOn(Spare, Axle)* is applicable
Add causal link: $PutOn(Spare,Axle) \xrightarrow{At(Spare,Axle)} Finish$
Add constraint : *PutOn(Spare, Axle) < Finish*

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

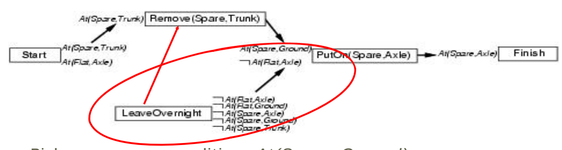


Pick an open precondition: *¬At(Flat, Axle)*
LeaveOverNight is applicable
conflict: *LeaveOverNight* also has the effect *¬ At(Spare,Ground)*

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

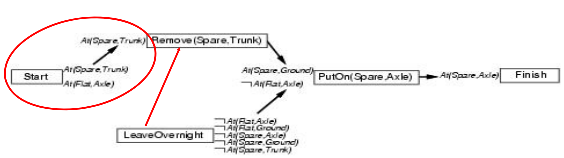
To resolve, add constraint : *LeaveOverNight < Remove(Spare, Trunk)*

Solving the problem



Pick an open precondition: *At(Spare, 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

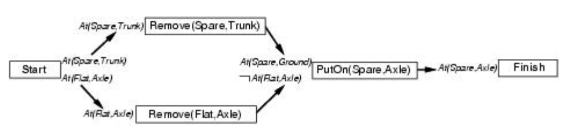


Pick an open precondition: *At(Spare, Trunk)*
Only *Start* is applicable
Add causal link: $Start \xrightarrow{At(Spare,Trunk)} Remove(Spare,Trunk)$
Conflict: of causal link with effect *At(Spare,Trunk)* in *LeaveOverNight*

- *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 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 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"?

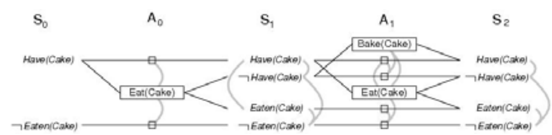
- Records only a restricted subset of possible negative interactions among actions.

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



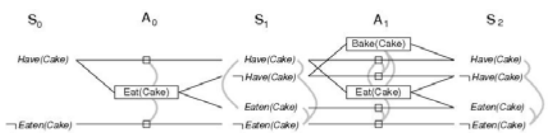
Start at level S0 and determine action level A0 and next level S1.

- 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



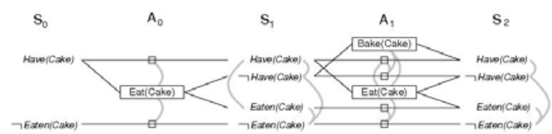
Level S1 contains all literals that could result from picking any subset of actions in A0

- 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 (explanation follows later)

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

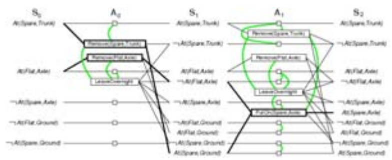
function GRAPHPLAN(*problem*) **return** *solution* or failure
    graph ← INITIAL-PLANNING-GRAPH(*problem*)
    goals ← GOALS[*problem*]
    loop do
        if *goals* all non-mutex in last level of graph **then do**
            solution ← EXTRACT-SOLUTION(*graph, goals,* LENGTH(*graph*))
            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).

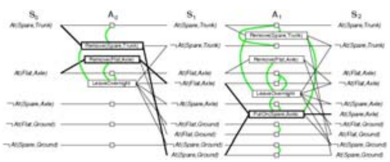
Add actions whose preconditions are satisfied by EXPAND-GRAPH (A0)

Also add persistence actions and mutex relations.

Add the effects at level S1

Repeat until goal is in level Si

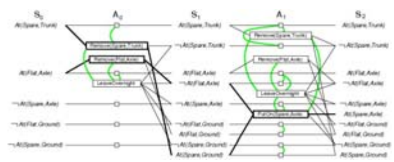
GRAPHPLAN example



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



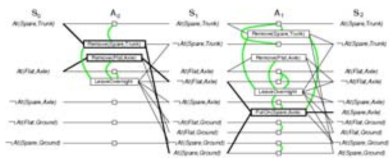
In S2, the goal literals exist and are not mutex with any other

- 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.

SATPLAN algorithm

function SATPLAN(*problem*, T_{max}) **return** *solution* or failure
  inputs: *problem*, a planning problem
    T_{max}, an upper limit to the plan length
  for $T = 0$ **to** T_{max} **do**
    cnf, *mapping* ← TRANSLATE-TO_SAT(*problem*, *T*)
    assignment ← SAT-SOLVER(*cnf*)
    if *assignment* is not null **then**
      return EXTRACT-SOLUTION(*assignment*, *mapping*)
  return failure

cnf, *mapping* ← TRANSLATE-TO_SAT(*problem*, *T*)

Distinct propositions for assertions about each time step.

- Superscripts denote the time step
  - $At(P1,SFO)^0 \wedge At(P2,JFK)^0$
- No CWA thus specify which propositions are not true
  - $\neg At(P1,SFO)^0 \wedge \neg At(P2,JFK)^0$
- Unknown propositions are left unspecified.

The goal is associated with a particular time-step

- But which one?

cnf, *mapping* ← TRANSLATE-TO_SAT(*problem*, *T*)

How to determine the time step where the goal will be reached?

- Start at $T=0$
  - Assert $At(P1,SFO)^0 \wedge At(P2,JFK)^0$
- Failure .. Try $T=1$
  - Assert $At(P1,SFO)^1 \wedge At(P2,JFK)^1$
- …
- Repeat this until some minimal path length is reached.
- Termination is ensured by T_{max}

cnf, mapping ← TRANSLATE-TO_SAT(*problem, T*)

How to encode actions into PL?

- Propositional versions of successor-state axioms

  $At(P1,JFK)^1 \Leftrightarrow$
  $(At(P1,JFK)^0 \wedge \neg(Fly(P1,JFK,SFO)^0 \wedge At(P1,JFK)^0)) \vee$
  $(Fly(P1,SFO,JFK)^0 \wedge At(P1,SFO)^0)$
- Such an axiom is required for each plane, airport and time step
- If more airports add another way to travel than additional disjuncts are required

Once all these axioms are in place, the satisfiability algorithm can start to find a plan.

assignment ← SAT-SOLVER(*cnf*)

Multiple models can be found

They are NOT satisfactory: (for T=1)

$Fly(P1,SFO,JFK)^0 \wedge Fly(P1,JFK,SFO)^0 \wedge Fly(P2,JFK.SFO)^0$

The second action is infeasible

Yet the plan IS a model of the sentence

$initial\ state \wedge all\ possible\ action\ descriptions \wedge goal^1$

Avoiding illegal actions: pre-condition axioms

$Fly(P1,SFO,JFK)^0 \Rightarrow At(P1,JFK)$

Exactly one model now satisfies all the axioms where the goal is achieved at $T=1$.

assignment ← SAT-SOLVER(*cnf*)

A plane can fly at two destinations at once

They are NOT satisfactory: (for T=1)

$Fly(P1,SFO,JFK)^0 \wedge Fly(P2,JFK,SFO)^0 \wedge Fly(P2,JFK.LAX)^0$

The second action is infeasible

Yet the plan allows spurious relations

Avoid spurious solutions: action-exclusion axioms

$\neg(Fly(P2,JFK,SFO)^0 \wedge Fly(P2,JFK,LAX))$

Prevents simultaneous actions

Lost of flexibility since plan becomes totally ordered : no actions are allowed to occur at the same time.

- Restrict exclusion to preconditions

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