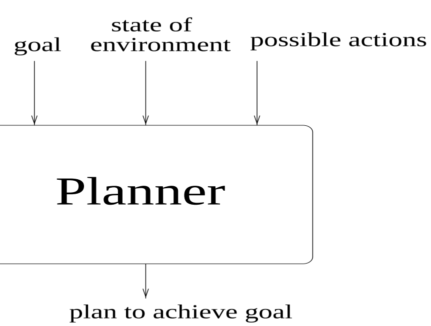
PLANNING

1 What is Planning?

- Key problem facing *agent* is *deciding what to do*.
- We want agents to be *taskable*: give them *goals* to achieve, have them decide for themselves how to achieve them.
- Basic idea is to give an agent:
  - representation of goal to achieve;
  - knowledge about what actions it can perform; and
  - knowledge about state of the world;

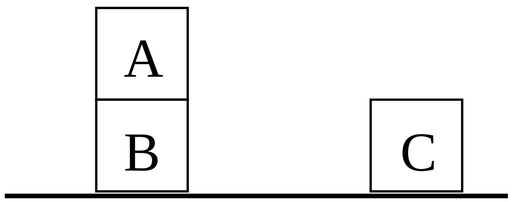
  and to have it generate a *plan* to achieve the goal.
- Essentially, this is

  automatic programming.



- Question: How do we *represent*. . .
  - goal to be achieved;
  - state of environment;
  - actions available to agent;
  - plan itself.
- We show how all this can be done in first-order logic. . .

- We'll illustrate the techniques with reference to the *blocks world*.
- Contains a robot arm, 3 blocks (A, B and C) of equal size, and a table-top.
- Initial state:



- To represent this environment, need an *ontology*.

$On(x, y)$	obj x on top of obj y
$OnTable(x)$	obj x is on the table
$Clear(x)$	nothing is on top of obj x
$Holding(x)$	arm is holding x

- Here is a FOL representation of the blocks world described above:

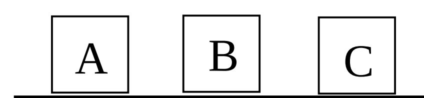
$$Clear(A)$$
$$On(A, B)$$
$$OnTable(B)$$
$$OnTable(C)$$
$$Clear(C)$$

- Use the *closed world assumption*: anything not stated is assumed to be *false*.

- A *goal* is represented as a FOL formula.
- Here is a goal:

$$OnTable(A) \wedge OnTable(B) \wedge OnTable(C)$$

- Which corresponds to the state:



- *Actions* are represented using a technique that was developed in the STRIPS planner.

- Each action has:
  - a *name* which may have arguments;
  - a *pre-condition list* list of facts which must be true for action to be executed;
  - a *delete list* list of facts that are no longer true after action is performed;
  - an *add list* list of facts made true by executing the action.

  Each of these may contain *variables*.

- Example 1:

  The *stack* action occurs when the robot arm places the object x it is holding is placed on top of object y.

$$\begin{array}{ll} & Stack(x, y) \\ \text{pre} & Clear(y) \wedge Holding(x) \\ \text{del} & Clear(y) \wedge Holding(x) \\ \text{add} & ArmEmpty \wedge On(x, y) \end{array}$$

- Example 2:

  The *unstack* action occurs when the robot arm picks an object x up from on top of another object y.

$$\begin{array}{ll} & UnStack(x, y) \\ \text{pre} & On(x, y) \wedge Clear(x) \wedge ArmEmpty \\ \text{del} & On(x, y) \wedge ArmEmpty \\ \text{add} & Holding(x) \wedge Clear(y) \end{array}$$

  Stack and UnStack are *inverses* of one-another.

- Example 3:

  The *pickup* action occurs when the arm picks up an object x from the table.

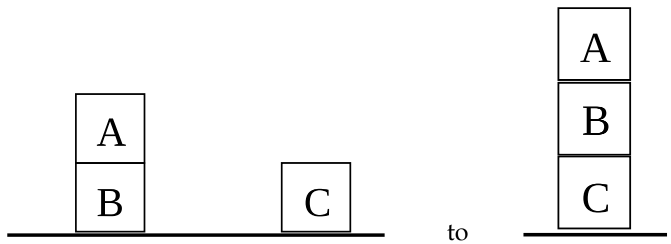
$$\begin{array}{ll} & Pickup(x) \\ \text{pre} & Clear(x) \wedge OnTable(x) \wedge ArmEmpty \\ \text{del} & OnTable(x) \wedge ArmEmpty \\ \text{add} & Holding(x) \end{array}$$

- Example 4:

  The *putdown* action occurs when the arm places the object x onto the table.

$$\begin{array}{ll} & PutDown(x) \\ \text{pre} & Holding(x) \\ \text{del} & Holding(x) \\ \text{add} & Holding(x) \wedge ArmEmpty \end{array}$$

- What is a plan?
  A sequence (list) of actions, with variables replaced by constants.
- So, to get from:



- We need the set of actions:

$$\begin{array}{c} Unstack(A) \\ Putdown(A) \\ Pickup(B) \\ Stack(B, C) \\ Pickup(A) \\ Stack(A, B) \end{array}$$

- In "real life", plans contain conditionals (`IF .. THEN...`) and loops (`WHILE... DO...`), but most simple planners cannot handle such constructs — they construct *linear plans*.
- Simplest approach to planning: *means-ends analysis*.
- Involves backward chaining from goal to original state.
- Start by finding an action that has goal as post-condition.
  Assume this is the *last* action in plan.
- Then figure out what the previous state would have been.
  Try to find action that has *this* state as post-condition.
- *Recurse* until we end up (hopefully!) in original state.


```
function plan(
    d : WorldDesc,        // initial env state
    g : Goal,             // goal to be achieved
    p : Plan,             // plan so far
    A : set of actions    // actions available)
    if d ⊨ g then
        return p
    else
        choose a in A such that
            add(a) ⊨ g and
            del(a) ⊭ g
        set g = pre(a)
        append a to p
        return plan(d, g, p, A)
```

- How does this work on the previous example?

- This algorithm not guaranteed to find the plan…
- … but it is *sound*: If it finds the plan is correct.
- Some problems:
  - negative goals;
  - maintenance goals;
  - conditionals & loops;
  - exponential search space;
  - logical consequence tests;

The Frame Problem

- A general problem with representing properties of actions:

  How do we know exactly what changes as the result of performing an action?

  If I pick up a block, does my hair colour stay the same?
- One solution is to write *frame axioms*.

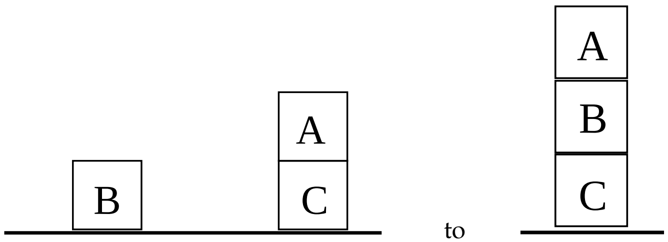
  Here is a frame axiom, which states that SP's hair colour is the same in all the situations s' that result from performing $Pickup(x)$ in situation s as it is in s.

$$\forall s, s'.Result(SP, Pickup(x), s) = s' \Rightarrow HCol(SP, s) = HCol(SP, s')$$

- Stating frame axioms in this way is unfeasible for real problems.
- (Think of all the things that we would have to state in order to cover all the possible frame axioms).
- STRIPS solves this problem by assuming that everything not explicitly stated to have changed remains unchanged.
- We will revisit this problem in a few lectures' time.
- It connects with the general problem of handling incomplete information, and non-monotonic reasoning.

Sussman's Anomaly

- Consider we have the following initial state and goal state:



- What operations will be in the plan?

- Clearly we need to *Stack* B on C at some point, and we also need to *Unstack* A from *C* and *Stack* it on B.
- Which operation goes first?
- Obviously we need to do the *UnStack* first, and the *Stack B* on *C*, but the planner has no way of knowing this.
- It also has no way of "undoing" a partial plan if it leads into a dead end.
- So if it chooses to $Stack(A, C)$ after the *Unstack*, it is sunk.
- This is a big problem with linear planners
- How could we modify our planning algorithm?

- Modify the middle of the algorithm to be:

1. if $d \models g$ then
2.   return p
3. else
4.   choose a in A such that
5. $add(a) \models g$ and
6. $del(a) \not\models g$

6a. $no\_clobber(add(a), del(a), rest\_of\_plan)$

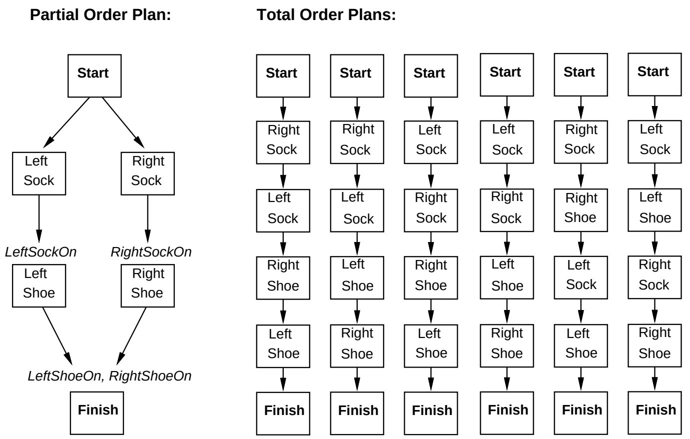
7.   set $g = pre(a)$
8.   append a to p
9.   return $plan(d, g, p, A)$

- But how can we do this?

Partial Order Planning

- The answer to the problem on the previous slide is to use partial order planning.
- Basically this gives us a way of checking before adding an action to the plan that it doesn't mess up the rest of the plan.
- The problem is that in this recursive process, we don't know what the rest of the plan is.
- Need a new representation *partially ordered plans*.

Representation

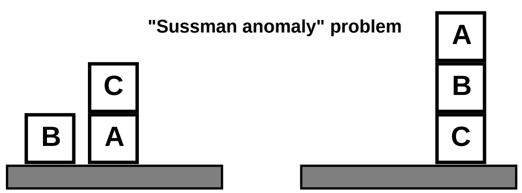


Partially ordered plans

- *Partially ordered* collection of steps with
  - *Start* step has the initial state description as its effect
  - *Finish* step has the goal description as its precondition
  - *causal links* from outcome of one step to precondition of another
  - *temporal ordering* between pairs of steps
- *Open condition* = precondition of a step not yet causally linked
- A plan is *complete* iff every precondition is achieved
- A precondition is *achieved* iff it is the effect of an earlier step and no *possibly intervening* step undoes it

Example

"Sussman anomaly" problem



Start State

Goal State

Clear(x) On(x,z) Clear(y)

PutOn(x,y)

~On(x,z) ~Clear(y) Clear(z) On(x,y)

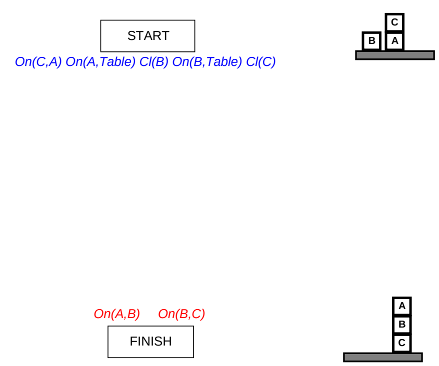
Clear(x) On(x,z)

PutOnTable(x)

~On(x,z) Clear(z) On(x,Table)

+ several inequality constraints

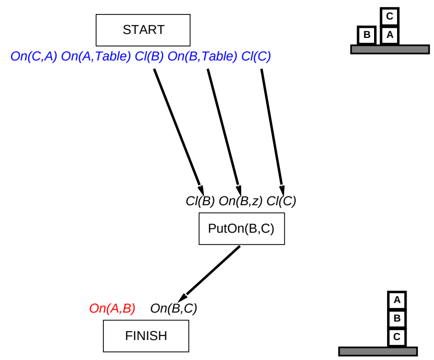
Example (2)



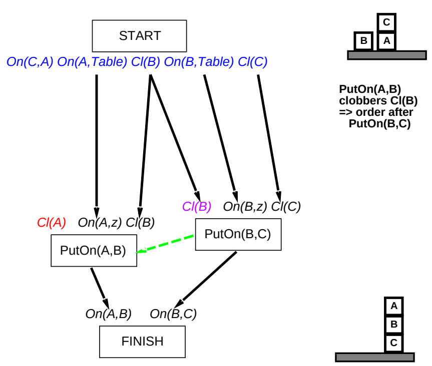
Planning process

- Operators on partial plans:
  - *add a link* from an existing action to an open condition
  - *add a step* to fulfill an open condition
  - *order* one step wrt another to remove possible conflicts
- Gradually move from incomplete/vague plans to complete, correct plans
- Backtrack if an open condition is unachievable or if a conflict is unresolvable

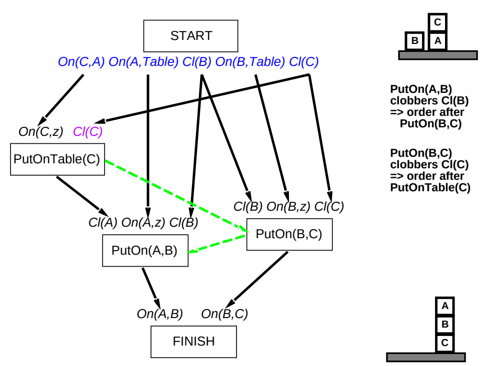
Example (3)



Example (4)



Example (5)



Summary

- This lecture has looked at planning.
- We looked mainly at a logical view of planning, using STRIPS operators.
- We also discussed the frame problem, and Sussman's anomaly.
- Sussman's anomaly motivated some thoughts about partial-order planning.