

UNIT IV

Planning

Classical Planning: Definition of Classical Planning, Algorithms for Planning with State-Space Search, Planning Graphs, other Classical Planning Approaches, and Analysis of Planning Approaches.

Planning and Acting in the Real World: Time, Schedules, and Resources, Hierarchical Planning, Planning and Acting in Nondeterministic Domains, Multi-agent Planning.

Knowledge representation: -

- The task of coming up with a sequence of actions that will achieve a goal is called Planning.
- “Deciding in *ADVANCE* what is to be done”
- A problem solving methodology
- Generating a set of action that are likely to lead to achieving a goal
- Deciding on a course of actions before acting
- **Representation for states and Goals:-**
 - In the STRIPS language, states are represented by conjunctions of function-free ground literals, that is, predicates applied to constant symbols, possibly negated.
 - For example,
 $\text{At(Home)} \wedge \neg \text{Have(Milk)} \wedge \neg \text{Have(Bananas)} \wedge \neg \text{Have(Drill)} \dots$
 - Goals are also described by conjunctions of literals.
 - For example,
 $\text{At(Home)} \wedge \text{Have(Milk)} \wedge \text{Have(Bananas)} \wedge \text{Have(Drill)}$
 - Goals can also contain variables. For example, the goal of being at a store that sells milk would be represented as
- **Representation for actions:-**
 - Our STRIPS operators consist of three components:
 - the *action description* is what an agent actually returns to the environment in order to do something.
 - the *precondition* is a conjunction of atoms (positive literals) that says what must be true before the operator can be applied.
 - the *effect* of an operator is a conjunction of literals (positive or negative) that describes how the situation changes when the operator is applied.
 - Here's an example for the operator for going from one place to another:
 - $\text{Op(Action:Go(there),}$
 - $\text{Precond:At(here) \wedge Path(here, there),}$
 - $\text{Effect:At(there) \wedge } \neg \text{At(here))}$
- **Representation of Plans:-**
 - Consider a simple problem:
 - Putting on a pair of shoes
 - Goal $\rightarrow \text{RightShoeOn} \wedge \text{LeftShoeOn}$
 - Four operators:

Op(Action:RightShoe,PreCond:RightSockOn,Effect:RightShoeON)
 Op(Action:RightSock , Effect: RightSockOn)
 Op(Action:LeftShoe, Precond:LeftSockOn, Effect:LeftShoeOn)
 Op(Action:LeftSock,Effect:LeftSockOn)

Given:-

- A description of an initial state
- A set of actions
- A (partial) description of a goal state

Problem:-

- Find a sequence of actions (plan) which transforms the initial state into the goal state.

Application areas:-

- Systems design
- Budgeting
- Manufacturing product
- Robot programming and control
- Military activities

Benefits of Planning:-

- Reducing search
- Resolving goal conflicts
- Providing basis for error recovery

3.1 Planning with State Space Search:

- Planning with state space search approach is used to construct a planning algorithm.
- This is most straightforward approach.
- The description of actions in a planning problem specifies both preconditions and effects.
- It is possible to search in either direction.
- Either from forward from the initial state or backward from the goal
- The following are the two types of state space search ,
 - Forward state-space search
 - Backward state-space search
- The following diagram shows the Forward state-space search



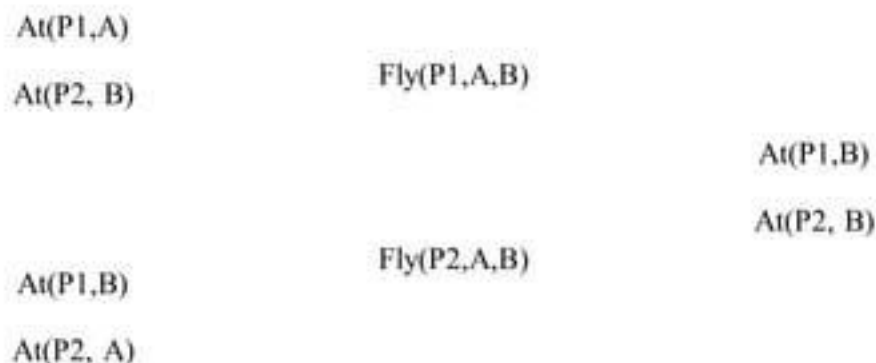
3.1.1 Forward state-space search:-

- Planning with forward state-space search is similar to the problem solving using Searching.

- It is sometimes called as progression Planning.
- It moves in the forward direction.
- we start in the problems initial state, considering sequence of actions until we find a sequence that reaches a goal state.
- The formulation of planning problems as state-space search problems is as follows,
 - The **Initial state** of the search is the initial state from the planning problem.
 - In general, each state will be a set of positive ground literals; literals not appearing are false.
 - The **actions** that are applicable to a state are all those whose preconditions are satisfied.
 - The successor state resulting from an action is generated by adding the positive effect literals and deleting the negative effect literals.
 - The goal test checks whether the state satisfies the goal of the planning problem.
 - The step cost of each action is typically 1.
- This method was too inefficient.
- It does not address the irrelevant action problem, (i.e.) all applicable actions are considered from each state.
- This approach quickly bogs down without a good heuristics.
- For Example:-
 - Consider an air cargo problem with 10 airports, where each airport has 5 planes and 20 pieces of cargo.
 - The Goal is to move the entire cargo from airport A to airport B.
 - There is a simple solution to the Problem,
 - Load the 20 pieces of cargo into one of the planes at A, then fly the plane to B, and unload the cargo.
 - But finding the solution can be difficult because the average branching factor is huge.

3.1.2 Backward state- space search:-

- Backward search is similar to bidirectional search.
- It can be difficult to implement when the goal states are described by a set of constraints rather than being listed explicitly.
- It is not always obvious how to generate a description of the possible predecessors of the set of goal states.
- The main advantage of this search is that it allows us to consider only relevant actions.
- An action is relevant to a conjunctive goal if it achieves one of the conjuncts of the goal.
- The following diagram shows the Backward state-space search



- For example:-
 - The goal in our 10-airport cargo problem is to have 20 pieces of cargo at airport B, or more precisely,

$$At(C1,B) \wedge At(C2,B) \wedge \dots \wedge At(C20,B)$$
 - Now consider the conjunct $At(C1,B)$. working backwards, we can seek actions that have this as an effect. There is only one $unload(C1,p,B)$, where plane p is unspecified.
 - In this search restriction to relevant actions means that backward search often has a much lower branching factor than forward search.
- Searching backwards is sometimes called regression planning.
- The principal question is:- what are the states from which applying a given action leads to the goal?
- Computing the description of these states is called regressing the goal through the action.
- consider the air cargo example;- we have the goal as,

$$At(C1,B) \wedge At(C2,B) \wedge \dots \wedge At(C20,B)$$
 and the relevant action $Unload(C1,p,B)$, which achieves the first conjunct.
- The action will work only if its preconditions are satisfied.
- Therefore , any predecessor state must include these preconditions : $In(C1,p) \wedge At(p,B)$, Moreover the subgoal $At(C1,B)$ should not be true in the predecessor state.
- The predecessor description is

$$In(C1,p) \wedge At(p,B) \wedge At(C2,B) \wedge \dots \wedge At(C20,B)$$
- In addition to insisting that actions achieve some desired literal, we must insist that the actions not undo any desired literals.
- An action that satisfies this restriction is called consistent.
- From definitions of relevance and consistency, we can describe the general process of constructing predecessors for backward search.
- Given a goal description G , let A be an action that is relevant and consistent. The corresponding predecessor 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
- Termination occurs when a predecessor description is generated that is satisfied by the initial state of the planning problem.

3.1.3 Heuristics for State-space search:-

Heuristic Estimate:-

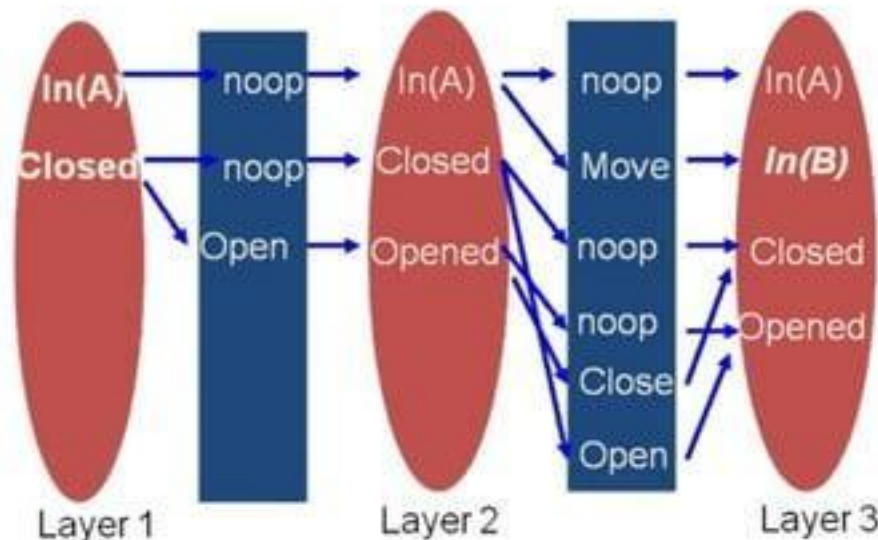
- The value of a state is a measure of how close it is to a goal state.
- This cannot be determined exactly (too hard), but can be approximated.
- One way of approximating is to use the relaxed problem.
 - Relaxation is achieved by ignoring the negative effects of the actions.
 - The relaxed action set, A' , is defined by:

$$A' = \{ \langle pre(a), add(a), 0 \rangle \mid a \in A \}$$

Relaxed Distance Estimate

- Current: In(A), Closed

Goal: In(B)



- Layers correspond to successive time points,
- # layers indicate minimum time to achieve goals.

Building the relaxed plan graph:-

- Start at the initial state
- Repeatedly apply all relaxed actions whose preconditions are satisfied.
 - Their (positive) effects are asserted at the next layer.
- If all actions applied and the goals are not all present in the final graph layer
Then the problem is unsolvable.

Extracting Relaxed solution

- When a layer containing all of the goals is reached, FF searches *backwards* for a plan.
- The earliest possible achiever is always used for any goal.
 - This maximizes the possibility for exploiting actions in the relaxed plan.
- The relaxed plan might contain many actions happening concurrently at a layer.
- The number of actions in the relaxed plan is an estimate of the true cost of achieving the goals.

How FF uses the Heuristics:-

- FF uses the heuristic to estimate how close each state is to a goal state
 - any state satisfying the goal propositions.

- The actions in the relaxed plan are used as a guide to which actions to explore when extending the plan.
- All actions in the relaxed plan at layer i that achieve at least one of the goals required at layer $i+1$ are considered helpful.
- FF restricts attention to the helpful actions when searching forward from a state.

Properties of the Heuristics:-

- The relaxed plan that is extracted is not guaranteed to be the optimal relaxed plan.
- ➔ the heuristic is not admissible.
 - FF can produce non-optimal solutions.
 - Focusing only on helpful actions is not completeness preserving.
- ➔ Enforced hill-climbing is not completeness preserving.

3.2 Partial Order Planning:-

- Formally a planning algorithm has three inputs:
 - A description of the world in some formal language,
 - A description of the agent's goal in some formal language, and
 - A description of the possible actions that can be performed.
- The planner's o/p is a sequence of actions which when executed in any world satisfying the initial state description will achieve the goal.
- **Representation for states and Goals:-**
 - In the STRIPS language, states are represented by conjunctions of function-free ground literals, that is, predicates applied to constant symbols, possibly negated.
 - For example,
 $At(Home) \wedge \neg Have(Milk) \wedge \neg Have(Bananas) \wedge \neg Have(Drill) \wedge \dots$
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 - Here's an example for the operator for going from one place to another:
 - **Op(Action:Go(there),**
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 - **Effect:At(there) ^ ¬At(there))**

Representation of Plans:-

- Consider a simple problem:
 - Putting on a pair of shoes
 - Goal $\rightarrow RightShoeOn \wedge LeftShoeOn$
 - Four operators:

Op(Action:RightShoe,PreCond:RightSockOn,Effect:RightShoeOn)
 Op(Action:RightSock , Effect: RightSockOn)
 Op(Action:LeftShoe, Precond:LeftSockOn, Effect:LeftShoeOn)
 Op(Action:LeftSock,Effect:LeftSockOn)

- **Least Commitment:-** The general strategy of delaying a choice during search is called Least commitment.
- **Partial-order Planner:-** Any planning algorithm that can place two actions into a plan without specifying which come first is called a partial order planner.
- **Linearization:-** The partial-order solution corresponds to six possible total order plans ; each of these is called a linearization of the partial order plan.
- **Total order planner:-** Planner in which plans consist of a simple lists of steps.
- A plan is defined as a data structure
 - A set of plan steps
 - A set of step ordering
 - A set of variable binding constraints
 - A set of causal links : $s_i \xrightarrow{c} s_j$
 "s_i achieves c for s_j"
- Initial plan before any refinements
 Start < Finish
 Refine and manipulate until a plan that is a solution

Plan(STEPS: { $S_1: Op(ACTION:Start),$
 $S_2: Op(ACTION:Finish,$
 PRECOND:RightShoeOn \wedge LeftShoeOn)},
 ORDERINGS: { $S_1 \prec S_2$ },
 BINDINGS: {},
 LINKS: {})

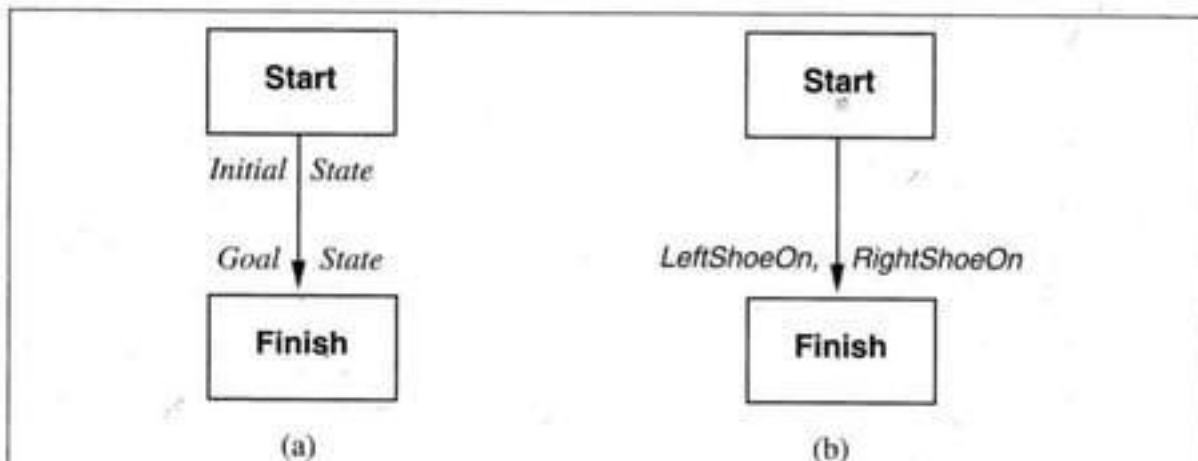
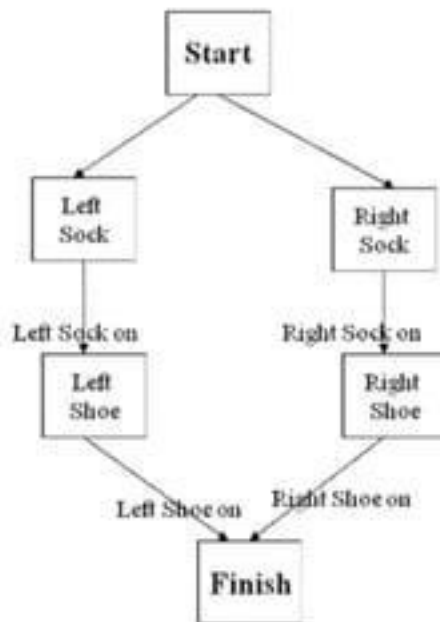


Figure 11.4 (a) Problems are defined by partial plans containing only *Start* and *Finish* steps. The initial state is entered as the effects of the *Start* step, and the goal state is the precondition of the *Finish* step. Ordering constraints are shown as arrows between boxes. (b) The initial plan for the shoes-and-socks problem.

- The following diagram shows the partial order plan for putting on shoes and socks, and the six corresponding linearization into total order plans.

Partial Order Plans:



Total Order Plans:



- Solutions
 - solution : a plan that an agent guarantees achievement of the goal
 - a solution is a complete and consistent plan
 - a complete plan : every precondition of every step is achieved by some other step
 - a consistent plan : no contradictions in the ordering or binding constraints. When we meet a inconsistent plan we backtrack and try another branch

3.2.1 Partial order planning Algorithm:-

The following is the Partial order planning algorithm,

```

function pop(initial-state, conjunctive-goal, operators)
  // non-deterministic algorithm
  plan = make-initial-plan(initial-state, conjunctive-goal);
  loop:
    begin
      if solution?(plan) then return plan;
      (S-need, c) = select-subgoal(plan) ; // choose an unsolved goal
      choose-operator(plan, operators, S-need, c);
      // select an operator to solve that goal and revise plan
      resolve-threats(plan); // fix any threats created
    end
  
```


end

function solution?(plan)

if causal-links-establishing-all-preconditions-of-all-steps(plan)

and all-threats-resolved(plan)

and all-temporal-ordering-constraints-consistent(plan)

and all-variable-bindings-consistent(plan)

then return true;

else return false;

end

function select-subgoal(plan)

 pick a plan step *S-need* from steps(plan) with a precondition *c*
 that has not been achieved;

return (*S-need*, *c*);

end

procedure choose-operator(plan, operators, *S-need*, *c*)

 // solve "open precondition" of some step

 choose a step *S-add* by either

Step Addition: adding a new step from operators that
 has *c* in its Add-list

or *Simple Establishment*: picking an existing step in Steps(plan)
 that has *c* in its Add-list;

if no such step **then return** fail;

 add causal link "*S-add* \rightarrow *c* *S-need*" to Links(plan);

 add temporal ordering constraint "*S-add* < *S-need*" to Orderings(plan);

if *S-add* is a newly added step **then**

begin

 add *S-add* to Steps(plan);

 add "*Start* < *S-add*" and "*S-add* < *Finish*" to Orderings(plan);

end

end

procedure resolve-threats(plan)

foreach *S-threat* that threatens link "*Si* \rightarrow *Sj*" in Links(plan)

begin // "declobber" threat

 choose either

Demotion: add "*S-threat* < *Si*" to Orderings(plan)

or *Promotion*: add "*Sj* < *S-threat*" to Orderings(plan);

if not(consistent(plan)) **then return** fail;

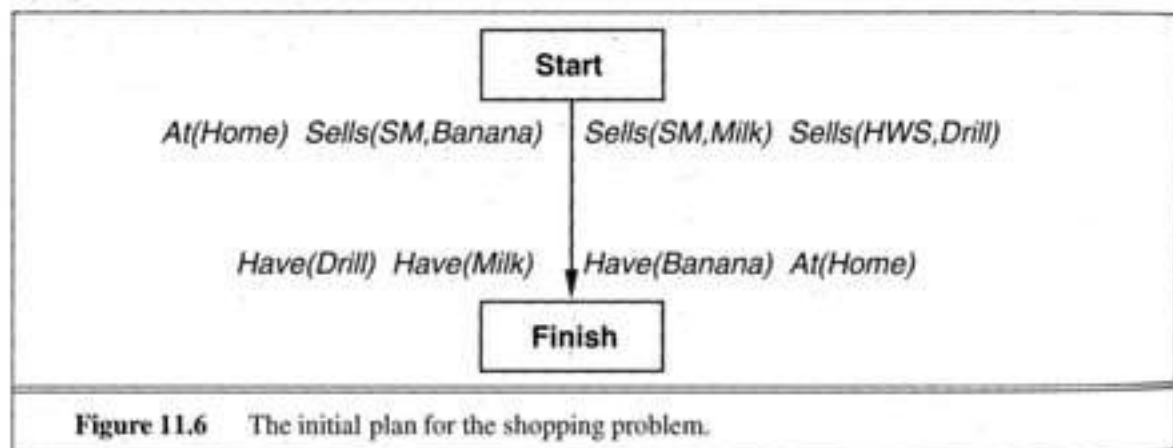
end

end

- **Partial Order Planning Example:-**

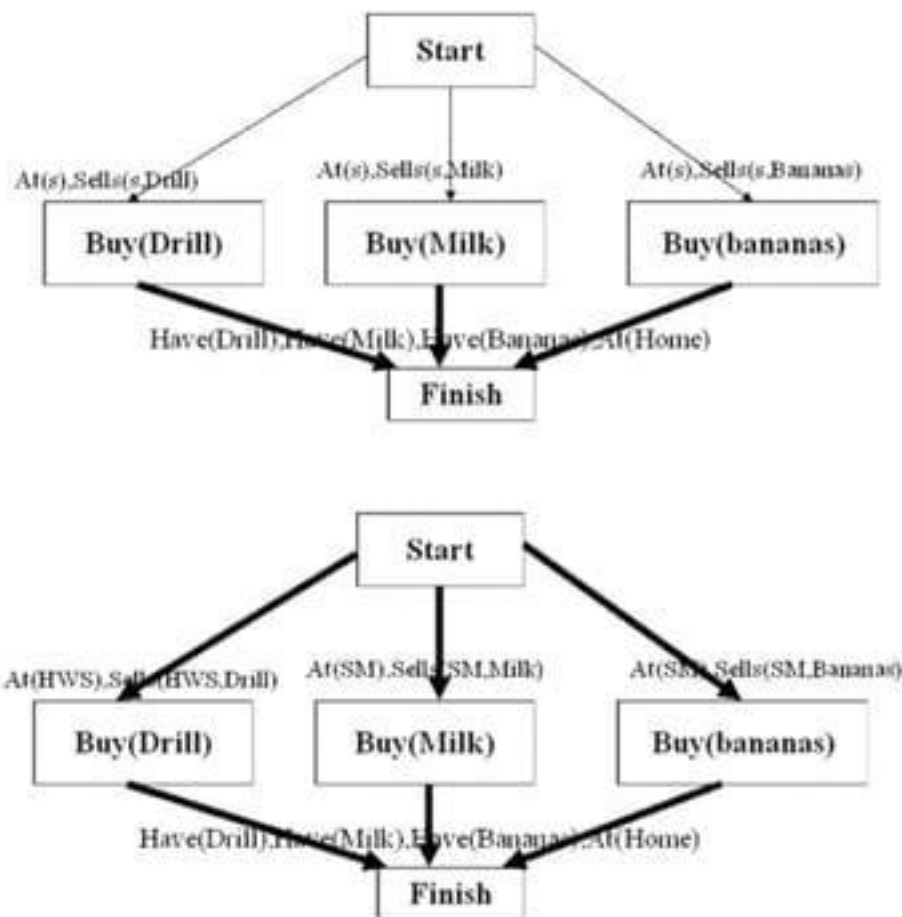
- Shopping problem: "get milk, banana, drill and bring them back home"
- assumption
 - 1) Go action "can travel the two locations"
 - 2) no need money

- initial state : operator start
 $Op(ACTION:Start, EFFECT:At(Home) \wedge Sells(HWS,Drill) \wedge Sells(SM,Milk), Sells(SM,Banana))$
- goal state : Finish
 $Op(ACTION:Finish, PRECOND:Have(Drill) \wedge Have(Milk) \wedge Have(Banana) \wedge At(Home))$
- actions:
 $Op(ACTION:Go(there), PRECOND:At(there), EFFECT:At(there) \wedge \neg At(there))$
 $Op(ACTION:Buy(x), PRECOND:At(store) \wedge Sells(store,x), EFFECT:Have(x))$
- There are many possible ways in which the initial plan elaborated
 - one choice : three Buy actions for three preconditions of Finish action
 - second choice:sells precondition of Buy
 - Bold arrows:causal links, protection of precondition
 - Light arrows:ordering constraints



- The following diagram shows the,
 - partial plan that achieves three of four preconditions of finish
 - Refining the partial plan by adding casual links to achieve the sells preconditions of the buy steps

SVCET



- causal links : protected links
a causal link is protected by ensuring that threats are ordered to come before or after the protected link
- demotion : placed before
promotion : placed after

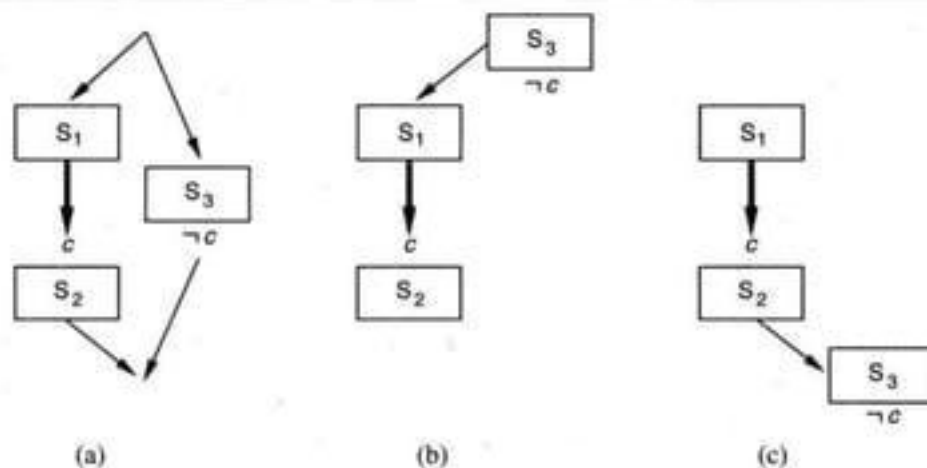
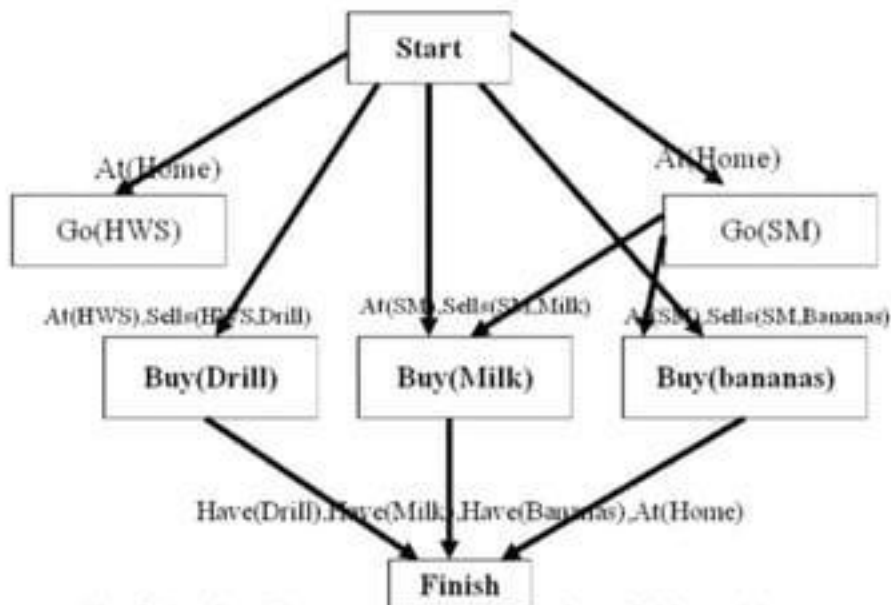
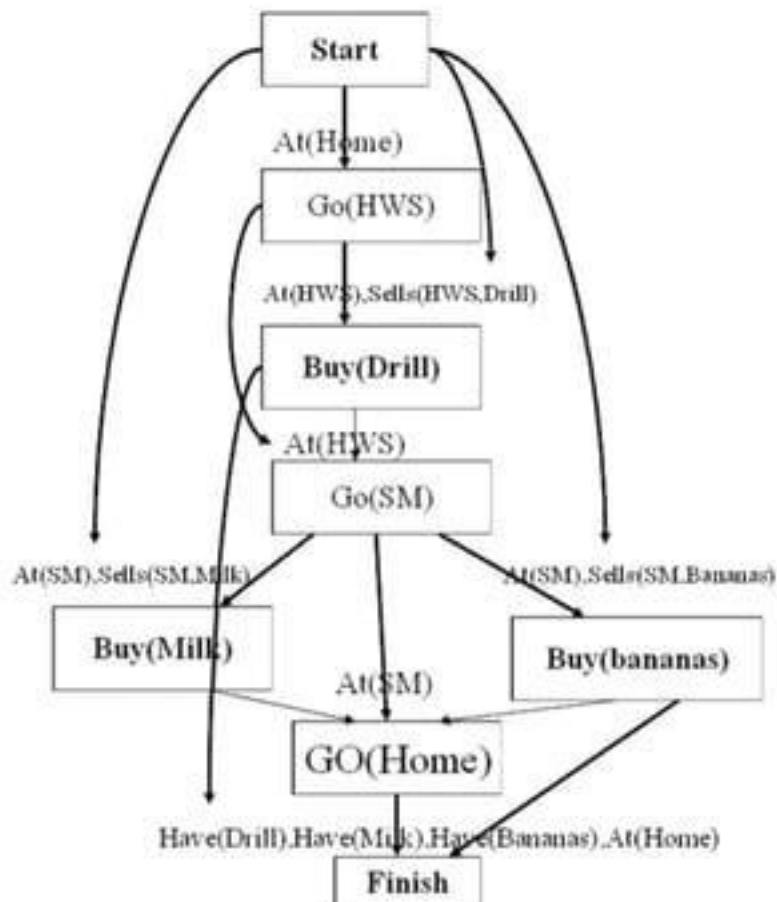


Figure 11.10 Protecting causal links. In (a), the step S_3 threatens a condition c that is established by S_1 and protected by the causal link from S_1 to S_2 . In (b), S_3 has been demoted to come before S_1 , and in (c) it has been promoted to come after S_2 .

- The following diagram shows the partial plan that achieves At Precondition of the three buy conditions



- The following diagram shows the solution of this problem,



- The following are the Knowledge engineering for plan,
- Methodology for solving problems with the planning approach
 - (1) Decide what to talk about
 - (2) Decide on a vocabulary of conditions, operators, and objects
 - (3) Encode operators for the domain
 - (4) Encode a description of the specific problem instance
 - (5) pose problems to the planner and get back plans
- (ex) The blocks world
 - (1) what to talk about
 - cubic blocks sitting on a table
 - one block on top of another
 - A robot arm pick up a block and moves it to another position
 - (2) Vocabulary
 - objects: blocks and table
 - $\text{On}(b,x)$: b is on x
 - $\text{Move}(b,x,y)$: move b from x to y
 - $\neg \text{exist } x \text{ On}(x,b) \text{ or } \forall x \neg \text{On}(x,b)$: precondition
 - $\text{clear}(x)$
 - (3) Operators
 - Op(ACTION:Move(b,x,y),
 PRECOND: $\text{On}(b,x) \wedge \text{Clear}(b) \wedge \text{Clear}(y)$,
 EFFECT: $\text{On}(b,y) \wedge \text{Clear}(x) \wedge \neg \text{On}(b,x) \wedge \neg \text{Clear}(y)$)
 - Op(ACTION:MoveToTable(b,x),
 PRECOND: $\text{On}(b,x) \wedge \text{Clear}(b)$,
 EFFECT: $\text{On}(b,\text{Table}) \wedge \text{Clear}(x) \wedge \neg \text{On}(b,x)$)

3.3 Planning Graph:-

- Planning graphs are an efficient way to create a representation of a planning problem that can be used to
 - Achieve better heuristic estimates
 - Directly construct plans
- Planning graphs only work for propositional problems.
- Planning graphs consists of a seq 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 that represent what *might be* possible at that step in the plan
 - *Might be* is the key to efficiency
 - Records only a restricted subset of possible negative interactions among actions.
- Each level consists of
 - *Literals* = all those that *could* be true at that time step, depending upon the actions executed at preceding time steps.
 - *Actions* = all those actions that *could* have their preconditions satisfied at that time step, depending on which of the literals actually hold.
- For Example:-

Init(Have(Cake))
 Goal(Have(Cake) \wedge Eaten(Cake))

Action(Eat(Cake),
 PRECOND: Have(Cake)
 EFFECT: \neg Have(Cake) \wedge Eaten(Cake))
 Action(Bake(Cake),
 PRECOND: \neg Have(Cake)
 EFFECT: Have(Cake))

- Steps to create planning graph for the example,
 - Create level 0 from initial problem state.

S_0

A_0

S_1

Have(Cake)

\neg Eaten(Cake)

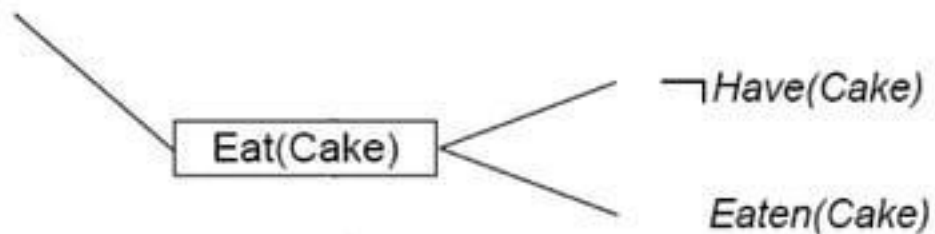
- Add all applicable actions.
 - Add all effects to the next state.

S_0

A_0

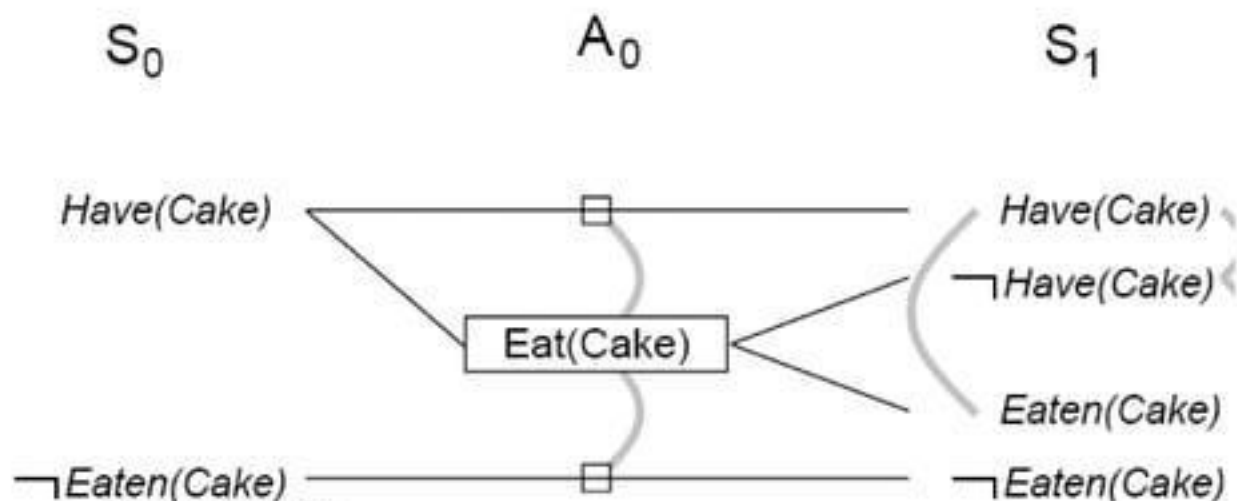
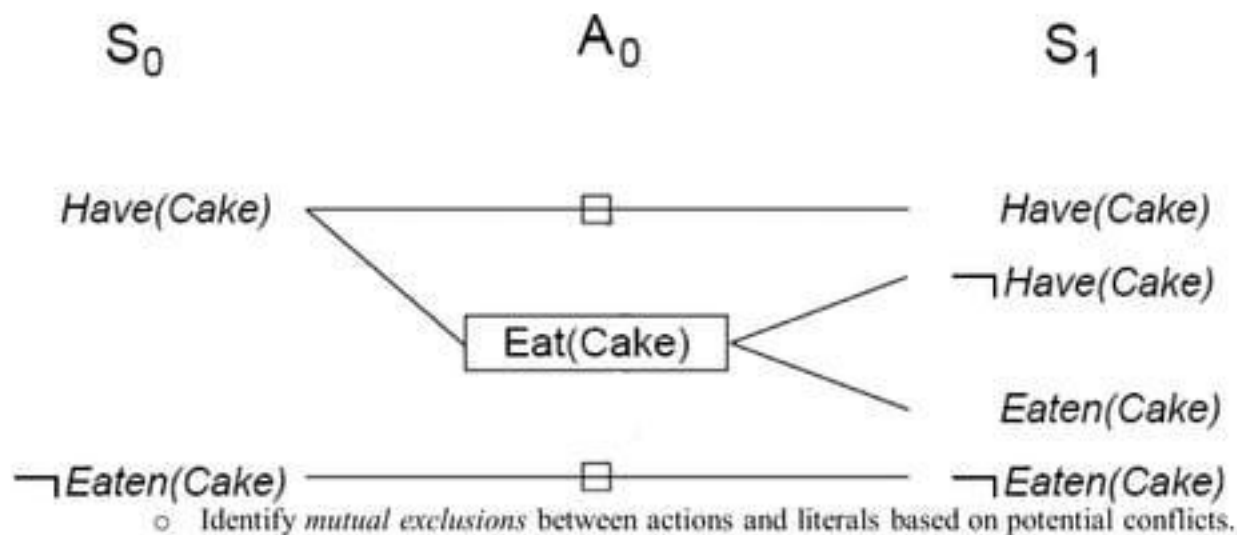
S_1

Have(Cake)

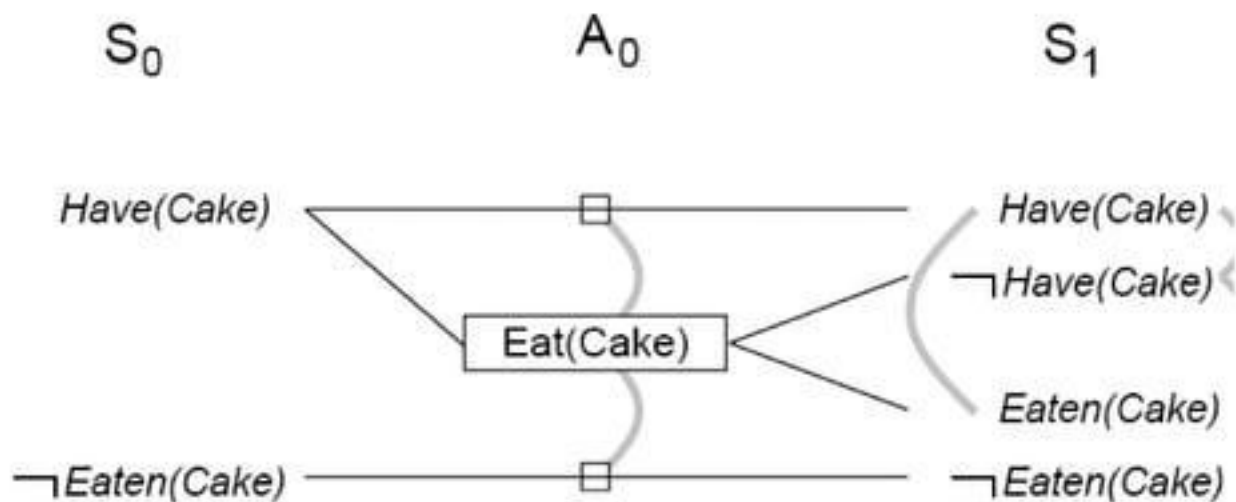


\neg Eaten(Cake)

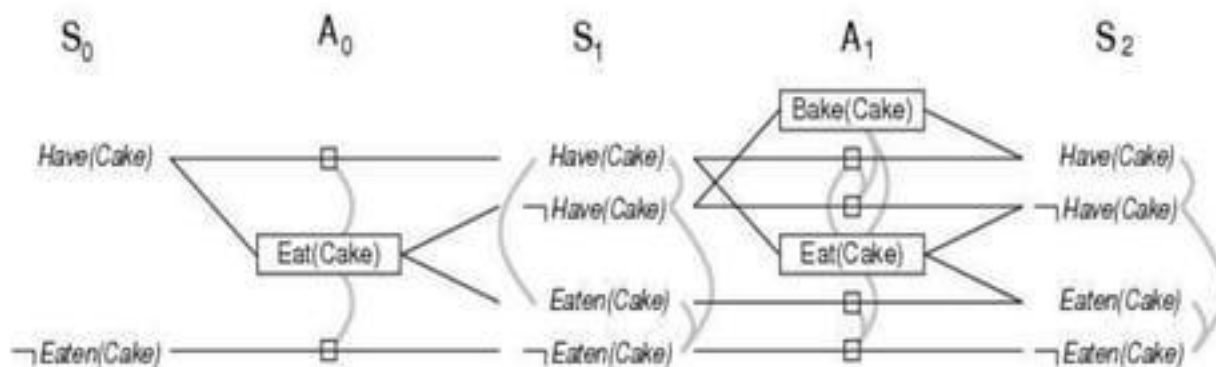
- Add *persistence actions* (inaction = no-ops) to map all literals in state S_i to state S_{i+1} .



- Mutual Exclusion:-
 - 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:
 - one is the negation of the other OR
 - each possible action pair that could achieve the literals is mutex (inconsistent support).
- Level S_1 contains all literals that could result from picking any subset of actions in A_0
 - Conflicts between literals that can not occur together (as a consequence of the selection action) are represented by mutex links.
 - S_1 defines multiple states and the mutex links are the constraints that define this set of states.



- Repeat process until graph levels off:
 - two consecutive levels are identical, or
 - contain the same amount of literals (explanation follows later)



- In figure
 - rectangle denotes actions
 - small square denotes persistence actions
 - straight lines denotes preconditions and effects
 - curved lines denotes mutex links

3.3.1 Planning Graphs for Heuristic Estimation:-

- PG's provide information about the problem
 - PG is a relaxed problem.
 - A literal that does not appear in the final level of the graph cannot be achieved by any plan.
 - $H(n) = \infty$
 - Level Cost: First level in which a goal appears
 - Very low estimate, since several actions can occur

- Improvement: restrict to one action per level using *serial PG* (add mutex links between *every* pair of actions, except persistence actions).
- Cost of a conjunction of goals
 - Max-level: maximum first level of any of the goals
 - Sum-level: sum of first levels of all the goals
 - Set-level: First level in which all goals appear without being mutex
- The following is the GraphPlan Algorithm,
- 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**

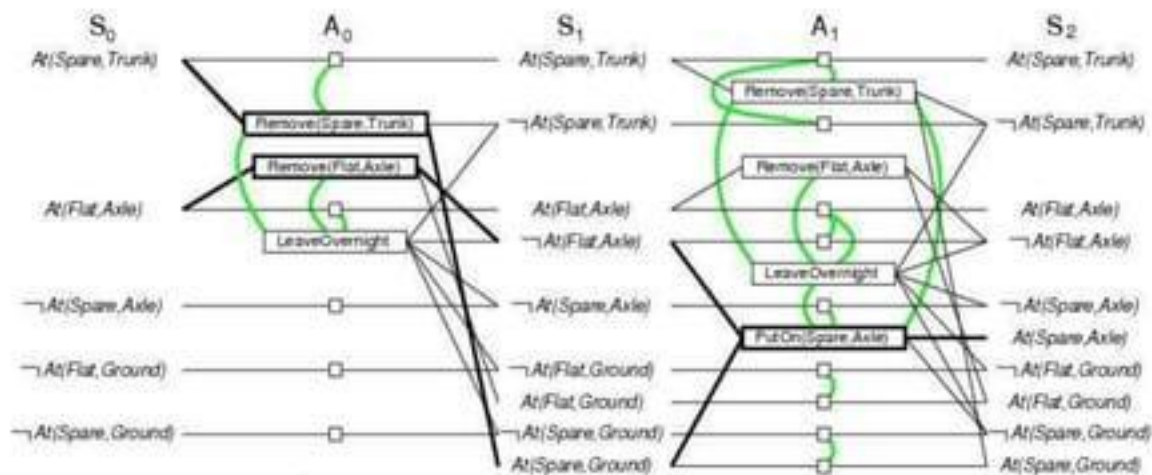
solution ← EXTRACT-SOLUTION(*graph*, *goals*, LENGTH(*graph*))

if *solution* ≠ failure **then return** *solution*

else if NO-SOLUTION-POSSIBLE(*graph*) **then return** failure

graph ← EXPAND-GRAPH(*graph*, *problem*)

- 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
- 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)
- 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.



3.3.2 Termination of GraphPlan:-

- Termination? YES
- PG are monotonically increasing or decreasing:
 - Literals increase monotonically: - Once a literal appears at a given level, it will appear at all subsequent levels. This is because of the persistence actions; Once a literal shows up, persistence actions cause it to stay forever.
 - Actions increase monotonically:- Once a literal appears at a given level, it will appear at all subsequent levels. This is a consequence of literals increasing; if the preconditions of an action appear at one level, they will appear at subsequent levels, and thus will the action
 - Mutexes decrease monotonically:- If two actions are mutex at a given level A_n , then they will also be mutex for all previous levels at which they both appear.
- Because of these properties and because there is a finite number of actions and literals, every PG will eventually level off

3.4 Planning and Acting in the Real World:

- In which we see how more expressive representation and more interactive agent architectures lead to planners that are useful in the real world.
- Planners that are used in the real world for tasks such as scheduling,
 - Hubble Space Telescope Observations
 - Operating factories
 - handling the logistics for military campaigns

3.4.1 Time, Schedules and Resources:

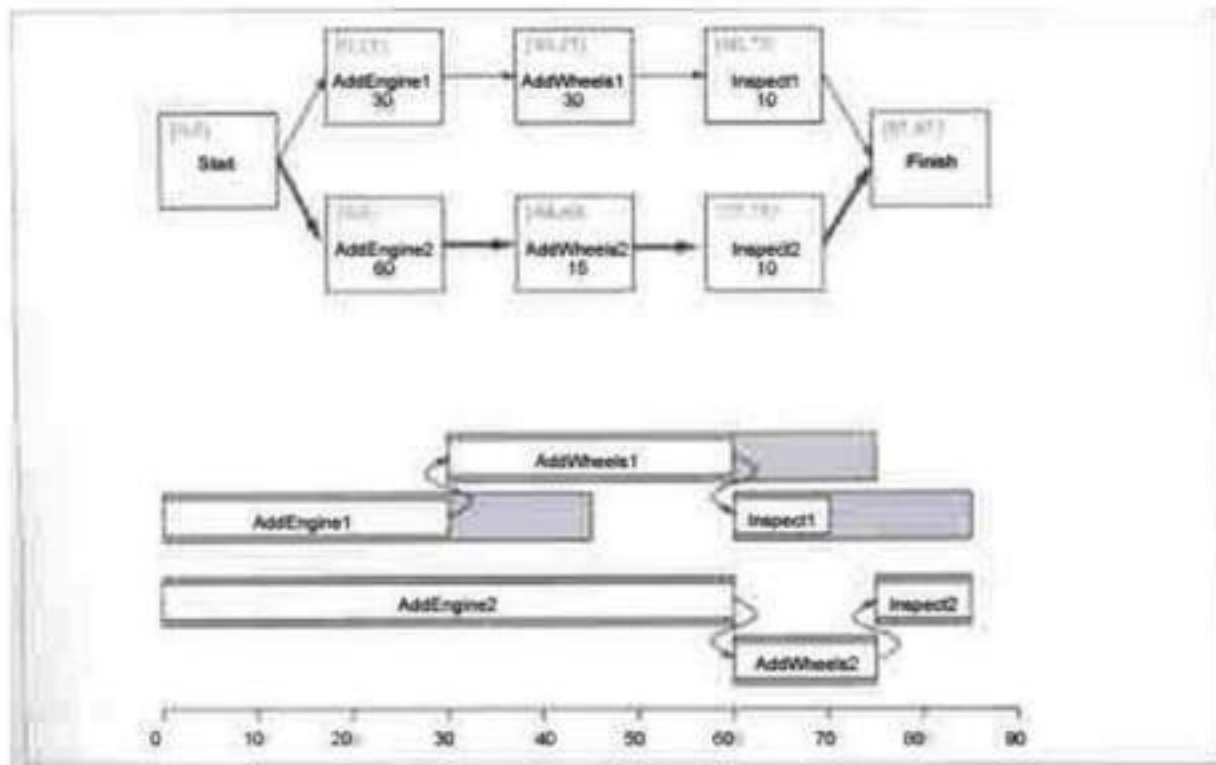
- Time is the essence in the general family of applications called **Job Shop Scheduling**.
- Such tasks require completing a set of jobs, each of which consists of a sequence of actions, where each action has a given duration and might require some resources.
- The problem is to determine a schedule that minimizes the total time required to complete all the jobs, while respecting the resource constraints.
- For Example:- The following problem is a job shop scheduling.

Init (chassis(C1) \wedge chassis(C2))

$\wedge \text{Engine}(\text{E1}, \text{C1}, 30) \wedge \text{Engine}(\text{E2}, \text{C2}, 60)$
 $\wedge \text{Wheels}(\text{W1}, \text{C1}, 30) \wedge \text{Wheels}(\text{W2}, \text{C2}, 15)$
 Goal $(\text{Done}(\text{C1}) \wedge \text{Done}(\text{C2}))$

Action $(\text{AddEngine}(\text{e}, \text{c}, \text{m}),$
 PRECOND: $\text{Engine}(\text{e}, \text{c}, \text{d}) \wedge \text{chassis}(\text{c}) \wedge \neg \text{EngineIn}(\text{c}),$
 EFFECT: $\text{EngineIn}(\text{c}) \wedge \text{Duration}(\text{d})$)
 Action $(\text{AddWheels}(\text{w}, \text{c}),$
 PRECOND: $\text{Wheels}(\text{w}, \text{c}, \text{d}) \wedge \text{chassis}(\text{c}),$
 EFFECT: $\text{WheelsOn}(\text{c}) \wedge \text{Duration}(\text{d})$)
 Action $(\text{Inspect}(\text{c}),$
 PRECOND: $\text{EngineIn}(\text{c}) \wedge \text{WheelsOn}(\text{c}) \wedge \text{chassis}(\text{c}),$
 EFFECT: $\text{Done}(\text{c}) \wedge \text{Duration}(10)$)

- The above table shows the Job Shop scheduling problem for assembling two cars.
- The notation Duration (d) means that an action takes d minutes to execute.
- $\text{Engine}(\text{E1}, \text{C1}, 30)$ means that E1 is an Engine that fits into chassis C1 and takes 30 minutes to Install
- The problem can be solved by POP (Partial order planning).
- We must now determine when each action should begin and end.
- The following diagram shows the solution for the above problem
- To find the start and end times of each action apply the Critical Path Method CPM.
- The critical path is the one that is the longest and upon which the other parts of the process cannot be shorter than.



- At the top, the solution is given as a partial order plan.

- The duration of each action is given at the bottom of each rectangle, with the earliest and latest start time listed as [ES, LS] in the upper left.
- The difference between these two numbers is the slack of an action
- Action with zero slack are on the critical path, shown with bold arrows.
- At the bottom of the figure the same solution is shown as timeline.
- Grey rectangles represent time intervals during which an action may be executed, provided that the ordering constraints are respected.
- The unoccupied portion of a grey rectangle indicates the slack.
- The following formula serve as a definition for ES and LS and also as the outline of a dynamic programming algorithm to compute them:

$$ES(Start) = 0$$

$$ES(B) = \max_i \{ ES(A) + Duration(A) \}$$

$$LS(Finish) = ES(Finish)$$

$$LS(A) = \min_i \{ LS(B) - Duration(A) \}$$

- The complexity of the critical path algorithm is just $O(Nb)$.
- where N is the number of actions and b is the branching factor.

Scheduling with resource constraints:

- Real scheduling problems are complicated by the presence of constraints on resources.
- Consider the above example with some resources.
- The following table shows the job shop scheduling problem for assembling two cars, with resources.

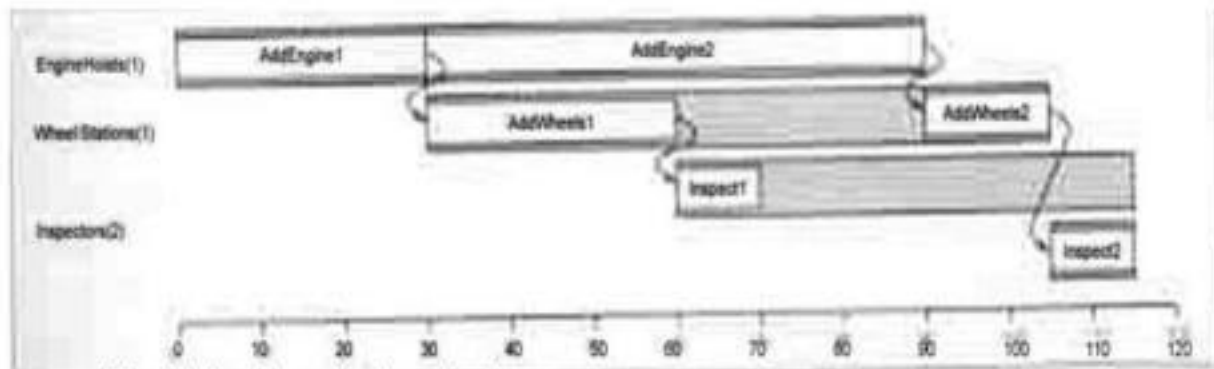
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Init (chassis(C1) ^ chassis(C2)
  ^ Engine (E1,C1,30) ^ Engine (E2,C2,60)
  ^ Wheels (W1,C1,30) ^ Wheels (W2,C2,15)
  ^ EngineHoists (1) ^ WheelStations (1) ^ Inspectors (2))
Goal (Done(C1) ^ Done(C2))

Action (AddEngine(e,c,m),
  PRECOND: Engine(e,c,d) ^ chassis(c) ^ ¬ EngineIn(c),
  EFFECT: EngineIn(c) ^ Duration (d)
  RESOURCE: EngineHoists (1))
Action (AddWheels(w,c),
  PRECOND: Wheels(w,c,d) ^ chassis(c),
  EFFECT: WheelsOn(c) ^ Duration (d),
  RESOURCE: WheelStations (1))
Action (Inspect(c),
  PRECOND: EngineIn(c) ^ WheelsOn (c) ^ chassis (c),
  EFFECT: Done (c) ^ Duration(10),
  RESOURCE: Inspectors (1))

```

- The available resources are on engine assembly station, one wheel assembly station, and two inspectors.
- The notation RESOURCE: means that the resource r is used during execution of an action, but becomes free again when the action is complete.
- The following diagram shows the solution to the job shop scheduling with resources.



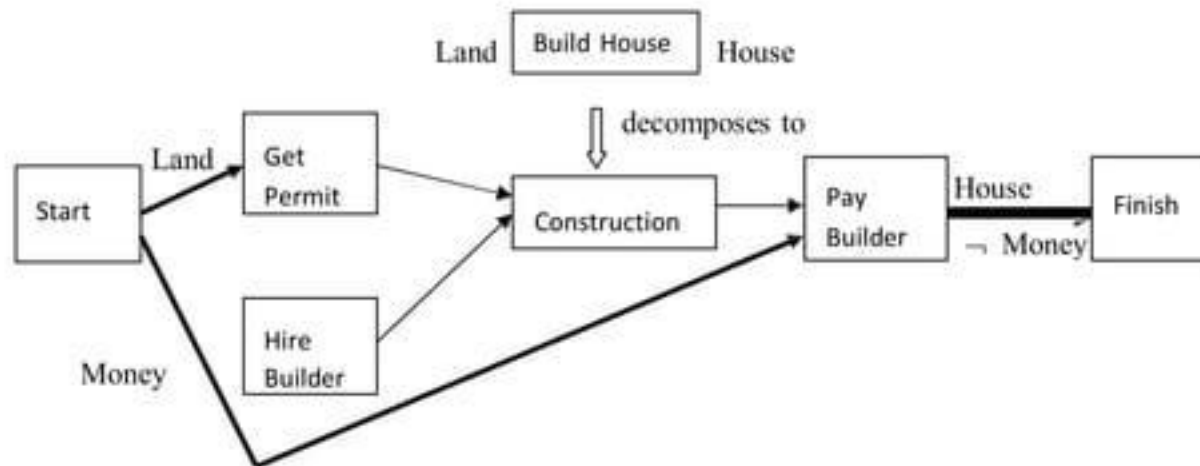
- The left hand margin lists the three resources
- Actions are shown aligned horizontally with the resources they consume.
- There are two possible schedules, depending on which assembly uses the engine station first.
- One simple but popular heuristic is the minimum slack algorithm.
- it schedules actions in a greedy fashion.
- On each iteration, it considers the unscheduled actions that have had all their predecessors scheduled and schedules the one with the least slack for the earliest possible start.
- It then updates the ES and LS times for each affected action and repeats.
- The heuristics is based on the same principle as the most-constrained variable heuristic in constraint satisfaction.

3.4.2 Hierarchical Task Network Planning:

- One of the most pervasive ideas for dealing with complexity is Hierarchical Decomposition.
- The key benefit of hierarchical structure is that, at each level of the hierarchy is reduced to a small number of activities at the next lower level
- So that the computational cost of finding the correct way to arrange those activities for the current problem is small.
- A planning method based on Hierarchical Task Networks or HTNs.
- This approach we take combines ideas from both partial-order planning and the area known as "HTN planning".
- In HTN planning, the initial plan, which describes the problem, is viewed as very high-level description of what is to be done. **For Example:** - Building a House.
- Plans are refined by applying a action decompositions.
- Each action decompositions reduces a high-level action to a partially ordered set of lower-level actions

3.4.2.1 Representing action decompositions:

- The following diagram shows the decomposition of a Building a house action.



- In pure HTN planning, plans are generated only by successive action decompositions.
- Therefore the HTN views planning as a process of making an activity description more concrete, rather than a process of constructing an activity description, starting from the empty activity.
- The action decompositions are represented as, action decompositions methods are stored in a plan library
- From which they are extracted and instantiated to fit the needs of the plan being constructed.
- Each method is an expression of the form Decompose (a, d).
- It means that an action a can be decomposed into the plan d, which is represented as a partial ordered plan.
- The following table shows the action descriptions for the house-building problem and a detailed decomposition for the BuildHouse action.
- The start action of the decomposition supplies all those preconditions of actions in the plan that are not supplied by other actions, such a things called external preconditions.
- In our example external preconditions are land and money.
- Similarly, the external effects, which are the preconditions of Finish, are all those effects of actions in the plan that are not negated by other actions.

Action (BuyLand, PRECOND: Money, EFFECT: Land \wedge \neg Money)

Action (GetLoan, PRECOND: GoodCredit, EFFECT: Money \wedge Mortgage)

Action (BuildHouse, PRECOND: Land, EFFECT: House)

Action (GetPermit, PRECOND: Land, EFFECT: Permit)

Action (HireBuilder, EFFECT: Contract)

Action (Construction, PRECOND: Permit \wedge Contract, EFFECT: HouseBuilt \wedge \neg Permit)

Action (PayBuilder, PRECOND: Money \wedge HouseBuilt, EFFECT: \neg Money \wedge House \wedge \neg Contract)

Decompose (BuildHouse,

Plan (Steps : {S1: GetPermit, S2: HireBuilder, S3: Construction, S4: PayBuilder}

ORDERINGS: {Start \cdot S1 \cdot S3 \cdot S4 Finish, Start \cdot S2 \cdot S3},

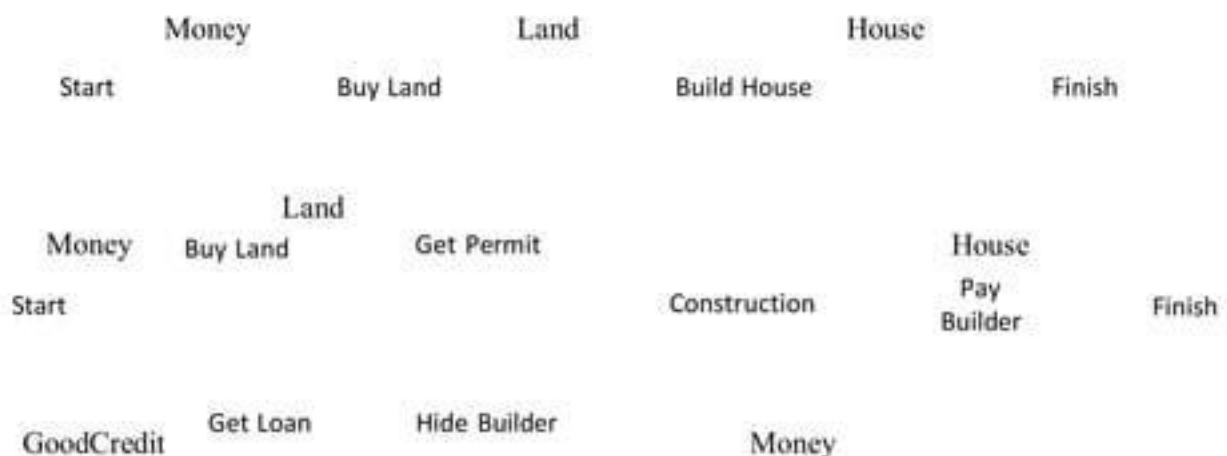
Links: {Start Land S1, Start Money S4, S1 permit S3, S2 Contract S3, S3 HouseBuilt S4, S4 House Finish, S4 \neg Money Finish}))

- Decomposition should be a correct implementation of the action.

- A plan library could contain several decompositions for any given high-level action.
- Decomposition should be a correct plan, but it could have additional preconditions and effects beyond those stated in the high-level action description.
- The precondition of the high-level action should be the intersection of the external preconditions of its decomposition.
- In which two other forms of information hiding should be noted as,
- First the high-level description completely ignores all internal effects of the decompositions
- Second the high-level description does not specify the intervals "inside" the activity during which the high-level preconditions are effects must hold.
- Information hiding of this kind is essential if hierarchical planning is to reduce complexity.

3.4.2.2 Modifying the planner for decomposition:

- In this we will see how to modify the Partial Order Planning to incorporate HTN planning.
- We can do that by modifying the POP successor function to allow decomposition methods to be applied to the current partial plan P.
- The new successor plans are formed by first selecting some non-primitive action a' in P and then, for any Decompose (a, d) method from the plan library such that a and a' unify with substitution θ , replacing a' with $d' = \text{SUBST}(\theta, d)$
- The following diagram shows the decomposition of a high-level action within an existing plan.
- Where The BuildHouse action is replaced by the decomposition from the above example.
- The external precondition land is supplied by the existing causal link from BuyLand.
- The external precondition Money remains open after the decomposition step, so we add a new action, GetLoan.
- To be more precise follow the below steps,
 - First the action a' is removed from P. Then for each step S in the decomposition d'
 - Second step is to hook up the ordering constraints for a' in the original plan to the steps in d' .
 - Third and final step is to hook up casual links.



- This completes the additions required for generating decompositions in the context of the POP Planner.

3.4.3 Planning and Acting in Non-deterministic domains:

- So far we have considered only classical planning domains that are fully observable, static and deterministic.
- Furthermore we have assumed that the action descriptions are correct and complete.
- Agents have to deal with both incomplete and incorrect information.
- Incompleteness arises because the world is partially observable, non-deterministic or both.
- Incorrectness arises because the world does not necessarily match my model of the world.
- The possibility of having complete or correct knowledge depends on how much indeterminacy there is in the world.
- **Bounded indeterminacy** actions can have unpredictable effects, but the possible effects can be listed in the action description axioms.
- **Unbounded indeterminacy** the set of possible preconditions or effects either is unknown or is too large to be enumerated completely.
- **Unbounded indeterminacy** is closely related to the **qualification problem**.
- There are four planning methods for handling indeterminacy.
- The following planning methods are suitable for bounded indeterminacy,
 - **Sensorless Planning:-**
 - Also called as **Confront Planning**
 - This method constructs standard, sequential plans that are to be executed without perception.
 - This algorithm must ensure that the plan achieves the goal in all possible circumstances, regardless of the true initial state and the actual action outcomes.
 - It relies on **coercion** – the idea that the world can be forced into a given state even when the agent has only partial information about the current state.
 - Coercion is not always possible.
 - **Conditional Planning:-**
 - Also called as **Contingency planning**
 - This method constructs a conditional plan with different branches for the different contingencies that could arise.
 - The agent plans first and then executes the plan as produced.
 - The agents find out which part of the plan to execute by including **sensing actions** in the plan to test for the appropriate conditions.
- The following planning methods are suitable for Unbounded indeterminacy,
 - **Execution Monitoring and Replanning:-**
 - In this, the agent can use any of the preceding planning techniques to construct a plan.
 - It also uses **Execution Monitoring** to judge whether the plan has a provision for the actual current situation or need to be revised.
 - **Replanning** occurs when something goes wrong.
 - In this the agent can handle unbounded indeterminacy.
 - **Continuous Planning:-**
 - It is designed to persist over a lifetime.
 - It can handle unexpected circumstances in the environment, even if these occur while the agent is in the middle of constructing a plan.

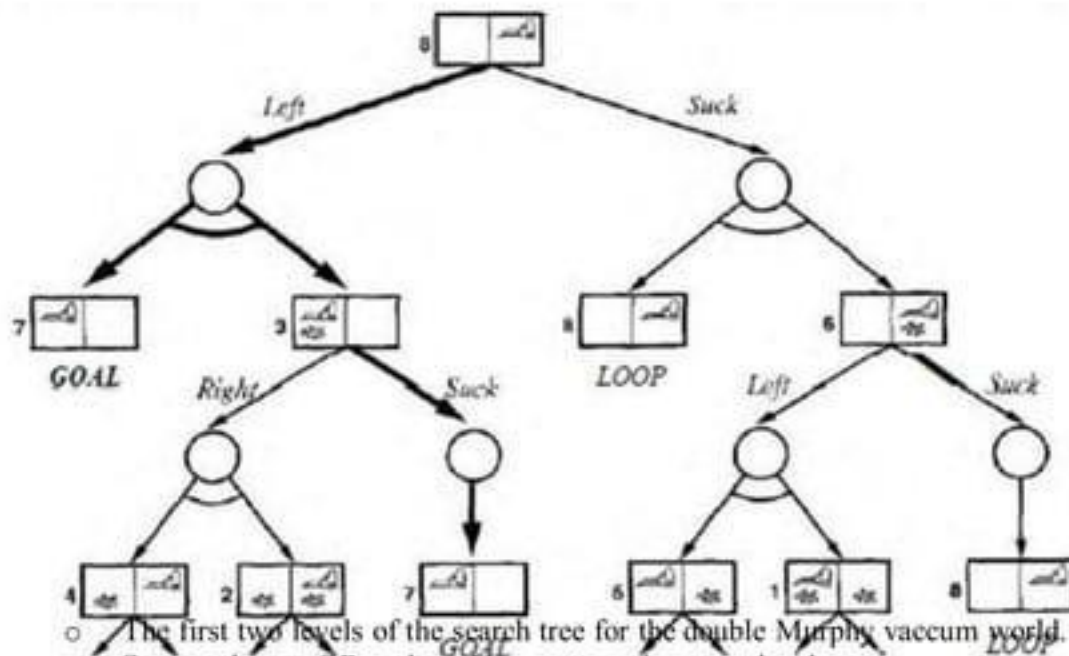
- It can also handle the abandonment of goals and the creation of additional goals by **goal formulation**.

3.4.4 Conditional Planning:-

- Conditional planning is a way to deal with uncertainty by checking what is actually happening in the environment at predetermined points in the plan.
- Conditional planning is simplest to explain for fully observable environments
- The partially observable case is more difficult to explain in this conditional planning.

3.4.4.1 Conditional planning in fully observable environments:

- Full observability means that the agent always knows the current state.
- CP in fully observable environments (FOE)
 - initial state : the robot in the right square of a clean world;
 - the environment is fully observable: $AtR \wedge CleanL \wedge CleanR$.
 - The goal state : the robot in the left square of a clean world.
 - Vacuum world with actions *Left*, *Right*, and *Suck*
 - Disjunctive effects: Action (*Left*, PRECOND : AtR , EFFECT : $AtL \wedge \neg AtR$)
 - Modified Disjunctive effects : Action (*Left*, PRECOND : AtR , EFFECT : $AtL \vee AtR$)
 - Conditional effects: Action(*Suck*, Precond: , Effect: (when AtL : $CleanL$) \wedge (when AtR : $CleanR$)
 - Action (*Left*, Precond: AtR , Effect: $AtL \vee (AtL \wedge \text{when } CleanL: !CleanL)$)
 - Conditional steps for creating conditional plans:
 - if test then planA else planB
 - e.g., if $AtL \wedge CleanL$ then *Right* else *Suck*
 - The search tree for the vacuum world is shown in the following figure



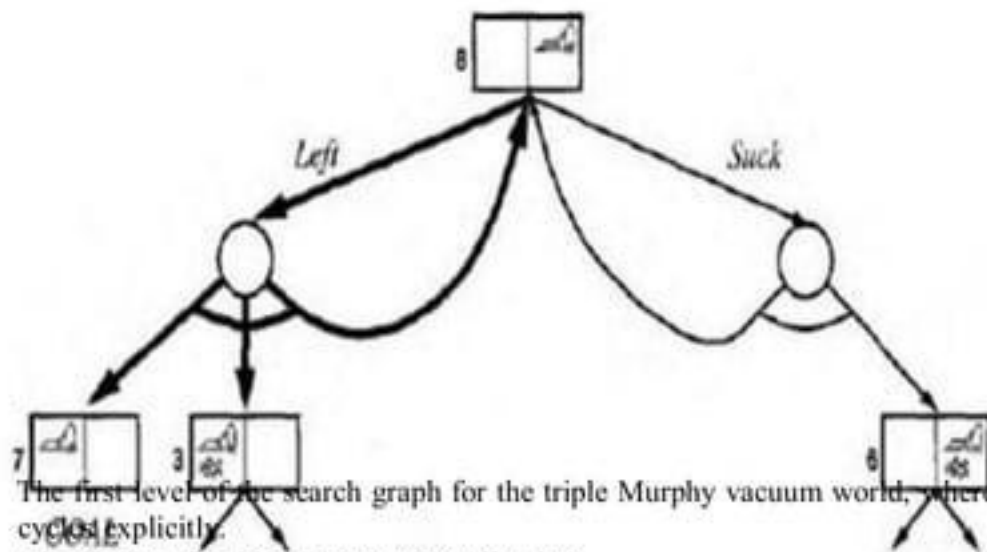
- Chance nodes, shown as circles, are AND nodes where every outcome must be handled, as indicated by the arc linking the outgoing branches.
- The solution is shown as **bold lines** in the tree.
- The following table shows the recursive depth first algorithm for AND-OR graph search.

function AND-OR-GRAPH-SEARCH(*problem*) **returns** a conditional plan, or failure
 OR-SEARCH(INITIAL-STATE[*problem*], *problem*, [])

function OR-SEARCH(*state*, *problem*, *path*) **returns** a conditional plan, or failure
if GOAL-TEST[*problem*](*state*) **then return** the empty plan
if *state* is on *path* **then return** failure
for each *action*, *state-set* **in** SUCCESSORS[*problem*](*state*) **do**
 plan ← AND-SEARCH(*state-set*, *problem*, [*state* | *path*])
 if *plan* ≠ failure **then return** [*action* | *plan*]
return failure

function AND-SEARCH(*state-set*, *problem*, *path*) **returns** a conditional plan, or failure
for each *s_i* **in** *state-set* **do**
 plan_i ← OR-SEARCH(*s_i*, *problem*, *path*)
 if *plan* = failure **then return** failure
return [if *s₁* **then** *plan*, **else if** *s₂* **then** *plan*, **else ... if** *s_{n-1}* **then** *plan*, -, **else** *plan*,]

- The following figure shows the part of the search graph,
- clearly there are no longer any acyclic solutions, and AND-OR-GRAPH-SEARCH would return with failure, there is however a cyclic solution, which is keep trying Left until it works.



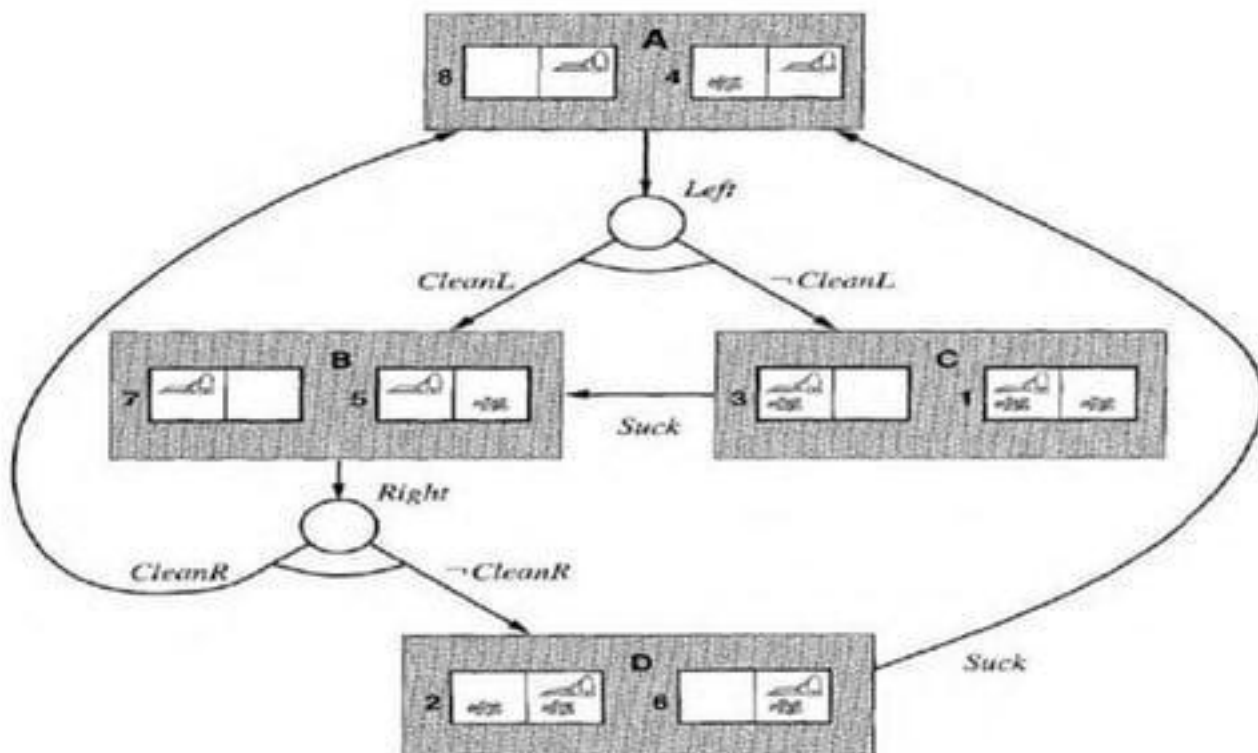
- The first level of the search graph for the triple Murphy vacuum world, where we have shown cycles explicitly.
- All solutions for this problem are cyclic plans.

- The cyclic solution is as follows,

$[L_1 : \text{Left, if } AtR \text{ then } L_1 \text{ else if } CleanL \text{ then } [] \text{ else } Suck]$

Conditional Planning in partially observable environments

- In the initial state of a partially observable planning problem, the agent knows only a certain amount about the actual state.
- The simplest way to model this situation is to say that the initial state belongs to a **state!set**
- The state set is a way of describing the agents initial belief state.
- Determine “both squares are clean” with local dirt sensing
 - the vacuum agent is AtR and knows about R, how about L?
- The following graph shows part of the AND-OR graph for the alternate double Murphy vacuum world,
- In which Dirt can sometimes be left behind when the agent leaves a clean square



- The agent cannot sense dirt in other squares.
- Sets of full state descriptions
 - $\{ (AtR \wedge CleanR \wedge CleanL), (AtR \wedge CleanR \wedge \neg CleanL) \}$
- Logical sentences that capture exactly the set of possible worlds in the belief state.
 - $AtR \wedge CleanR$
- **Knowledge propositions** describing the agent's knowledge

$$K(AtR) \wedge K(CleanR)$$

- **closed-world assumption** - if a knowledge proposition does not appear in the list, it is assumed false.
- Now we need to decide how sensing works.

- There are two choices here,
 - **Automatic sensing:-** Which means that at every time step the agent gets all the variable percepts
 - **Active sensing:-** Which means the percepts are obtained only by executing specific sensory actions such as
 - CheckDirt
 - CheckLocation

*Action(Left, PRECOND: AtR,
EFFECT: $K(AtL) \wedge \neg K(AtR) \wedge \text{when CleanR: } \neg K(CleanR) \wedge$
 $\text{when CleanL: } K(CleanL) \wedge$
 $\text{when } \neg CleanL: K(\neg CleanL))$.*

*Action(CheckDirt, EFFECT:
 $\text{when } AtL \wedge CleanL: K(CleanL) \wedge$
 $\text{when } AtL \wedge \neg CleanL: K(\neg CleanL) \wedge$
 $\text{when } AtR \wedge CleanR: K(CleanR) \wedge$
 $\text{when } AtR \wedge \neg CleanR: K(\neg CleanR))$*

3.4.4.2 Execution Monitoring and Replanning:

- An execution monitoring agent checks its percepts to see whether everything is going to according plan.
- Murphy's law tells us that even the best-laid plans of mice, men and conditional planning agents frequently fail.
- The problem is unbounded indeterminacy – some unanticipated circumstances will always arise for which the agents action description are incorrect.
- Therefore, execution monitoring is a necessity in realistic environments.
- we will consider two kinds of execution monitoring,
 - Simple, but weak form called action monitoring – whereby the agent checks the environment to verify that the next action will work.
 - more complex, but more effective form called plan monitoring – in which the agent verifies the entire remaining plan.
- A **replanning** agent knows what to do when something unexpected happens, call a planner again to come up with a new plan to reach the goal.
- To avoid spending too much time planning, this is usually done by trying to repair the old plan – to find a way from the current unexpected state back onto the plan
- Together **Execution Monitoring and replanning** form a general strategy that can be applied to both fully and partially observable environments
- It can be applied to a variety of planning representations as state-space, partial-order and conditional plans.
- The following table shows a simple approach to state-space planning.
- The planning agent starts with a goal and creates an initial plan to achieve it.
- The agent then starts executing actions one by one.
- The replanning agent keeps track of both the remaining unexpected plan segment plan and the complete original plan whole-plan
- It uses **action monitoring**: before carrying out the next action of plan, the agent examines its percepts to see whether any preconditions of the plan have unexpectedly become unsatisfied.

- If they have, the agent will try to get back on track by replanning a sequence of actions that should take it back to some point in the whole-plan.
- The following table **has an agent that does action monitoring and replanning**
- It uses a complete state-space planning algorithm called PLANNER as a subroutine.
- If the preconditions of the next action are not met, the agent loops through the possible point p in whole-plan, trying to find one that PLANNER can plan a path to.
- This path is called repair.
- If PLANNER succeeds in finding a repair, the agent appends repair and the tail of the plan after p, to create the new plan.
- The agent then returns the first step in the plan.

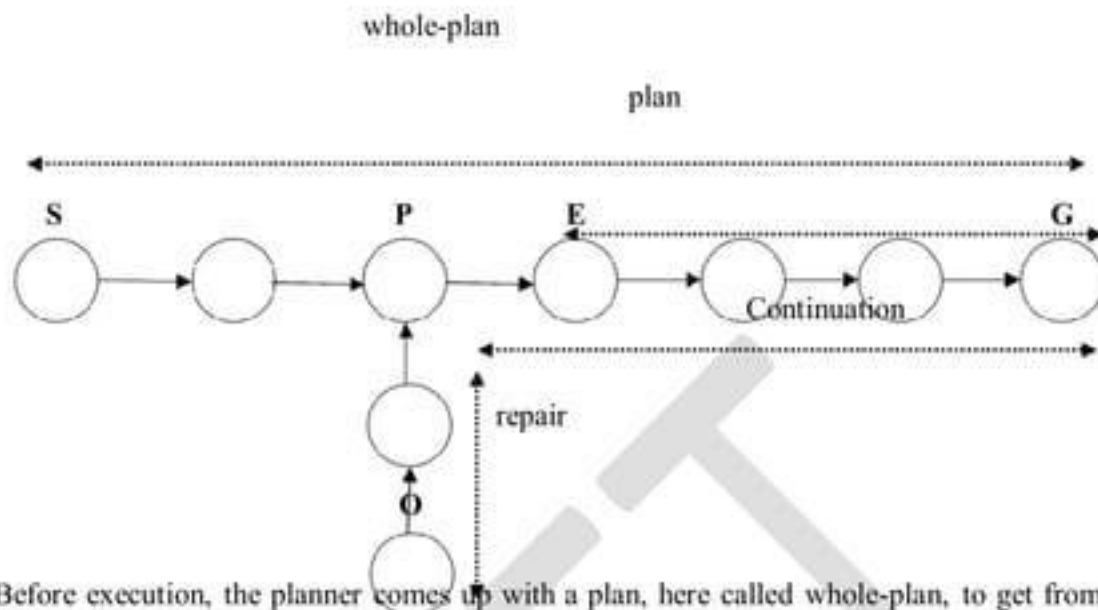
Function REPLANNING-AGENT(percept) **returns** an action

Static: KB, a Knowledge base (includes action descriptions)
 Plan, a plan, initially []
 Whole-plan, a plan, initially []
 Goal, a goal

TELL(KB,MAKE-PERCEPT-SENTENCE(percept,t))
 Current ← STATE-DESCRIPTION(KB,t)
If plan = [] **the**
 whole-plan ← plan ← PLANNER(current,goal,KB)
If PRECONDITIONS(FIRST(plan)) not currently true in KB **then**
 Candidates ← SORT(whole-plan, ordered by distance to current)
 Find state s in candidates such that
 Failure repair ← PLANNER(current,s,KB)
 Continuation ← the tail of whole-plan starting at s
 Whole-plan ← plan ← APPEND(repair, continuation)

Return POP(plan)

- The following diagram shows the schematic illustration of the process.
- The illustration of process is also called as Plan Monitoring.
- The replanner notices that the preconditions of the first action in plan are not satisfied by the current state.
- It then calls the planner to come up with a new subplan called repair that will get from the current situation to some state s on whole-plan.



- Before execution, the planner comes up with a plan, here called whole-plan, to get from S to G.
- The agent executes the plan until the point Marked E.
- Before executing the remaining plan, it checks preconditions as usual and finds that it is actually in state O rather than state E.
- It then calls its planning algorithm to come up with repair, which is a plan to get from O to some point P on the original whole-plan.
- The new plan now becomes the concatenation of repair and continuation.
- For example:-
 - Problem of achieving a chair and table of matching color

Init(Color(Chair, Blue) A Color(Table, Green)
^ ContainsColor(BC, Blue) A PaintCan(BC))
^ ContainsColor(RC, Red) ^ PaintCan(RC)

Goal(Color(Chair, x) A Color(Table, x))

Action(Paint(object,color),
PRECOND: HavePaint(color)
EFFECT: Color(object, color))

Action(Open(can),
PRECOND: PaintCan(can) A ContainsColor(can,color)
EFFECT: HavePaint(color)

- The agents PLANNER should come up with the following plan as,

[Start, Open(BC); Paint(Table, Blue); Finish]

- If the agent constructs a plan to solve the painting problem by painting the chair and table red, only enough paint for the chair
- Plan monitoring
 - Detect failure by checking the *preconditions for success* of the *entire remaining* plan
 - Useful when a goal is serendipitously achieved
 - While you're painting the chair, someone comes painting the table with the same color
 - Cut off execution of a doomed plan and don't continue until the failure actually occurs
 - While you're painting the chair, someone comes painting the table with a different color
- If one insists on checking every precondition, it might never get around to actually doing anything
- RP - monitors during execution

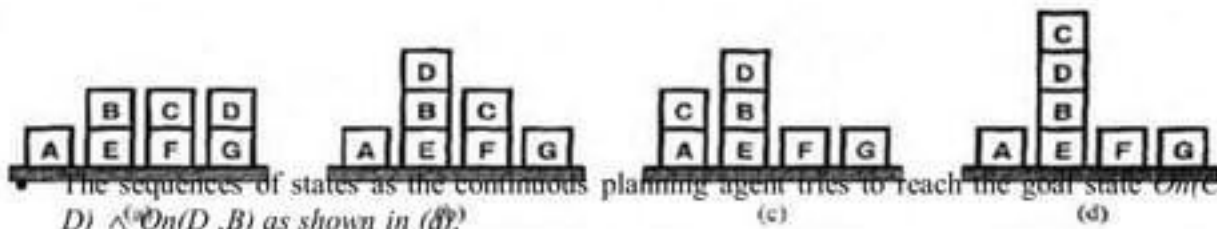
3.4.4.3 Continuous Planning

- Continuous planning agent
 - execute some steps ready to be executed
 - refine the plan to resolve standard deficiencies
 - refine the plan with additional information
 - fix the plan according to unexpected changes
 - recover from execution errors
 - remove steps that have been made redundant
- Goal \rightarrow Partial Plan \rightarrow Some actions \rightarrow Monitoring the world \rightarrow New Goal
- The continuous planning agent monitors the world continuously, updating its world model from new percepts even if its deliberations are still continuing.
- For example:-
 - use the blocks world domain problem
 - The action we will need is $\text{Move}(x, y)$, which moves block x onto block y , provided that both are clear.
 - The following is the action schema,

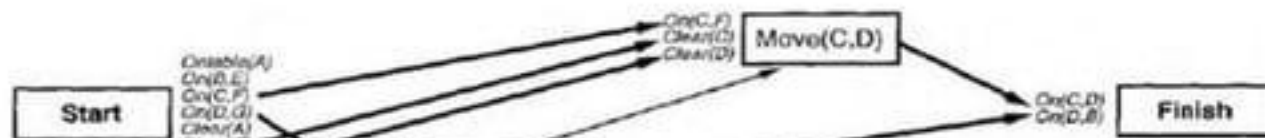
Action ($\text{Move}(x, y)$),

$\text{PRECOND: Clear}(x) \wedge \text{Clear}(y) \wedge \text{On}(x, z)$,

$\text{EFFECT: On}(x, y \wedge \text{Clear}(z) \wedge \neg \text{Clear}(y) \wedge \neg \text{On}(x, z))$
 - Goal: $\text{On}(C, D) \wedge \text{On}(D, B)$
 - *Start* is used as the label for the current state
 - The following seven diagram shows the continuous planning agent approach towards the goal
 - Plan and execution
 - Steps in execution:
 - Ordering - $\text{Move}(D, B)$, then $\text{Move}(C, D)$
 - Another agent did $\text{Move}(D, B)$ - *change the plan*
 - Remove the redundant step
 - Make a mistake, so $\text{On}(C, A)$
 - Still one open condition
 - *Planning one more time* - $\text{Move}(C, D)$
 - Final state: start \rightarrow finish



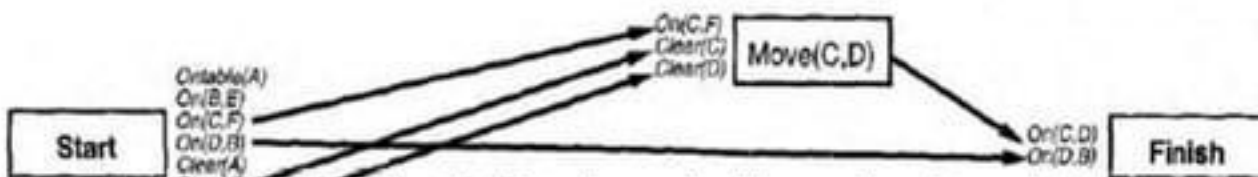
- The start state is (a).
- At (b), another agent has interfered, putting D on B.
- At (c), the agent has executed $Move(C, D)$ but has failed, dropping C on A instead.
- It retries $Move(C, D)$, reaching the goal state (d).



- The initial plan constructed by the continuous planning agent.
- The plan is indistinguishable, so far, from that produced by a normal POP.



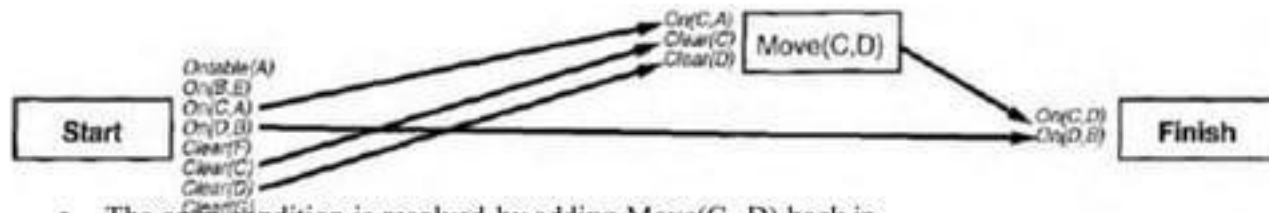
- After someone else moves D onto B, the unsupported links supplying $Clear(B)$ and $On(D, G)$ are dropped, producing this plan.



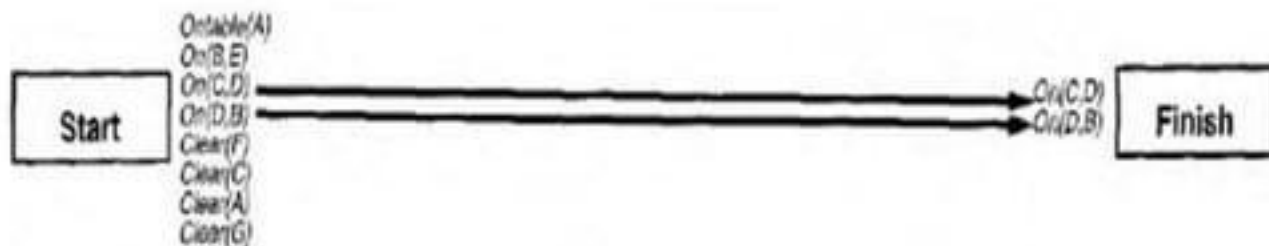
- The link supplied by $Move(D, B)$ has been replaced by one from $Start$, and the new-redundant step $Move(D, B)$ has been dropped.



- After Move(C, D) is executed and removed from the plan, the effects of the Start step reflect the fact that C ended up on A instead of the intended D.
- The goal precondition On(C, D) is still open.



- The open condition is resolved by adding Move(C, D) back in.



- After Move(C, D) is executed and dropped from the plan, the remaining open condition On(C, D) is resolved by adding a causal link from the new start step.
- Now the plan is completed.
- From this example, we can see that continuous planning is quite similar to POP.
- On each iteration, the algorithm finds something about the plan that needs fixing a so-called **plan-flaw** and fixes it.
- The POP algorithm can be seen as a flaw-removal algorithm where the two flaws are open preconditions and causal conflicts.
- On the other hand, the continuous planning agent addresses a much broader range of flaws as follows,
 - Missing goals
 - Open precondition
 - Causal conflicts
 - Unsupported links
 - Redundant actions
 - Unexecuted actions
 - Unnecessary historical goal
- The following table shows the continuous-POP-Agent algorithm

Function CONTINUOUS-POP-AGENT (percept) **returns** an action

Static: plan, a plan, initially with just Start, Finish

Action ← NoOp (the default)

EFFECTS [Start] = UPDATE(EFFECTS [Start], percept)

REMOVE-FLAW (plan) // possibly updating action

Return action

- It has a cycle of “perceive, remove flaw act”
- It keeps a persistent plan in its KB, and on each turn it removes one ,flaw from the plan.
- It then takes an action and repeats the loop.

- It is a continuous partial-order planning agent.
- After receiving a percept the agent removes flaw from its constantly updated plan and then returns an action.
- Often it will take many steps of flaw-removal planning, during which it returns NoOp, before it is ready to take a real action.

3.4.4.4 Multiagent Planning

- So far we have dealt with **single-agent environments**
- Multiagent environments can be **cooperative** or **competitive**.
- For example:-
 - the problem is team planning in double tennis.
- Plans can be constructed that specify actions for both players on the team
- Our objective is to construct plans efficiently.
- To do this we need requires some form of **coordination**, possibly achieved by **communication**.
- The following table shows the double tennis problem,


Agents(A, B) ← declares that there are two agents

Init(*At*(A, [Left, Baseline]) ∧ *At*(B, [Right, Net]) ∧
Approaching(Ball, [Right, Baseline]) ∧ *Partner*(A, B) ∧ *Partner*(B, A)
Goal(*Returned*(Ball) ∧ *At*(agent, [x, Net]))

Action(*Hit*(agent, Ball),
 PRECOND: *Approaching*(Ball, [x, y]) ∧ *At*(agent, [x, y]) ∧
Partner(agent, partner) ∧ ¬ *At*(partner, [x, y])
 EFFECT: *Returned*(Ball))

Action(*Go*(agent, [x, y]),
 PRECOND: *At*(agent, [a, b]),
 EFFECT: *At*(agent, [x, y]) ∧ ¬ *At*(agent, [a, b]))

• In the above table, Two agents are playing together and can be in one of four locations as follows,



- [Left, Baseline]
- [Right, Baseline]
- [Left, Net]
- [Right, Net]
- The ball can be returned if exactly one player is in the right place.

Cooperation: Joint goals and plans

- An agent (A, B) declares that there are two agents, A and B who are participating in the plan.
- Each action explicitly mentions the agent as a parameter, because we need to keep track of which agent does what.
- A solution to a multiagent planning problem is a **joint plan** consisting of actions for each agent

- A joint plan is a solution if the goal will be achieved when each agent performs its assigned actions.
- The following plan is a solution to the tennis problem
 - PLAN 1 :
 - $A : [Go(A, [Right, Baseline]), Hit(A, Ball)]$
 - $B : [NoOp(B), NoOp(B)]$.
- If both agents have the same KB, and if this is the only solution, then everything would be fine; the agents could each determine the solution and then jointly execute it.
- Unfortunately for the agents, there is another plan that satisfies the goal just as well as the first
 - PLAN 2:
 - $A : [Go(A, [Left, Net]), NoOp(A)]$
 - $B : [Go(B, [Right, baseline]), Hit(B, Ball)]$
- If A chooses plan 2 and B chooses plan 1, then nobody will return the ball.
- Conversely, if A chooses 1 and B chooses 2, then they will probably collide with each other; no one returns the ball and the net may remain uncovered.
- So the agents need a mechanism for **coordination** to reach the same joint plan

Multibody Planning:

- concentrates on the construction of correct joint plans, deferring the coordination issue for the time being, we call this **Multibody planning**
- Our approach to multibody planning will be based on partial-order planning
- we will assume full observability, to keep things simple
- There is one additional issue that doesn't arise in the single-agent case; the environment is no longer truly **static**.
- Because other agents could act while any particular agent is deliberating.
- Therefore we need **synchronization**
- We will assume that each action takes the same amount of time and that actions at each point in the joint plan are simultaneous.
- At any point in time, each agent is executing exactly one action.
- This set of concurrent actions is called a **joint action**.
- For example, Plan 2 for the tennis problem can be represented as this sequence of joint actions:

$$\langle Go(A, [Left, Net]), Go(B, [Right, baseline]) \rangle$$

$$\langle NoOp(A), Hit(B, Ball) \rangle$$

Coordination Mechanisms:

- The simplest method by which a group of agents can ensure agreement on a joint plan is to adopt a **convention** prior to engaging in joint activity.
- A convention is any constraint on the selection of joint plans, beyond the basic constraint that the joint plan must work if all agents adopt it
- For example
 - the convention "stick to your side of the court" would cause the doubles partners to select plan 2

- the convention "one player always stays at the net" would lead them to plan 1
- In the absence of an applicable convention, agents can use communication to achieve common knowledge of a feasible join plan
- For example:
 - a doubles tennis player could shout "Mine!" or "Yours!" to indicate a preferred joint plan.

Competition:

- Not all multiagent environments involve cooperative agents
- Agents with conflicting utility functions are in **competition** with each other
- One example: chess-playing. So an agent must
 - (a) recognize that there are other agents
 - (b) compute some of the other agent's possible plans
 - (c) compute how the other agent's plans interact with its own plans
 - (d) decide on the best action in view of these interactions