Planning

Chapter 11
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Monkey & Bananas

- A hungry monkey is in a room. Suspended from the roof, just out of his reach, is a bunch of bananas. In the corner of the room is a box. The monkey desperately wants the bananas but he can't reach them. What shall he do?

Monkey & Bananas (2)

- After several unsuccessful attempts to reach the bananas, the monkey walks to the box, pushes it under the bananas, climbs on the box, picks the bananas and eats them.

- The hungry monkey is now a happy monkey.

Planning

- To solve this problem the monkey needed to devise a plan, *a sequence of actions that would allow him to reach the desired goal.*
- Planning is a topic of traditional interest in Artificial Intelligence as it is an important part of many different AI applications, such as robotics and intelligent agents.
- To be able to plan, a system needs to be able to reason about the individual and cumulative effects of a series of actions. This is a skill that is only observed in a few animal species and only mastered by humans.

Planning vs. Problem Solving

- Planning is a special case of Problem Solving (Search).
- Problem solving searches a *state-space* of possible *actions*, starting from an *initial state* and following any path that it believes will lead it the *goal state*. Recording the actions along the path from the initial state to the goal state gives you a plan.
- Planning has two distinct features:
  1. The planner does not have to solve the problem in order (from initial to goal state). It can suggest actions to solve any sub-goals at anytime.
  2. Planners assume that most parts of the world are independent so they can be stripped apart and solved individually (turning the problem into practically sized chunks).

Planning using STRIPS

- The "classical" approach most planners use today is derived from the STRIPS language.
- STRIPS was devised by SRI in the early 1970s to control a robot called Shakey.
- Shakey's task was to negotiate a series of rooms, move boxes, and grab objects.
- The STRIPS language was used to derive plans that would control Shakey's movements so that he could achieve his goals.
- The STRIPS language is very simple but expressive language that lends itself to efficient planning algorithms.
- The representation in Prolog is derived from the original STRIPS representation.

STRIPS Representation

- Planning can be considered as a logical inference problem:
  - a plan is inferred from facts and logical relationships.
- STRIPS represented planning problems as a series of *state descriptions* and *operators* expressed in first-order predicate logic.

State descriptions represent the state of the world at three points during the plan:
- *Initial state*, the state of the world at the start of the problem;
- *Current state*, and
- *Goal state*, the state of the world we want to get to.

Operators are actions that can be applied to change the state of the world.
- Each operator has *outcomes* i.e. how it affects the world.
- Each operator can only be applied in certain circumstances. These are the *preconditions* of the operator.

Planning in Prolog

- To show the development of a planning system we will implement the Monkey and Bananas problem in Prolog using STRIPS.
- When beginning to produce a planner there are certain *representation considerations* that need to be made:
  - How do we represent the state of the world?
  - How do we represent operators?
  - Does our representation make it easy to:
    - check preconditions;
    - alter the state of the world after performing actions; and
    - recognise the goal state?

Representing the World

- In the Monkey&Banana problem we have:
  - *objects*: a monkey, a box, the bananas, and a floor.
  - *locations*: we'll call them a, b, and c.
  - *relations of objects to locations*. For example:
    - the monkey is at location a;
    - the monkey is on the floor;
    - the bananas are hanging;
    - the box is in the same location as the bananas.
- To represent these relations we need to choose appropriate predicates and arguments:
  - at(monkey,a).
  - on(monkey,floor).
  - status(bananas,hanging).
  - at(box,X), at(bananas,X).

Initial and Goal State

- Once we have decided on appropriate state predicates we need to represent the Initial and Goal states.
- Initial State:

```
on(monkey, floor),
on(box, floor),
at(monkey, a),
at(box, b),
at(bananas, c),
status(bananas, hanging).
```

- Goal State:

```
on(monkey, box),
on(box, floor),
at(monkey, c),
at(box, c),
at(bananas, c),
status(bananas, grabbed).
```

I'm a clever monkey.
A
B
C

- Only this last state can be known without knowing the details of the Plan (i.e. how we're going to get there).

Representing Operators

- STRIPS operators are defined as:
  - **NAME**: How we refer to the operator e.g. go(Agent, From, To).
  - **PRECONDITIONS**: What states need to hold for the operator to be applied. e.g. [at(Agent, From)].
  - **ADD LIST**: What new states are added to the world as a result of applying the operator e.g. [at(Agent, To)].
  - **DELETE LIST**: What old states are removed from the world as a result of applying the operator. e.g. [at(Agent, From)].
- We will specify operators within a Prolog predicate **`opn/4`**:

```
opn( go(Agent,From,To),          ←—— Name
     [at(Agent, From)],          ←—— Preconditions
     [at(Agent, To)],            ←—— Add List
     [at(Agent, From)] ).        ←—— Delete List
```

The Frame Problem

- When representing operators we make the assumption that the only effects our operator has on the world are those specified by the add and delete lists.
- In real-world planning this is a hard assumption to make as we can never be absolutely certain of the extent of the effects of an action.
  - This is known in AI as the *Frame Problem.*
- Real-World systems, such as Shakey, are notoriously difficult to plan for because of this problem. Plans must constantly adapt based on incoming sensory information about the new state of the world otherwise the operator preconditions will no longer apply.

All Operators

Operator	Preconditions	Delete List	Add List
go(X,Y)	at(monkey,X)	at(monkey,X)	at(monkey,Y)
	on(monkey, floor)		
push(B,X,Y)	at(monkey,X)	at(monkey,X)	at(monkey,Y)
	at(B,X)	at(B,X)	at(B,Y)
	on(monkey,floor)		
	on(B,floor)		
climb_on(B)	at(monkey,X)	on(monkey,floor)	on(monkey,B)
	at(B,X)		
	on(monkey,floor)		
	on(B,floor)		
grab(B)	on(monkey,box)	status(B,hanging)	status(B,grabbed)
	at(box,X)		
	at(B,X)		
	status(B,hanging)		

Finding a solution

1. Look at the state of the world:
   - Is it the goal state? If so, the list of operators so far is the plan to be applied.
   - If not, go to Step 2.
2. Pick an operator:
   - Check that it has not already been applied (to stop looping).
   - Check that the preconditions are satisfied.

   If either of these checks fails, backtrack to get another operator.
3. Apply the operator:
   1. Make changes to the world: delete from and add to the world state.
   2. Add operator to the list of operators already applied.
   3. Go to Step 1.

Finding a solution in Prolog

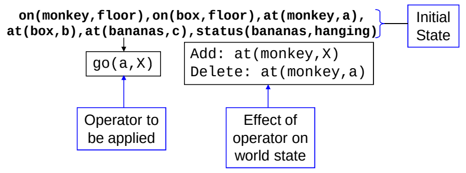
- The main work of generating a plan is done by the **`solve/4`** predicate.

```
    % First check if the Goal states are a subset of the current state.
solve(State, Goal, Plan, Plan):-
     is_subset(Goal, State).

solve(State, Goal, Sofar, Plan):-
     opn(Op, Precons, Delete, Add),   % get first operator
     notmember(Op, Sofar),            % check for looping
     is_subset(Precons, State),       % check preconditions hold
     delete_list(Delete, State, Remainder),  % delete old facts
     append(Add, Remainder, NewState),       % add new facts
     solve(NewState, Goal, [Op|Sofar], Plan).% recurse
```

Representing the plan

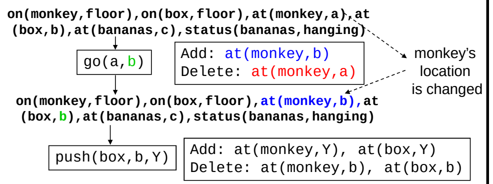
- **`solve/4`** is a *linear planner*: It starts at the initial state and tries to find a series of operators that have the cumulative effect of adding the goal state to the world.
- We can represent its behaviour as a flow-chart.



on(monkey,floor),on(box,floor),at(monkey,a),
at(box,b),at(bananas,c),status(bananas,hanging)
Initial State
go(a,X)
Add: at(monkey,X)
Delete: at(monkey,a)
Operator to be applied
Effect of operator on world state

- When an operator is applied the information in its preconditions is used to instantiate as many of its variables as possible.
- Uninstantiated variables are carried forward to be filled in later.

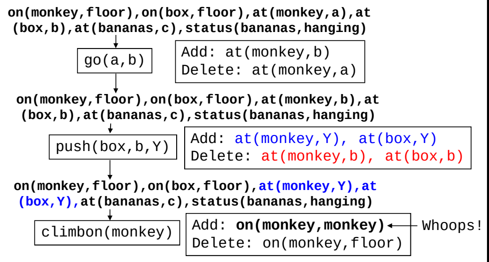
Representing the plan (2)



on(monkey,floor),on(box,floor),at(monkey,a),at
(box,b),at(bananas,c),status(bananas,hanging)
go(a,b)
Add: at(monkey,b)
Delete: at(monkey,a)
monkey's location is changed
on(monkey,floor),on(box,floor),at(monkey,b),at
(box,b),at(bananas,c),status(bananas,hanging)
push(box,b,Y)
Add: at(monkey,Y), at(box,Y)
Delete: at(monkey,b), at(box,b)

- `solve/4` chooses the push operator this time as it is the next operator after `go/2` stored in the database and `go(a,X)` is now stored in the SoFar list so `go(X,Y)` can't be applied again.
- The preconditions of `push/3` require the monkey to be in the same location as the box so the variable location, X, from the last move inherits the value b.

Representing the plan (3)



on(monkey,floor),on(box,floor),at(monkey,a),at
(box,b),at(bananas,c),status(bananas,hanging)
go(a,b)
Add: at(monkey,b)
Delete: at(monkey,a)
on(monkey,floor),on(box,floor),at(monkey,b),at
(box,b),at(bananas,c),status(bananas,hanging)
push(box,b,Y)
Add: at(monkey,Y), at(box,Y)
Delete: at(monkey,b), at(box,b)
on(monkey,floor),on(box,floor),at(monkey,Y),at
(box,Y),at(bananas,c),status(bananas,hanging)
climbon(monkey)
Add: on(monkey,monkey)
Delete: on(monkey,floor)
Whoops!

- The operator only specifies that the monkey must climb on something in the same location; not that it must be something other than itself!
- This instantiation fails once it tries to satisfy the preconditions for the **`grab/1`** operator. **`solve/4`** backtracks and matches **`climbon(box)`** instead.

Representing the plan (4)

```
on(monkey,floor),on(box,floor),at(monkey,a),at
(box,b),at(bananas,c),status(bananas,hanging)
        go(a,b)
on(monkey,floor),on(box,floor),at(monkey,b),at
(box,b),at(bananas,c),status(bananas,hanging)
        push(box,b,Y)      Y = c
on(monkey,floor),on(box,floor),at(monkey,Y),at
(box,Y),at(bananas,c),status(bananas,hanging)
        climbon(box)
on(monkey,box),on(box,floor),at(monkey,Y),at(b
ox,Y),at(bananas,c),status(bananas,hanging)
        grab(bananas)      Y = c
on(monkey,box),on(box,floor),at(monkey,c),at(b
ox,c),at(bananas,c),status(bananas,grabbed)  <--  GOAL
```

For the monkey to grab the bananas it must be in the same location, so the variable location Y inherits c. This creates a complete plan.

Monkey & Bananas Program

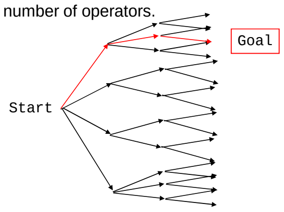
Putting all the clauses together, plus the following, we may easily obtain a plan using the query test(Plan).

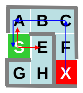
```
test(Plan) :- solve([ on(monkey, floor),
                      on(box, floor),
                      at(monkey, a),
                       at(box, b),
                      at(bananas, c),
                      status(bananas, hanging) ],
                    [ status(bananas, grabbed) ],
                    [], Plan).

?- test(Plan).
Plan = [grab(banana),
        climbon(box),
        push(box,b,c),
        go(a,b)]
```

Inefficiency of forwards planning

- Linear planners like this, that progress from the initial state to the goal state can be unsuitable for problems with a large number of operators.





- Searching backwards from the Goal state usually eliminates spurious paths.
  - This is also called **Means Ends Analysis.**

Backward state-space search

- To solve a list of *Goals* in state *State*, leading to *CurrentPlan*, do:
  - If all the *Goals* are in *State* then *Plan = CurrentPlan*. *Otherwise* do the following:
    1. Select a still unsolved *Goal* from *Goals*.
    2. Find an *Action* that adds *Goal* to the current state.
    3. Enable *Action* by solving recursively the preconditions of *Action*, giving *PrePlan*.
    4. *PrePlan* plus *Action* are recorded into CurrentPlan and the program goes to step 1.
  - i.e. we search backwards from the Goal state, generating new states from the preconditions of actions, and checking to see if these are facts in our initial state.

Backward state-space search

- Backward state-space search will usually lead straight from the Goal State to the Initial State as the branching factor of the search space is usually larger going forwards compared to backwards.
- However, more complex problems can contain operators with different conditions so the backward search would be required to choose between them.
  - It would require *heuristics*.
- Also, linear planners like these will blindly pursue sub-goals without considering whether the changes they are making undermine future goals.
  - they need someway of *protecting their goals*.

Implementing Backward Search

```
plan(State, Goals,[],State):-            % Plan is empty
   satisfied( State, Goals).             % Goals true in State

plan(State, Goals, Plan, FinalState):-
   append(PrePlan,[Action|PostPlan],Plan),   % Divide plan

   member(Goal,Goals),
   notmember(Goal,State),           % Select a goal

   opn(Action,PreCons,Add),
   member(Goal,Add),                % Relevant action

   can(Action),                     % Check action is possible

   plan(State,PreCons,PrePlan,MidState1),    % Link Action to
                                               Initial State.

   apply(MidState1,Action,MidState2),        % Apply Action
   plan(MidState2,Goals,PostPlan,FinalState).
                      % Recurse to link Action to rest of Goals.
```

Implementing Backward Search

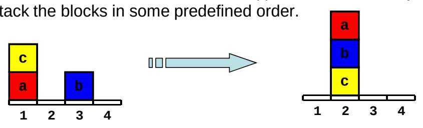
```
opn(move( Block, From, To),                      % Name
   [clear( Block), clear( To), on( Block, From)], % Precons
   [ on(Block,To), clear(From)]).                % Add List

can(move(Block,From,To)):-
     is_block( Block),    % Block to be moved
     object( To),         % "To" is a block or a place
     To \== Block,        % Block cannot be moved to itself
     object( From),       % "From" is a block or a place
     From \== To,         % Move to new position
     Block \== From.      % Block not moved from itself


satisfied(_,[]).               % All Goals are satisfied
satisfied(State,[Goal|Goals]):-
     member(Goal,State),        % Goal is in current State
     satisfied(State,Goals).
```

Blocks World

- Blocks World is THE classic Toy-World problem of AI. It has been used to develop AI systems for vision, learning, language understanding, and planning.
- It consists of a set of solid blocks placed on a table top (or, more often, a simulation of a table top). The task is usually to stack the blocks in some predefined order.

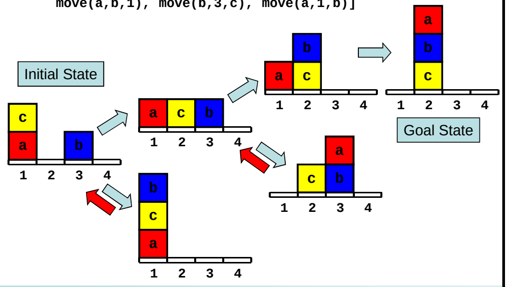


- It lends itself well to the planning domain as the rules, and state of the world can be represented simply and clearly.
- Solving simple problems can often prove surprisingly difficult so it provides a robust testing ground for planning systems.

Protecting Goals

- Backward Search produces a very inefficient plan:

```
Plan = [move(b,3,c), move(b,c,3),move(c,a,2), move(a,1,b),
        move(a,b,1), move(b,3,c), move(a,1,b)]
```



Protecting Goals

- The plan is inefficient as the planner pursues *different goals* at *different times*.
- After achieving one goal (e.g. on(b,c) where on(c,a)) it must destroy it in order to achieve another goal (e.g. clear(a)).
- It is difficult to give our planner *foresight* so that it knows which preconditions are needed to satisfy later goals.
- *Instead we can get it to protect goals it has already achieved*.
- This forces it to backtrack and find an alternate plan if it finds itself in a situation where it must destroy a previous goal.
- Once a goal is achieved it is added to a *Protected* list and then every time a new *Action* is chosen the Action's *delete list* is checked to see if it will remove a Protected goal.

Best-first Planning

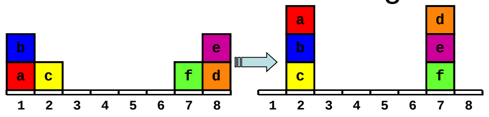
- So far, our planners have generated plans using *depth-first search* of the space of possible actions.
- As they use no domain knowledge when choosing alternative paths, the resulting plans are very inefficient.
- There are three ways *heuristic guidance* could be incorporated;
  1. *The order in which goals are pursued.* For example, when building structures you should always start with the foundations then work up.
  2. *Choosing between actions that achieve the same goal.* You might want to choose an action that achieves as many goals as possible, or has preconditions that are easy to satisfy.
  3. *Evaluating the cost of being in a particular state.*

Best-first Planning

- The state space of a planning problem can be generated by
  - regressing a goal through all the actions that satisfy that goal, and
  - generating all possible sets of sub-goals that satisfy the preconditions for this action.

  = this is known as *Goal Regression*.
- The *'cost'* of each of these sets of sub-goals can then be evaluated.
  - cost = a measure of how difficult it will be to complete a plan when a particular set of goals are left to be satisfied.
- By ordering these sets of sub-goals based on the heuristic evaluation function and *always choosing the 'cheapest' set*, our planner can derive a plan using *best-first search*.

Partial Order Planning



- Our current planners will *always consider all possible orderings of actions* even when they are completely independent.
- In the above example, the only important factor is that *the two plans do not interact.*
  - The order in which moves alternate between plans is unimportant.
  - Only the order within plans matters.
- Goals can be generated without precedence constraints (e.g. on(a,b), on(d,e)) and then left unordered *unless* later pre-conditions introduce new constraints (e.g. on(b,c) must precede on(a,b) as \+clear(a)).

  = A *Partial-Order Planner* (or Non-Linear Planner).

Summary

- A Plan is a sequence of actions that changes the state of the world from an Initial state to a Goal state.
- Planning can be considered as a *logical inference problem*.
- *STRIPS* is a classic planning language.
  - It represents the state of the world as a list of facts.
  - *Operators* (actions) can be applied to the world if their preconditions hold.
    - The effect of applying an operator is to *add* and *delete* states from the world.
- A linear planner can be easily implemented in Prolog by:
  - representing operators as `opn(Name,[PreCons],[Add],[Delete]).`
  - choosing operators and applying them in a depth-first manner,
  - using backtracking-through-failure to try multiple operators.

Summary

- *Backward State-Space* can be used to plan backwards from the Goal state to the Initial state.
  - It often creates more direct plans,
  - but is still inefficient as it pursues goals in any order.
- *Blocks World* is a very common Toy-World problem in AI.
- *Goal Protection*: previously completed goals can be protected by making sure that later actions do not destroy them.
  - Forces generation of direct plans through backtracking.
- *Best-first Planning* can use knowledge about the problem domain, the order of actions, and the cost of being in a state to generate the 'cheapest' plan.
- *Partial-Order Planning* can be used for problems that contain multiple sets of goals that do not interact.