COS30019: Introduction to Artificial Intelligence

AI Planning

Planning

- The Planning problem
- Planning with State-space search
- Partial-order planning
- 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
  - STanford Research Institute Problem Solver
  - Action Description Language

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) ∧ City(from) ∧ City(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,Melb) ∧ At(P2,Syd) ∧ Plane(P1) ∧ Plane(P2) ∧ City(Melb)) ∧ City(Syd))

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

    With θ ={*p/P1,from/Melb,to/Syd*}

    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,Melb) ∧ At(P2,Syd) ∧ Plane(P1) ∧ Plane(P2) ∧ City(Melb) ∧ City(Syd)
  - 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: City, to: City),

  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, Melb) ∧ At(C2,Syd) ∧ At(P1,Melb) ∧ At(P2,Syd) ∧ Cargo(C1) ∧ Cargo(C2) ∧ Plane(P1) ∧ Plane(P2) ∧ City(Syd) ∧ City(Melb))

Goal(At(C1,Syd) ∧ At(C2,Melb))

Action(Load(c,p,a)

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

EFFECT: *¬At(c,a) ∧In(c,p))*

Action(Unload(c,p,a)

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

EFFECT: *At(c,a) ∧ ¬In(c,p))*

Action(Fly(p,from,to)

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

EFFECT: *¬ At(p,from) ∧ At(p,to))*

[Load(C1,P1,Melb), Fly(P1,Melb,Syd), Load(C2,P2,Syd), Fly(P2,Syd,Melb)]

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: $On(b,x) \land Clear(b) \land Clear(y) \land Block(b) \land (b \neq x) \land (b \neq y) \land (x \neq y)$

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

Action(MoveToTable(b,x)

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

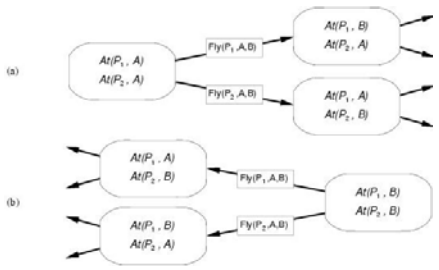
EFFECT: $On(b,Table) \land Clear(x) \land \neg On(b,x))$

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

Planning with state-space search

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

Progression and regression



Progression algorithm

- Formulation as state-space search problem:
  - Initial state = initial state of the planning problem
    - Literals not appearing are false
  - Actions = those whose preconditions are satisfied
    - Add positive effects, delete negative
  - Goal test = does the state satisfy the goal
  - Step cost = each action costs 1
- No functions … any graph search that is complete is a complete planning algorithm.
  - 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 = $At(C1, B) \land At(C2, B) \land \ldots \land At(C20, B)$
    - Relevant action for first conjunct: *Unload(C1,p,B)*
    - Works only if pre-conditions are satisfied.
    - Previous state= $In(C1, p) \land At(p, B) \land At(C2, B) \land \ldots \land At(C20, B)$
    - 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

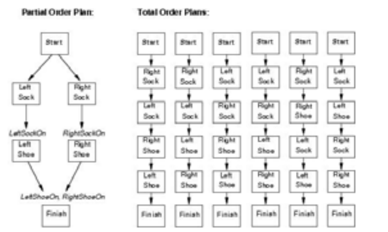
Shoe example

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)*

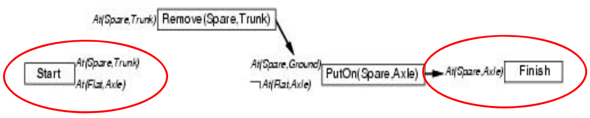
EFFECT: *At(Spare,Axle) ∧ ¬Ar(Spare,Ground))*

Action(LeaveOvernight

PRECOND:

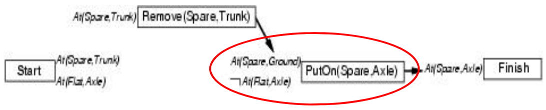
EFFECT: *¬ At(Spare,Ground) ∧ ¬ At(Spare,Axle) ∧ ¬ At(Spare,trunk) ∧ ¬ At(Flat,Ground) ∧ ¬ At(Flat,Axle))*

Solving the problem



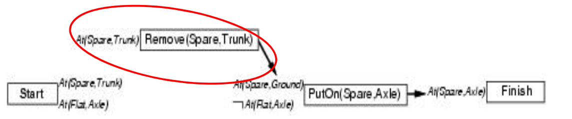
- Initial plan: Start with EFFECTS and Finish with PRECOND.

Solving the problem



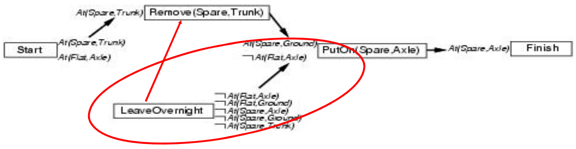
- Initial plan: Start with EFFECTS and Finish with PRECOND.
- Pick an open precondition: *At(Spare, Axle)*
- Only *PutOn(Spare, Axle)* is applicable
- Add causal link: $PutOn(Spare,Axle) \xrightarrow{At(Spare,Axle)} Finish$
- Add constraint : *PutOn(Spare, Axle) < Finish*

Solving the problem



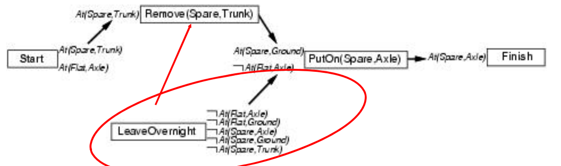
- Pick an open precondition: *At(Spare, Ground)*
- Only *Remove(Spare, Trunk)* is applicable
- Add causal link: $Remove(Spare,Trunk) \xrightarrow{At(Spare,Ground)} PutOn(Spare,Axle)$
- Add constraint : *Remove(Spare, Trunk) < PutOn(Spare,Axle)*

Solving the problem



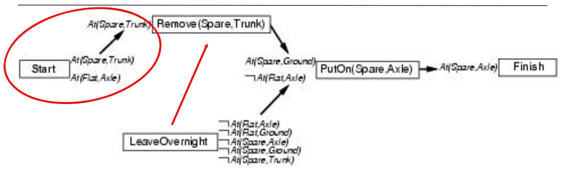
- Pick an open precondition: *¬At(Flat, Axle)*
- *LeaveOverNight* is applicable
- conflict: *LeaveOverNight* also has the effect *¬ At(Spare,Ground)*
- $Remove(Spare,Trunk) \xrightarrow{At(Spare,Ground)} PutOn(Spare,Axle)$
- To resolve, add constraint : *LeaveOverNight < Remove(Spare, Trunk)*

Solving the problem



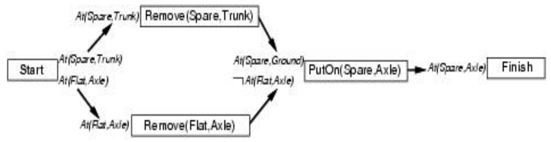
- Pick an open precondition: *At(Spare, Ground)*
- *LeaveOverNight* is applicable
- conflict: $Remove(Spare,Trunk) \xrightarrow{At(Spare,Ground)} PutOn(Spare,Axle)$
- To resolve, add constraint : *LeaveOverNight < Remove(Spare, Trunk)*
- Add causal link: $LeaveOverNight \xrightarrow{\neg At(Spare,Ground)}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

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

Planning with propositional logic

- Planning can be done by proving theorem in situation calculus.
- Here: test the *satisfiability* of a logical sentence:

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

- 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