Context: Plan-Space Planning

In **state-space planning**, a program searches through a space of *world states*, seeking to find a path or paths that will take it from its initial state to a goal state.

State-space planning is too inflexible, because:

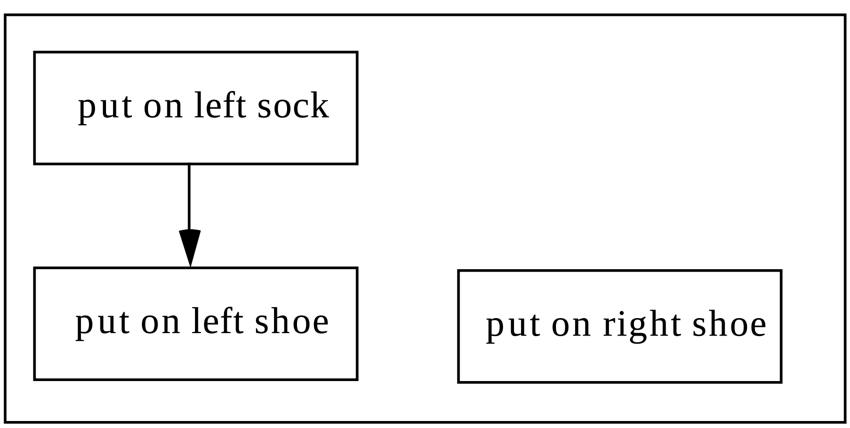
- it creates plans that are total orderings of a set of steps, and
- it assembles these plans in exactly the same order.

Plan-Space Planning Redux

In **plan-space planning**, a program searches through a space of *plans*, seeking a plan that will take it from its initial state to a goal state.

In this approach, we redefine some of the terms of our search:

- A **plan** is a **set of steps** and a **set of constraints** on the ordering of the steps.
- A **state** is a plan.
- The **goal state** is a plan that achieves all specified goals.
- An **operator** creates a new plan from an old plan.



Kinds of Operators

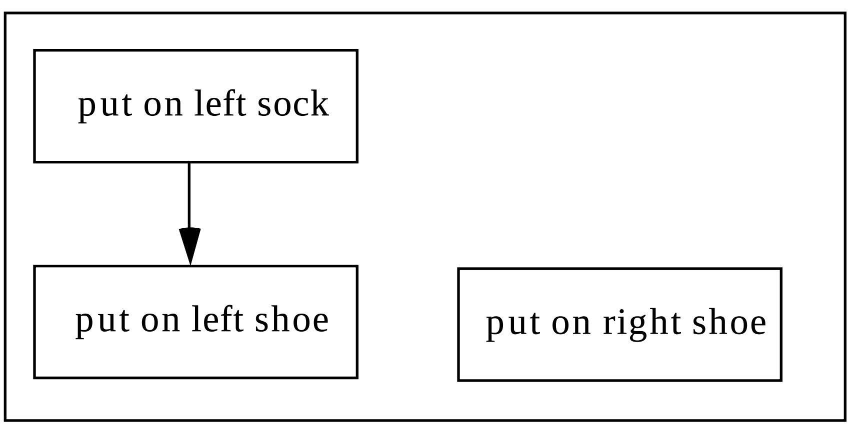
A **refinement operator**

- takes as input a partial plan, and
- adds either a step or a constraint to it.

That is, it makes the plan *more specific* by making one or more decisions left open in the partial plan.

A **modification operator**

- changes a constraint, or
- removes a step or a constraint, or
- does some combination of the two.



Whereas refinement operators allow the planner to "move forward" toward a goal, modification operators allow the planner to *back up*.

What is a Plan?

A plan, whether partial or complete, consists of:

- a specification of its precondition state and its postcondition state
- a set of actions, or “steps”, S_i
- a set of orderings on steps, $\{ (S_i < S_j), \ldots \}$

An example of a partial plan:

- Precondition
  ```
  armEmpty and clear( A ) and
  on( A, B ) and on( B, TABLE )
  ```
  Postcondition
  ```
  armEmpty and clear( B ) and
  on( B, A ) and on( A, TABLE )
  ```
- $S = \{ S_1 , S_2 \}$
  S_1 = stack(B, A)
  S_2 = stack(A, TABLE)
- ORDER = $\{ (S_2 < S_1), \ldots \}$

How Do We Make Plans?

A plan-space planning algorithm will do something like:

1. `P := empty-plan(I, G)`
2. Loop:
   a. If `P` is a solution, return `P`.
   b. Choose `F := find-flaw( P )`
   c. Choose `M := find-method( P, F )`
   d. If there is no such method, return failure.
   e. `P := fix-flaw(P, F, M)`

This algorithm introduces some new concepts...

- An *empty plan* is a plan with no steps and no constraints.

  This plan says, "Yeah, I plan to get from A to B," but does not contain actions to do it.

- A *solution* is any plan that achieves the I -> G.

  So, Step2a is where we do our goal test in this algorithm.

Flaws and Methods

1. `P := empty-plan(I, G)`

2. Loop:
   a. If `P` is a solution, return `P`.
   b. Choose `F := find-flaw( P )`
   c. Choose `M := find-method( P, F )`
   d. If there is no such method, return failure.
   e. `P := fix-flaw(P, F, M)`

A *flaw* is anything wrong with a plan.

- It might be something that is undone, such as "no action achieves this part of the goal" or "no action achieves this precondition of a step in the plan".

- However, this algorithm can construct a partial plan that is internally inconsistent. (How?)

  In such a case, a flaw can be an inconsistency, such as executing one step might undo a precondition for another step.

A *method* is a way to fix a flaw.

Usually, a flaw is a something undone, and so a method might *add a step or a constraint* to the plan.

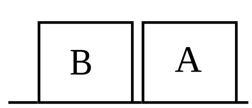
A Demo of Plan-Space Planning

Assume that a robot is given this set of operators:

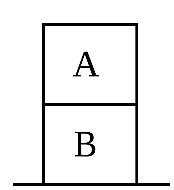
```
stack( x, y )

  precondition: clear( y ), holding( x )
  add:          armEmpty, on( x, y )
  delete:       clear( y ), holding( x )

unstack( x, y )

  precondition: on( x, y ), clear( x ), armEmpty
  add:          holding( x ), clear( y )
  delete:       on( x, y ), armEmpty

pickup( x )

  precondition: clear( x ), on( x, TABLE ), armEmpty
  add:          holding( x )
  delete:       on( x, TABLE ), armEmpty

putdown( x )

  precondition: holding( x )
  add:          on( x, TABLE ), armEmpty
  delete:       holding( x )
```

Solve:

Initial state:



Goal state:



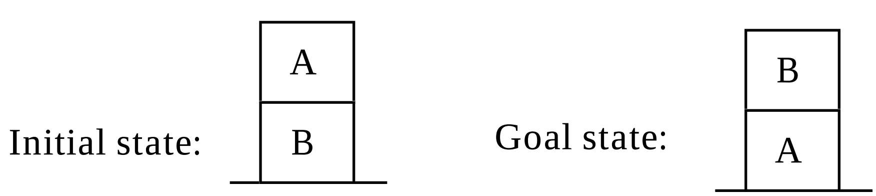
demonstration of above

An Exercise

Assume that a robot is given this set of operators:

```
stack( x, y )

  precondition: clear( y ), holding( x )
  add:          armEmpty, on( x, y )
  delete:       clear( y ), holding( x )

unstack( x, y )

  precondition: on( x, y ), clear( x ), armEmpty
  add:          holding( x ), clear( y )
  delete:       on( x, y ), armEmpty

pickup( x )

  precondition: clear( x ), on( x, TABLE ), armEmpty
  add:          holding( x )
  delete:       on( x, TABLE ), armEmpty

putdown( x )

  precondition: holding( x )
  add:          on( x, TABLE ), armEmpty
  delete:       holding( x )
```

Solve:

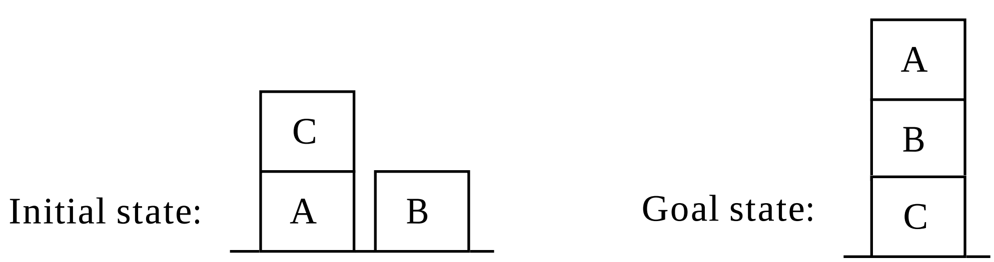


solution to above

Another Exercise

```
stack( x, y )

  precondition: clear( y ), holding( x )
  add:          armEmpty, on( x, y )
  delete:       clear( y ), holding( x )

unstack( x, y )

  precondition: on( x, y ), clear( x ), armEmpty
  add:          holding( x ), clear( y )
  delete:       on( x, y ), armEmpty

pickup( x )

  precondition: clear( x ), on( x, TABLE ), armEmpty
  add:          holding( x )
  delete:       on( x, TABLE ), armEmpty

putdown( x )

  precondition: holding( x )
  add:          on( x, TABLE ), armEmpty
  delete:       holding( x )
```

Solve:



solution to above

Flaws and Fixes in a Program

How can a **program** uses this approach to make plans?

The interesting new ideas here are:

- What is a **flaw** in a plan?
- What is a **method** for fixing a flaw?
- How does the program identify each?

First, a formal definition:

A proposition a is **necessarily true** before executing step s in plan p if both of the following are true:

- There is a step s_p in p such that s_p necessarily comes before s and s_p adds a.

- For every step s_d in p that may delete a, either s_d necessarily comes before s_p or s_d necessarily comes after s.

$$s_{d1} \longrightarrow s_p \longrightarrow a \longrightarrow s \longrightarrow s_{d2}$$

What does "necessarily" mean here?

Using the Modal Truth Criterion

Now, we can define flaws and methods:

- A flaw is any precondition a of a step s that is not *necessarily true* before executing s.

- To fix a flaw, do both of the following:
  - *Make sure that a is made true before executing s.*

    You can add a new step s_p and make it necessarily prior to s.

    Or you can choose an s_p that is already in the plan and add an ordering constraint.

  - *Make sure that a is not clobbered by some s_d.*

    You can change the variable bindings on some s_d so that it necessarily does not delete a.

    Or you can add an ordering so that s_d must either come before s_p or come after s.

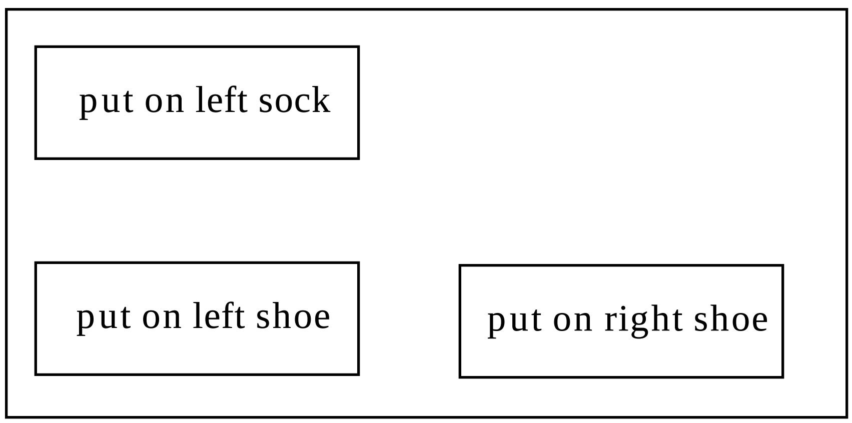
Applying the MTC

A flaw is any precondition a of a step s that is not *necessarily true* before executing s.

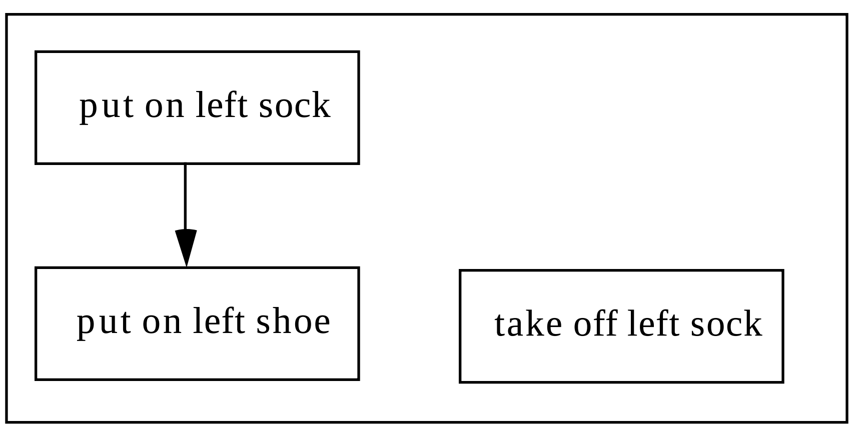
To fix a flaw, do both of the following:

- Make sure that a is made true before executing s.
- Make sure that a is not clobbered by some s_d.

Example 1:



Example 2:



Partial-Order Planning

This style ofplanning is called *partial-order planning* (POP), because it enables a planner to construct plans that are only partially ordered and thus only complete enough to accomplish its goal.

Such a plan leaves the agent that will use it as much flexibility as possible at “execution time”.

The POP algorithm that uses the MTC and causal links is the culmination of a progression of increasingly more sophisticated planning algorithms.

POP satisfies our three key ideas from two sessions ago:

- States and operators are decomposable.
- It can add an action to the plan at any place.
- It decomposes a problem into sub-tasks, solves them separately, and re-assemble the solutions.

Sometimes, though, it comes up short in practice. So it is the subject of continued research!