Planning

Chapter 11.1-11.3

Some material adopted from notes by
Andreas Geyer-Schulz and Chuck Dyer

Overview

- What is planning?
- Approaches to planning
  - GPS / STRIPS
  - Situation calculus formalism
  - Partial-order planning

Planning Problem

- Find a **sequence of actions** that achieves a **goal** when executed from an **initial state**.
- That is, given
  - A set of operators (possible actions)
  - An initial state description
  - A goal (description or conjunction of predicates)
- Compute a sequence of operations: a **plan**.

Typical Assumptions (1)

- **Atomic time**: Each action is indivisible
  - Can’t be interrupted halfway through putting on pants
- **No concurrent actions** allowed
  - Can’t put on socks at the same time
- **Deterministic actions**
  - The result of actions are completely known – no uncertainty

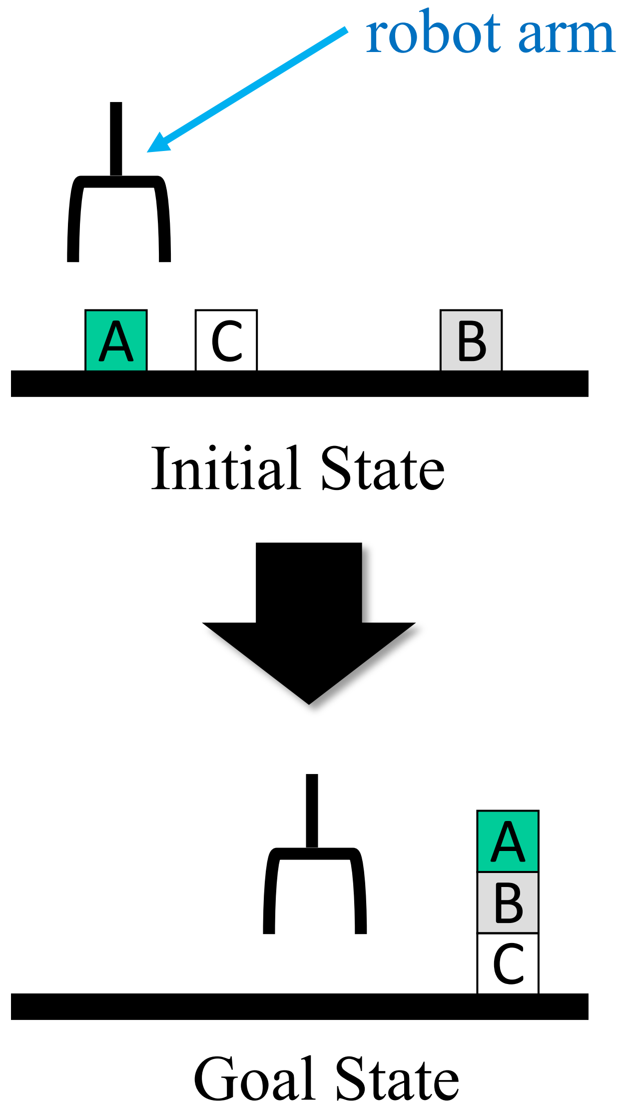
Typical Assumptions (2)

- Agent is the **sole cause of change** in the world
  - Nobody else is putting on your socks
- Agent is **omniscient:**
  - Has complete knowledge of the state of the world
- **Closed world assumption**:
  - Everything known-true about the world is in the *state description*
  - Anything not known-true is known-false

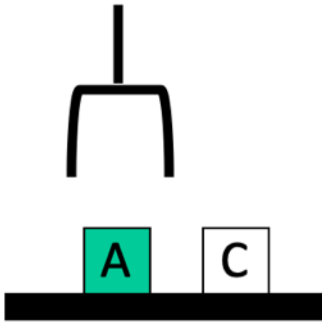
Classic Planning

Find **sequence of actions** to reach a **goal** in a discrete, deterministic, static, fully-observable environment

- State space search and logical reasoning could be used
- But classic planning developed custom representations & algorithms to do it more effectively
- The approach uses a **knowledge base** and reasoning about the state of the world and possible actions
- We'll look first at doing this in the simple **blocks world**



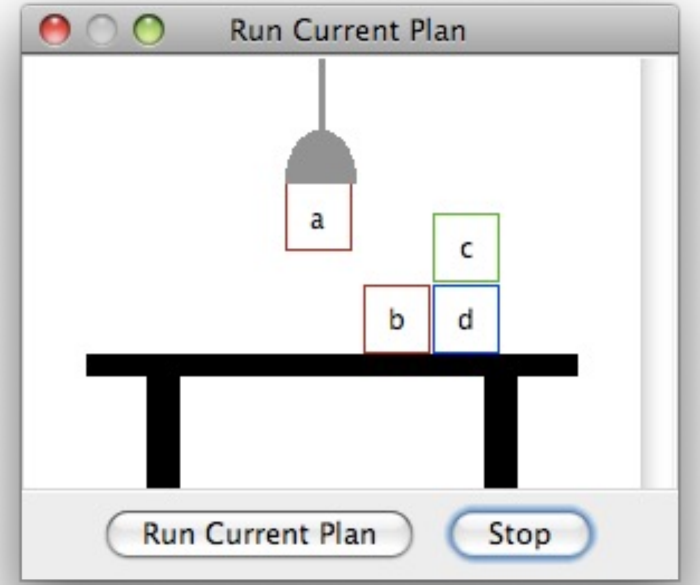
Blocks world



The blocks world is a "micro-world" with a **table**, a set of **blocks**, and a **robot hand**

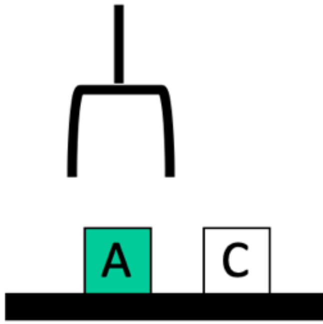
Some constraints for a simple model:

- Only one block can be on another block
- Any number of blocks can be on the table
- The hand can only hold one block



Meant to be a simple model!
(Applet demo at:
http://aispace.org/planning/index.shtml)

Blocks world



Typical representation uses a logic notation to represent the state of the world:

ontable(a) ontable(c)
clear(a) clear(c)
handempty

And possible **actions/ operators** with their preconditions and effects:

Pickup Putdown
Stack Unstack

Typical BW planning problem

Initial state:

clear(a)

clear(b)

clear(c)

ontable(a)

ontable(b)

ontable(c)

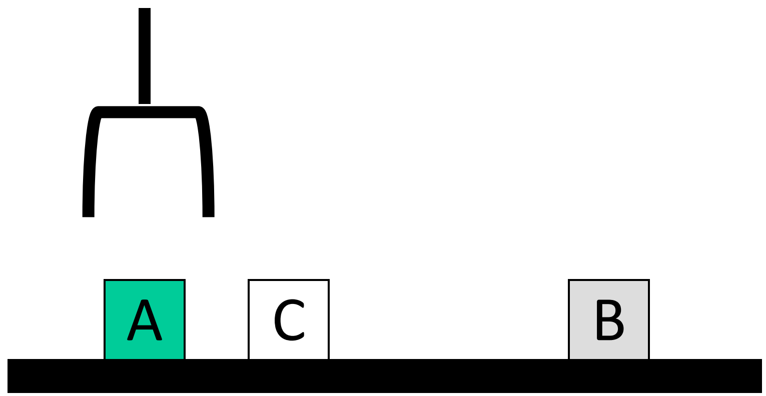
handempty

Goal:

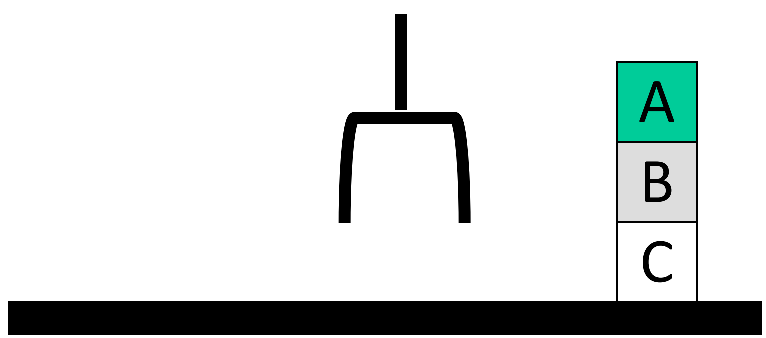
on(b,c)

on(a,b)

ontable(c)



Initial state asserts everything that's true initially



Goal state asserts things we want to be true eventually

Typical BW planning problem

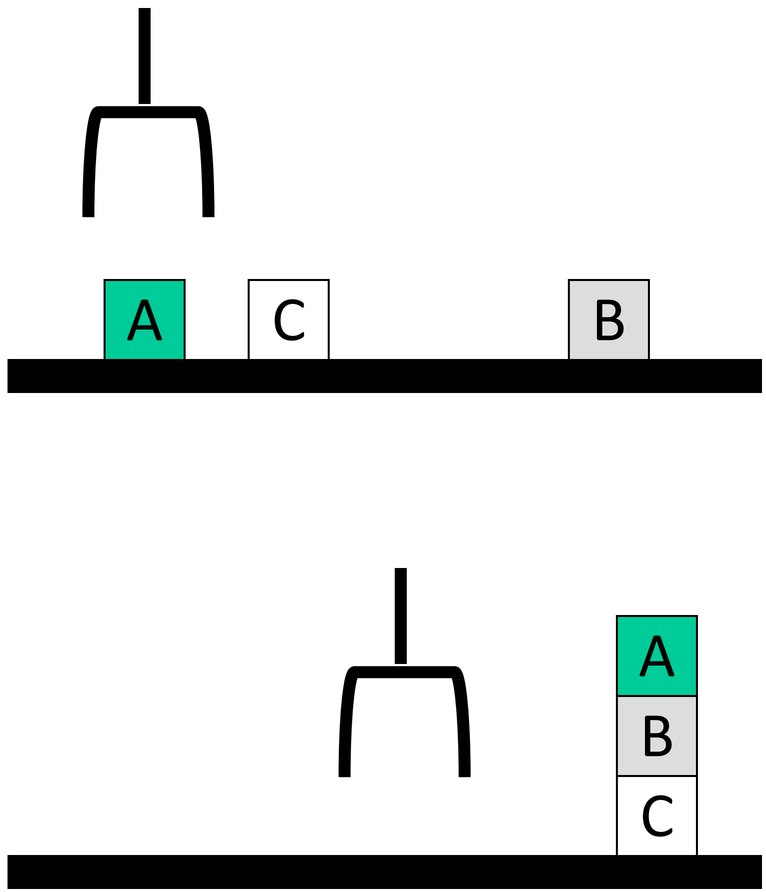
Logical assertions/ **KB**
describing initial &
final states

Initial state:

clear(a)
clear(b)
clear(c)
ontable(a)
ontable(b)
ontable(c)
handempty

Goal state:

on(b,c)
on(a,b)
ontable(c)



Sequence
of robot
actions

Plan:

pickup(b)
stack(b,c)
pickup(a)
stack(a,b)

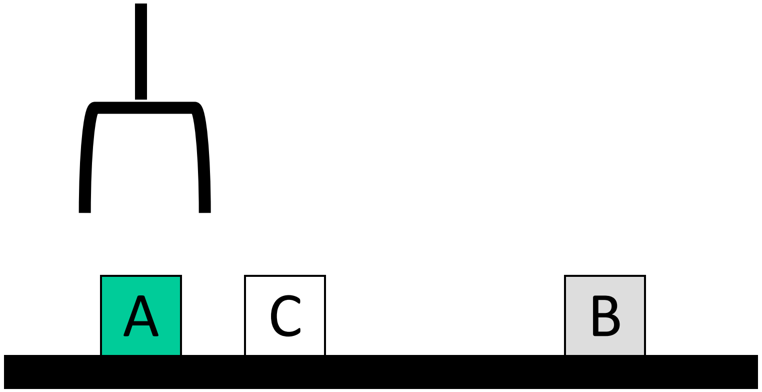
Another BW planning problem

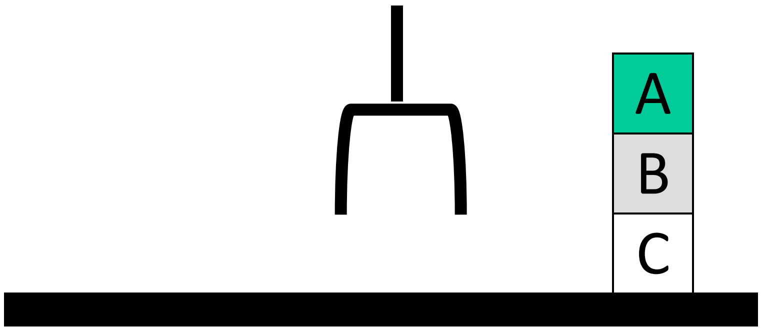
Initial state:

clear(a)
clear(b)
clear(c)
ontable(a)
ontable(b)
ontable(c)
handempty

Goal:

on(a,b)
on(b,c)
ontable(c)





Simple approach:

- find a way to achieve each goal in order

Note: Goals in a different order!

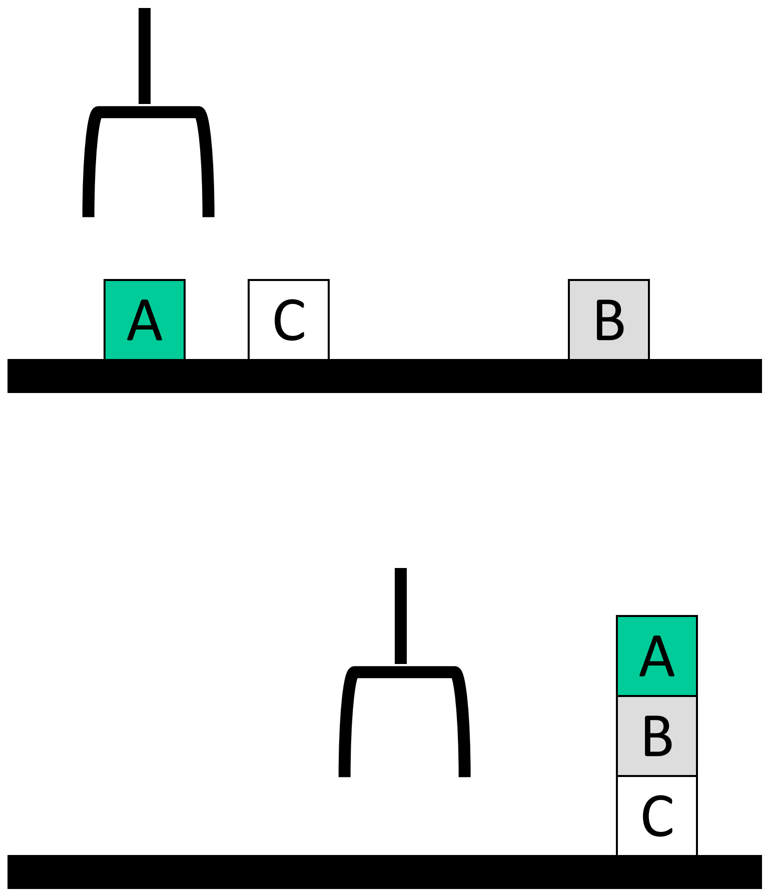
Another BW planning problem

Initial state:

- clear(a)
- clear(b)
- clear(c)
- ontable(a)
- ontable(b)
- ontable(c)
- handempty

Goal:

- on(a,b)
- on(b,c)
- ontable(c)



A plan:

- pickup(a)
- stack(a,b)
- unstack(a,b)
- putdown(a)
- pickup(b)
- stack(b,c)
- pickup(a)
- stack(a,b)

Note: Goals in a different order!

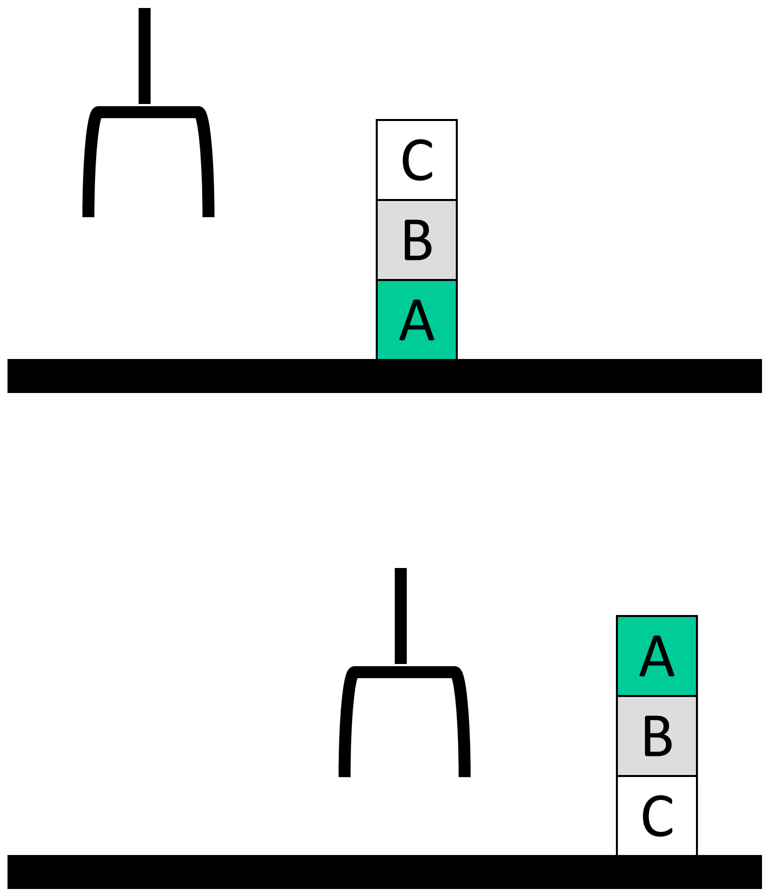
Yet Another BW planning problem

Initial state:

- clear(c)
- ontable(a)
- on(b,a)
- on(c,b)
- handempty

Goal:

- on(a,b)
- on(b,c)
- ontable(c)



Plan:

- unstack(c,b)
- putdown(c)
- unstack(b,a)
- putdown(b)
- pickup(a)
- stack(a,b)
- unstack(a,b)
- putdown(a)
- pickup(b)
- stack(b,c)
- pickup(a)
- stack(a,b)

Note: not very efficient!

Planning vs. problem solving

- Problem solving methods solve similar problems
- Planning is more powerful and efficient because of the representations and methods used
- States, goals, and actions are decomposed into sets of sentences (usually in first-order logic)
- Search often proceeds through *plan space* rather than *state space* (though there are also state-space planners)
- Sub-goals can be planned independently, reducing the complexity of the planning problem

Major Approaches

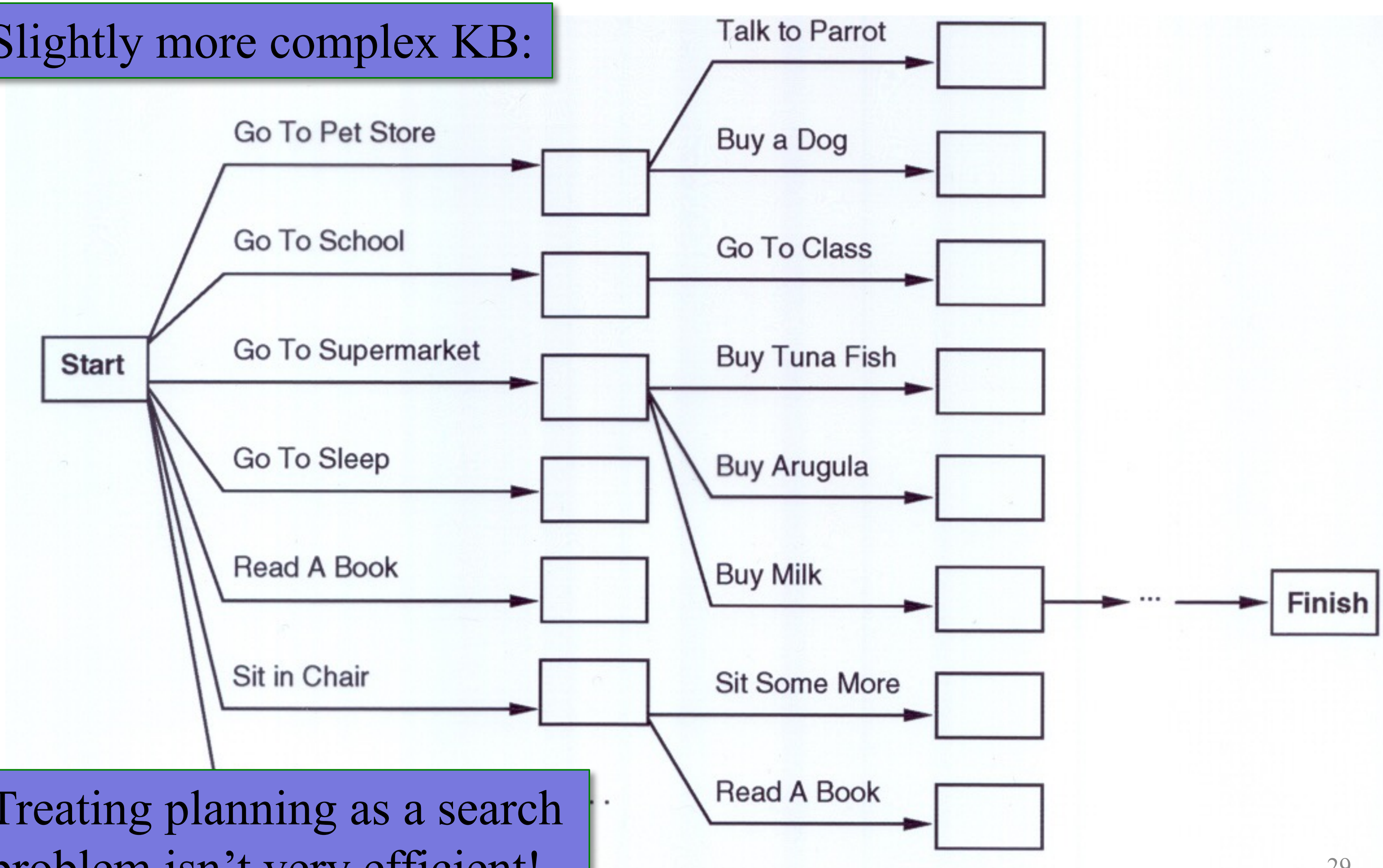
- **Planning as search**
- **GPS / STRIPS**
- **Situation calculus**
- **Partial order planning**
- **Hierarchical decomposition (HTN planning)**
- **Planning with constraints (SATplan, Graphplan)**
- ***Reactive planning***

Planning as Search (?)

- Can think of planning as a search problem
  - **Actions:** generate successor states
  - **States:** completely described & only used for successor generation, heuristic fn. evaluation & goal testing
  - **Goals:** represented as a goal test and using a heuristic function
  - **Plan representation:** unbroken sequences of actions forward from initial states or backward from goal state

"Get a quart of milk, a bunch of bananas and a variable-speed cordless drill."

Slightly more complex KB:



Treating planning as a search problem isn't very efficient!

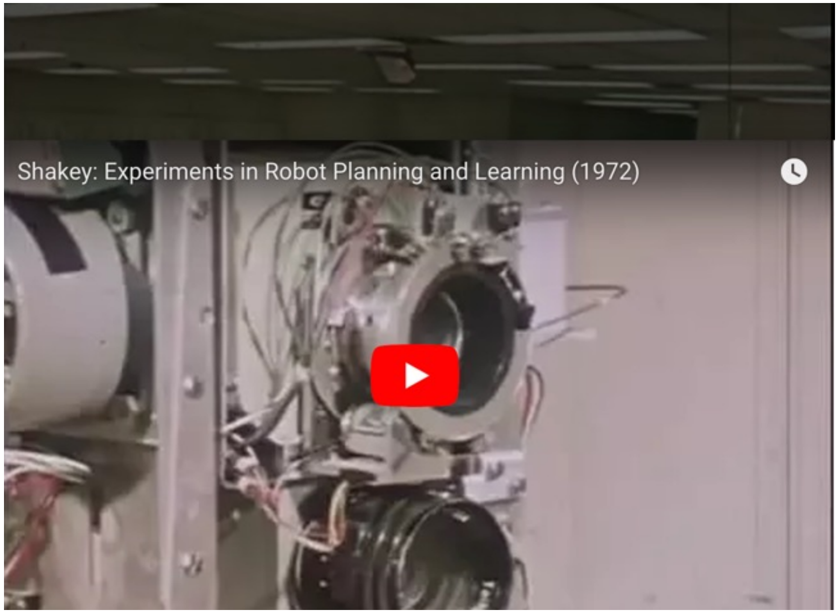
General Problem Solver

- The **General Problem Solver (GPS)** system
  - An early planner (Newell, Shaw, and Simon)
- Generate actions that *reduce difference* between current state and goal state
- Uses *Means-Ends Analysis*
  - Compare what is **given** or **known** with what is desired
  - Select a reasonable thing to do next
  - Use a **table of differences** to identify procedures to reduce differences
- GPS is a **state space planner**
  - Operates on state space problems specified by an initial state, some goal states, and a set of operations

History: Shakey the robot

First general-purpose mobile robot to be able to reason about its own actions

Shakey the Robot: 1st Robot to Embody Artificial Intelligence (2017, 6 min.)



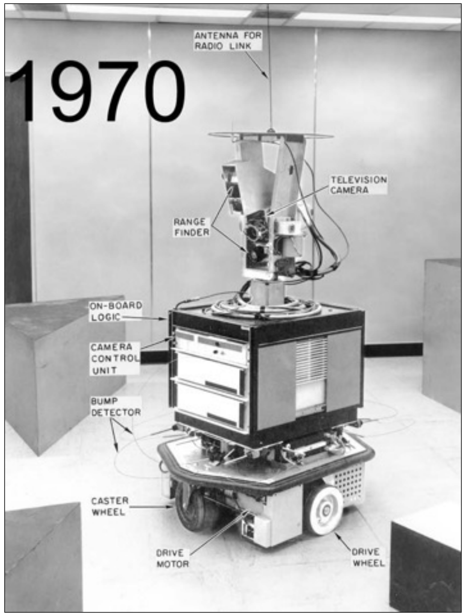
Shakey: Experiments in Robot Planning and Learning (1972, 24 min)

Strips planning representation

- Classic approach first used in the STRIPS (Stanford Research Institute Problem Solver) planner
- A State is a conjunction of ground literals

  at(Home) $\wedge$ $\neg$have(Milk) $\wedge$ $\neg$have(bananas) ...
- Goals are conjunctions of literals, but may have variables, assumed to be existentially quantified

  at(?x) $\wedge$ have(Milk) $\wedge$ have(bananas) ...
- Need not fully specify state
  - Non-specified conditions either don't-care or assumed false
  - Represent many cases in small storage
  - May only represent changes in state rather than entire situation
- Unlike theorem prover, not seeking whether goal is true, but is there a sequence of actions to attain it



Shakey the robot

Blocks World Operators

- Classic basic **operations** for the Blocks World
  - **stack(X,Y):** put block X on block Y
  - **unstack(X,Y):** remove block X from block Y
  - **pickup(X):** pickup block X
  - **putdown(X):** put block X on the table
- Each represented by
  - list of **preconditions**
  - list of new facts to be added (**add-effects**)
  - list of facts to be removed (**delete-effects**)
  - optionally, set of (simple) variable **constraints**

Blocks World Stack Action

stack(X,Y):

- **preconditions**(stack(X,Y), [holding(X), clear(Y)])
- **adds**(stack(X,Y), [handempty, on(X,Y), clear(X)])
- **deletes**(stack(X,Y), [holding(X), clear(Y)]).
- **constraints**(stack(X,Y), [X≠Y, Y≠table, X≠table])

Blocks World Operators II

operator(<u>stack</u>(X,Y),

Precond [holding(X), clear(Y)],

Add [handempty, on(X,Y), clear(X)],

Delete [holding(X), clear(Y)],

Constr [X≠Y, Y≠table, X≠table]).

operator(<u>pickup</u>(X),

[ontable(X), clear(X), handempty],

[holding(X)],

[ontable(X), clear(X), handempty],

[X≠table]).

operator(<u>unstack</u>(X,Y),

[on(X,Y), clear(X), handempty],

[holding(X), clear(Y)],

[handempty, clear(X), on(X,Y)],

[X≠Y,Y≠table, X≠table]).

operator(<u>putdown</u>(X),

[holding(X)],

[ontable(X), handempty, clear(X)],

[holding(X)],

[X≠table]).

STRIPS planning

- STRIPS maintains two additional data structures:
  - State List - all currently true predicates.
  - Goal Stack - push down stack of goals to be solved, with current goal on top

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- If current goal not satisfied by present state, find action that adds it and push action and its preconditions (subgoals) on stack

STRIPS planning

- STRIPS maintains two additional data structures:
  - State List - all currently true predicates.
  - Goal Stack - push down stack of goals to be solved, with current goal on top
- If current goal not satisfied by present state, find action that adds it and push action and its preconditions (subgoals) on stack
- When a current goal is satisfied, POP from stack
- When an action is on top stack, record its application on plan sequence and use its add and delete lists to update current state

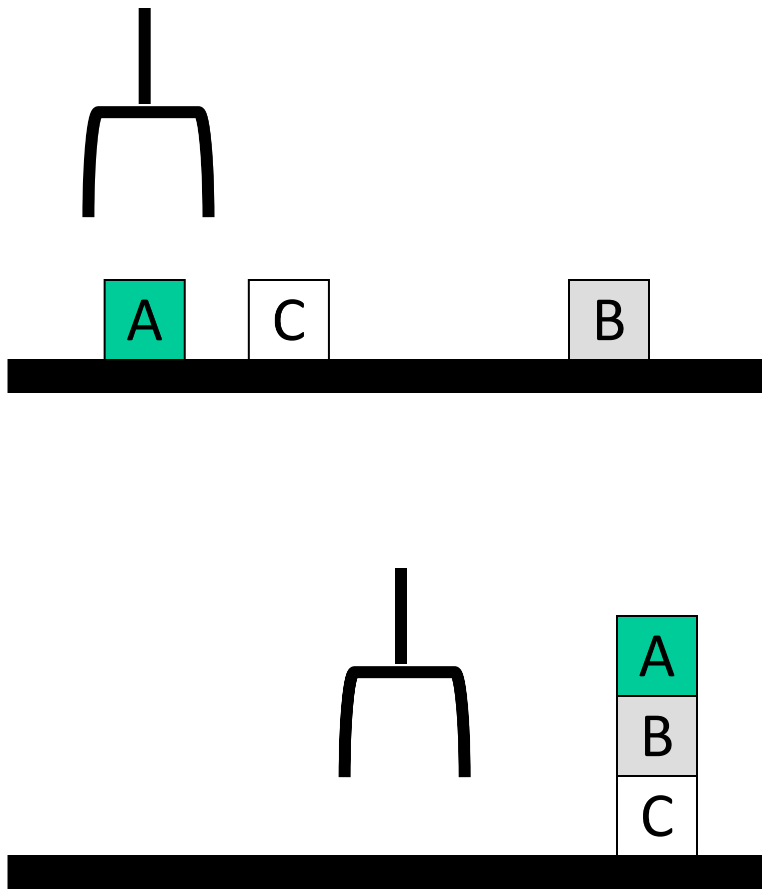
Typical BW planning problem

Initial state:

clear(a)
clear(b)
clear(c)
ontable(a)
ontable(b)
ontable(c)
handempty

Goal:

on(b,c)
on(a,b)
ontable(c)



A plan:

pickup(b)
stack(b,c)
pickup(a)
stack(a,b)

😃

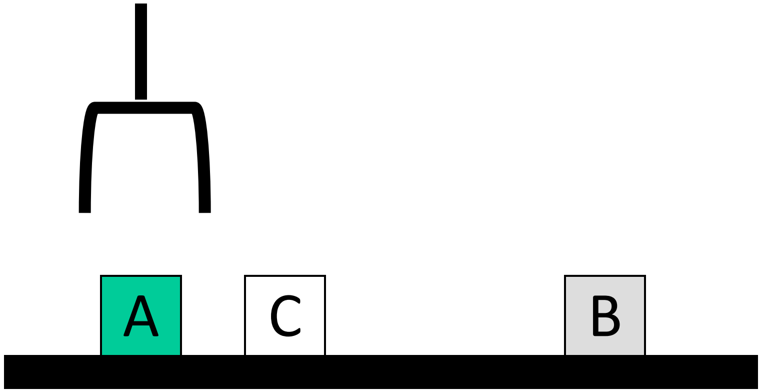
Another BW planning problem

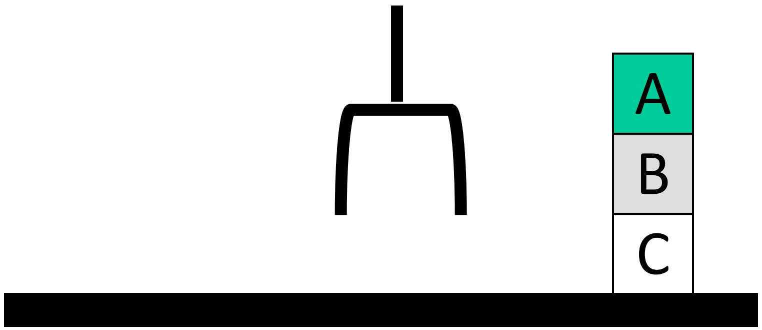
Initial state:

- clear(a)
- clear(b)
- clear(c)
- ontable(a)
- ontable(b)
- ontable(c)
- handempty

Goal:

- on(a,b)
- on(b,c)
- ontable(c)





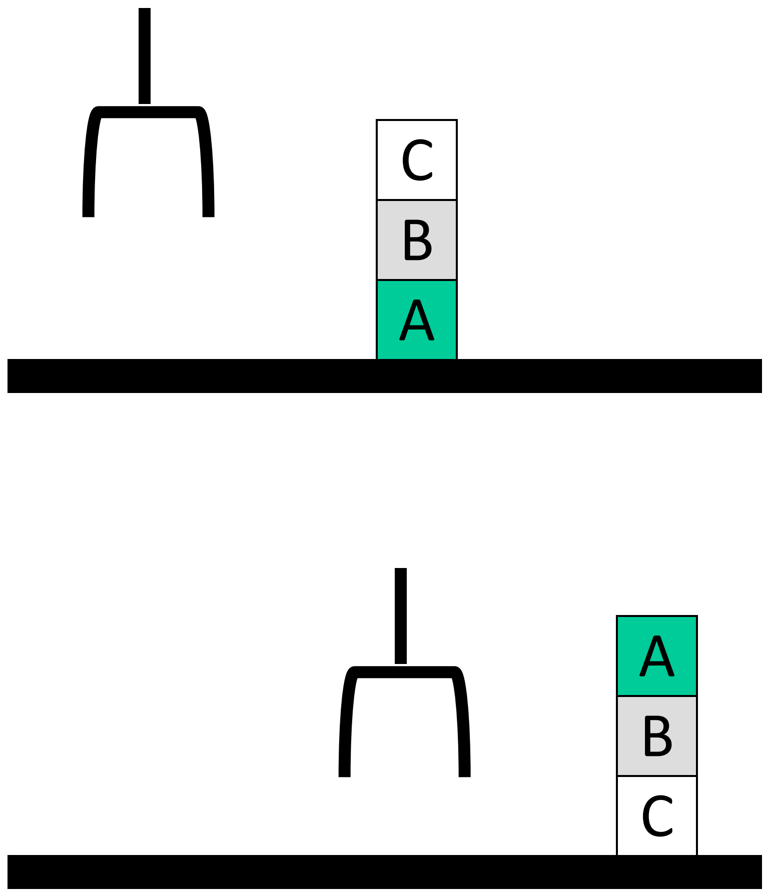
A plan:

- pickup(a)
- stack(a,b)
- unstack(a,b)
- putdown(a)
- pickup(b)
- stack(b,c)
- pickup(a)
- stack(a,b)

Yet Another BW planning problem 😐

Initial state:
- clear(c)
- ontable(a)
- on(b,a)
- on(c,b)
- handempty

Goal:
- on(a,b)
- on(b,c)
- ontable(c)



Plan:
- unstack(c,b)
- putdown(c)
- unstack(b,a)
- putdown(b)
- pickup(b)
- stack(b,a)
- unstack(b,a)
- putdown(b)
- pickup(a)
- stack(a,b)
- unstack(a,b)
- putdown(a)
- pickup(b)
- stack(b,c)
- pickup(a)
- stack(a,b)

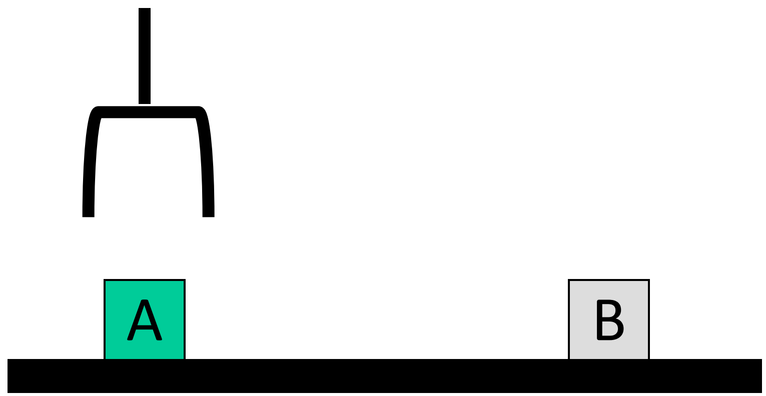
Yet Another BW planning problem

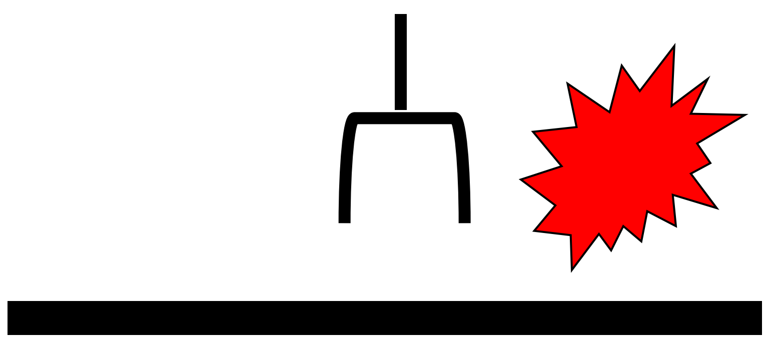
Initial state:

- ontable(a)
- ontable(b)
- clear(a)
- clear(b)
- handempty

Goal:

- on(a,b)
- on(b,a)



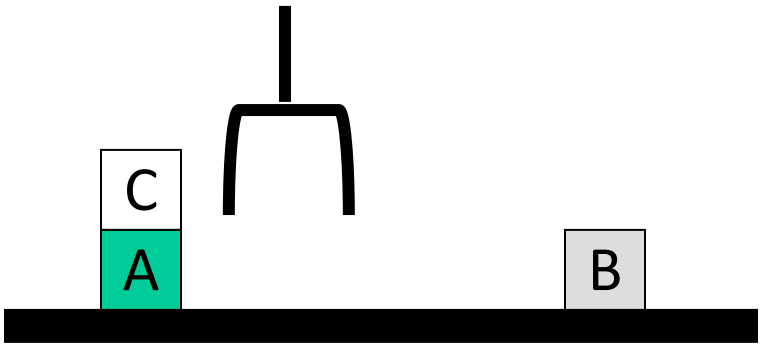


Plan:

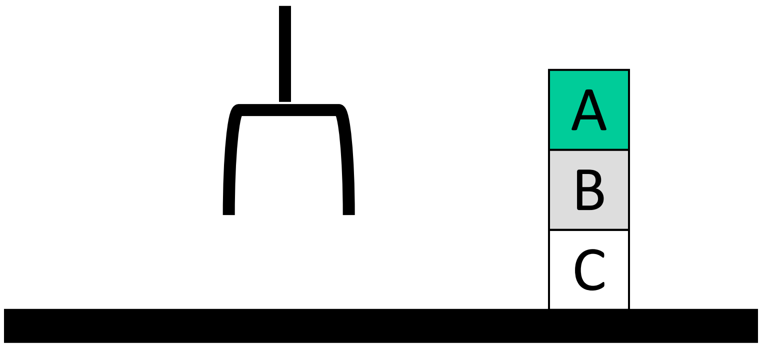
??

Goal interaction

- Simple planning algorithms assume independent sub-goals
  - Solve each separately and concatenate the solutions
- Sussman Anomaly: an example of goal interaction problem:
  - Solving on(A,B) first (via unstack(C,A),stack(A,B)) is undone when solving 2nd goal on(B,C) (via unstack(A,B), stack(B,C))
  - Solving on(B,C) first will be undone when solving on(A,B)
- Classic STRIPS couldn't handle this, although minor modifications can get it to do simple cases



Initial state



Goal state

State-Space Planning

- STRIPS searches thru a space of situations (where you are, what you have, etc.)
- Find plan by searching **situations** to reach goal
- **Progression planner**: searches forward
  - From initial state to goal state
  - Prone to exploring irrelevant actions
- **Regression planner**: searches backward from goal
  - Works **iff** operators have enough information to go both ways
  - Ideally leads to reduced branching: planner is only considering things that are relevant to the goal
  - but it's harder to define good heuristics – so most current systems favor forward search

Heuristics for Planning Problems

- Need an **admissible** heuristic to apply to planning states
  - Estimate of the distance (number of actions) to the goal
- Planning typically uses **relaxation** to create heuristics
  - Ignore all or some selected preconditions
  - Ignore delete lists: Movement towards goal is never undone
  - Use state abstraction (group together "similar" states and treat them as though they are identical) – e.g., ignore fluents*
  - Assume subgoal independence (use max cost; or, if subgoals actually are independent, sum the costs)
  - Use pattern databases to store exact solution costs of recurring subproblems

* an aspect of the world that changes - *R&N 266*

Plan-Space Planning

- Alternative: **search through space of *plans***, not situations
- The system represents plans and the actions within those plans. The emphasis is on the order and structure of actions.
- Start from a **partial plan**; expand and refine until a complete plan that solves the problem is generated
- **Refinement operators** add constraints to the partial plan and modification operators for other changes
- We can still use STRIPS-style operators:

  Op(ACTION: PutOnRightShoe, PRECOND: RightSockOn, EFFECT: RightShoeOn)
  Op(ACTION: PutOnRightSock, EFFECT: RightSockOn)
  Op(ACTION: PutOnLeftShoe, PRECOND: LeftSockOn, EFFECT: LeftShoeOn)
  Op(ACTION: PutOnLeftSock, EFFECT: LeftSockOn)

Partial-Order Planning

- A **linear planner** builds a plan as a **totally ordered sequence** of plan steps
- A **non-linear planner (aka partial-order planner)** builds up a plan as a set of steps with some temporal constraints
  - E.g., S1<S2 (step S1 must come before S2)

PutOnRightSock < PutOnRightShoe

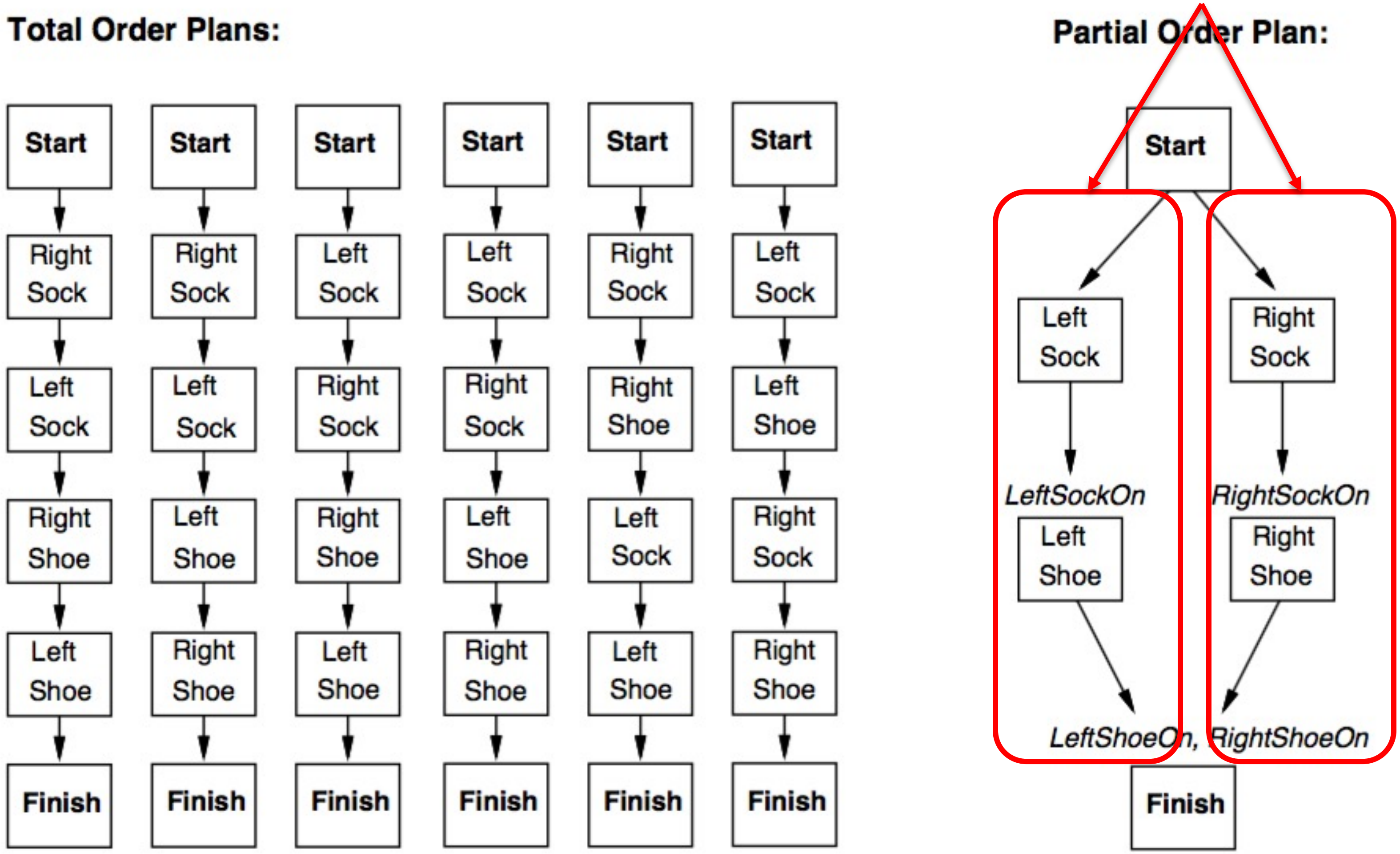
The order here *does* matter, so the planner has to know that.

Partial-Order Planning

- A **linear planner** builds a plan as a **totally ordered sequence** of plan steps
- A **non-linear planner (aka partial-order planner)** builds up a plan as a set of steps with some temporal constraints
  - E.g., S1<S2 (step S1 must come before S2)
- Partially ordered plan (POP) **refined** by either:
  - adding a new **plan step**, or
  - adding a new **constraint** to the steps already in the plan.
- Linearize a POP by topological sort

Linear *vs.* POP: Shoes

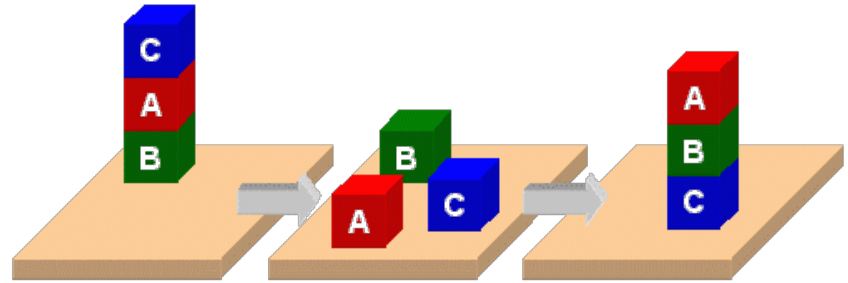
Do these sequences in any order



FYI

PDDL

PDDL



- **Planning Domain Description Language**
- Based on STRIPS with various extensions
- First defined by Drew McDermott (Yale) et al.
  - Classic spec: PDDL 1.2; good reference guide
- Used in biennial International Planning Competition (IPC) series (1998-2020)
- Many planners use it as a standard input

FYI

PDDL Representation

- Task specified via two files: **domain file** and **problem file**
  - Both use a logic-oriented notation with Lisp syntax
- **Domain file** defines a domain via *requirements*, *predicates*, *constants*, and *actions*
  - Used for many different problem files
- **Problem file:** defines problem by describing its *domain*, *objects*, *initial state* and *goal state*
- **Planner:** takes a domain and a problem and produces a plan


```
(define (domain BW)
  (:requirements :strips)
  (:constants red green blue yellow small large)
  (:predicates (on ?x ?y) (on-table ?x) (color  ?x ?y) ... (clear ?x))
  (:action pick-up
     :parameters (?obj1)
     :precondition (and (clear ?obj1) (on-table ?obj1)
                        (arm-empty))
     :effect (and (not (on-table ?obj1))
                  (not (clear ?obj1))
                  (not (arm-empty))
                  (holding ?obj1)))
  ... more actions ...)
```

Allows basic add and delete effects in actions

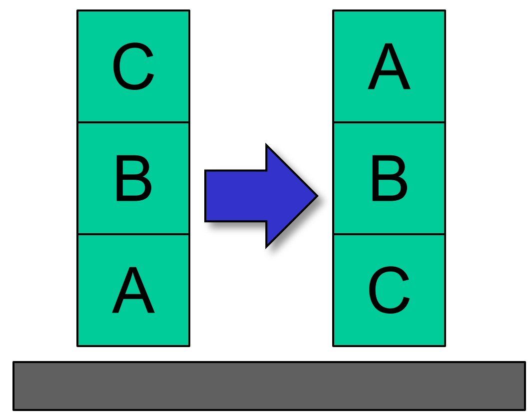
Variables begin with a ?

Blocks Word Domain File

FYI

Blocks Word Problem File


```
(define (problem 00)
    (:domain BW)
    (:objects A B C)
    (:init (arm-empty)
            (on B A)
            (on C B)
            (clear C))
    (:goal (and (on A B)
                 (on B C))))
```



Blocks Word Problem File


```
(define (problem 00)
    (:domain BW)
    (:objects A B C)
    (:init (arm-empty)
            (on B A)
            (on C B)
            (clear C))
    (:goal (and (on A B)
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```
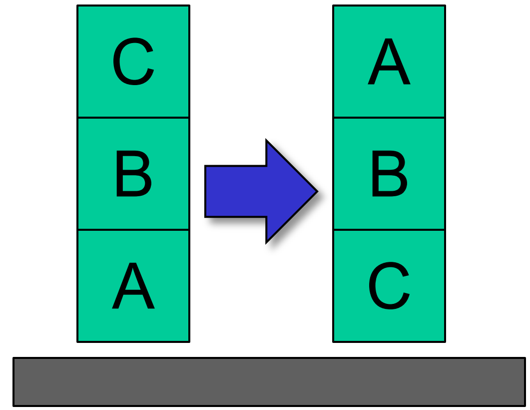
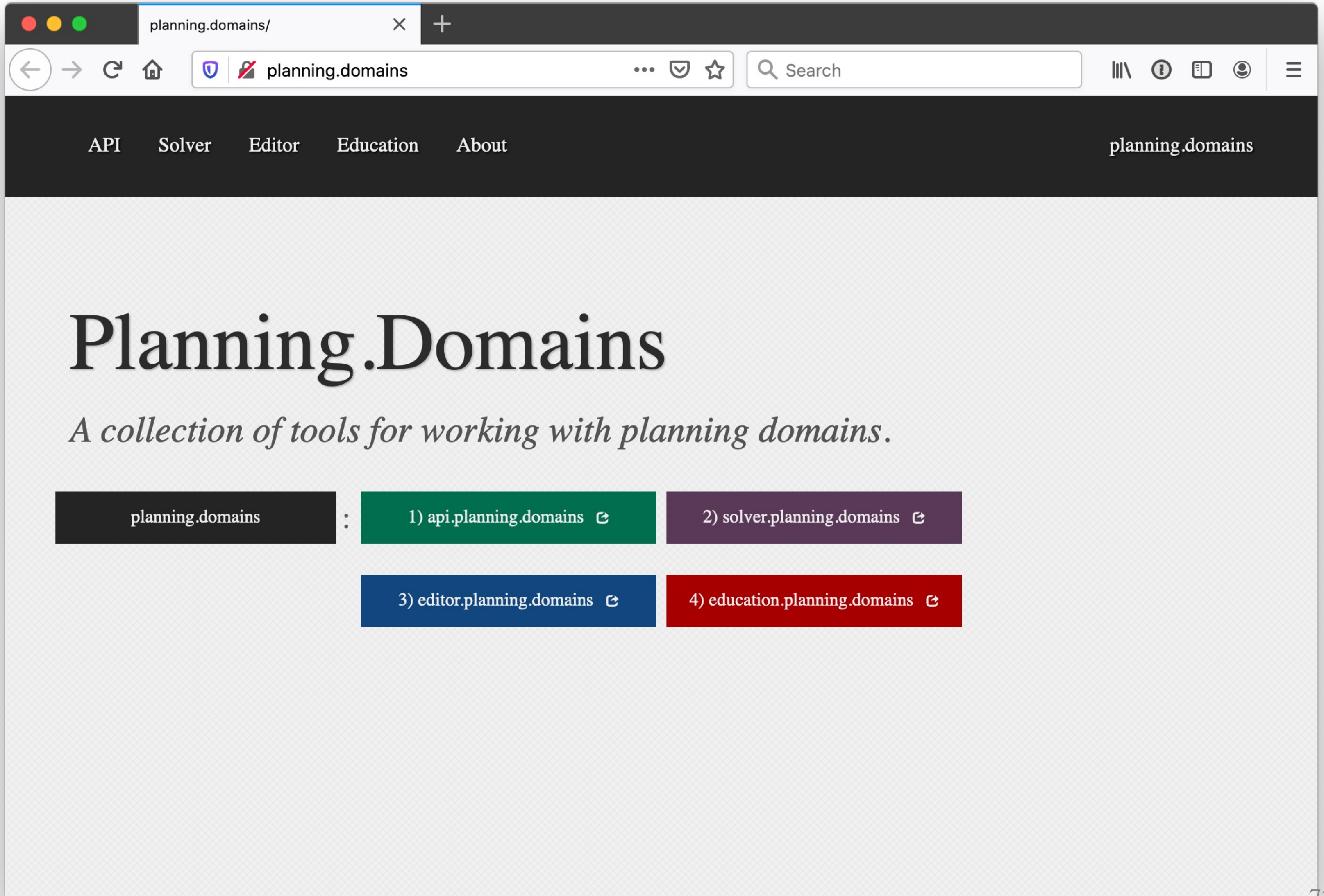



Begin plan
1 (unstack c b)
2 (put-down c)
3 (unstack b a)
4 (stack b c)
5 (pick-up a)
6 (stack a b)
End plan

FYI

http://planning.domains/



FYI

Planning.domains

- Open-source environment for providing planning services using PDDL (GitHub)
- Default planner is ff
  - very successful forward-chaining heuristic search planner producing sequential plans
  - Can be configured to work with other planners
- Use interactively or call via web-based API

Real-World Planning Domains

- Real-world domains are complex
- Don't satisfy assumptions of STRIPS or partial-order planning methods
- Some of the characteristics we may need to deal with:
  - Modeling and reasoning about resources
  - Representing and reasoning about time
  - Planning at different levels of abstractions
  - Conditional outcomes of actions
  - Uncertain outcomes of actions
  - Exogenous events
  - Incremental plan development
  - Dynamic real-time replanning

Scheduling

Planning under uncertainty

HTN planning

Planning Summary

- Planning representations
  - Situation calculus
  - STRIPS representation: Preconditions and effects
- Planning approaches
  - State-space search (STRIPS, forward chaining, ….)
  - Plan-space search (partial-order planning, HTNs, …)
  - *Constraint-based search (GraphPlan, SATplan, …)*
- Search strategies
  - Forward planning
  - Goal regression
  - Backward planning
  - Least-commitment
  - Nonlinear planning