CS 687
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Planning
Classical Planning, Strips, Situation Calculus, POP
Chapter 10, Russell & Norvig

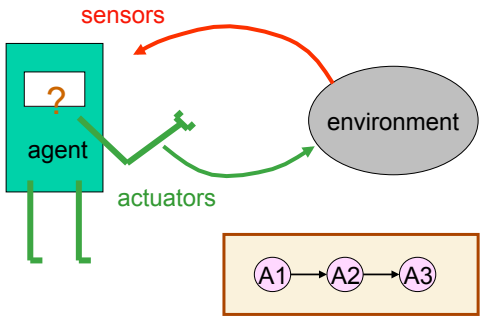
Planning

- How to devise plan of actions to reach the goal
- Strategy 1: search based problem solving
- Strategy 2: hybrid logical agent

- Methods
- Situation Calculus
- State Space Search (STRIPS – restricted FOL)
- Plan based search

Planning

- Search based – all the planning is done ahead of time
- Things may have changed between the time of planning and execution of the plan
- Need to interleave planning with executing – specially in case of stochastic env.



Planning

- Stochastic environments
- Multi-agent environments
- Partially observable environments

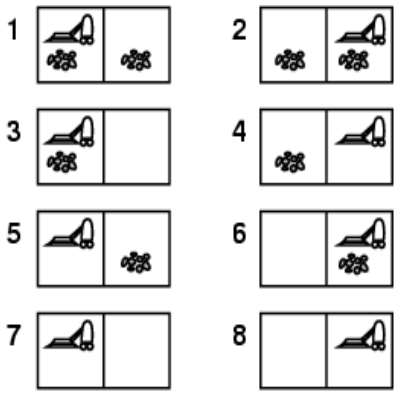
- Need to plan in order to deal with contingencies

- Lack of knowledge on the world which is incomplete
- Sometimes plans need to be hierarchical

- Instead of the world states – plan in belief states
- And still use the state based strategies

Example: vacuum world

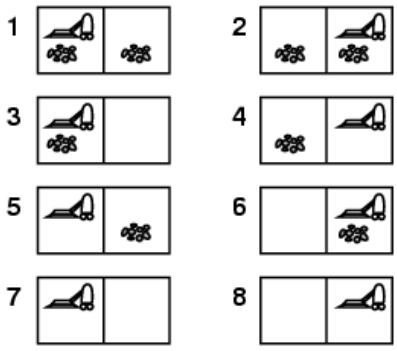
- Deterministic, fully observable
- Actions L, R, S (left, right, suck)
- start in #5. Solution?



- Graph search to get to the goal state 8
- Graph corresponding to actions edges not drawn here

Example: vacuum world

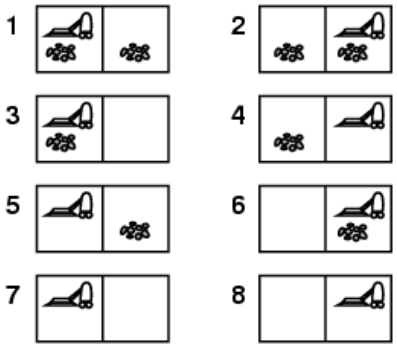
- Sensorless – don't know where you are, not sure if there is dirt
- start in {*1,2,3,4,5,6,7,8*} Solution?



- Cannot do anything – state is unknown
- Strategy represent belief state

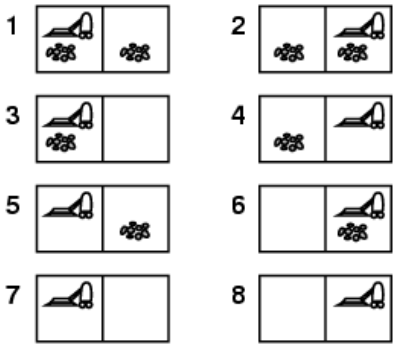
Example: Vacuum world

- Deterministic world and partially observable
  - Partially observable: location, dirt at current location – we have local sensing
  - Outcomes of actions are deterministic
  - Percept: *[L, Clean],* i.e., start in #5 or #7
    Solution?
  - Planning in belief space
  - each belief state corresponds
  - to a set of worlds stages



Example: Vacuum world

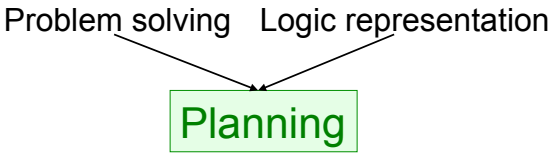
- Non-deterministic and/or partially observable
  - Nondeterministic: *Suck* may dirty a clean carpet
  - Partially observable: location, dirt at current location.
  - Percept: *[L, Clean],* i.e., start in #5 or #7
    Solution?



Representations in Planning

Planning opens up the black-boxes by using logic to represent:

- Actions
- States
- Goals



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 Stanford Research Institute Problem Solver (Fikes and Nilson 1971)

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)*
    - *no negation allowed, symbols must be grounded*
  - 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

  Add fluents which appear as positive literals in effect

  Delete fluents which appear as negative literals in effect

Language semantics?

- How do actions affect states?
  - An action is applicable in any state that satisfies the precondition.
  - Action schema applicability involves a substitution θ for the variables in the PRECOND.
  - Instantiate free variables
  - E.g. initial state

    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

    - Closed world assumption – any atom not mentioned is false

Expressiveness and extensions

- STRIPS is simplified
  - Important limit: function-free literals
    - Allows for propositional representation
    - Function symbols lead to infinitely many states and actions
- 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)*

Blocks world

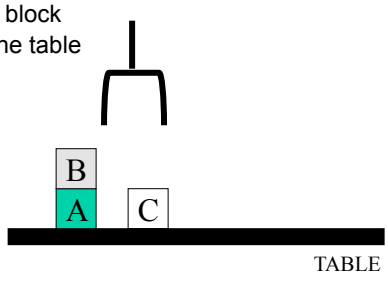
The **blocks world** is a micro-world that consists of a table, a set of blocks and a robot hand.

Some domain constraints:

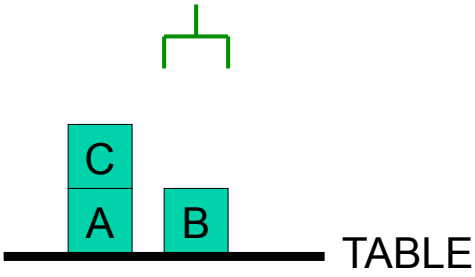
- Only one block can be on another block
- Any number of blocks can be on the table
- The hand can only hold one block

Typical representation:

ontable(a)
ontable(c)
on(b,a)
handempty
clear(b)
clear(c)

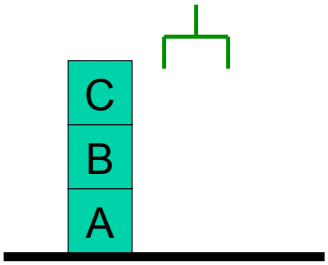


State Representation



Conjunction of propositions:
BLOCK(A), BLOCK(B), BLOCK(C),
ON(A,TABLE), ON(B,TABLE), ON(C,A),
CLEAR(B), CLEAR(C), HANDEMPTY

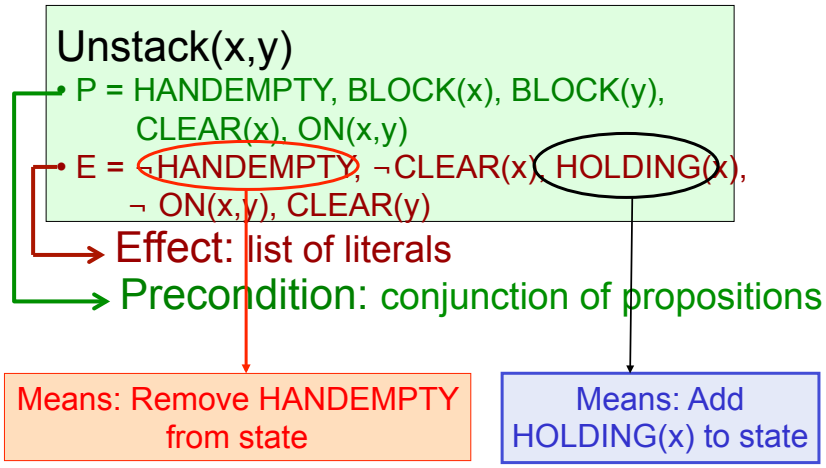
Goal Representation



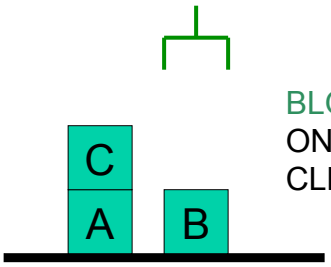
Conjunction of propositions:
ON(A,TABLE), ON(B,A), ON(C,B)

The goal G is achieved in a state S if all the propositions in G are also in S

Action Representation



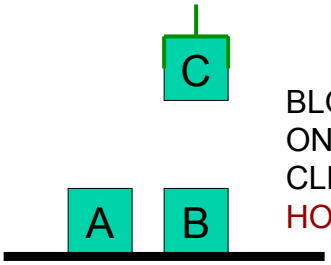
Example



BLOCK(A), BLOCK(B), BLOCK(C),
ON(A,TABLE), ON(B,TABLE), ON(C,A),
CLEAR(B), CLEAR(C), HANDEMPTY

Unstack(C,A)
• P = HANDEMPTY, BLOCK(C), BLOCK(A),
CLEAR(C), ON(C,A)
• E = ¬HANDEMPTY, ¬CLEAR(C), HOLDING(C),
¬ ON(C,A), CLEAR(A)

Example



BLOCK(A), BLOCK(B), BLOCK(C),
ON(A,TABLE), ON(B,TABLE), ~~ON(C,A),~~
CLEAR(B), ~~CLEAR(C)~~, ~~HANDEMPTY~~,
HOLDING(C), CLEAR(A)

Unstack(C,A)
- P = HANDEMPTY, BLOCK(C), BLOCK(A), CLEAR(C), ON(C,A)
- E = ¬HANDEMPTY, ¬CLEAR(C), HOLDING(C), ¬ ON(C,A), CLEAR(A)

Action Representation

Action(Unstack(x,y)
- P: HANDEMPTY, BLOCK(x), BLOCK(y), CLEAR(x), ON(x,y)
- E: ¬HANDEMPTY, ¬CLEAR(x), HOLDING(x), ¬ ON(x,y), CLEAR(y)

Action(Stack(x,y)
- P: HOLDING(x), BLOCK(x), BLOCK(y), CLEAR(y)
- E: ON(x,y), ¬CLEAR(y), ¬HOLDING(x), CLEAR(x), HANDEMPTY

Action(Pickup(x)
- P: HANDEMPTY, BLOCK(x), CLEAR(x), ON(x,TABLE)
- E: ¬HANDEMPTY, ¬CLEAR(x), HOLDING(x), ¬ON(x,TABLE)

Action(PutDown(x)
- P: HOLDING(x)
- E: ON(x,TABLE), ¬HOLDING(x), CLEAR(x), HANDEMPTY

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))*

PLAN:
[Load(C1,P1,SFO), Fly(P1,SFO,JFK), Load(C2,P2,JFK), Fly(P2,JFK,SFO)]

Example: Spare tire problem

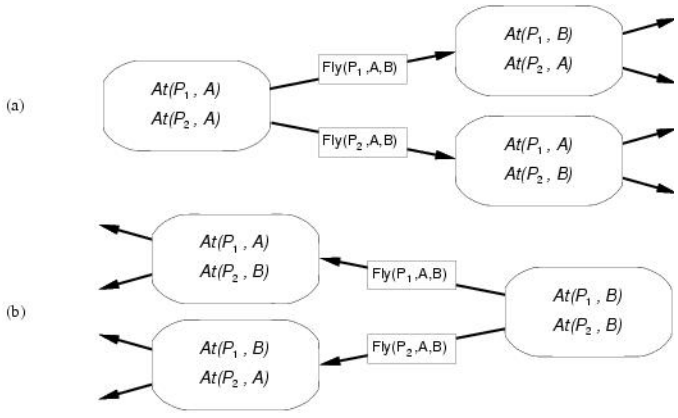
Init(At(Flat, Axle) ∧ At(Spare,trunk))
Goal(At(Spare,Axle))
Action(Remove(Spare,Trunk)
PRECOND: *At(Spare,Trunk)*
EFFECT: *¬At(Spare,Trunk) ∧ At(Spare,Ground))*
Action(Remove(Flat,Axle)
PRECOND: *At(Flat,Axle)*
EFFECT: *¬At(Flat,Axle) ∧ At(Flat,Ground))*
Action(PutOn(Spare,Axle)
PRECOND: *At(Spare,Groundp)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

Planning with state-space search

- The relationship between planning and state space search has been established
- 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

Progression Example

- Buy(isbn) effect Own(isbn)

- Goal state Own(1237121736813)
- How to reach the goal state

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.

Situation Calculus Planning

- Formulate planning problem in FOL
- Use theorem prover to find proof (aka plan)

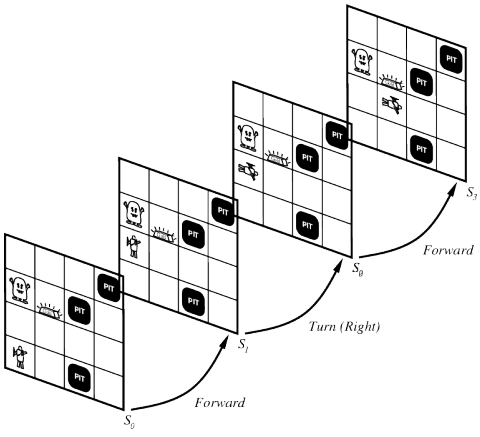
- Instead of using propositional logic
- Use first order logic – enable to use power of universal quantification
- Represent better the notion of time through notion of *situation*

Representing change

- Representing change in the world in logic can be tricky.
- One way is just to change the KB
  - Add and delete sentences from the KB to reflect changes
  - How do we remember the past, or reason about changes?
- **Situation calculus** is another way
- A **situation** is a snapshot of the world at some instant in time
- When the agent performs an action A in situation S1, the result is a new situation S2.

Stituation Calculus

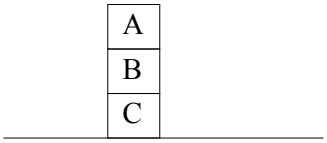
- Wumpus world



Situation Calculus

Initial state

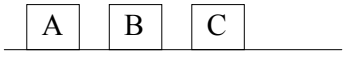
On(A,Table, s_0)
On(B,Table, s_0)
On(C,Table, s_0)
Clear(A, s_0)
Clear(B, s_0)
Clear(C, s_0)
Clear(Table, s_0)



Goal

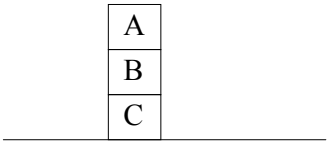
Find a state (situation) s, such that

On(A,B, s)
On(B,C, s)
On(C,Table, s)



Initial state

On(A,Table, s_0)
On(B,Table, s_0)
On(C,Table, s_0)
Clear(A, s_0)
Clear(B, s_0)
Clear(C, s_0)
Clear(Table, s_0)



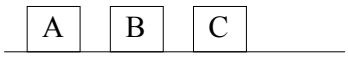
Goal

On(A,B, s)
On(B,C, s)
On(C,Table, s)

Note: It is not necessary that the goal describes all relations

Clear(A, s)

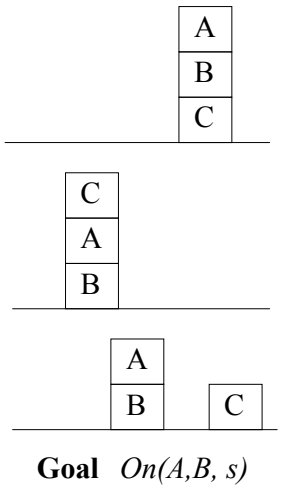
Assume a simpler goal *On(A,B, s)*



Initial state

On(A,Table, s_0)
On(B,Table, s_0)
On(C,Table, s_0)
Clear(A, s_0)
Clear(B, s_0)
Clear(C, s_0)
Clear(Table, s_0)

3 possible goal configurations



Goal *On(A,B, s)*

- Knowledge base
- Two types of axioms

- Effect axioms – describe changes in situations from actions
- Frame axioms – things preserved from previous situations

Effect Axioms

Effect axioms:

Moving x from y to z. $MOVE(x, y, z)$

Effect of move changes on **On** relations

$$On(x, y, s) \wedge Clear(x, s) \wedge Clear(z, s) \rightarrow On(x, z, DO(MOVE(x, y, z)$$

$$On(x, y, s) \wedge Clear(x, s) \wedge Clear(z, s) \rightarrow \neg On(x, y, DO(MOVE(x, y, z)$$

Effect of move changes on **Clear** relations

$$On(x, y, s) \wedge Clear(x, s) \wedge Clear(z, s) \rightarrow Clear(y, DO(MOVE(x, y, z)$$

$$On(x, y, s) \wedge Clear(x, s) \wedge Clear(z, s) \wedge (z \neq Table)$$
$$\rightarrow \neg Clear(z, DO(MOVE(x, y, z), s))$$

Frame axioms

- Represent things that remain unchanged

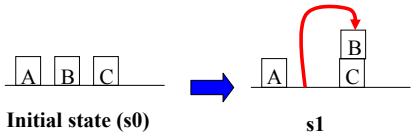
On relations:

$$On(u, v, s) \wedge (u \neq x) \wedge (v \neq y) \rightarrow On(u, v, DO(MOVE(x, y, z), s))$$

Clear relations:

$$Clear(u, s) \wedge (u \neq z) \rightarrow Clear(u, DO(MOVE(x, y, z), s))$$

Blocks World



Initial state (s0) **s1**

$s_0 =$

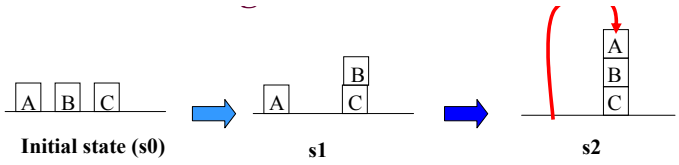
$On(A, Table, s_0)$ $Clear(A, s_0)$ $Clear(Table, s_0)$
$On(B, Table, s_0)$ $Clear(B, s_0)$
$On(C, Table, s_0)$ $Clear(C, s_0)$

Action: $MOVE(B, Table, C)$

$s_1 = DO(MOVE(B, Table, C), s_0)$

$On(A, Table, s_1)$ $Clear(A, s_1)$ $Clear(Table, s_1)$
$On(B, C, s_1)$ $Clear(B, s_1)$
$\neg On(B, Table, s_1)$ $\neg Clear(C, s_1)$
$On(C, Table, s_1)$

Blocks World



Initial state (s0) **s1** **s2**

$s_1 = DO(MOVE(B, Table, C), s_0)$

$On(A, Table, s_1)$ $Clear(A, s_1)$ $Clear(Table, s_1)$
$On(B, C, s_1)$ $Clear(B, s_1)$
$\neg On(B, Table, s_1)$ $\neg Clear(C, s_1)$
$On(C, Table, s_1)$

Action: $MOVE(A, Table, B)$

$s_2 = DO(MOVE(A, Table, B), s_1)$

$= DO(MOVE(A, Table, B), DO(MOVE(B, Table, C), s_0))$

$On(A, B, s_2)$ $\neg On(A, Table, s_2)$ $\neg Clear(B, s_2)$
$On(B, C, s_2)$ $\neg On(B, Table, s_2)$ $\neg Clear(C, s_2)$
$On(C, Table, s_2)$ $Clear(A, s_2)$ $Clear(Table, s_2)$

Situation calculus

- A **situation** is a snapshot of the world at an interval of time during which nothing changes
- Every true or false statement is made with respect to a particular situation.
  - Add **situation variables** to every predicate.
  - at(hunter,1,1) becomes at(hunter,1,1,s0): at(hunter,1,1) is true in situation (i.e., state) s0.
- Add a new function, **result(a,s),** that maps a situation s into a new situation as a result of performing action a. For example, result(forward, s) is a function that returns the successor state (situation) to s
- Example: The action agent-walks-to-location-y could be represented by
  - (∀x)(∀y)(∀s) (at(Agent,x,s) ^ ~onbox(s)) -> at(Agent,y,result(walk(y),s))

Situation calculus planning

- **Initial state**: a logical sentence about (situation) S_0

  At(Home, S_0) ^ ~Have(Milk, S_0) ^ ~ Have(Bananas, S_0) ^ ~Have(Drill, S_0)
- **Goal state**:

  (∃s) At(Home,s) ^ Have(Milk,s) ^ Have(Bananas,s) ^ Have(Drill,s)
- **Operators** are descriptions of actions:

  ∀(a,s) Have(Milk,Result(a,s)) <=> ((a=Buy(Milk) ^ At(Grocery,s)) v (Have(Milk, s) ^ a~=Drop(Milk)))
- Result(a,s) names the situation resulting from executing action a in situation s.
- Action sequences are also useful: Result'(l,s) is the result of executing the list of actions (l) starting in s:

  (∀s) Result'([],s) = s

  (∀a,p,s) Result'([a|p]s) = Result'(p,Result(a,s))

Situation calculus planning II

- A solution is thus a plan that when applied to the initial state yields a situation satisfying the goal query:

  At(Home,Result'(p,S_0))
  ^ Have(Milk,Result'(p,S_0))
  ^ Have(Bananas,Result'(p,S_0))
  ^ Have(Drill,Result'(p,S_0))

- Thus we would expect a plan (i.e., variable assignment through unification) such as:

  p = [Go(Grocery), Buy(Milk), Buy(Bananas), Go(HardwareStore), Buy(Drill), Go(Home)]

SC planning: analysis

- This is fine in theory, but remember that problem solving (search) is exponential in the worst case
- Also, resolution theorem proving only finds *a* proof (plan), not necessarily a good plan
- Another important issue: **the Frame Problem**

The Frame Problem

- In SC, need not only axioms to describe what changes in each situation, but also need axioms to describe what stays the same (can do this using successor-state axioms)
- Qualification problem: difficulty in specifying all the conditions that must hold in order for an action to work
- Ramification problem: difficulty in specifying all of the effects that will hold after an action is taken

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

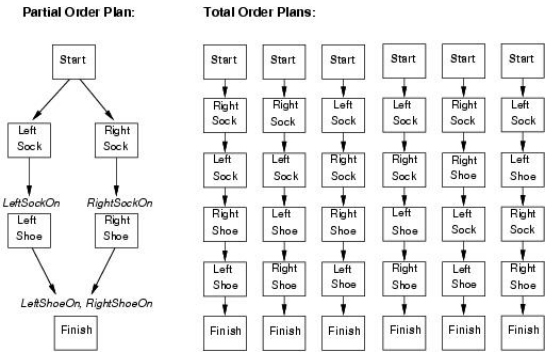
Shoe example

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
    - 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) $A \xrightarrow{p} B$
  - 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.

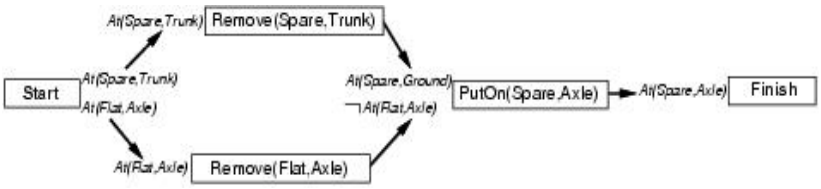
Process summary

- 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

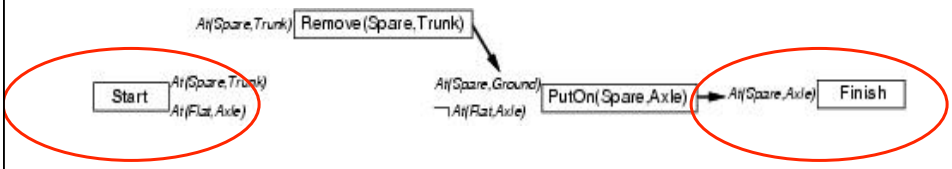
Init(At(Flat, Axle) ∧ At(Spare,trunk))
Goal(At(Spare,Axle))
Action(Remove(Spare,Trunk)
PRECOND: *At(Spare,Trunk)*
EFFECT: *¬At(Spare,Trunk) ∧ At(Spare,Ground))*
Action(Remove(Flat,Axle)
PRECOND: *At(Flat,Axle)*
EFFECT: *¬At(Flat,Axle) ∧ At(Flat,Ground))*
Action(PutOn(Spare,Axle)
PRECOND: *At(Spare,Groundp)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

POP Solving the problem



- Remove *LeaveOverNight* and causal links
- Add RemoveFlatAxle and finish

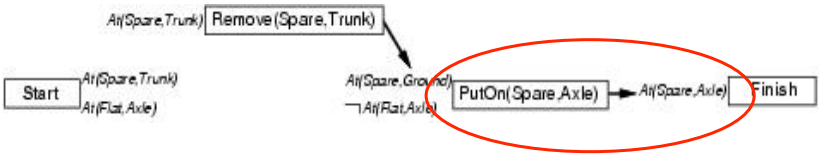
Solving the problem



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

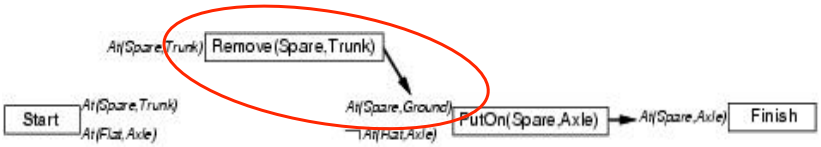
- Idea: search through the space of plans as opposed state space
- Start – empty plan
- Flaw – nothing achieves the goal
- Insert – PutOn action
- Flaw – nothing achieves the precondition – keep on adding

Solving the problem



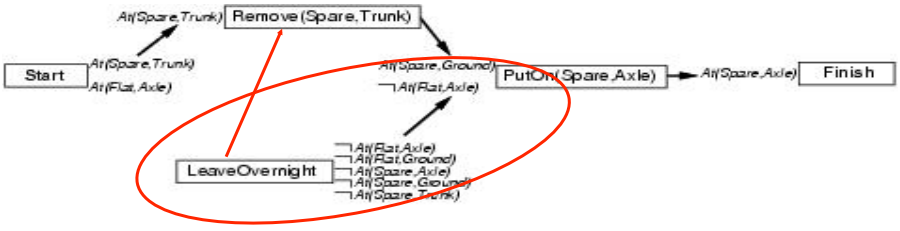
- Initial plan: Start with EFFECTS and Finish with PRECOND.
- Pick an open precondition: *At(Spare, Axle)*
- Only *PutOn(Spare, Axle)* is applicable
- Add causal link: $PutOn(Spare,Axle) \xrightarrow{At(Spare,Axle)} Finish$
- Add constraint : *PutOn(Spare, Axle) < Finish*

Solving the problem



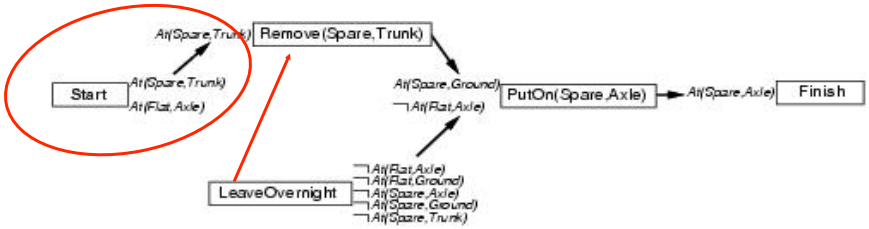
- Pick an open precondition: *At(Spare, Ground)*
- Only *Remove(Spare, Trunk)* is applicable
- Add causal link: $\mathrm{Re}\,move(Spare,Trunk) \xrightarrow{At(Spare,Ground)} PutOn(Spare,Axle)$
- Add constraint : *Remove(Spare, Trunk)* < *PutOn(Spare,Axle)*

Solving the problem



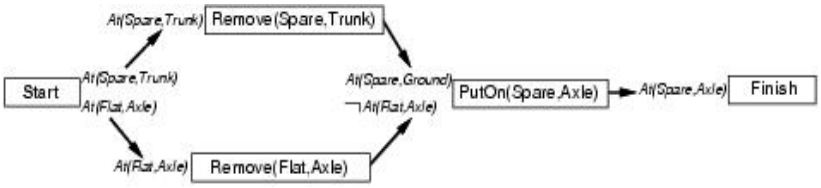
- Pick an open precondition: ¬*At(Flat, Axle)*
- *LeaveOverNight* is applicable
- conflict: *LeaveOverNight* also has the effect ¬ *At(Spare,Ground)*
- $\mathrm{Re}\,move(Spare,Trunk) \xrightarrow{At(Spare,Ground)} PutOn(Spare,Axle)$
- To resolve, add constraint : *LeaveOverNight* < *Remove(Spare, Trunk)*

Solving the problem



- Pick an open precondition: *At(Spare, 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* and causal links
- Add RemoveFlatAxle and finish

Planning graphs

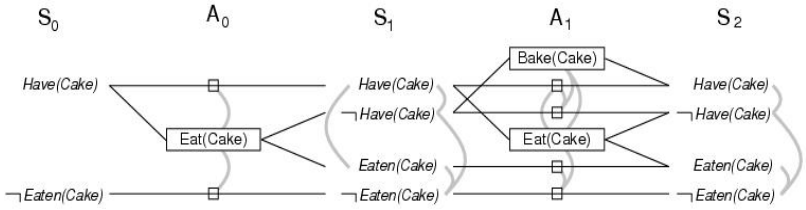
- Used to achieve better heuristic estimates.
  - A solution can also directly extracted using GRAPHPLAN.
- Uses special data structure that can be used to give better heuristics
- Consists of a sequence of levels that correspond to time steps in the plan.
  - Level 0 is the initial state.
  - Each level 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:

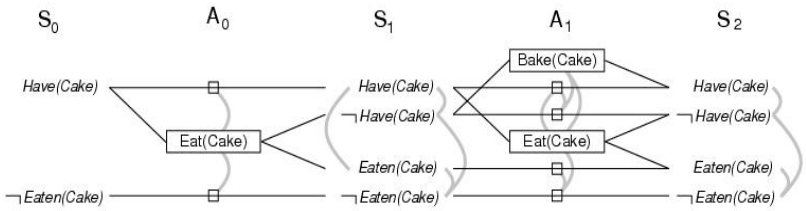
  Init(Have(Cake))
  Goal(Have(Cake) ∧ Eaten(Cake))
  Action(Eat(Cake), PRECOND: Have(Cake)
  EFFECT: ¬Have(Cake) ∧ Eaten(Cake))
  Action(Bake(Cake), PRECOND: ¬ Have(Cake)
  EFFECT: Have(Cake))

Cake example



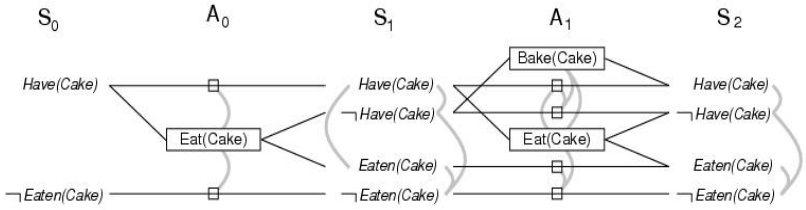
- Start at level S0 and determine action level A0 and next level S1.
  - A0 >> all actions whose preconditions are satisfied in the previous level.
  - Connect precond and effect of actions S0 --> S1
  - Inaction is represented by *persistence actions*.
- Level A0 contains the actions that could occur
  - 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

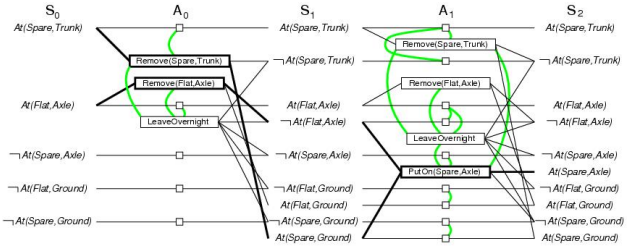
function GRAPHPLAN(*problem*) **return** *solution* or failure
    graph ← INITIAL-PLANNING-GRAPH(*problem*)
    goals ← GOALS[*problem*]
    loop do
        if *goals* all non-mutex in last level of graph **then do**
            solution ← EXTRACT-SOLUTION(*graph, goals,* LENGTH*(graph)*)
         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

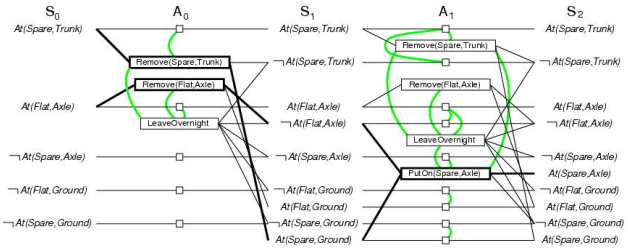
This example goes beyond STRIPS: negative literal in pre-condition (ADL description)

GRAPHPLAN example



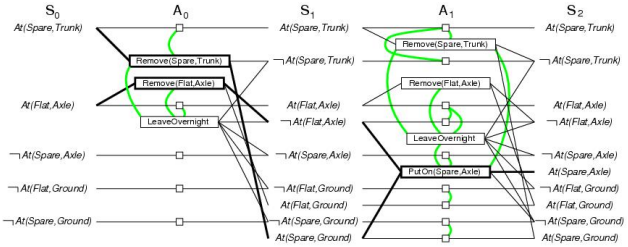
- Initially the plan consist of 5 literals from the initial state and the CWA literals (S0).
- Add actions whose preconditions are satisfied by EXPAND-GRAPH (A0)
- Also add persistence actions and mutex relations.
- Add the effects at level S1
- Repeat until goal is in level Si

GRAPHPLAN example



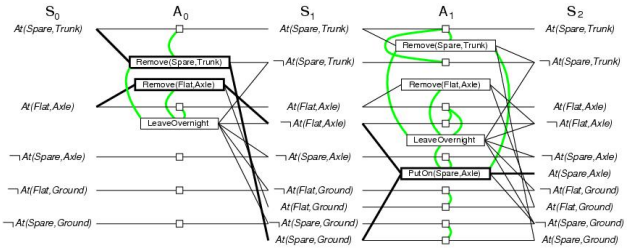
- EXPAND-GRAPH also looks for mutex relations
  - Inconsistent effects
    - E.g. Remove(Spare, Trunk) and LeaveOverNight due to At(Spare,Ground) and **not** At(Spare, Ground)
  - Interference
    - E.g. Remove(Flat, Axle) and LeaveOverNight At(Flat, Axle) as PRECOND and **not** At(Flat,Axle) as EFFECT
  - 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:

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

- 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