Robot Design Lab

Task Planning: Representation and Algorithms

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Abstract Representation for Task Planning

- Real world is absurdly complex. Therefore, we should approximate the world.
  - **Only represent** what the planner needs to reason about

- S = {abstract states}
    - e.g., states might include a robot's location, but not its position and orientation

- A = {abstract actions}
    - e.g., the action "move robot from location-1 to location-2" may need complex lower-level implementation

- Formal representation defines a language (syntax and semantics) for describing the planning domain, initial state and goal in abstract terms.
  - This makes it easier for the planner to generate plans automatically.

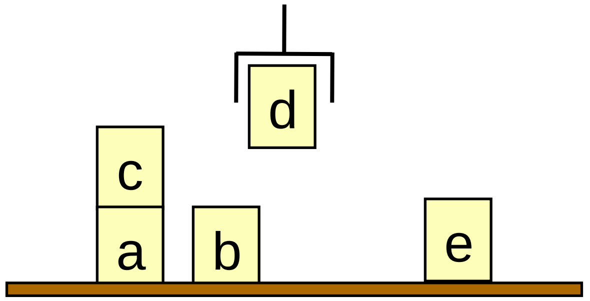
Contents

Example: The Blocks World

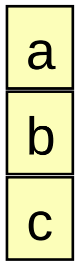
- Infinitely wide table, finite number of children's blocks
- Ignore where a block is located on the table
- A block can sit on the table or on another block
- There's a robot gripper that can hold at most one block

There is one location (table), one gripper (robot hand), and some blocks

- Want to move blocks from one configuration to another
  - e.g.,



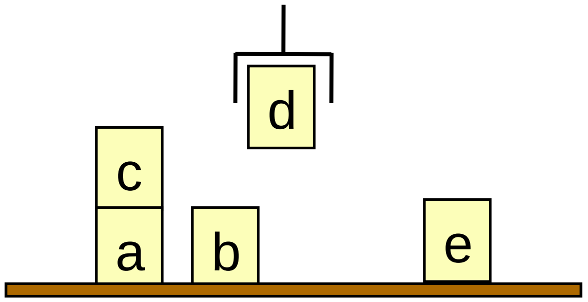
initial state



goal

Classical Representation: Symbols (1/2)

- **Constant symbols** for concrete things:
  - The blocks: a, b, c, d, e

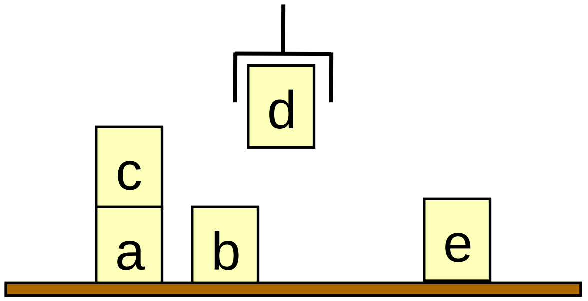


- **Predicates** to represent conditions:
  - ontable(*x*) - block *x* is on the table
  - on(*x*,*y*) - block *x* is on block *y*
  - clear(*x*) - block *x* has nothing on it
  - holding(*x*) - the robot hand is holding block *x*
  - handempty - the robot hand isn't holding anything

- Predicates have the form predicate-symbol(arguments).

Classical Representation: Symbols (2/2)

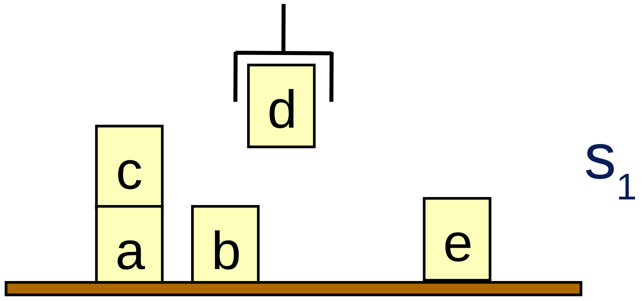
- Predicates have the form predicate-symbol(arguments).
- Arguments in predicates are variables that can be substituted with constant symbols.
  - ontable(a)
  - on(c,a)
  - clear(c)
  - holding(d)
  - ontable(b)
  - ontable(e)



- The process of substituting all variables in a predicate with constant symbols is called **grounding** the predicate.

States

- *State*: a set of ground predicates
  - Represents the conditions or facts that are true in that state.
  - Since we have only a finite no. of predicates and a finite no. of constant symbols, we have only a finite no. of possible states.



s_1 = {ontable(a), ontable(b), ontable(e), on(c,a), clear(c), clear(b), clear(e), holding(d)}

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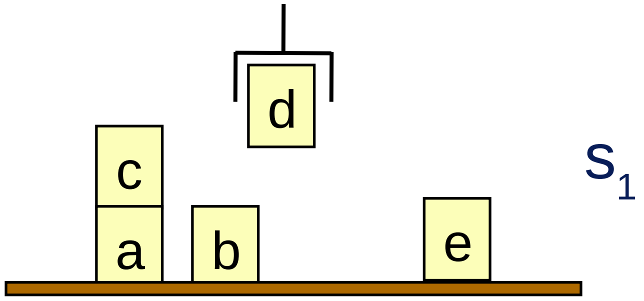

s_1 = {ontable(a), ontable(b), ontable(e), on(c,a), clear(c), clear(b), clear(e), holding(d)}

- handempty is false, and therefore it is not included in $s_{1.}$
- **Closed world assumption:** What is not known to be true is assumed to be false.

Operators

Operators are generalizations of actions.

Operator: a triple o=(name(o), precond(o), effects(o))

- precond(o): *preconditions*
  - Predicates and their negations that must be true in order to use the operator.
- effects(o): *effects*
  - Predicates and their negations that the operator will make true.
- name(o): a syntactic expression of the form $n(x_1,\ldots,x_k)$
  - n is an *operator symbol* - must be unique for each operator.
  - $(x_1,\ldots,x_k)$ is a list of every variable symbol (parameter) that appears in o.

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Rather than writing each operator as a triple, we'll usually write like this:

pickup(x)

;; gripper picks up block x from the top of the table

Precond: ontable(x), clear(x), handempty

Effects: ¬ontable(x), ¬clear(x), ¬handempty, holding(x)

¬ indicates negation

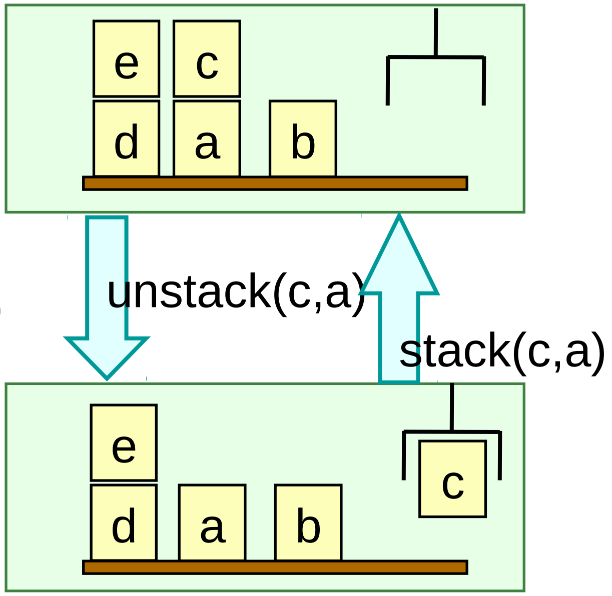
Classical Operators

unstack(x,y)

;; pick block x from the top of block y

Precond: on(x,y), clear(x), handempty

Effects: ¬on(x,y), ¬clear(x), ¬handempty, holding(x), clear(y)



stack(x,y)

;; put block x on top of block y

Precond: holding(x), clear(y)

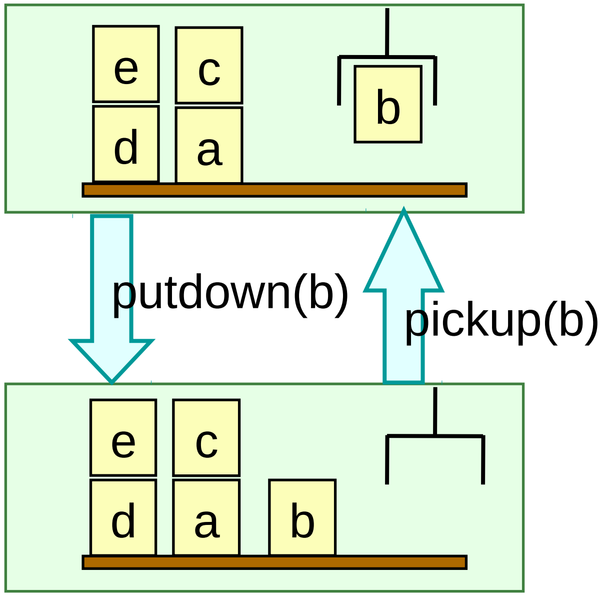
Effects: ¬holding(x), ¬clear(y), on(x,y), clear(x), handempty

pickup(x)

;; pick up block x from the top of the table

Precond: ontable(x), clear(x), handempty

Effects: ¬ontable(x), ¬clear(x), ¬handempty, holding(x)



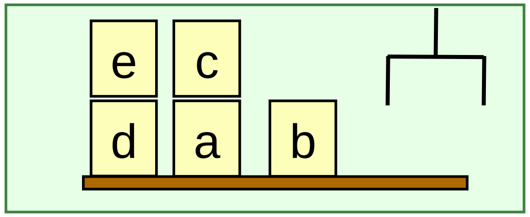
putdown(x)

;; put down block x on top of the table

Precond: holding(x)

Effects: ¬holding(x), ontable(x), clear(x), handempty

Actions



pickup(*x*)

;; gripper picks up block *x*

Precond: ontable(*x*), clear(*x*), handempty

Effects: ¬ontable(*x*), ¬clear(*x*), ¬handempty, holding(*x*)

An *action* is a **ground** instance (via substitution) of an operator

- Suppose we substitute *x* with b.
- Then we get the following action:

pickup(b)

precond: ontable(b), clear(b), handempty

effects: ¬ontable(b), ¬clear(b), ¬handempty, holding(b)

- i.e., The robot's gripper picks up block b off the table.

Notation

Let *a* be an operator or action. Then

- $\text{precond}^+(a)$ = {predicates that appear positively in *a*'s preconditions}
- $\text{precond}^-(a)$ = {predicates that appear negatively in *a*'s preconditions}
- $\text{effects}^+(a)$ = {predicates that appear positively in *a*'s effects}
- $\text{effects}^-(a)$ = {predicates that appear negatively in *a*'s effects}

- Example:

  pickup(b)

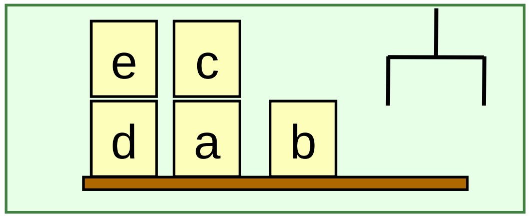
  precond: ontable(b), clear(b), handempty

  effects: ¬ontable(b), ¬clear(b), ¬handempty, holding(b)

- precond^+(pickup(b)) = {ontable(b), clear(b), handempty}
- precond^-(pickup(b)) = { }
- effects^+(pickup(b)) = {holding(b)}
- effects^-(pickup(b)) = {ontable(b), clear(b), handempty)}

Applicability

s_2



Let s be a state and a be an action

a is *applicable* to (or *executable* in) s if s satisfies precond(a)

- $\text{precond}^+(a) \subseteq s$
- $\text{precond}^-(a) \cap s = \varnothing$

An action:

pickup(b)

precond: ontable(b), clear(b), handempty

effects: ¬ontable(b), ¬clear(b), ¬handempty, holding(b)

A state it's applicable to

s_2 = {ontable(d), ontable(a), **ontable(b)**, on(e,d), on(c,a), clear(e), clear(c), **clear(b)**, **handempty**}

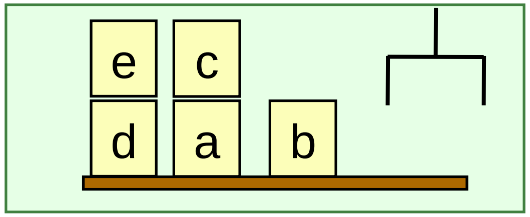
Executing an Applicable Action

Remove *a*'s negative effects from the state,
and add *a*'s positive effects to the state

$\gamma(s,a) = s' = (s - \text{effects}^-(a)) \cup \text{effects}^+(a)$

pickup(b)
    precond: ontable(b), clear(b), handempty

    effects: ¬ontable(b), ¬clear(b),
             ¬handempty, holding(b)



s_2

s_2 = {ontable(d), ontable(a), **ontable(b)**, on(e,d), on(c,a), clear(e), clear(c), **clear(b)**, **handempty**}

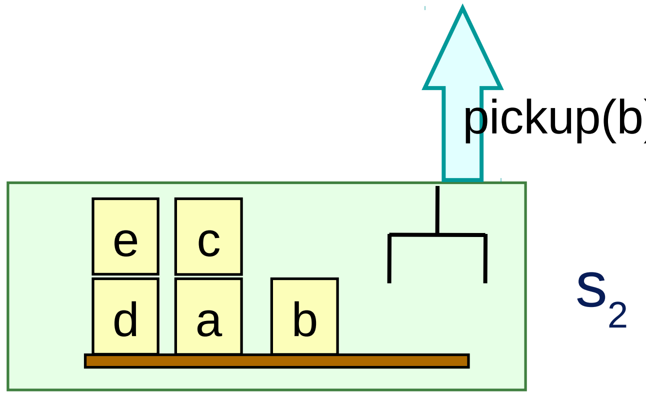
Executing an Applicable Action

Remove *a*'s negative effects from the state,
and add *a*'s positive effects to the state

$\gamma(s,a) = s' = (s - \text{effects}^{-}(a)) \cup \text{effects}^{+}(a)$

pickup(b)
    precond: ontable(b), clear(b), handempty

    effects: ¬ontable(b), ¬clear(b),
    ¬handempty, holding(b)



S$_2$

pickup(b)

s_2 = {ontable(d), ontable(a), **ontable(b)**, on(e,d), on(c,a), clear(e), clear(c), **clear(b)**, **handempty**}

Executing an Applicable Action

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pickup(b)
precond: ontable(b), clear(b), handempty

effects: ¬ontable(b), ¬clear(b),
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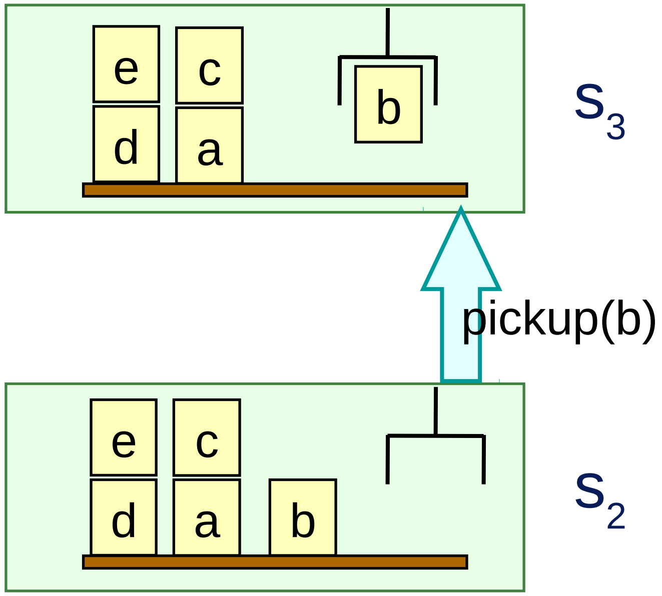


s_3 = {ontable(d), ontable(a), ~~ontable(b)~~,
on(e,d), on(c,a), clear(e), clear(c),
~~clear(b)~~, ~~handempty~~, **holding(b)**}

↑ pickup(b)

s_2 = {ontable(d), ontable(a), **ontable(b)**,
on(e,d), on(c,a), clear(e), clear(c),
clear(b), **handempty**}

Executing an Applicable Action

Remove *a*'s negative effects from the state,
and add *a*'s positive effects to the state

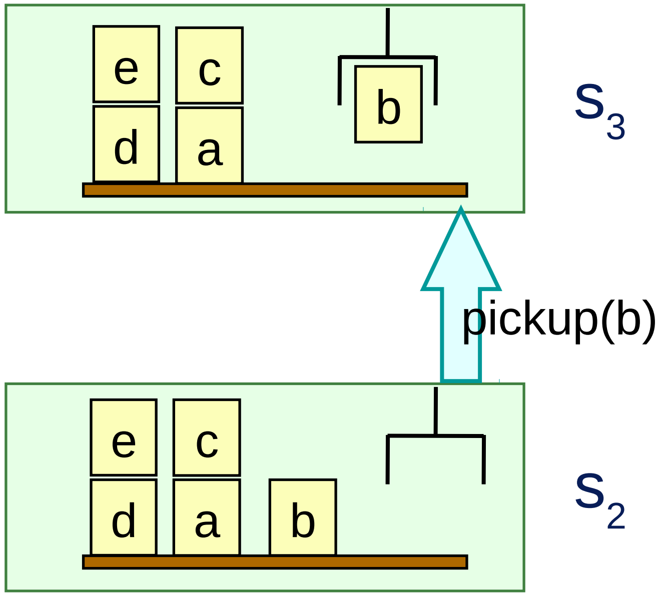
$\gamma(s,a) = s' = (s - \text{effects}^{-}(a)) \cup \text{effects}^{+}(a)$

γ is called the **state transition function.**

$\gamma(s_2,\text{pickup(b)}) = s_3$

pickup(b)
precond: ontable(b), clear(b), handempty

effects: ¬ontable(b), ¬clear(b),
¬handempty, holding(b)



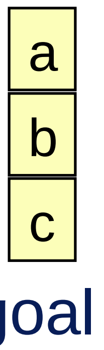
s_3 = {ontable(d), ontable(a), ~~**ontable(b)**~~,
on(e,d), on(c,a), clear(e), clear(c),
~~**clear(b)**~~, ~~**handempty**~~, **holding(b)**}

$\uparrow$ pickup(b)

s_2 = {ontable(d), ontable(a), **ontable(b)**,
on(e,d), on(c,a), clear(e), clear(c),
clear(b), **handempty**}

Goal

- Goal: a set of ground predicates or its negations
  - Represents the conditions that should hold in a goal state.
  - Positive goal conditions should be present in the goal state and negavite goal conditions should be absent in the goal state.



goal = {on(b,c), on(a,b)}

Classical Task Planning Problems

- **Planning domain:**
  - Constant symbols
  - Predicates
  - Operators
- ***Given a planning domain,***
  - The ***statement* of a planning problem**: a triple $P=(O,s_0,g)$
    - » O is the collection of operators
    - » s_0 is the initial state
    - » g is a set of ground predicates or their negations (the goal)
      - Based on g, we can find a set of goal states $\boldsymbol{S_g}$ that satisfy g.

Plans and Solutions

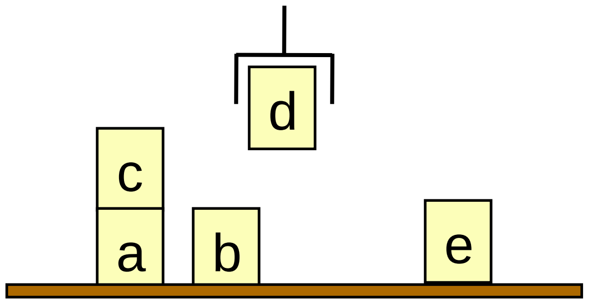
Let $P=(O,s_0,g)$ be a planning problem

Plan: any sequence of actions $\pi = \langle a_1, a_2, \ldots, a_n \rangle$ such that each a_i is a ground instance of an operator in O

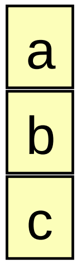
π is a *solution* for $P=(O,s_0,g)$ if it is executable and achieves g

- i.e., if there are states $s_0, s_1, \ldots, s_n$ such that
  - $\gamma(s_0,a_1) = s_1$
  - $\gamma(s_1,a_2) = s_2$
  - …
  - $\gamma(s_{n-1},a_n) = s_n$
  - s_n satisfies g (that is, all positive ground predicates in g are present in s_n and all negative ground predicates in g are absent in s_n)
  - Length of a plan is the no. of actions it contains.

Example: The Blocks World



initial state



goal

- Initial state, s_0:
  - s_0 = {ontable(a), ontable(b), ontable(e), on(c,a), clear(c), clear(b), clear(e), holding(d)}
- Goal
  - g = {on(b,c), on(a,b)}
- Now, we have to come up with a plan (sequence of actions) that will take us from s_0 to any state that satisfies g.
  - π = <putdown(d), unstack(c,a), putdown(c), pickup(b), stack(b,c), pickup(a), stack(a,b)>
  - *Note: Refer Slide11 to see the definitions of all operators.*

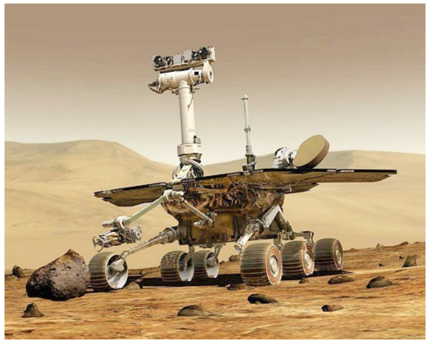
Task Planning Deals with…

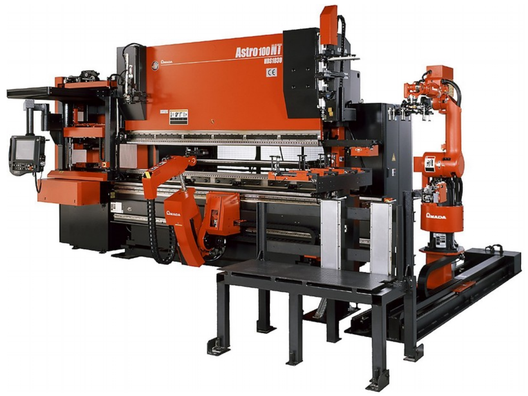
Given a planning domain and a planning problem, how can the robot **autonomously find a plan**, i.e. a sequence of actions, in order to go from the initial state to a state that satisfies the goal?

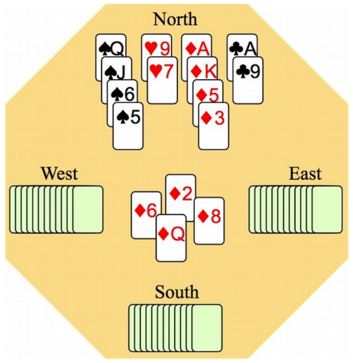
Algorithms that do this are called **planners**.

Three Main Types of Planners

1. Domain-specific planners
   - Made or tuned for a specific planning domain
     - Most successful real-world planning systems work this way (Mars exploration, sheet metal bending, playing bridge, etc.)
   - Won't work well (if at all) in other planning domains
2. Domain-independent planners --> focus of most research
   - In principle, works in any planning domain
   - In practice, need restrictions on what kind of planning domains it can be applied
   - **e.g. Classical task planning**
3. Configurable planners
   - Domain-independent planning engine
   - Input includes info about how to solve problems in some domain







Restrictive Assumptions in Classical Task Planning

A0: Finite system:

- Finite no. of states and actions.

A1: Fully observable:

- The agent always knows the current state of the world.

A2: Deterministic:

- Each action has only one outcome.
- If an action is applied to a state, it will bring the world to a single new state.

A3: Static (no exogenous events):

- Changes to the world state can be caused only through the agent‘s own actions.

A4: Attainment goals:

- Goal is specified explicitly and corresponds to a set of goal states $\boldsymbol{S_g}$.

A5: Sequential plans:

- A plan is a linearly ordered sequence of actions (a_1, a_2, … a_n).

A6: Implicit time:

- No time durations; a linear sequence of instantaneous states and actions.

A7: Off-line planning:

- Planner doesn’t know the execution status of the plan while it is generating the plan.

Planning is Searching…

- Nearly all planning procedures are search procedures.
- In this lecture, we will look at ***state-space planning,*** which is used by classical task planners.
  - Similar to path planning algorithms.
  - Here, each node represents a **state** of the world.
  - Finds a path that starts at the initial state and ends at a goal state.

Planning is Searching…

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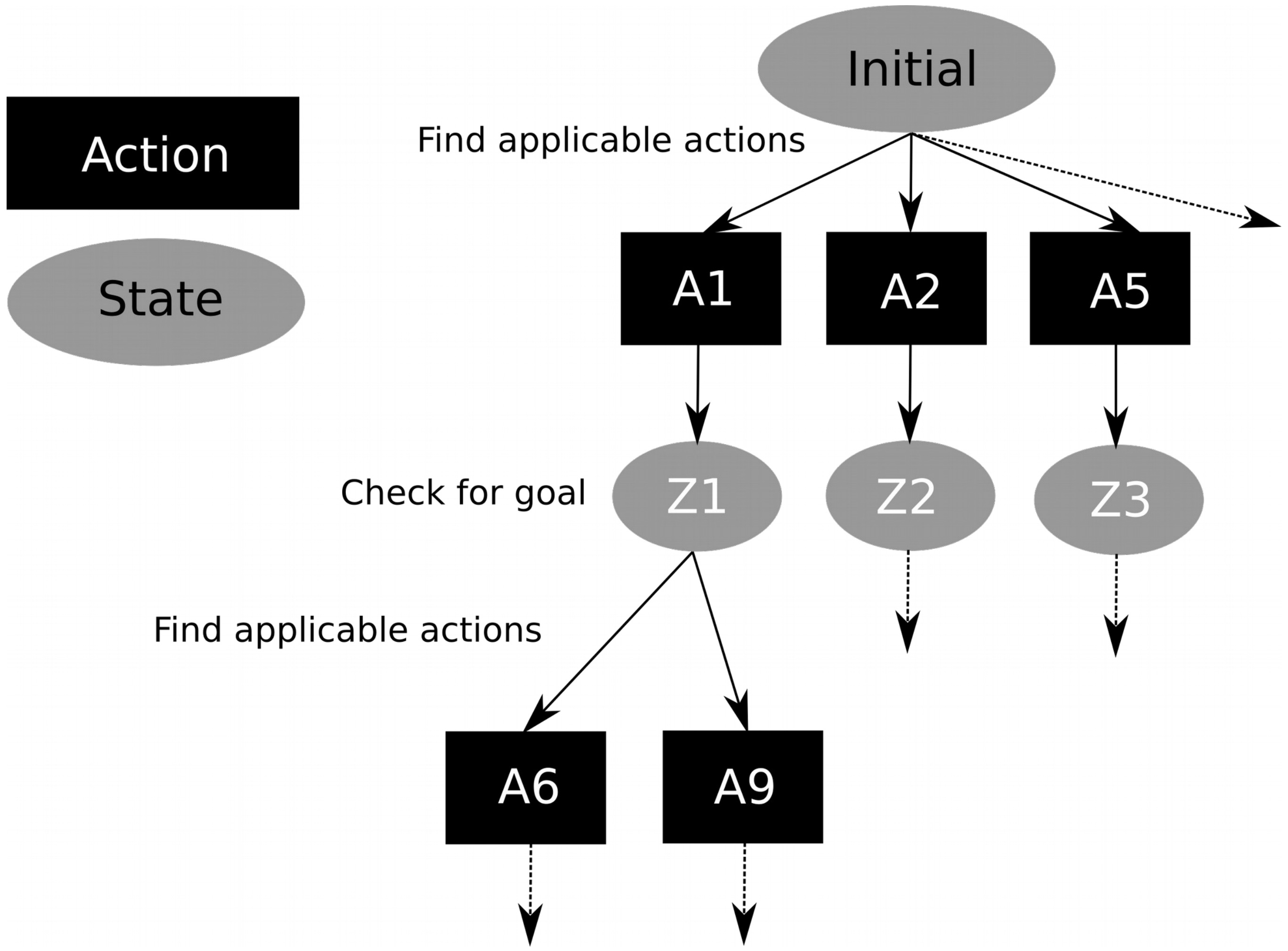
  - Similar to path planning algorithms.
  - Here, each node represents a **state** of the world.
  - Finds a path that starts at the initial state and ends at a goal state.

  - Search proceeds as follows:
    1. The algorithm starts the search at the initial state.
    2. If the initial state satisfies the goal, then search ends and we get a plan of length zero.
    3. If not, the algorithm applies all **applicable actions** to the initial state to produce new states.
    4. It checks if any of the new states **satisfies the goal**.
    5. If yes, search ends.
    6. If not, then search continues by applying actions to each of the new states.
    7. Search continues until either all reachable states have been examined or a goal state has been reached.
    8. If a goal state is reached, the algorithm **returns the sequence of actions** that led from the initial state to the found goal state.

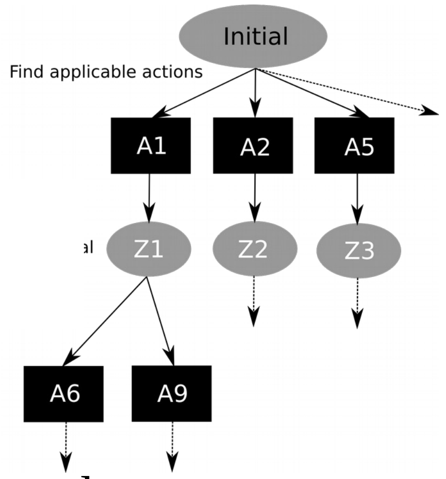
State-Space Planning: Forward Search



Properties

- Forward-search is *sound*
    - Any plan that is returned is guaranteed to be a solution
- Forward-search also is *complete*
    - If a solution exists then Forward-search will return a solution.

Deterministic Implementations

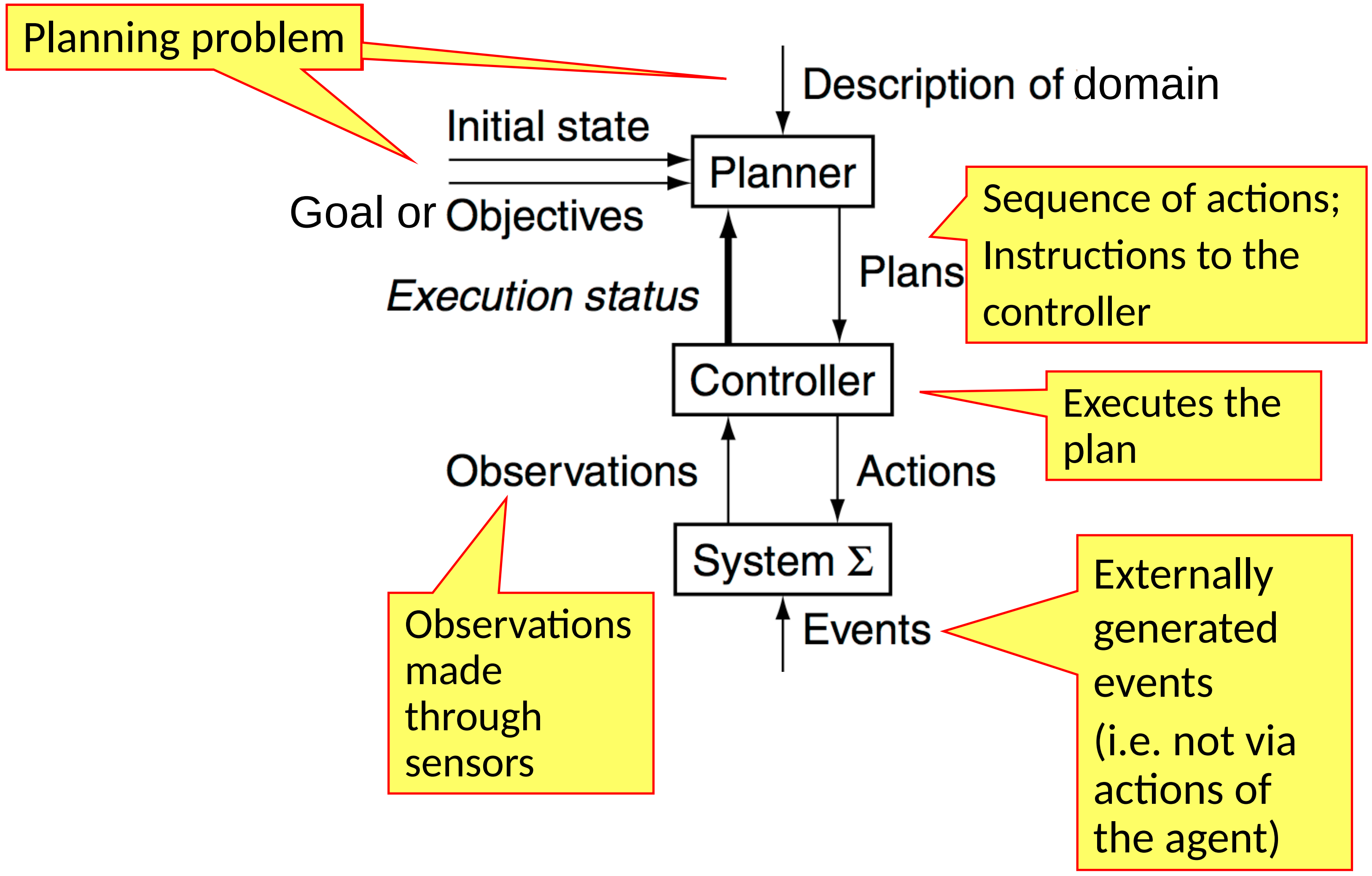


- Some deterministic implementations of forward search:
  - **breadth-first search**
  - **best-first search (e.g., A*)**

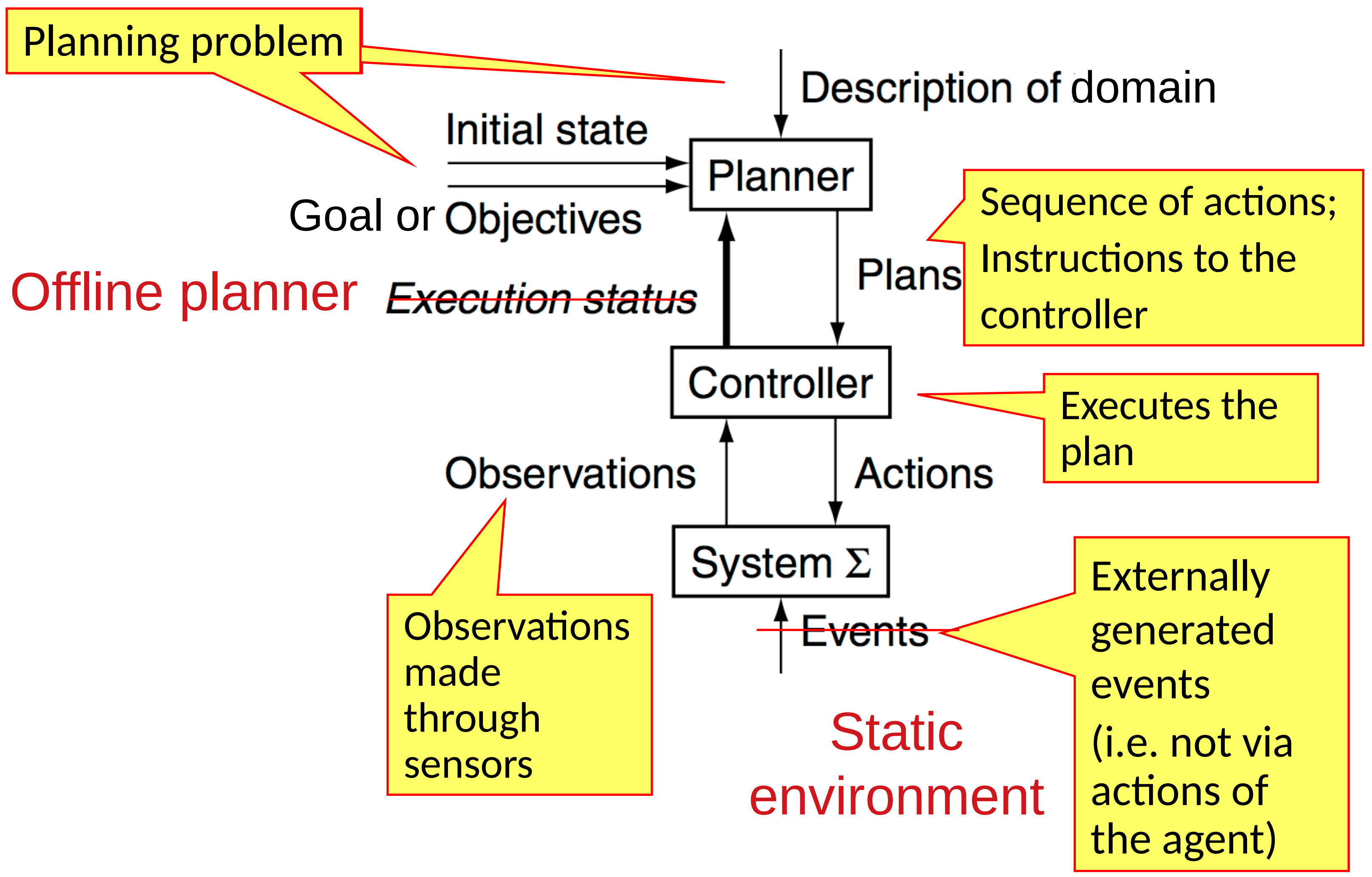
- Breadth-first and best-first search are sound and complete.
  - But they usually aren't practical because they require too much memory.
  - Memory requirement is exponential in the length of the solution.

- Forward search can have a very large branching factor.
  - E.g., many applicable actions that don't progress toward goal.
  - Why this is bad:
    - » Deterministic implementations can waste time trying lots of irrelevant actions.
  - Need a good heuristic function and/or pruning procedure.

Conceptual Model of Planning and Acting



Classical Planning and Acting



Summary

- An example: Blocks world
- Classical representation of the planning domain (constant symbols, predicates, operators), states and actions.
- Applicability of an action to a state
- State transition function
- Assumptions needed for classical task planning
- Statement of a classical task planning problem
- Three types of planners: domain-dependent, domain-independent, configurable
- State-space planning: Forward search
- Conceptual model of planning and acting (plan execution).

Next Part:
Behaviour Trees and Plan Execution