

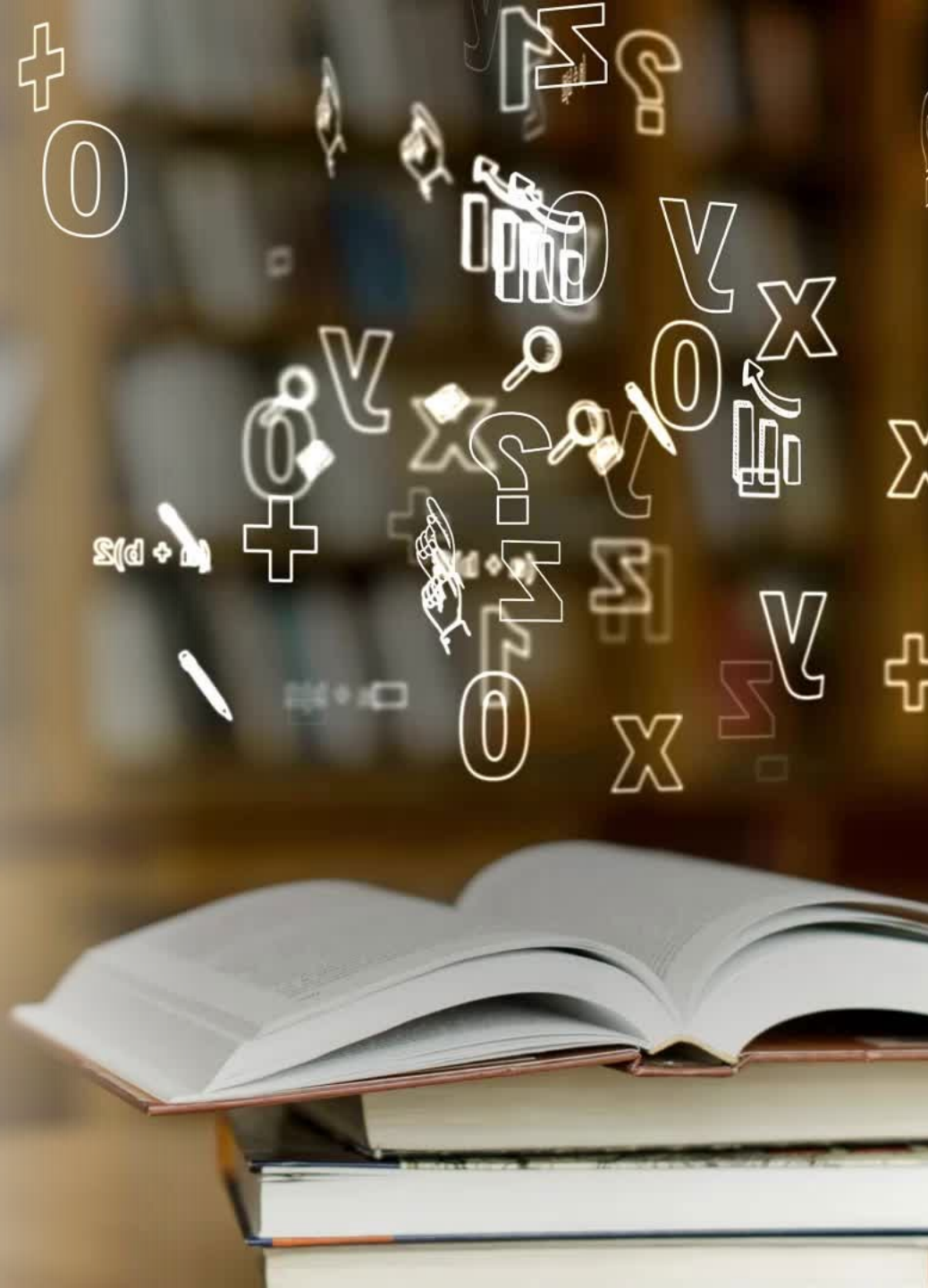
# CS 5/7320

## Artificial Intelligence

### Automated Planning AIMA Chapter 11

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with figures from the AIMA textbook



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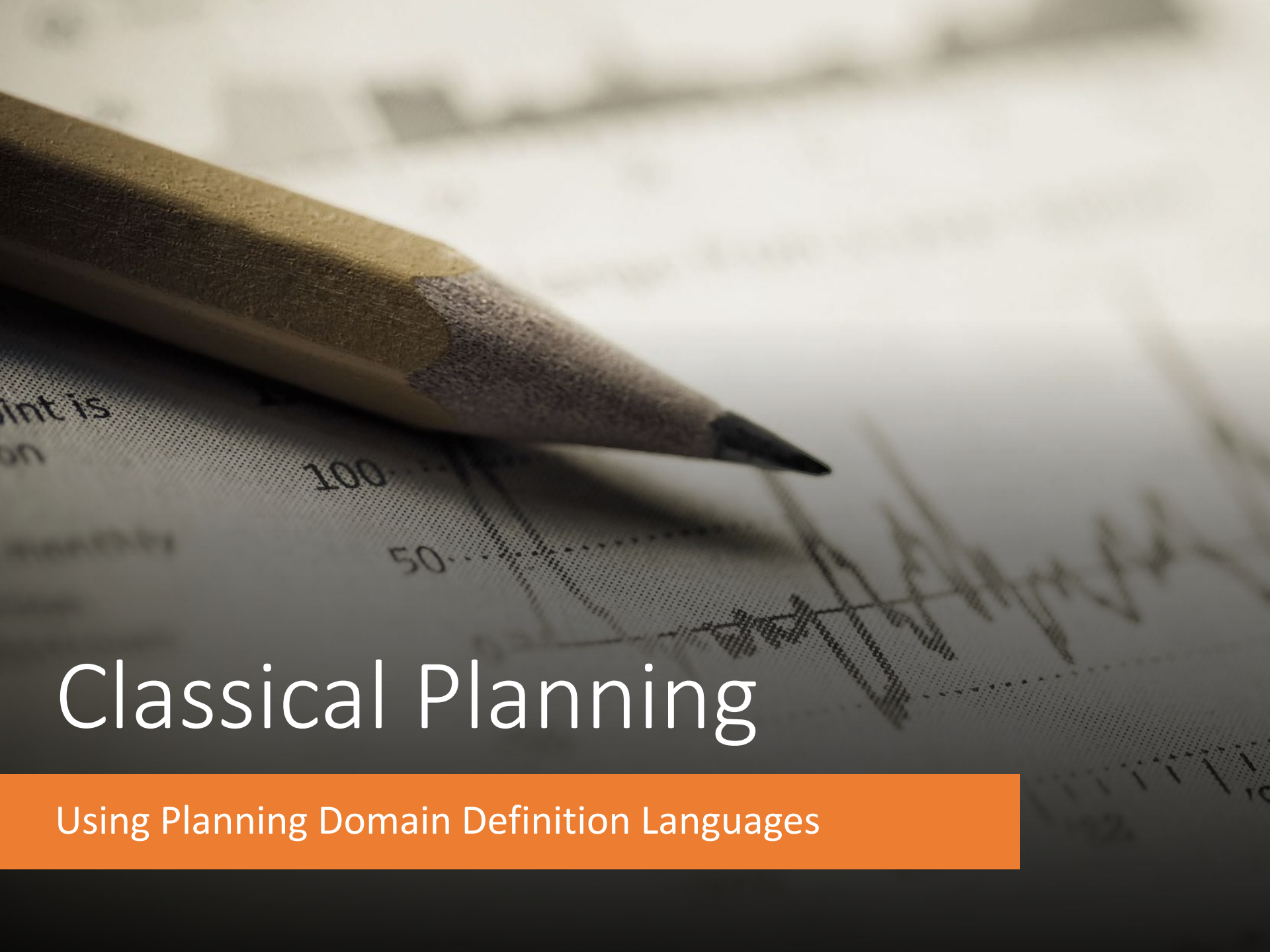
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Classical Planning

Hierarchical Planning

Monitoring and Replanning



# Classical Planning

Using Planning Domain Definition Languages

# Classical Planning

- Find a sequence of actions to accomplish a goal in a discrete, deterministic, static, fully observable environment.
- Options we have already discussed:
  - Chapter 3 : **Search** with a custom heuristic evaluation function.
  - Chapter 7: Propositional **logic** with custom code.
- Issue: Large state space.
- Solution: Factored state representation using a Planning Domain Definition Language (PDDL)

# Planning Domain Definition Language (PDDL)

an aspect of the world that  
can change over time

- **State**: a conjunction of ground atomic fluents (in 1-conjunctive normal form; 1-CNF).
- **Action Schema** (=precondition-effect description)

*Action*(*Fly*(*p*, *from*, *to*)),  
PRECOND: *Plane*(*p*)  $\wedge$  *Airport*(*from*)  $\wedge$   
*Airport*(*to*)  $\wedge$  *At*(*p*, *from*)  
EFFECT:  $\neg$  *At*(*p*, *from*)  $\wedge$  *At*(*p*, *to*)

$\underbrace{\neg \text{At}(p, \text{from})}_{\text{DEL}(\text{Fly})}$

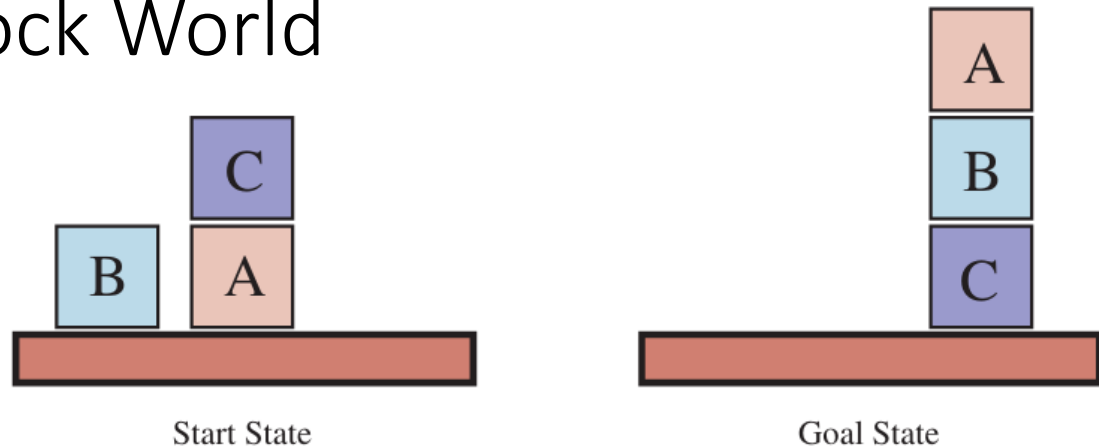
$\underbrace{\text{At}(p, \text{to})}_{\text{ADD}(\text{Fly})}$

- Action  $a$  is applicable to state  $s$  if  $s$  entails the precondition of  $a$ .
- The effect of  $a$  on  $s$  is to remove the negated fluents and adds the positive fluents.

$$\text{RESULT}(s, a) = (s - \text{DEL}(a)) \cup \text{ADD}(a)$$

- The **goal** is just like a precondition. E.g.,  $\text{At}(\text{Plane}_1, \text{SFO}) \wedge \text{At}(\text{Plane}_2, \text{JFK})$

# Example: Block World



$Init(On(A, Table) \wedge On(B, Table) \wedge On(C, A)$   
 $\wedge Block(A) \wedge Block(B) \wedge Block(C) \wedge Clear(B) \wedge Clear(C) \wedge Clear(Table))$   
 $Goal(On(A, B) \wedge On(B, C))$   
 $Action(Move(b, x, y),$   
    PRECOND:  $On(b, x) \wedge Clear(b) \wedge Clear(y) \wedge Block(b) \wedge Block(y) \wedge$   
             $(b \neq x) \wedge (b \neq y) \wedge (x \neq y),$   
    EFFECT:  $On(b, y) \wedge Clear(x) \wedge \neg On(b, x) \wedge \neg Clear(y))$   
 $Action(MoveToTable(b, x),$   
    PRECOND:  $On(b, x) \wedge Clear(b) \wedge Block(b) \wedge Block(x),$   
    EFFECT:  $On(b, Table) \wedge Clear(x) \wedge \neg On(b, x))$

**Figure 11.4** A planning problem in the blocks world: building a three-block tower. One solution is the sequence  $[MoveToTable(C, A), Move(B, Table, C), Move(A, Table, B)]$ .

# Algorithms

- **Forward state-space search:** Needs heuristics\* to deal with the state space.
- **Backward search** (= regression search): keeps the branching factor low.  
Issue: How do we define heuristics?
- Convert the PDDL description into propositional form and use an efficient solvers for the **Boolean satisfiability problem (SAT)**.

## \*Heuristics for Planning

Use the factored state description to calculate a heuristic function  $h(s)$  that estimates the distance from  $s$  to the goal. If it is admissible (does not overestimate the distance) then A\* can be used.

Example relaxations to create a heuristic:

- Ignore-preconditions: any action can be used in any state
- Ignore delete-list: no negative effects, problem progresses monotonic towards the goal.
- Serializable subgoals: subgoals can be achieved without undoing a previous subgoal.
- State abstraction to reduce the number of states. E.g., ignore some fluents.

## Example: maze

State:  $PosX(x) \wedge PosY(y)$

Ignore-precondition that checks for walls





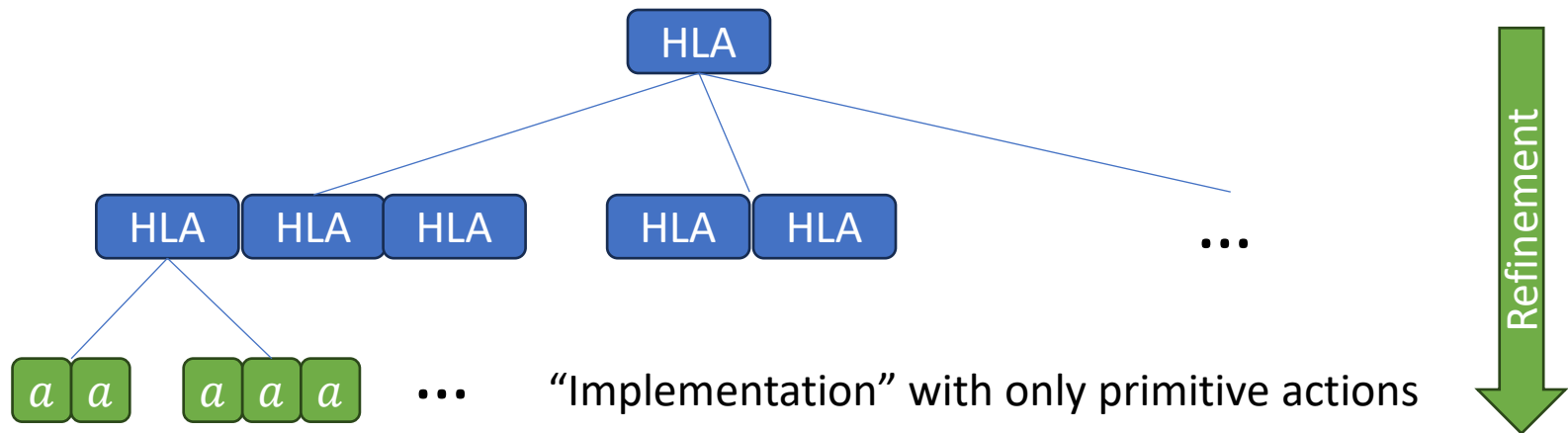
# Hierarchical Planning

Manage complexity using high-level actions.



# High-level Actions

- A **high-level action (HLA)** have one or several refinements into a sequence of HLAs or primitive actions.



- An HLA achieves the goal if at least one implementation achieves the goal.

# Example: Refinement

- Two refinements for the HLA *Go(Home, SFO)* to go from home to the SFO airport:

```
Refinement( Go(Home, SFO),  
    STEPS: [Drive(Home, SFO LongTermParking),  
            Shuttle(SFO LongTermParking, SFO)] )  
Refinement( Go(Home, SFO),  
    STEPS: [Taxi(Home, SFO)] )
```

- The agent can choose which implementation of the HLA to use.

# Search for Primitive Solutions

- The top HLA is often just “Act” and the agent needs to find an implementation that achieves the goal.
- Classical Planning
  - For each primitive action, provide a refinement of *Act* with steps  $[a_i, Act]$ .
  - This can recursively build any sequence of actions.
  - To stop the recursion, define:

*Refinement*(*Act*),  
PRECOND: goal is reached  
STEPS: []

- **Issue:** This approach has to search through all possible sequences!
- **Improvement:**
  - Reduce the number of need refinements + increase the number of steps in each refinement.

# Implementation: Search for Primitive Solutions

```
function HIERARCHICAL-SEARCH(problem, hierarchy) returns a solution or failure  
  frontier  $\leftarrow$  a FIFO queue with [Act] as the only element  
  while true do  
    if IS-EMPTY(frontier) then return failure  
    plan  $\leftarrow$  POP(frontier)           // chooses the shallowest plan in frontier  
    hla  $\leftarrow$  the first HLA in plan, or null if none  
    prefix, suffix  $\leftarrow$  the action subsequences before and after hla in plan  
    outcome  $\leftarrow$  RESULT(problem.INITIAL, prefix)  
    if hla is null then           // so plan is primitive and outcome is its result  
      if problem.IS-GOAL(outcome) then return plan  
    else for each sequence in REFINEMENTS(hla, outcome, hierarchy) do  
      add APPEND(prefix, sequence, suffix) to frontier
```

**Figure 11.8** A breadth-first implementation of hierarchical forward planning search. The initial plan supplied to the algorithm is [*Act*]. The REFINEMENTS function returns a set of action sequences, one for each refinement of the HLA whose preconditions are satisfied by the specified state, *outcome*.

# Searching for Abstract Solutions

- Search for primitive solutions has to refine all HLAs all the way to primitive actions to determine if a plan is workable.
- **Idea:** Determine what HLAs do.
  - Write precondition-effect descriptions for HLAs (this is difficult because of neg. effects!)
  - This results in an exponential reduction of the search space.
- **Reachable set:** the set of states reachable with a sequence of HLAs  $[h_1, h_2]$  in state  $s$ .

$$REACH(s, [h_1, h_2]) = \bigcup_{s' = REACH(s, h_1)} REACH(s', h_2)$$

- A sequence of HLAs achieves the goal if its reachable set intersects the goal set.
- Typical implementation:
  1. Use a simplified (optimistic) version of precondition-effect descriptions to find a high-level plan that works.
  2. Check if a refinement of that plan that works really exists. If not, go back to 1.



# Monitoring and Replanning

Planning and Acting in Partially Observable, Nondeterministic, and  
Unknown Environments

# Belief States

- For **nondeterministic** or **partially observable** environments we need belief states.
- A belief state is a set of possible physical states the agent might be in.
- Belief states need to be extended for factored state representation.
  - The belief state becomes a logical formulas of fluents.
  - Fluents that do not appear in the formula are unknown.

Technical note: If we manage to keep the belief state in 1-CNF (fluents are combined with ANDs), then the complexity is reduced from being exponential in the number of fluents to linear!



# Percept Schema

- For **partially observable** environments we need to be able to define what percepts the agent can get when.
- The agent uses a percept schema to reason about percepts that it can obtain during executing a plan.
- Example: Whenever the agent sees an object, then it will perceive its color.

$$\text{Percept}(\text{Color}(x, c)),$$
$$\text{PRECOND: } \text{Object}(x) \wedge \text{inView}(x)$$

The agent can now reason that it needs to get an object inView to see the color.

- Percept schemata and observability
  - Fully observable: Percept schemas have no preconditions.
  - Partially observable: Some percepts have preconditions.
  - Sensorless agent: has no percept schemas.

# Sensorless Planning (Conformant planning)

- We assume the underlying planning problem is deterministic.
- Similar to sensorless search in Chapter 4. Differences:
  - Transition model is a set of action schemata.
  - Belief state is represented as a logical formula where unknown fluents are missing.
- Update:

$$b' = \text{RESULT}(b, a) = \{s' : s' = \text{RESULT}_P(s, a) \text{ and } s \in b\}$$

*RESULT<sub>P</sub>* represents the physical transition model which adds positive and negative literals to the state description. The state description becomes more and more complete.

# Contingency Planning

- We can create a conditional plan for partially observable planning problems.
- We already have introduced conditional plans in Chapter 4 and just need to augment it by:
  - Action schemata instead of a transition function.
  - Percept schemata to reason about how to get needed percepts.
  - The state has a factored representation as facts in 1-CNF.
- Use **AND-OR search** over belief states.
- **Issues:**
  - Contingency plans become very complicated with **non-deterministic effects** like failures in actions or percepts. E.g., moving north fails 1 out of 100 times.
  - Plan fails with **incorrect model of the world**. E.g., actions with missing preconditions or missing effects, missing fluents, exogenous effects.

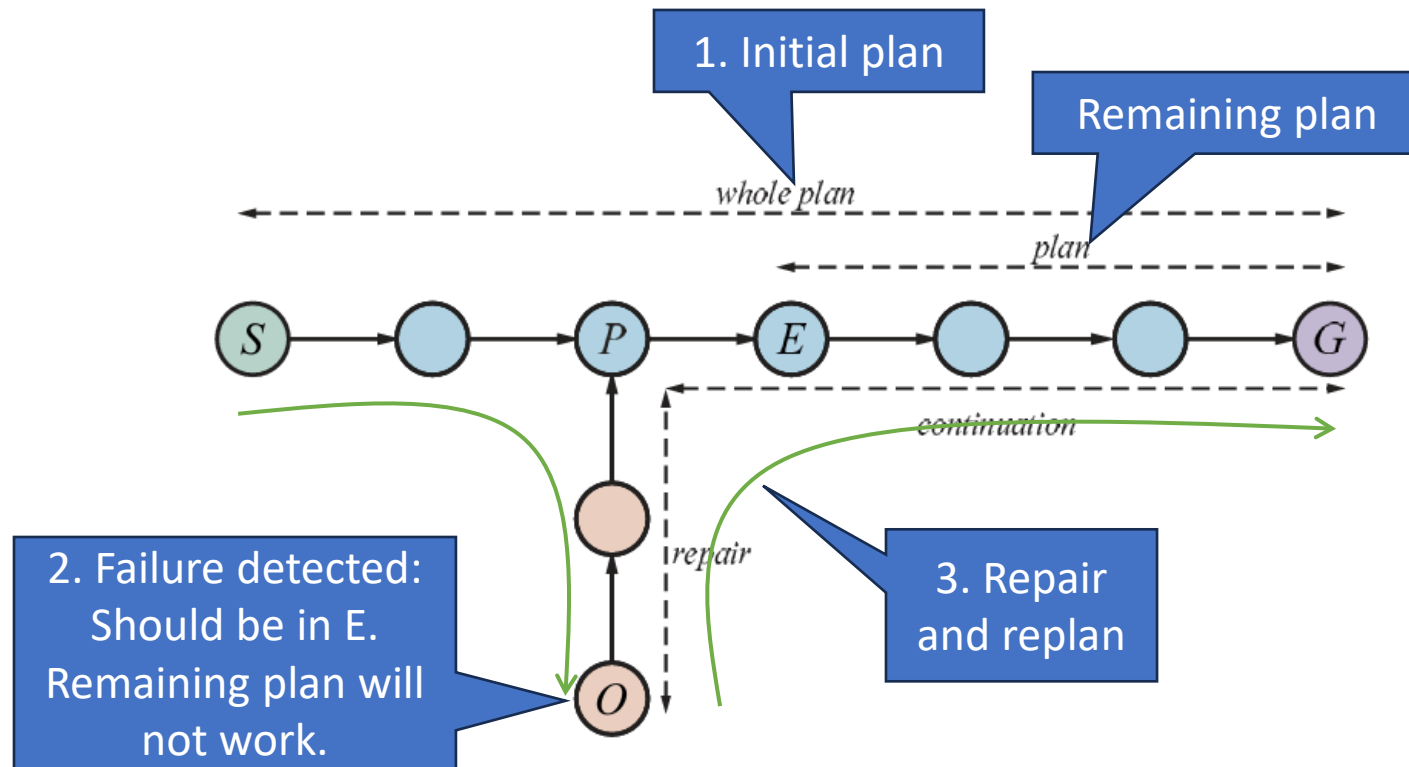
→ Online Planning

# Online Planning

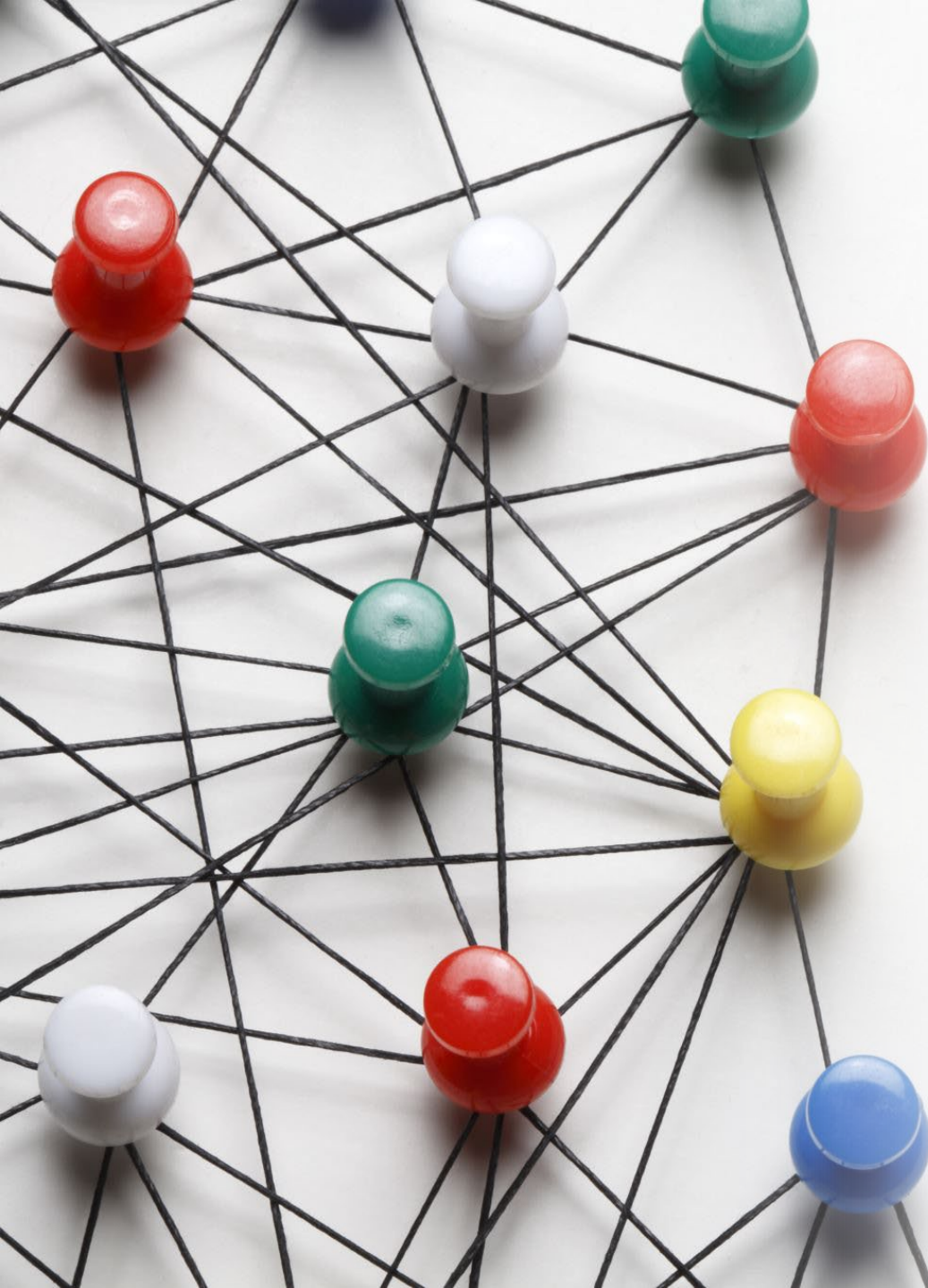
- Online planning = **replan during execution** when necessary.
- Requires **execution monitoring** to determine the need for replanning. The agent can perform
  - Action monitoring: only execute action if the preconditions are met
  - Plan monitoring: verify that the remaining plan will still succeed
  - Goal monitoring: check if a better set of goals has become available
- Often contingency plans can be made simpler by having unlikely branches just say “REPLAN.”
- Process:



# Example: Plan Monitoring with Repair



**Figure 11.12** At first, the sequence “whole plan” is expected to get the agent from  $S$  to  $G$ . The agent executes steps of the plan until it expects to be in state  $E$ , but observes that it is actually in  $O$ . The agent then replans for the minimal *repair* plus *continuation* to reach  $G$ .



# Summary

- **Action schemata** make specifying the transition function easier.
- **Hierarchical planning** lets us deal with the exponential size of the state space. The agent can reason at a more abstract level of high-level actions and the states are typically discrete.
- **Online planning with monitoring and replanning** is very flexible and can deal with many types of issues (sensor/actuator failure, imperfect models of the environment)