Planning

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Lessons Learned So Far

- Many problems can be solved by search.
- We need to clearly define a state, an action, and a goal to perform that search.
- State spaces get big fast; we need accurate heuristics to explore them efficiently.
- We can only develop domain-independent heuristics when we use some common representation for all problems.

Representing Time

We can avoid reasoning about time by only considering the present, adding and removing facts from the knowledge base as needed.

Add fact "I am at A1."

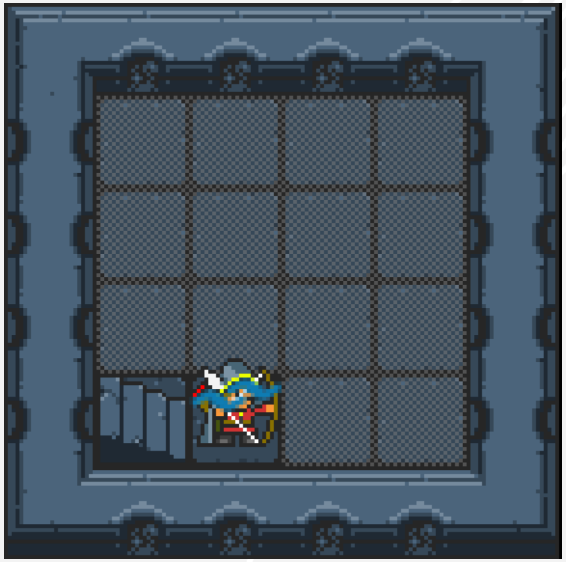
Representing Time

We can avoid reasoning about time by only considering the present, adding and removing facts from the knowledge base as needed.

Remove fact "I am at A1."

Add fact "I am at B1."

Add fact "I feel a breeze."



Representing Time

When we only consider the present, we can search the space of logical facts to learn new things about the present, but we can't search the space of world states to reason about the future.

Representing Time

We can reason explicitly about time by discretizing it and adding it as a parameter to facts which are time-sensitive.

"I am at A1 at time 0."

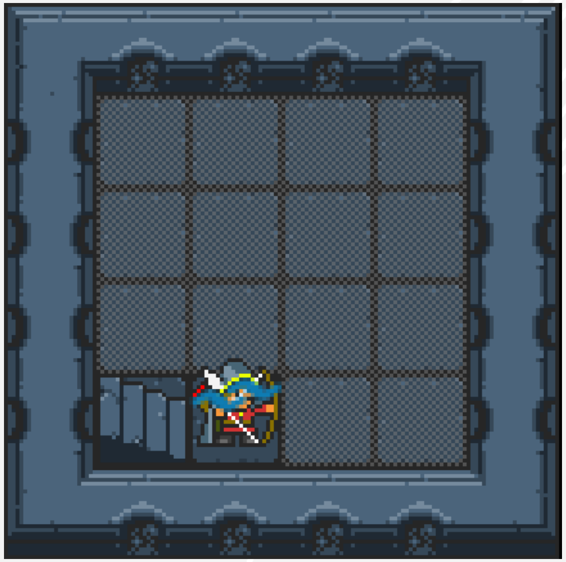
Representing Time

We can reason explicitly about time by discretizing it and adding it as a parameter to facts which are time-sensitive.

"I am at A1 at time 0."

"I am at B1 at time 1."

"I feel a breeze at time 1."



Representing Time

Representing time as a discrete value will work, but it complicates the knowledge engineering process and explodes the number of possible ground facts.

If time is not bound, the number of ground facts becomes infinite!

Frame Problem

Representing about time adds another complication: We need to know both what changes and also what stays the same.

“I have the arrow at time 0.”

“I am at A1 at time 0.”

Frame Problem

Representing about time adds another complication: We need to know both what changes and also what stays the same.

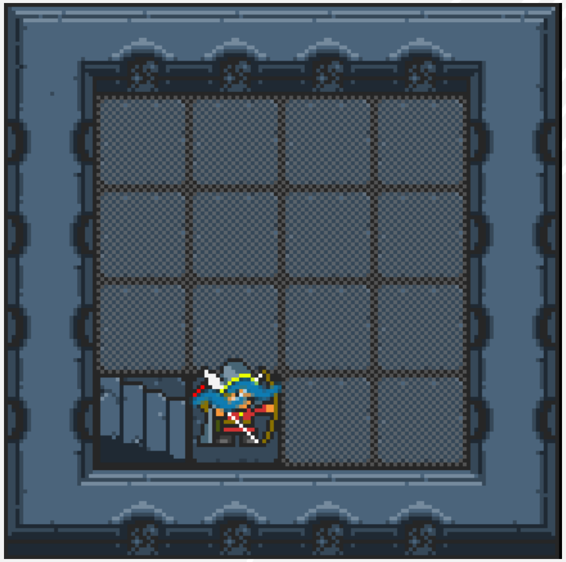
"I have the arrow at time 0."

"I am at A1 at time 0."

"I am at B1 at time 1."

Do I still have the arrow?

I can't prove that, so I guess not!



Frame Axioms

One solution to this is to add **frame axioms** which describe all the things that don't change.

$$\forall t\ arrow(t_i) \land up(t_i) \rightarrow arrow(t_{i+1})$$

We have to do this for every time-sensitive predicate!

This *really* complicates the knowledge engineering.

Planning

Planning is the science of reasoning about a sequence of actions that achieves some goal.

Planning uses a simple representation of state, action, and goal to deal with time and the frame problem.

Planning uses a logic-like representation of states and actions to allow domain-independent heuristics.

Planning Problem

Given:

1. A description of the world in the initial state
2. A set of action templates
3. A goal

Find a sequence of ground actions which, when taken from the initial state, achieves the goal.

Actions

Actions have:

- **preconditions** which must be true before the action can be taken
- **effects** which become true after the action has been taken

Planning Problem

Given:

1. A description of the world in the initial state
2. A set of action templates describing each action's preconditions and effects
3. A goal

Find:

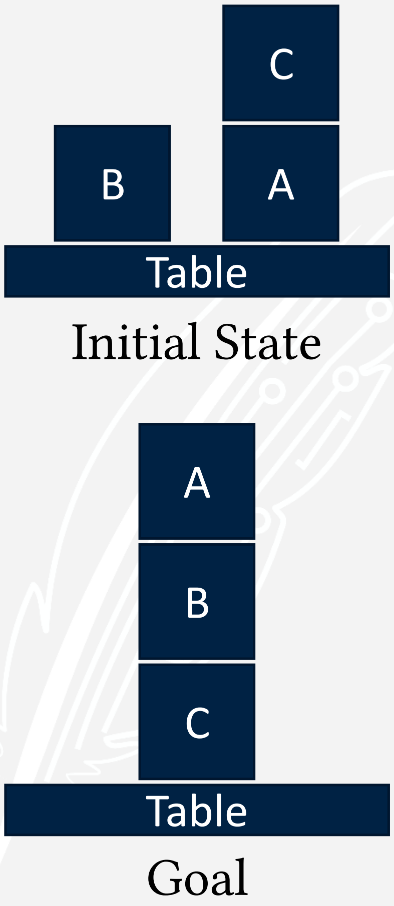
1. A sequence of ground actions
2. Such that each action's preconditions are true before the action is taken
3. And such that, after all actions have been taken, the goal has been achieved

Logical Language

The initial state, goal, preconditions, and effects are all described using a conjunction of function-free predicate literals (note: no quantifiers).

Blocks World

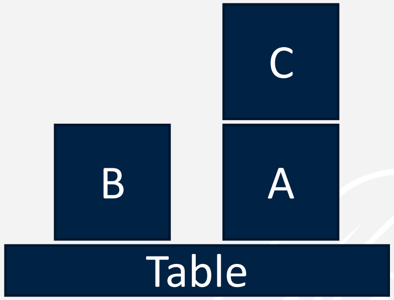
- Some number of labeled blocks on a table.
- Blocks can be stacked on top of one another.
- A block can only be moved when nothing is stacked on it.
- The goal describes a particular arrangement.



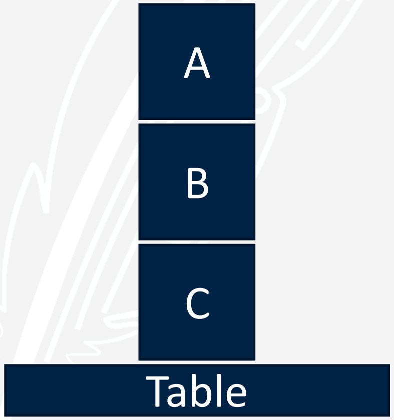
Blocks World: Language

The constant $Table$ represents the table.

The predicate $on(b, i)$ means that block b is stacked on top of thing i, where a thing is another block or the table.



Initial State

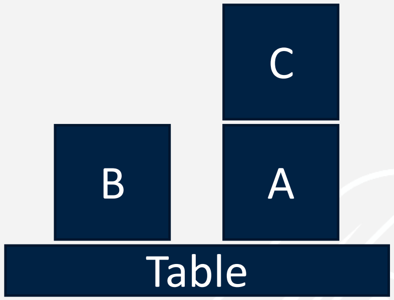


Goal

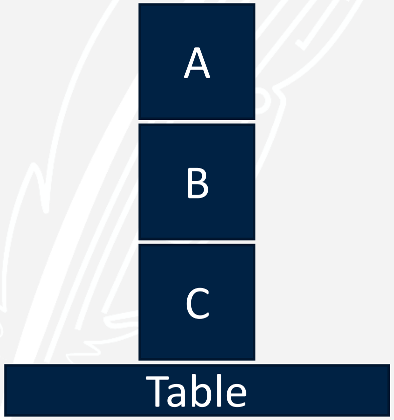
Blocks World: Initial State

Initial State: block$(A) \wedge$ $block(B) \wedge block(C) \wedge on(B, Table) \wedge on(C, A) \wedge on(A, Table)$

Planning uses the **closed world assumption**, meaning that facts not explicitly stated to be true are false. Thus, if we need to, we can assume things like $\neg on(B, A)$.



Initial State

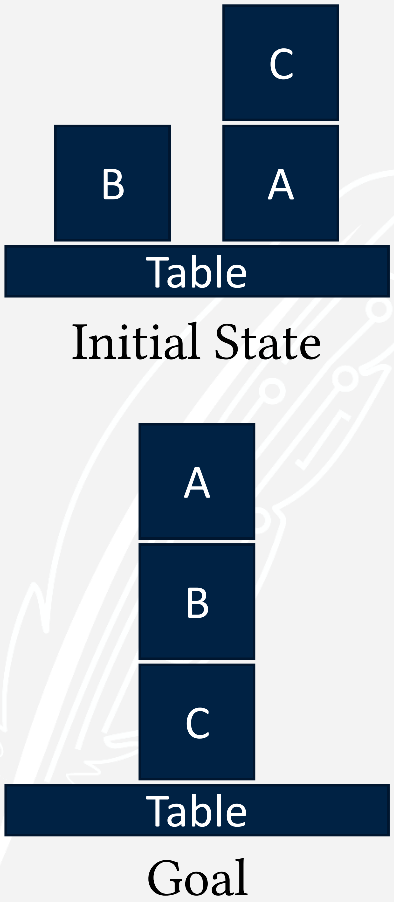


Goal

Blocks World: Goal

Goal: $on(A, B) \wedge on(B, C)$

A goal is a conjunction of things which must be true, but it is *not* a complete description of the goal state (note how it does not specify the position of C). This means there are potentially many **goal states**.



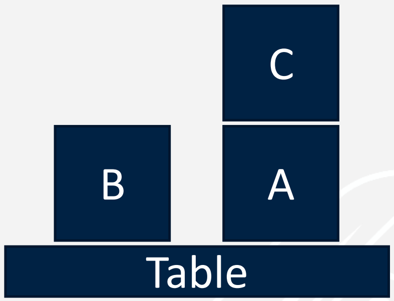
Blocks World: Action Template

Action $move(b, from, to)$:

Precondition: $block(b) \land on(b, from) \land \neg\exists x\ on(x, b) \land \neg\exists y\ on(y, to)$

Effect: $on(b, to) \land \neg on(b, from)$

How would we express the action of moving a block if we could use first order logic?



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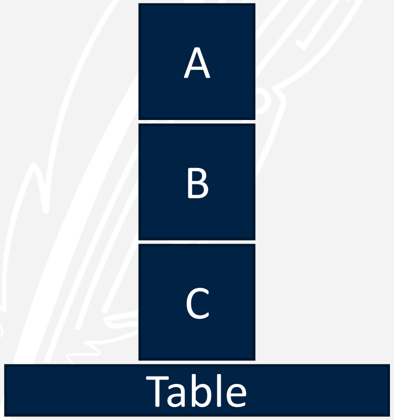

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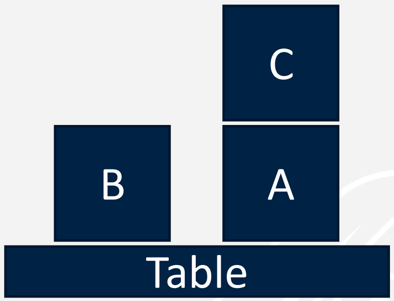
Effect: $on(b, to) \land \neg on(b, from)$

Note that we need to state which things are no longer true.



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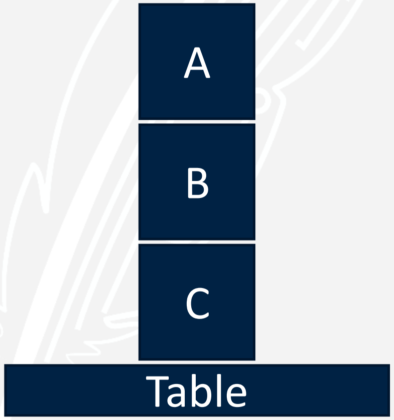

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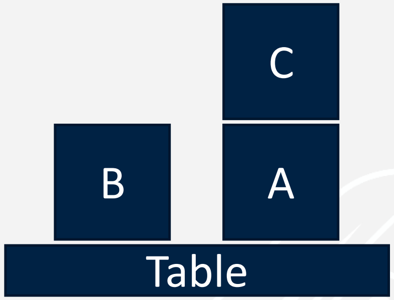
Blocks World: Action Template

Action $move(b, from, to)$:

Precondition: $block(b) \wedge on(b, from) \wedge \neg\exists x\ on(x, b) \wedge \neg\exists y\ on(y, to)$

Effect: $on(b, to) \wedge \neg on(b, from)$

But we can’t use first order quantifiers! How can we compensate?



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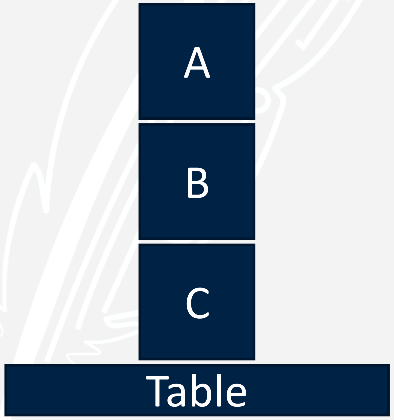


Goal

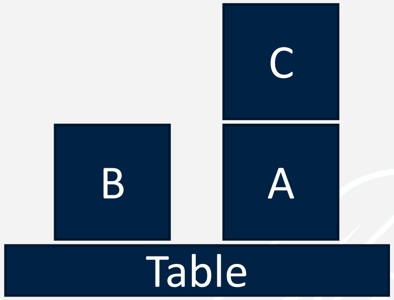
Blocks World: Action Template

Action $move(b, from, to)$:

Precondition: $block(b) \wedge on(b, from) \wedge \neg\exists x\ on(x, b) \wedge \neg\exists y\ on(y, to)$

Effect: $on(b, to) \wedge \neg on(b, from)$

The predicate $clear(i)$ indicates that thing i has nothing stacked on it.



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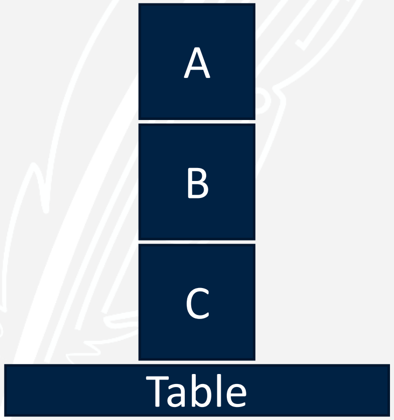


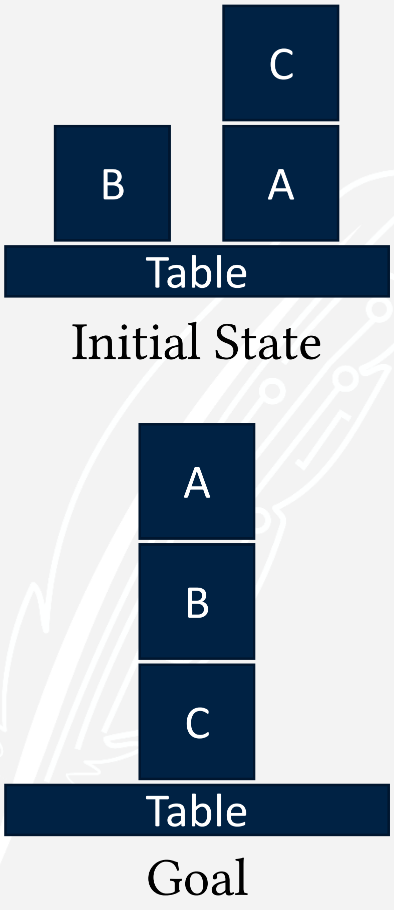
Goal

Blocks World: Action Template

Action $move(b, from, to)$:

Precondition: $block(b) \wedge on(b, from) \wedge clear(b) \wedge clear(to)$

Effect: $on(b, to) \wedge \neg on(b, from)$

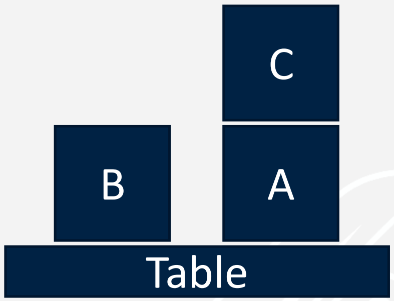


Blocks World: Action Template

Action $move(b, from, to)$:

Precondition: $block(b) \land on(b, from) \land clear(b) \land clear(to)$

Effect: $on(b, to) \land \neg on(b, from) \land \neg clear(to) \land clear(from)$



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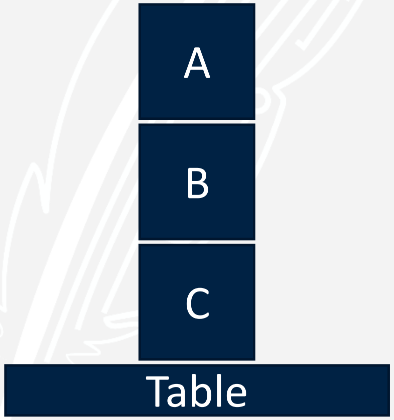


Goal

Blocks World: Action Template

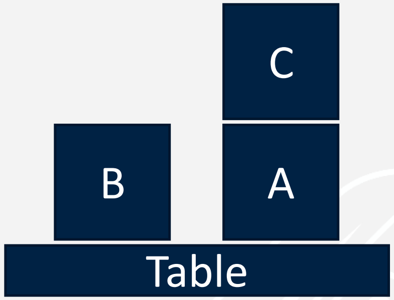
Action $move(b, from, to)$:

Precondition: $block(b) \land on(b, from) \land clear(b) \land clear(to)$

Effect: $on(b, to) \land \neg on(b, from) \land \neg clear(to) \land clear(from)$

But what will happen when we move something off the table?

We need a second action.



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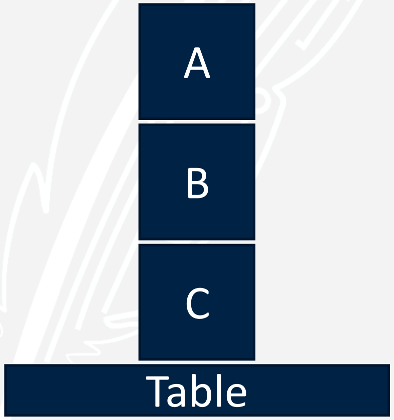


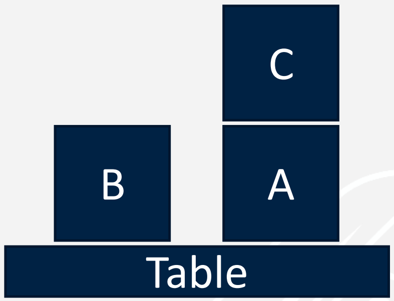
Goal

Blocks World: Action Template

Action $moveToTable(b, from)$:

Precondition: $block(b) \wedge on(b, from) \wedge clear(b)$

Effect: $on(b, Table) \wedge \neg on(b, from) \wedge clear(from)$



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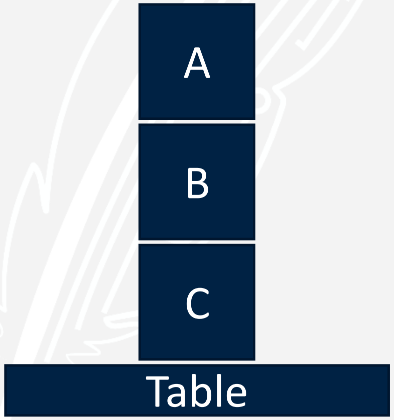


Goal

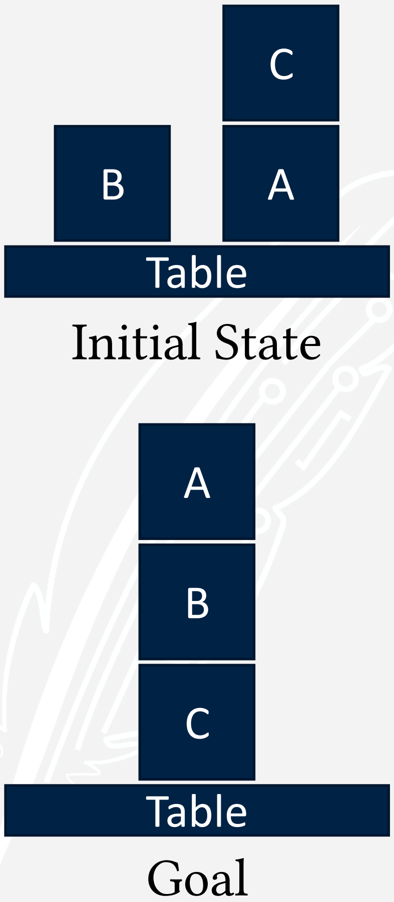
Blocks World: Action

Action $moveToTable(b, from)$:

Precondition: $block(b) \wedge on(b, from) \wedge clear(b)$

Effect: $on(b, Table) \wedge \neg on(b, from) \wedge clear(from)$

This is a template, but a plan must be made of ground actions.



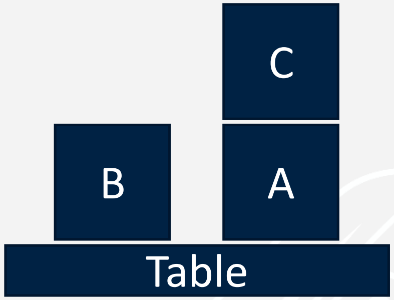
Blocks World: Action

Action $moveToTable(b, from)$:

Precondition: $block(b) \wedge$
$on(b, from) \wedge clear(b)$

Effect: $on(b, Table) \wedge$
$\neg on(b, from) \wedge clear(from)$

Ground: $moveToTable(C, A)$



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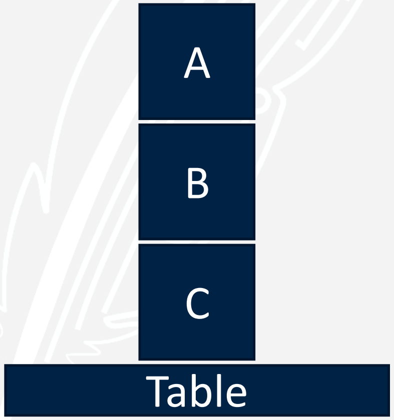


Goal

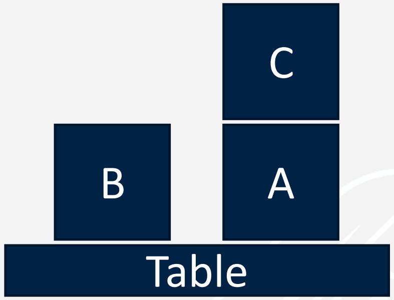
Blocks World: Action

Action $moveToTable(C, A)$:

Precondition: $block(C) \wedge on(C, A) \wedge clear(C)$

Effect: $on(C, Table) \wedge \neg on(C, A) \wedge clear(A)$

Ground: $moveToTable(C, A)$



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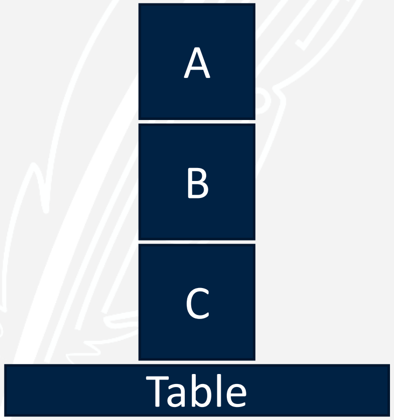
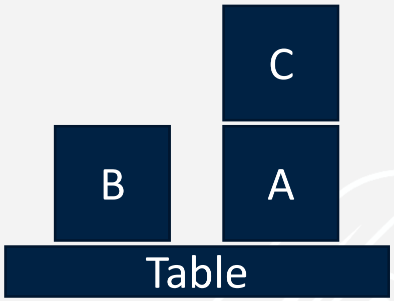


Goal

Blocks World: Plan

Find a plan which achieves the goal:

1. $moveToTable(C, A)$
2. $move(B, Table, C)$
3. $move(A, Table, B)$



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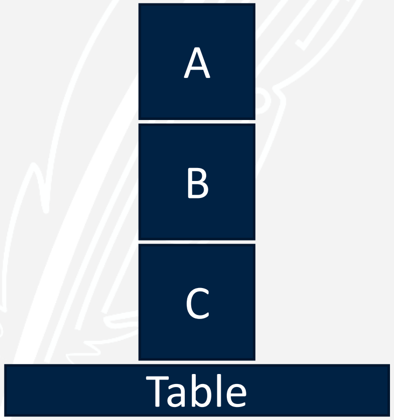


Goal

Complexity of Planning

Blocks World:

- 4 objects
- 1 action template with 3 parameters
- 1 action template with 2 parameters

Ground actions: $4^3 + 4^2 = 80$

Complexity of Planning

Blocks World:

- 5 objects
- 1 action template with 3 parameters
- 1 action template with 2 parameters

Ground actions: $5^3 + 5^2 = 150$

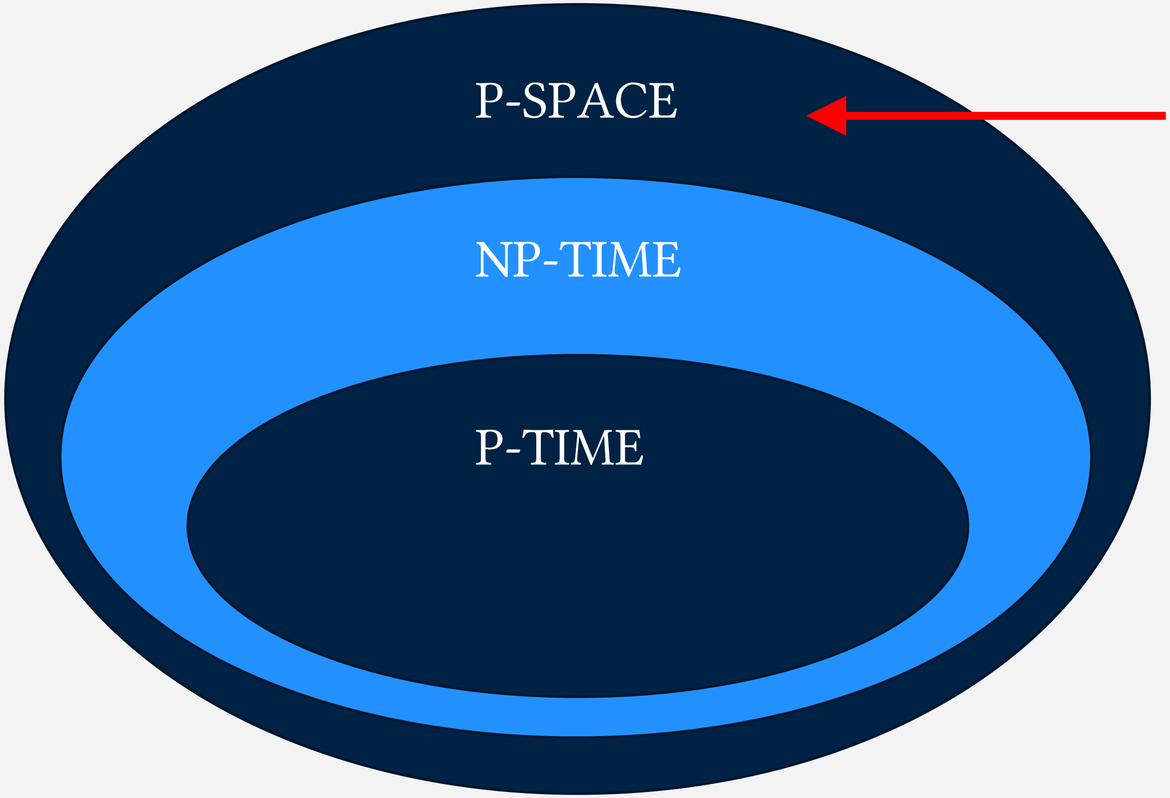
Complexity of Planning

Blocks World:

- 6 objects
- 1 action template with 3 parameters
- 1 action template with 2 parameters

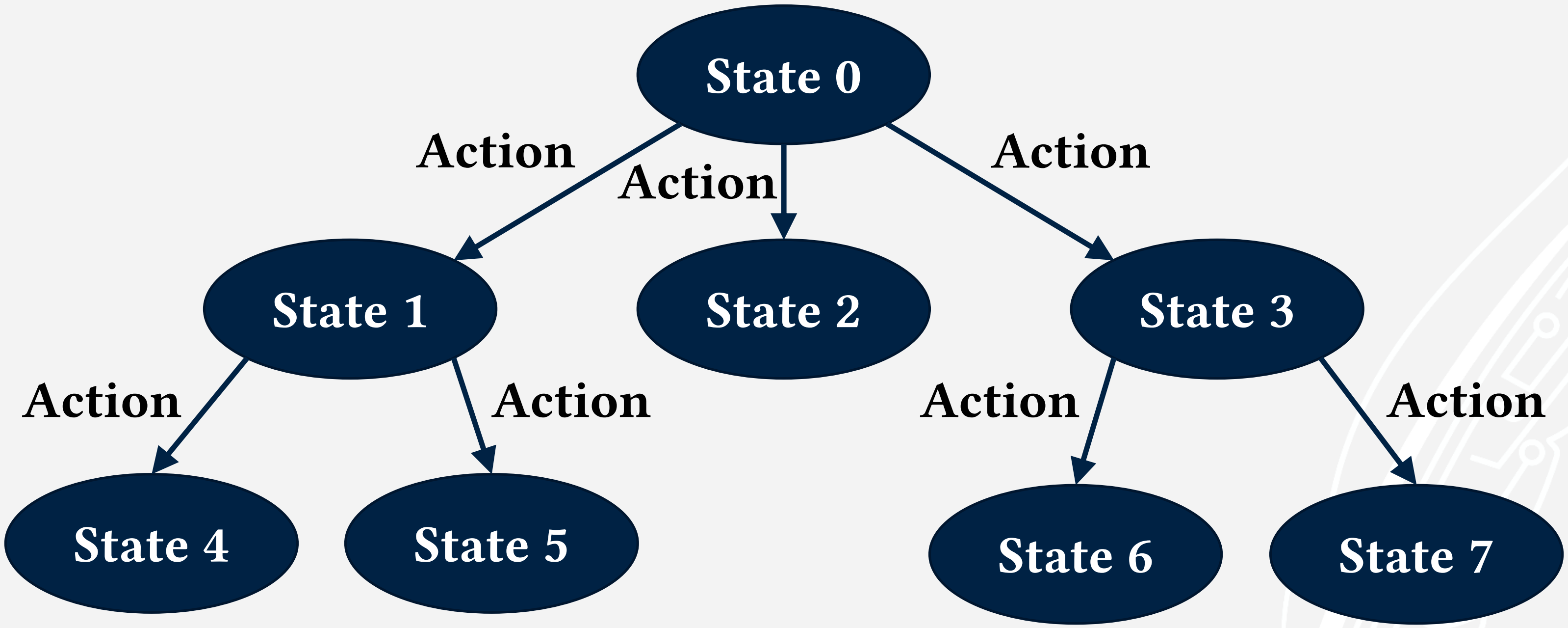
Ground actions: $6^3 + 6^2 = 252$

Complexity of Planning



Given a problem, deciding if a plan exists is here.

Planning as Search



Story of Planning

- State-space planning? Space too large!
- Least-commitment planning
- Plan-graph based planning
- SAT-based planning
- State-space planning, thanks to good heuristics

GPS: General Problem Solver

- Developed in 1959 by Herbert A. Simon, J. C. Shaw, and Allen Newell
- One of the first programs to separate the description of the problem from the strategy for solving it
- Considered the first planner
- Quickly mired in combinatorial explosion
- Fails to reason about interleaved goals

GPS: General Problem Solver

```
Let the initial state be the current state.
To satisfy some goal G:
    For each conjunct C of G:
        If C is true in the current state, do nothing.
        Else:
            Choose an action A which achieves C.
            For each precondition P of A, satisfy P.
            If all preconditions were satisfied:
                Add the action to the plan.
                Update the current state.
```

$$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$$

$$on(A, B) \wedge on(B, C)$$

$$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$$

$$on(A, B) \wedge on(B, C)$$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$

$move(B, Table, C)$

$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$

$on(A, B) \wedge on(B, C)$

$block(A) \land block(B) \land block(C) \land on(B, Table) \land clear(B) \land on(A, Table) \land on(C, A) \land clear(C)$

$block(B) \land on(B, Table) \land clear(B) \land clear(C)$

$move(B, Table, C)$

$on(B, C) \land \neg on(B, Table) \land clear(Table) \land \neg clear(C)$

$on(A, B) \land on(B, C)$

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$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$

$move(B, Table, C)$

$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$

$on(A, B) \wedge on(B, C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$

$move(B, Table, C)$

$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$

$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$

$move(A, Table, B)$

$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$

$on(A, B) \wedge on(B, C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

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$move(B, Table, C)$

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$move(A, Table, B)$

$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$

$on(A, B) \wedge on(B, C)$

$$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$$

$$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$$

$$move(B, Table, C)$$

$$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$$

$$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$$

$$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$$

$$move(A, Table, B)$$

$$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$$

$$on(A, B) \wedge on(B, C)$$

$block(A) \land block(B) \land block(C) \land on(B, Table) \land clear(B) \land on(A, Table) \land on(C, A) \land clear(C)$

$block(B) \land on(B, Table) \land clear(B) \land clear(C)$

$move(B, Table, C)$

$on(B, C) \land \neg on(B, Table) \land clear(Table) \land \neg clear(C)$

$block(A) \land block(B) \land block(C) \land on(B, C) \land clear(B) \land on(A, Table) \land on(C, A)$

$block(A) \land on(A, Table) \land clear(A) \land clear(B)$

$move(A, Table, B)$

$on(A, B) \land \neg on(A, Table) \land clear(Table) \land \neg clear(B)$

$on(A, B) \land on(B, C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$

$move(B, Table, C)$

$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$

$block(C) \wedge on(C, A) \wedge clear(C)$

$moveToTable(C, A)$

$on(C, Table) \wedge \neg on(C, A) \wedge clear(A)$

$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$

$move(A, Table, B)$

$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$

$on(A, B) \wedge on(B, C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$

$move(B, Table, C)$

$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$

$block(C) \wedge on(C, A) \wedge clear(C)$

$moveToTable(C, A)$

$on(C, Table) \wedge \neg on(C, A) \wedge clear(A)$

$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$

$move(A, Table, B)$

$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$

$on(A, B) \wedge on(B, C)$

$$block(A) \land block(B) \land block(C) \land on(B, Table) \land clear(B) \land on(A, Table) \land on(C, A) \land clear(C)$$

$$block(B) \land on(B, Table) \land clear(B) \land clear(C)$$

$$move(B, Table, C)$$

$$on(B, C) \land \neg on(B, Table) \land clear(Table) \land \neg clear(C)$$

$$block(A) \land block(B) \land block(C) \land on(B, C) \land clear(B) \land on(A, Table) \land on(C, A)$$

$$block(C) \land on(C, A) \land clear(C)$$

$$moveToTable(C, A)$$

$$on(C, Table) \land \neg on(C, A) \land clear(A)$$

$$block(A) \land on(A, Table) \land clear(A) \land clear(B)$$

$$move(A, Table, B)$$

$$on(A, B) \land \neg on(A, Table) \land clear(Table) \land \neg clear(B)$$

$$on(A, B) \land on(B, C)$$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$

$move(B, Table, C)$

$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$

$block(C) \wedge on(C, A) \wedge clear(C)$

$moveToTable(C, A)$

$on(C, Table) \wedge \neg on(C, A) \wedge clear(A)$

$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$

$move(A, Table, B)$

$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$

$on(A, B) \wedge on(B, C)$

$$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$$

$$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$$

$$move(B, Table, C)$$

$$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$$

$$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$$

$$block(B) \wedge on(B, C) \wedge clear(B)$$

$$moveToTable(B, C)$$

$$on(B, Table) \wedge \neg on(B, C) \wedge clear(C)$$

$$block(C) \wedge on(C, A) \wedge clear(C)$$

$$moveToTable(C, A)$$

$$on(C, Table) \wedge \neg on(C, A) \wedge clear(A)$$

$$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$$

$$move(A, Table, B)$$

$$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$$

$$on(A, B) \wedge on(B, C)$$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B,Table) \wedge clear(B) \wedge on(A,Table) \wedge on(C,A) \wedge clear(C)$

$block(B) \wedge on(B,Table) \wedge clear(B) \wedge clear(C)$

$move(B,Table,C)$

$on(B,C) \wedge \neg on(B,Table) \wedge clear(Table) \wedge \neg clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B,C) \wedge clear(B) \wedge on(A,Table) \wedge on(C,A)$

$block(B) \wedge on(B,C) \wedge clear(B)$

$moveToTable(B,C)$

$on(B,Table) \wedge \neg on(B,C) \wedge clear(C)$

$block(C) \wedge on(C,A) \wedge clear(C)$

$moveToTable(C,A)$

$on(C,Table) \wedge \neg on(C,A) \wedge clear(A)$

$block(A) \wedge on(A,Table) \wedge clear(A) \wedge clear(B)$

$move(A,Table,B)$

$on(A,B) \wedge \neg on(A,Table) \wedge clear(Table) \wedge \neg clear(B)$

$on(A,B) \wedge on(B,C)$

$$block(A) \land block(B) \land block(C) \land on(B, Table) \land clear(B) \land on(A, Table) \land on(C, A) \land clear(C)$$

$$block(B) \land on(B, Table) \land clear(B) \land clear(C)$$

$$move(B, Table, C)$$

$$on(B, C) \land \neg on(B, Table) \land clear(Table) \land \neg clear(C)$$

$$block(A) \land block(B) \land block(C) \land on(B, C) \land clear(B) \land on(A, Table) \land on(C, A)$$

$$block(B) \land on(B, C) \land clear(B)$$

$$moveToTable(B, C)$$

$$on(B, Table) \land \neg on(B, C) \land clear(C)$$

$$block(C) \land on(C, A) \land clear(C)$$

$$moveToTable(C, A)$$

$$on(C, Table) \land \neg on(C, A) \land clear(A)$$

$$block(A) \land on(A, Table) \land clear(A) \land clear(B)$$

$$move(A, Table, B)$$

$$on(A, B) \land \neg on(A, Table) \land clear(Table) \land \neg clear(B)$$

$$on(A, B) \land on(B, C)$$

$$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$$

$$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$$

$$move(B, Table, C)$$

$$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$$

$$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$$

$$block(B) \wedge on(B, C) \wedge clear(B)$$

$$moveToTable(B, C)$$

$$on(B, Table) \wedge \neg on(B, C) \wedge clear(C)$$

$$block(C) \wedge on(C, A) \wedge clear(C)$$

$$moveToTable(C, A)$$

$$on(C, Table) \wedge \neg on(C, A) \wedge clear(A)$$

$$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$$

$$move(A, Table, B)$$

$$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$$

$$on(A, B) \wedge on(B, C)$$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$

$move(B, Table, C)$

$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$

$block(B) \wedge on(B, C) \wedge clear(B)$

$moveToTable(B, C)$

$on(B, Table) \wedge \neg on(B, C) \wedge clear(C)$

$block(C) \wedge on(C, A) \wedge clear(C)$

$moveToTable(C, A)$

$on(C, Table) \wedge \neg on(C, A) \wedge clear(A)$

$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$

$move(A, Table, B)$

$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$

$on(A, B) \wedge on(B, C)$

$$block(A) \wedge block(B) \wedge block(C) \wedge on(B,Table) \wedge clear(B) \wedge on(A,Table) \wedge on(C,A) \wedge clear(C)$$

$$block(B) \wedge on(B,Table) \wedge clear(B) \wedge clear(C)$$

$$move(B,Table,C)$$

$$on(B,C) \wedge \neg on(B,Table) \wedge clear(Table) \wedge \neg clear(C)$$

$$block(A) \wedge block(B) \wedge block(C) \wedge on(B,C) \wedge clear(B) \wedge on(A,Table) \wedge on(C,A)$$

$$block(B) \wedge on(B,C) \wedge clear(B)$$

$$moveToTable(B,C)$$

$$on(B,Table) \wedge \neg on(B,C) \wedge clear(C)$$

$$block(A) \wedge block(B) \wedge block(C) \wedge on(B,Table) \wedge clear(B) \wedge on(A,Table) \wedge on(C,A) \wedge clear(C)$$

$$block(C) \wedge on(C,A) \wedge clear(C)$$

$$moveToTable(C,A)$$

$$on(C,Table) \wedge \neg on(C,A) \wedge clear(A)$$

$$block(A) \wedge on(A,Table) \wedge clear(A) \wedge clear(B)$$

$$move(A,Table,B)$$

$$on(A,B) \wedge \neg on(A,Table) \wedge clear(Table) \wedge \neg clear(B)$$

$$on(A,B) \wedge on(B,C)$$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$

$move(B, Table, C)$

$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$

$block(B) \wedge on(B, C) \wedge clear(B)$

$moveToTable(B, C)$

$on(B, Table) \wedge \neg on(B, C) \wedge clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(C) \wedge on(C, A) \wedge clear(C)$

$moveToTable(C, A)$

$on(C, Table) \wedge \neg on(C, A) \wedge clear(A)$

$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$

$move(A, Table, B)$

$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$

$on(A, B) \wedge on(B, C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$

$move(B, Table, C)$

$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$

$block(B) \wedge on(B, C) \wedge clear(B)$

$moveToTable(B, C)$

$on(B, Table) \wedge \neg on(B, C) \wedge clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(C) \wedge on(C, A) \wedge clear(C)$

$moveToTable(C, A)$

$on(C, Table) \wedge \neg on(C, A) \wedge clear(A)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(C, Table) \wedge clear(C) \wedge on(A, Table) \wedge clear(A)$

$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$

$move(A, Table, B)$

$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$

$on(A, B) \wedge on(B, C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$

$move(B, Table, C)$

$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$

$block(B) \wedge on(B, C) \wedge clear(B)$

$moveToTable(B, C)$

$on(B, Table) \wedge \neg on(B, C) \wedge clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(C) \wedge on(C, A) \wedge clear(C)$

$moveToTable(C, A)$

$on(C, Table) \wedge \neg on(C, A) \wedge clear(A)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(C, Table) \wedge clear(C) \wedge on(A, Table) \wedge clear(A)$

$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$

$move(A, Table, B)$

$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$

$on(A, B) \wedge on(B, C)$

$block(A) \land block(B) \land block(C) \land on(B, Table) \land clear(B) \land on(A, Table) \land on(C, A) \land clear(C)$

$block(B) \land on(B, Table) \land clear(B) \land clear(C)$

$move(B, Table, C)$

$on(B, C) \land \neg on(B, Table) \land clear(Table) \land \neg clear(C)$

$block(A) \land block(B) \land block(C) \land on(B, C) \land clear(B) \land on(A, Table) \land on(C, A)$

$block(B) \land on(B, C) \land clear(B)$

$moveToTable(B, C)$

$on(B, Table) \land \neg on(B, C) \land clear(C)$

$block(A) \land block(B) \land block(C) \land on(B, Table) \land clear(B) \land on(A, Table) \land on(C, A) \land clear(C)$

$block(C) \land on(C, A) \land clear(C)$

$moveToTable(C, A)$

$on(C, Table) \land \neg on(C, A) \land clear(A)$

$block(A) \land block(B) \land block(C) \land on(B, Table) \land clear(B) \land on(C, Table) \land clear(C) \land on(A, Table) \land clear(A)$

$block(A) \land on(A, Table) \land clear(A) \land clear(B)$

$move(A, Table, B)$

$on(A, B) \land \neg on(A, Table) \land clear(Table) \land \neg clear(B)$

$on(A, B) \land on(B, C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(B) \wedge on(B, Table) \wedge clear(B) \wedge clear(C)$

$move(B, Table, C)$

$on(B, C) \wedge \neg on(B, Table) \wedge clear(Table) \wedge \neg clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, C) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A)$

$block(B) \wedge on(B, C) \wedge clear(B)$

$moveToTable(B, C)$

$on(B, Table) \wedge \neg on(B, C) \wedge clear(C)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(A, Table) \wedge on(C, A) \wedge clear(C)$

$block(C) \wedge on(C, A) \wedge clear(C)$

$moveToTable(C, A)$

$on(C, Table) \wedge \neg on(C, A) \wedge clear(A)$

$block(A) \wedge block(B) \wedge block(C) \wedge on(B, Table) \wedge clear(B) \wedge on(C, Table) \wedge clear(C) \wedge on(A, Table) \wedge clear(A)$

$block(A) \wedge on(A, Table) \wedge clear(A) \wedge clear(B)$

$move(A, Table, B)$

$on(A, B) \wedge \neg on(A, Table) \wedge clear(Table) \wedge \neg clear(B)$

This goal was undone!

$on(A, B) \wedge on(B, C)$

Why Planning is Hard

Planning problems can be broken down into individual goals, but these goals can’t be solved independently.

Solving one affects how others are solved:

- Sometimes goals interfere with one another
- Sometimes goals synergize with one another

Designing Planners

A good planner needs to:

- Cope with goal interference
- Leverage goal synergy
- Aggressively prune the search space
  - Abstraction
  - Heuristics

Designing Planners

A planner is **sound** if it produces only valid plans (i.e. plan guaranteed to work).

A planner is **complete** if it is guaranteed to find a solution when one exists.