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.
- 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* ∧ *Unknown*
    - FO-literals (grounded and function-free): *At(Plane1, Melbourne)* ∧ *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 $\theta = \{p/P1, from/JFK, to/SFO\}$

    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 ¬*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) ∧ (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) ∧ ¬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) ∧ 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)*

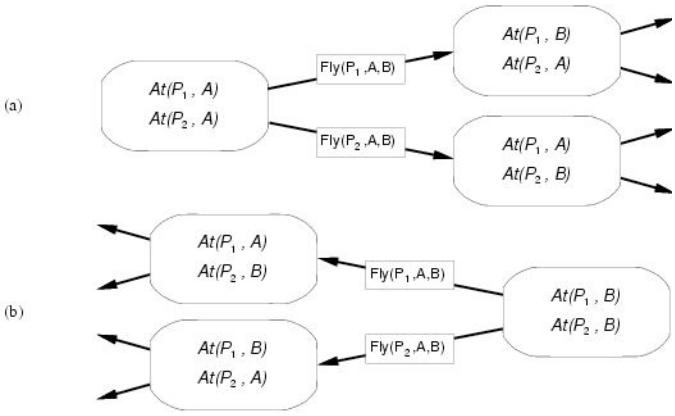
EFFECT: *On(b,Table) ∧ Clear(x) ∧ ¬ On(b,x))*

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.
- 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 assumptio:**

    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**

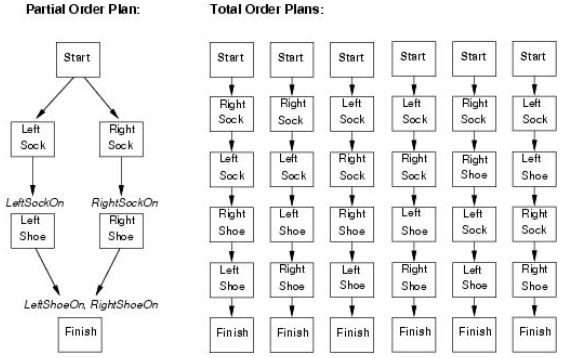
Shoe example

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

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



POL 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.

POL 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 POL

- 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.**

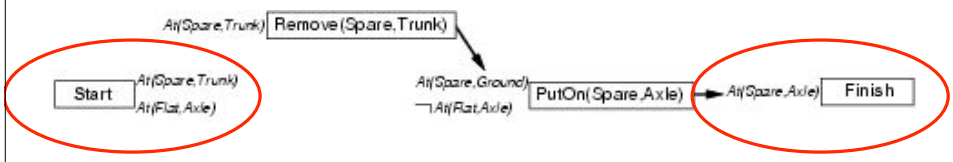
Process summary

- 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

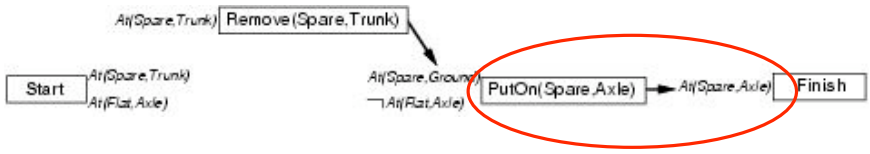
Init(At(Flat, Axle) ∧ At(Spare,trunk))
Goal(At(Spare,Axle))
Action(Remove(Spare,Trunk)
PRECOND: *At(Spare,Trunk)*
EFFECT: *¬At(Spare,Trunk) ∧ At(Spare,Ground))*
Action(Remove(Flat,Axle)
PRECOND: *At(Flat,Axle)*
EFFECT: *¬At(Flat,Axle) ∧ At(Flat,Ground))*
Action(PutOn(Spare,Axle)
PRECOND: *At(Spare,Groundp)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



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

Solving the problem

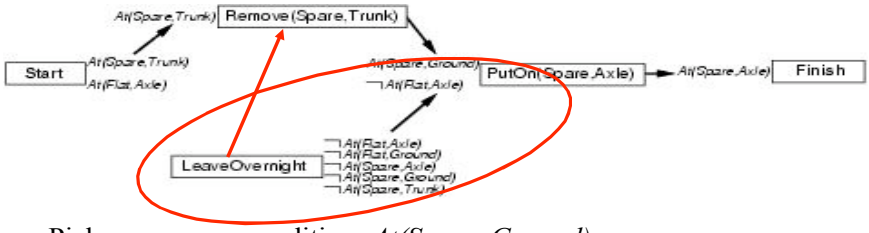


- Intial plan: Start with EFFECTS and Finish with PRECOND.
- Pick an open precondition: *At(Spare, Axle)*
- Only *PutOn(Spare, Axle)* is applicable
- Add causal link: $PutOn(Spare, Axle) \xrightarrow{At(Spare,Axle)} Finish$
- Add constraint : *PutOn(Spare, Axle)* < *Finish*

Solving the problem

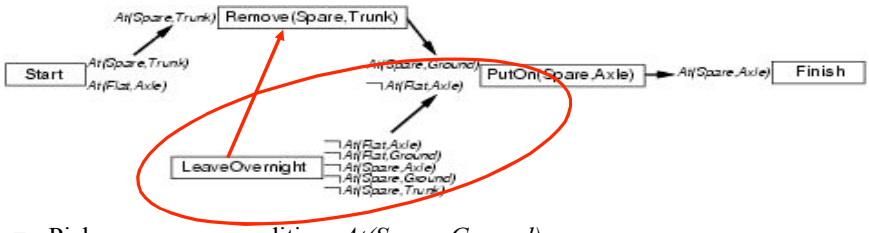
- Pick an open precondition: *At(Spare, Ground)*
- Only *Remove(Spare, Trunk)* is applicable
- Add causal link: $\text{Re}move(Spare,Trunk) \xrightarrow{At(Spare,Ground)} PutOn(Spare,Axle)$
- Add constraint : *Remove(Spare, Trunk) < PutOn(Spare,Axle)*

Solving the problem



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

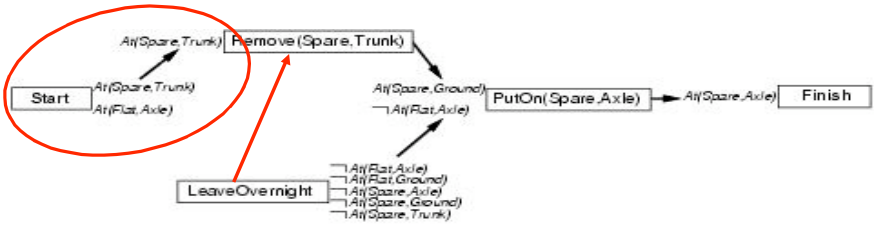
Solving the problem



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

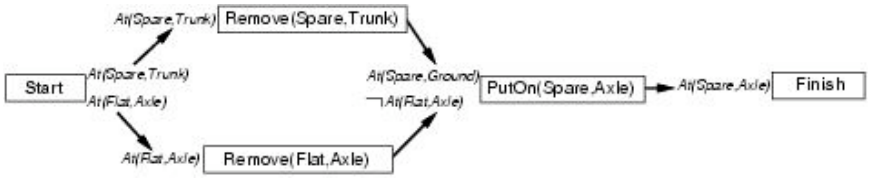
$$LeaveOverNight \xrightarrow{\neg At(Spare,Ground)} PutOn(Spare,Axle)$$

Solving the problem



- Pick an open precondition: *At(Spare, Trunk)*
- Only *Start* is applicable
- Add causal link: $Start \xrightarrow{At(Spare,Trunk)} \mathrm{Re}move(Spare,Trunk)$
- 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.

Planning graphs

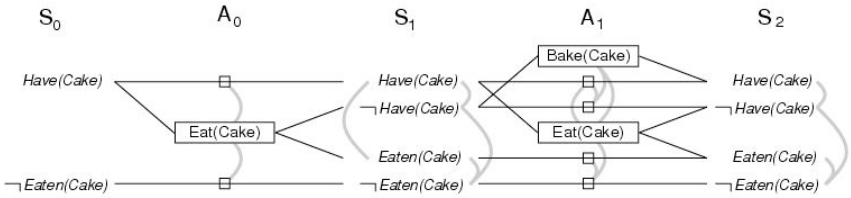
- Used to achieve better heuristic estimates.
  - **A solution can also directly extracted using GRAPHPLAN.**
- Consists of a sequence of levels that correspond to time steps in the plan.
  - **Level 0 is the initial state.**
  - **Each level consists of a set of literals ans a set of actions.**
    - *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:

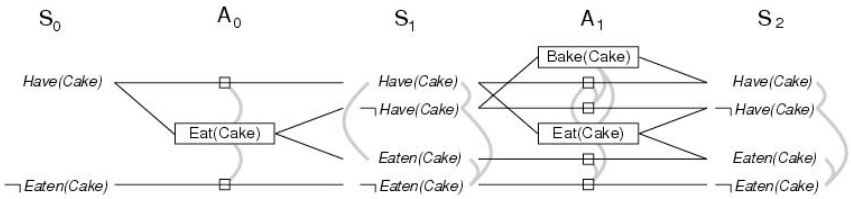
  Init(Have(Cake))
  Goal(Have(Cake) ∧ Eaten(Cake))
  Action(Eat(Cake), PRECOND: Have(Cake)
  EFFECT: ¬Have(Cake) ∧ Eaten(Cake))
  Action(Bake(Cake), PRECOND: ¬ Have(Cake)
  EFFECT: Have(Cake))

Cake example



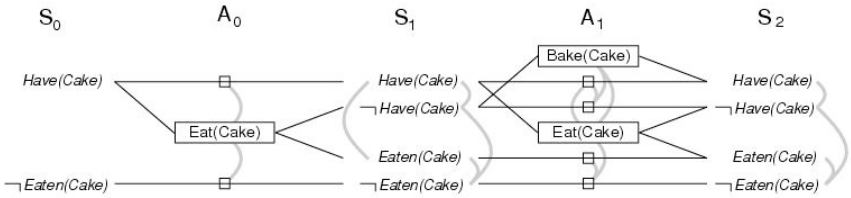
- Start at level S0 and determine action level A0 and next level S1.
  - **A0 >> all actions whose preconditions are satisfied in the previous level.**
  - **Connect precond and effect of actions S0 --> S1**
  - **Inaction is represented by persistence actions.**
- Level A0 contains the actions that 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 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).
  - **Max-level, sum-level ans set-level heuristics.**

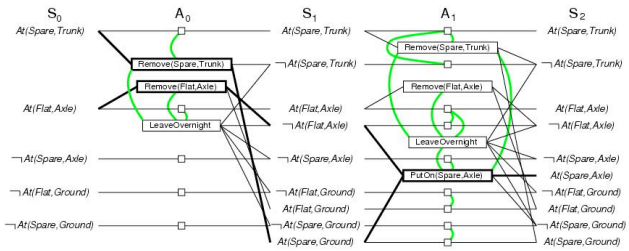
PG is a relaxed problem.

The GRAPHPLAN Algorithm

- How to extract a solution directly from the PG

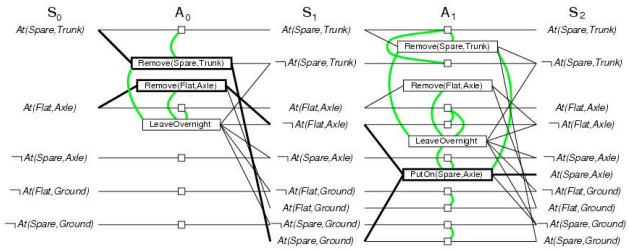
function GRAPHPLAN(*problem*) **return** *solution* or failure
  graph ← INITIAL-PLANNING-GRAPH(*problem*)
  goals ← GOALS[*problem*]
  loop do
    if *goals* all non-mutex in last level of graph **then do**
      solution ← EXTRACT-SOLUTION(*graph, goals,* LENGTH*(graph)*)
      if *solution* ≠ failure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

GRAPHPLAN example



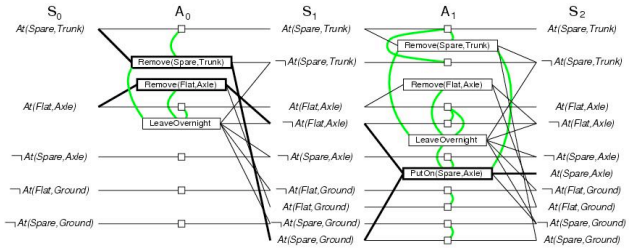
- Initially the plan consist of 5 literals from the initial state and the CWA literals (S0).
- Add actions whose preconditions are satisfied by EXPAND-GRAPH (A0)
- Also add persistence actions and mutex relations.
- Add the effects at level S1
- Repeat until goal is in level Si

GRAPHPLAN example



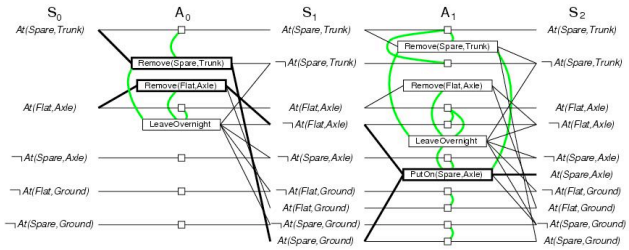
- EXPAND-GRAPH also looks for mutex relations
  - **Inconsistent effects**
    - E.g. Remove(Spare, Trunk) and LeaveOverNight
  - **Interference**
    - E.g. Remove(Flat, Axle) and LeaveOverNight
  - **Competing needs**
    - E.g. PutOn(Spare,Axle) and Remove(Flat, Axle)
  - **Inconsistent support**
    - E.g. in S2, At(Spare,Axle) and At(Flat,Axle)

GRAPHPLAN example



- In S2, the goal literal exists and is 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 anc 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:

  initial state ∧ *all possible action descriptions* ∧ *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**