COL864: Special Topics in AI
Semester I, 2022-23

Task Planning

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Outline

- Last Class
  - State Estimation
- This Class
  - Symbolic Representations for Task Planning
    - How can we represent such problems?
    - How can we (efficiently) search for a plan?
- Reference Material
  - Primary reference are the lecture notes. For basic background refer to AIMA Classical Planning Ch. 10 (Sec 10.1 - 10.3)

Acknowledgements

These slides are intended for teaching purposes only. Some material has been used/adapted from web sources and from slides by Nicholas Roy, Wolfram Burgard, Dieter Fox, Sebastian Thrun, Siddharth Srinivasa, Dan Klein, Pieter Abbeel, Max Likhachev and others.

Task Planning

- Motion planning
  - Generating collision free trajectories.
- Task Planning
  - Presence of Semantic constraints
    - Till now, generating collision free trajectories.
    - Now, consider when an action a_i must be performed before action a_j (opening a box before placing and object inside it)
  - Need to scale decision making
    - Consider an assembly task: packing objects in a container and transporting it.
    - Intuitively, we solve such problems by thinking about abstract actions "picking an object and placing in the box" assuming that precise motions can be determined later.
    - Characteristic of long-horizon tasks.
- Planning vs. Scheduling
  - Scheduling
    - Tasks are fixed (scheduling classes in a week). There may be constraints on the tasks. Don't need to determine "which" tasks are to be done.
  - Planning
    - We need to decide "which" set of tasks or steps we need to them as well as to schedule them.

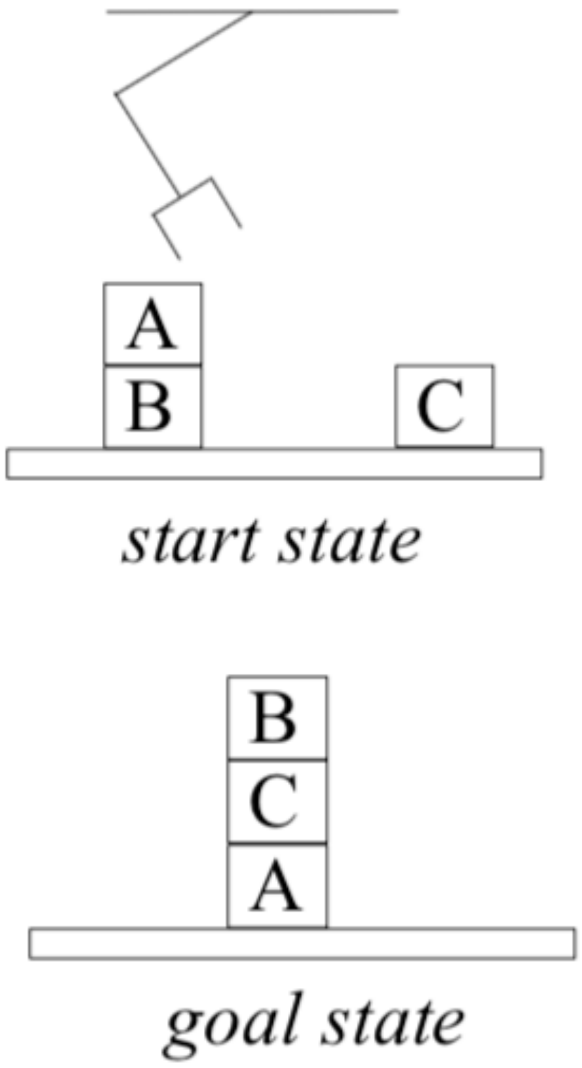
Other examples:
https://www.youtube.com/watch?v=lY4PKBqp9ZM&t=179s

Task Planning: In Essence

- High-level objective is to be attained by performing a sequence of actions.
- Problem is to determine if an action sequence even exists.
- If it exists then we want optimality
  - Minimizing the total number of actions.
  - Minimizing total time.
- Task Planning
  - Requires a model of the world and how an autonomous agent can interact with the world.
  - Given a particular world state, the robot can take some action to transition to another state.
  - Process of finding a task plan –
    - Autonomously reasoning about the state of the world using an internal model and coming up with a sequence of actions (or a plan) to achieve a goal.
  - Certain syntax (languages) are used to represent task planning problems.

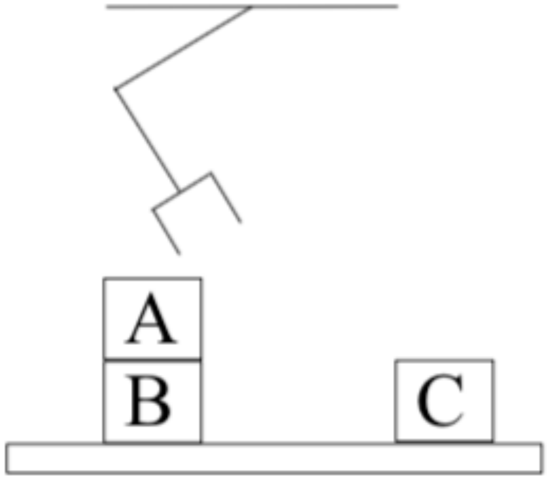
Defining a Planning Domain

- Example: Block worlds
  - Re-order the blocks from the start state to the goal state.
  - Assume that the arm can reach/move all the top blocks.
  - Planning task: determining the order of actions.
- Abstraction
  - The precise poses of B and C are less relevant, what matters is whether B is on C or not.
  - The precise motion of the gripper is less relevant. Its symbolic effect matters, i.e., the block went on top of another.
- Symbolic Representation
  - States: “On(X, Y)” that aggregate low level positions that represent this relationship.
  - Actions: “Move(X, Y)” to denote all ways in which the robot can move X on Y.

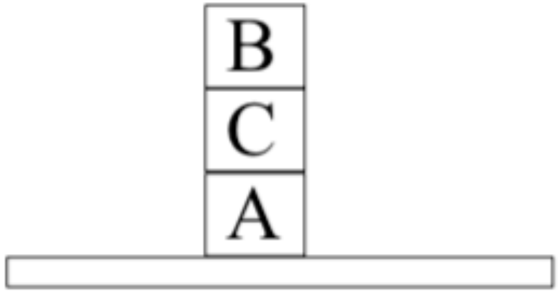


Planning Domains

- World or Domain
  - Describe the world (domain) using logic.
- Actions
  - Describe the actions available to the agent as
    - When they can be executed.
    - What happens if they are executed.
- Initial and Goal states
- Task
  - Find a plan that moves the agent from start state to goal



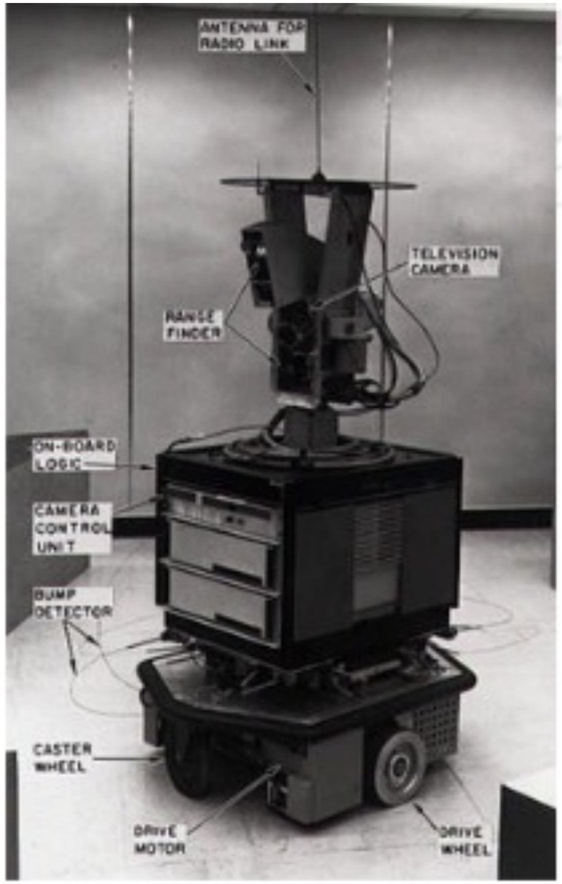
start state



goal state

History: STRIPS Planning

- STRIPS: Stanford Research Institute Problem Solver
  - Represent the world using a knowledge-base of first-order logic.
  - Actions change what is currently true.
  - Describe the actions available, defined by preconditions and effects
- Planning Domain Description Language
  - Standard language for planning domains
  - International programming competitions
- Separate definitions of:
  - A domain, which describes a class of tasks.
    - Predicates and operators.
- A task, which is an instance of domain.
  - Objects. Start and goal states.
- A predicate is a first-order logic function returning True or False, given a set of objects.

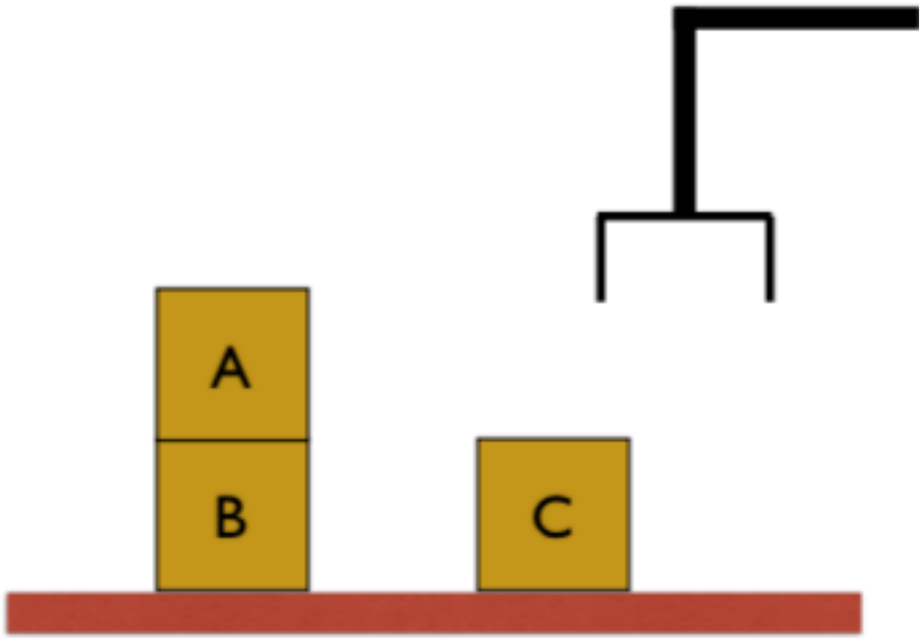


Core idea: A "task-agnostic" domain description and a "task-specific" problem

PDDL: Predicates

- A predicate returns True or False given a set of objects.

```
(define (domain blocksworld)

(:predicates (clear ?x)
             (on-table ?x)
             (arm-empty)
             (holding ?x)
             (on ?x ?y))
```



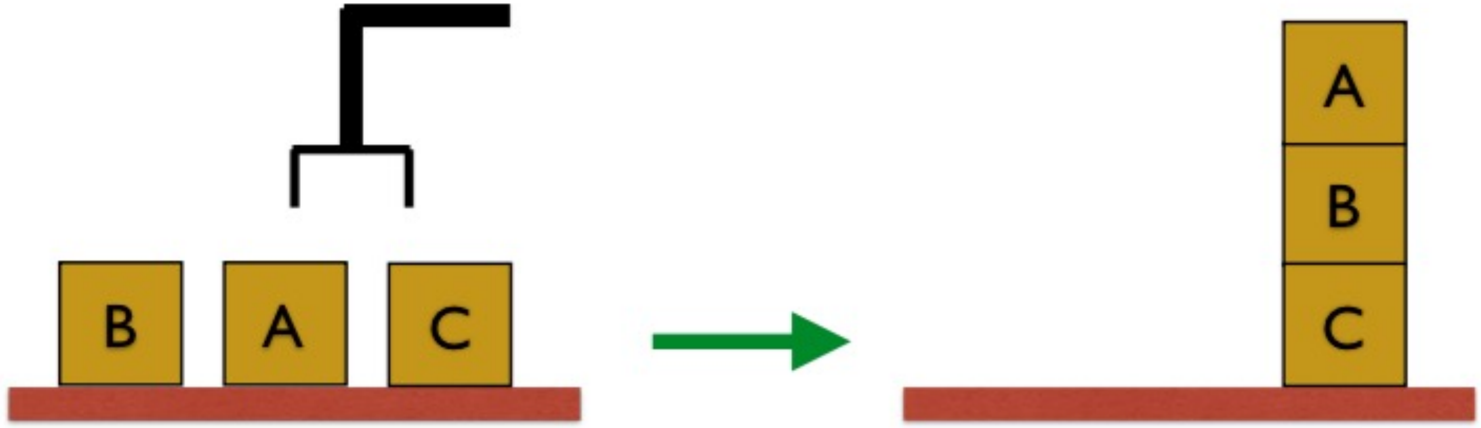
PDDL: Operators

Operators:

- Name
- Parameters
- Preconditions
- Effects

```
(:action pickup
 :parameters (?ob)
 :precondition (and (clear ?ob) (on-table ?ob) (arm-empty))
 :effect (and (holding ?ob) (not (clear ?ob)) (not (on-table ?ob))
            (not (arm-empty))))
```

PDDL: Problem Instance



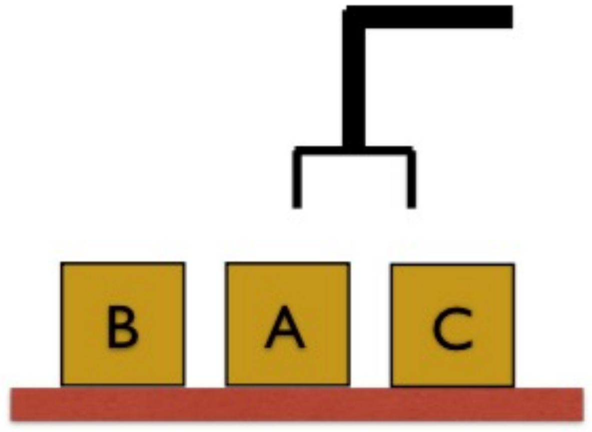

```
(define (problem pb3)
   (:domain blocksworld)
   (:objects a b c)
   (:init (on-table a) (on-table b)   (on-table c)
          (clear a)  (clear b) (clear c) (arm-empty))
   (:goal (and (on a b) (on b c))))
```

Start state

Goal state

PDDL: States

- A state describes the configuration of the world at a moment of time.
- A conjunction of positive literal predicates.
  - A literal is a “ground” predicate where the variables are bound to object instances.
- Closed world assumption
  - The state contains a list of literals (ground predicates) that are true.
  - The other literals not listed are assumed to be False or not true in the world.
  - This is also known as knowledge base semantics.
  - Implications
    - Avoiding the need for inference i.e., determine the state of other literals when some literals are known to be true or false.
    - No uncertainty about which actions can be executed.
    - No uncertainty about the goal.



(on-table a)
(on-table b)
(on-table c)
(clear a)
(clear b)
(clear c)
(arm-empty)

PDDL: Operators

- Implicit Markov assumption.

```
(:action putdown
  :parameters  (?ob)
  :precondition (and (holding ?ob))
  :effect (and (clear ?ob) (arm-empty) (on-table ?ob)
               (not (holding ?ob))))
```

PDDL: Goals

- A conjunction of literal predicates.
  - **(and (on a b) (on b c))**
- Predicates not listed are don’t cares.
- Each goal is thus a *partial* state expression.
  - Implies a set of goal states.

Formal Specification

- Predicates *P*
  - A set of predicates *P*, each with p_n parameters.
- Objects *O*
- Literal predicates *L*
  - A set of predicates from *P* with bound parameters from *O*.
- States
  - A list of positive ground literals, $s \subseteq L$
  - Goal test : a list of positive ground literals, $g \subseteq L$
- Operator List:
  - Name
  - Parameters
  - Preconditions
  - Effects

PDDL: Action Execution

Start state:

(on-table a) (on-table b) (on-table c)
(clear a) (clear b) (clear c) (arm-empty)

Action: pickup(a)

- Check preconditions
- Decide to execute.
- Delete negative effects.
- Add positive effects.

```
(:action pickup
  :parameters (?ob)
  :precondition (and (clear ?ob) (on-table ?ob) (arm-empty))
  :effect (and (holding ?ob) (not (clear ?ob)) (not (on-table ?ob))
               (not (arm-empty))))
```

Next state:

~~(on-table a)~~ (on-table b) (on-table c)
~~(clear a)~~ (clear b) (clear c) ~~(arm-empty)~~
(holding a)

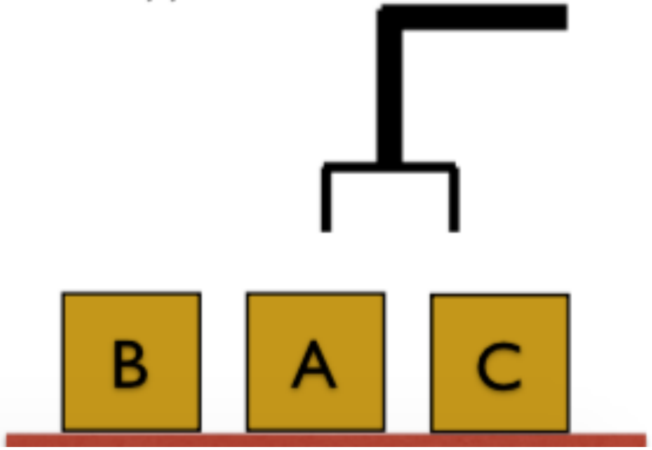
PDDL: Example

State: (on-table a) (on-table b) (on-table c)
(clear a) (clear b) (clear c) (arm-empty))

Goal: (and (on a b) (on b c))

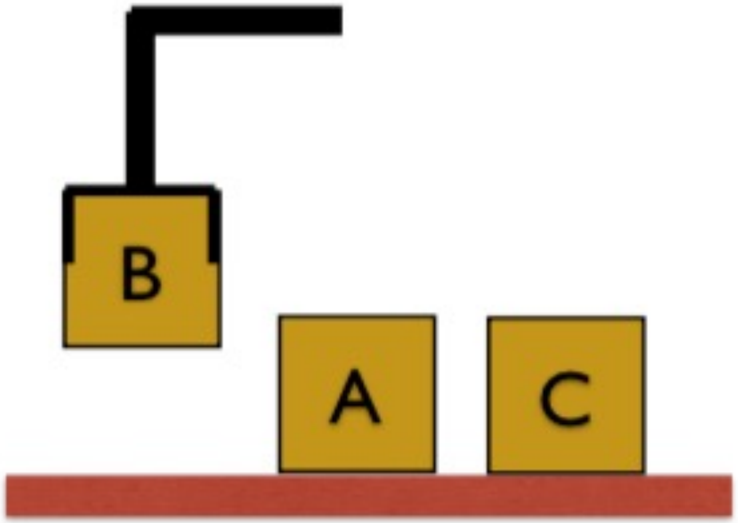
```
(:action pickup
  :parameters (?ob)
  :precondition (and (clear ?ob) (on-table ?ob) (arm-empty))
  :effect (and (holding ?ob) (not (clear ?ob))
               (not (on-table ?ob))
               (not (arm-empty))))
```

pickup(b)



PDDL: Example

after pickup(b) …



State: (on-table a) ~~(on-table b)~~ (on-table c)
(clear a) ~~(clear b)~~ (clear c) ~~(arm-empty)~~ (holding b))

Goal: (and (on a b) (on b c))

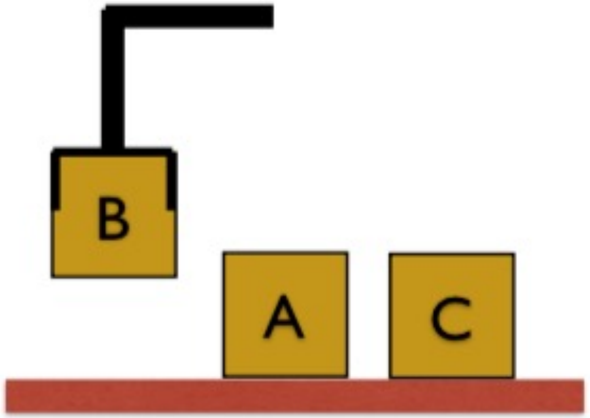
PDDL: Example

State: (on-table a) (on-table c)
(clear a) (clear c) (holding b))

Goal: (and (on a b) (on b c))

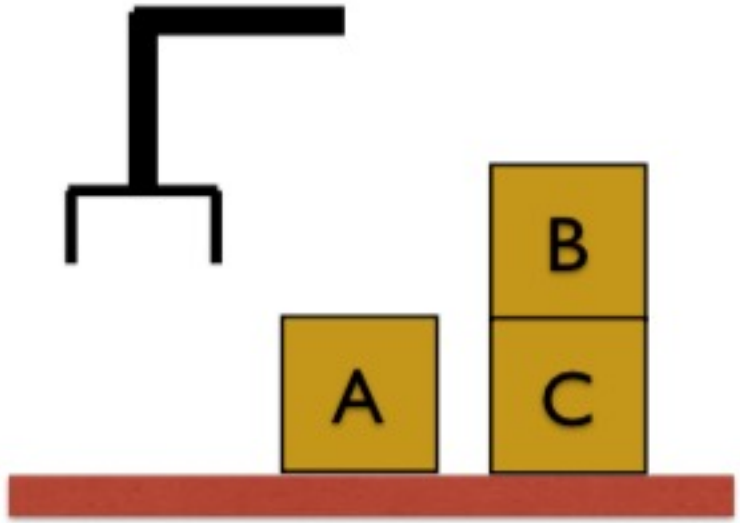
```
(:action stack
  :parameters  (?ob ?underob)
  :precondition (and  (clear ?underob) (holding ?ob))
  :effect (and (arm-empty) (clear ?ob) (on ?ob ?underob)
               (not (clear ?underob)) (not (holding ?ob))))
```

stack(b, c)



PDDL: Example

after stack(b, c) …

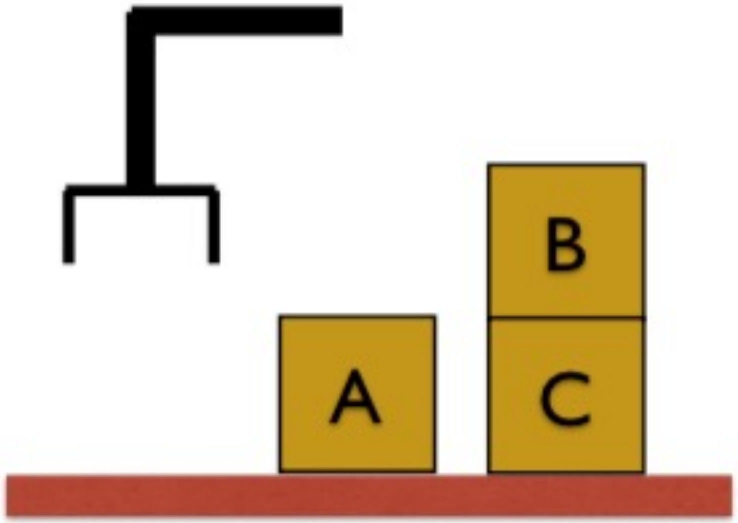


State: (on-table a) (on-table c)
(clear a) ~~(clear c) (holding b)~~
(arm-empty) (clear b) (on b, c))

Goal: (and (on a b) (on b c))

PDDL: Example

after stack(b, c) …

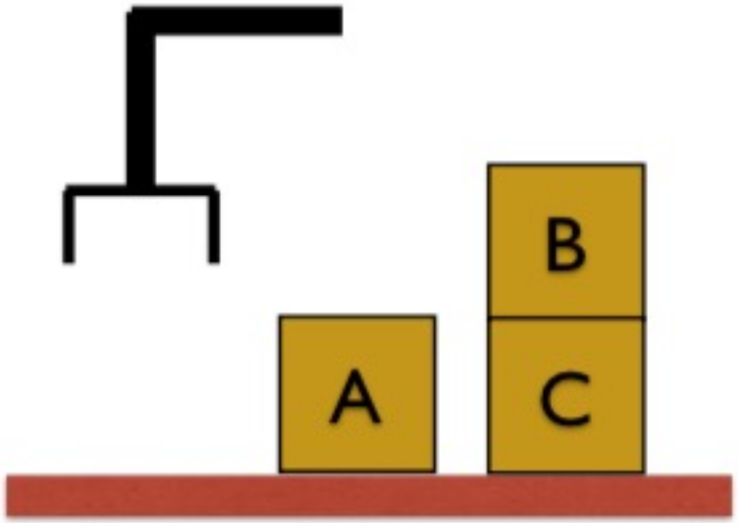


State: (on-table a) (on-table c)
(clear a) ~~(clear c) (holding b)~~
(arm-empty) (clear b) (on b, c))

Goal: (and (on a b) (on b c))

PDDL: Example

after stack(b, c) …



State: (on-table a) (on-table c)
(clear a) ~~(clear c) (holding b)~~
(arm-empty) (clear b) (on b, c))

Goal: (and (on a b) (on b c))

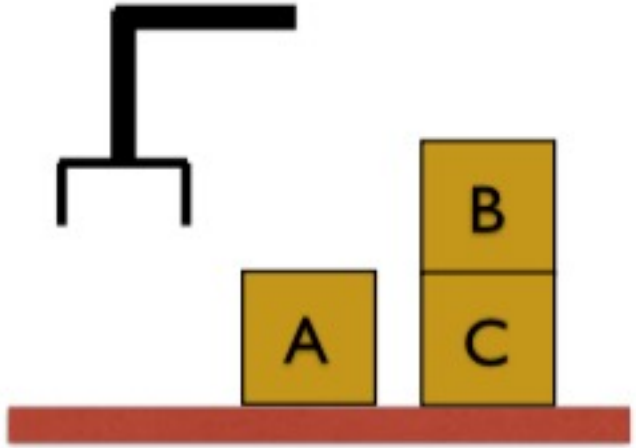
PDDL: Example

State: (on-table a) (on-table c)
(clear a) (arm-empty) (clear b) (on b, c))

Goal: (and (on a b) (on b c))

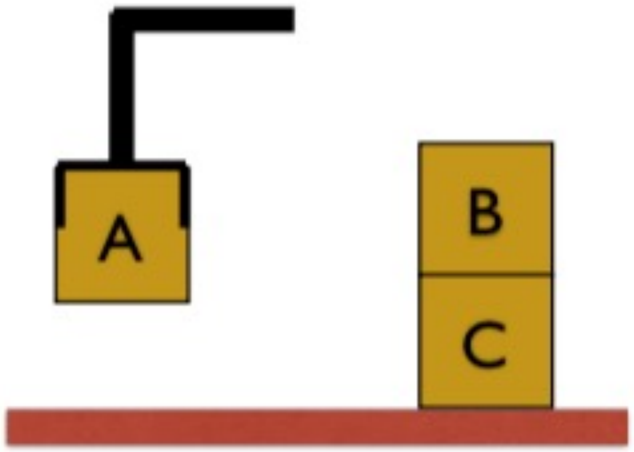
```
(:action pickup
  :parameters (?ob)
  :precondition (and (clear ?ob) (on-table ?ob) (arm-empty))
  :effect (and (holding ?ob) (not (clear ?ob)) (not (on-table ?ob))
               (not (arm-empty))))
```

pickup(a)



PDDL: Example

after pickup(a)



State: ~~(on-table a)~~ (on-table c)
~~(clear a) (arm-empty)~~ (clear b) (on b, c) (holding a))

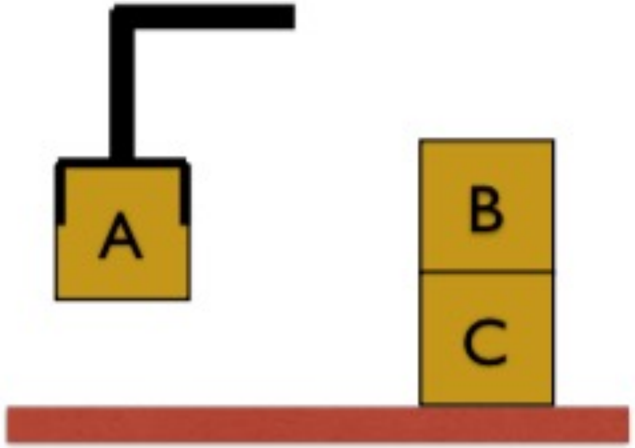
Goal: (and (on a b) (on b c))

PDDL: Example

State: (on-table c)
(on b, c) (clear b) (holding a))
Goal: (and (on a b) (on b c))

```
(:action stack
  :parameters  (?ob ?underob)
  :precondition (and  (clear ?underob) (holding ?ob))
  :effect (and (arm-empty) (clear ?ob) (on ?ob ?underob)
               (not (clear ?underob)) (not (holding ?ob))))
```

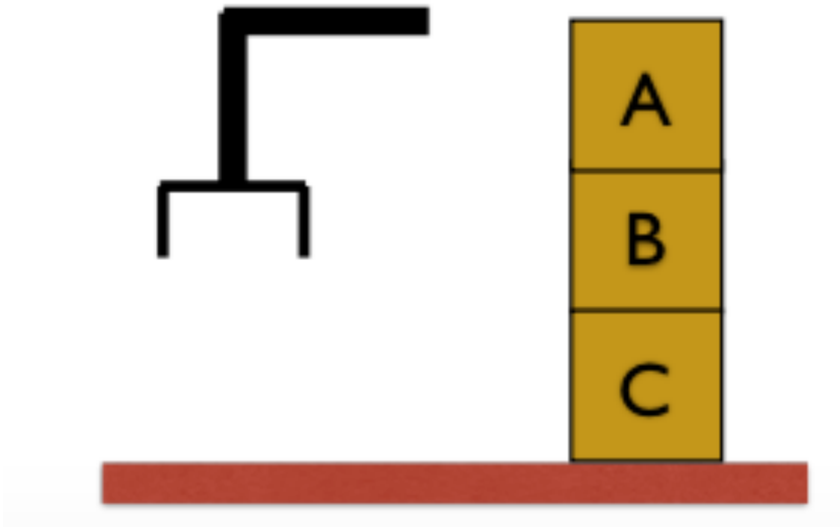
stack(a, b)



PDDL: Example

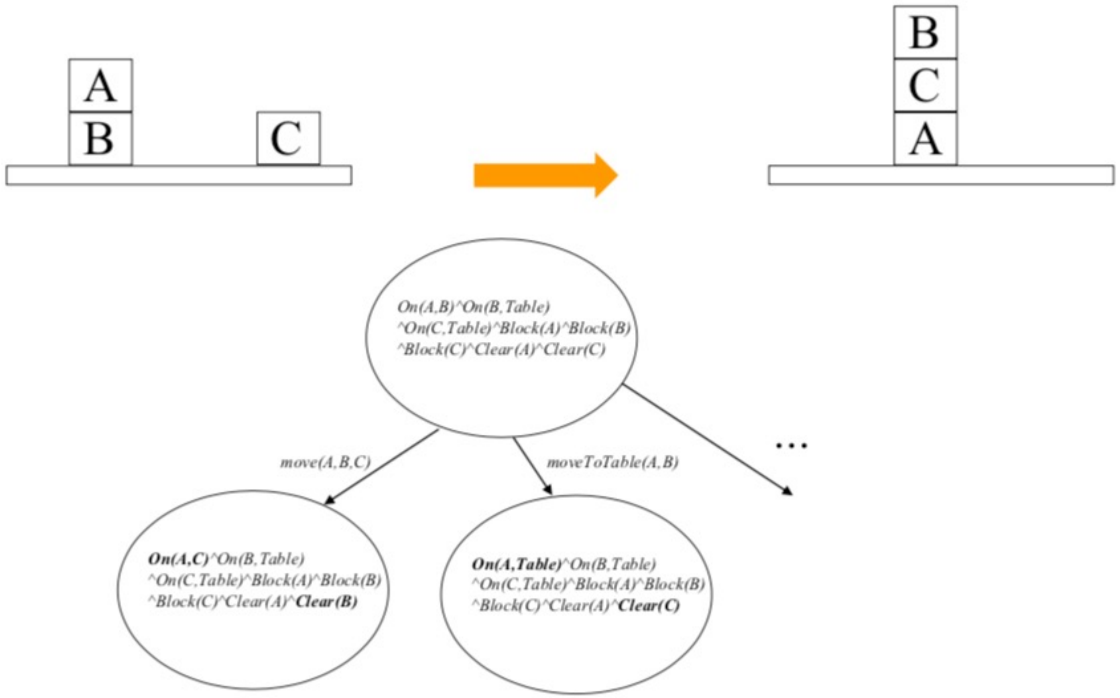
State: (on-table c)
(on a b) (clear b) (on b, c) (holding a))

Goal: (and (on a b) (on b c))



Planning: As a Graph Search

- Search Problem
  - Nodes are states
  - Actions are applicable operators
  - Goal expression as a goal test
- How to search the graph for a plan?
  - Direct search
  - Informed search
    - Domain independent heuristics.



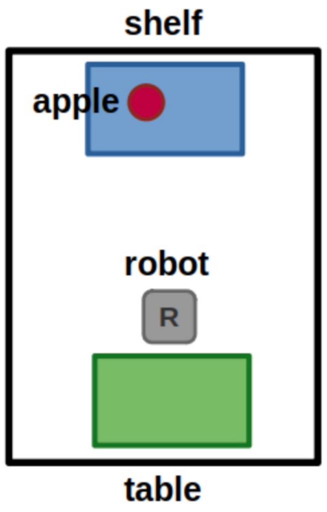
Another Example: Object Fetching

The agent is in an indoor area. There are rooms and hallways. There are objects in the environment.

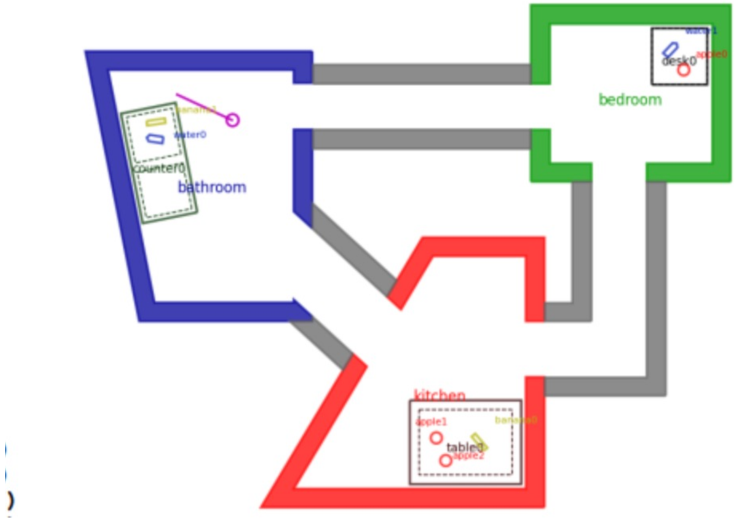
Problem: “take an apple from the shelf and put it on the table”

Example plan:
Move to the shelf
Pick up the apple
Move back to the table
Place the apple

Example courtesy Sebastian Castro



Simple task planning example world: A robot can move between a finite set of locations, and can pick and place objects at those locations.



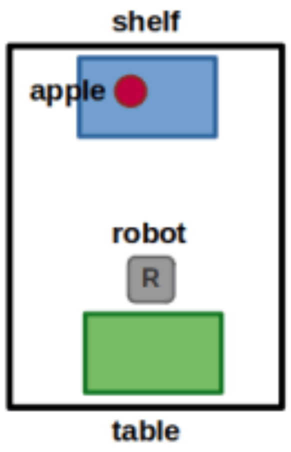
Example: Object Fetching

- **Domain: The task-agnostic part**
  - **Predicates:** `(Robot ?r)`, `(Object ?o)`, `(Location ?loc)`, `(At ?r ?loc)`, `(Holding ?r ?o)`, etc.
  - **Actions:** `move(?r ?loc1 ?loc2)`, `pick(?r ?o ?loc)`, `place(?r ?o ?loc)`
- **Problem: The task-specific part**
  - **Objects:** `(Robot robot)`, `(Location shelf)`, `(Location table)`, `(Object apple)`
  - **Initial state:** `(HandEmpty robot)`, `(At robot table)`, `(At apple shelf)`
  - **Goal specification:** `(At apple table)`

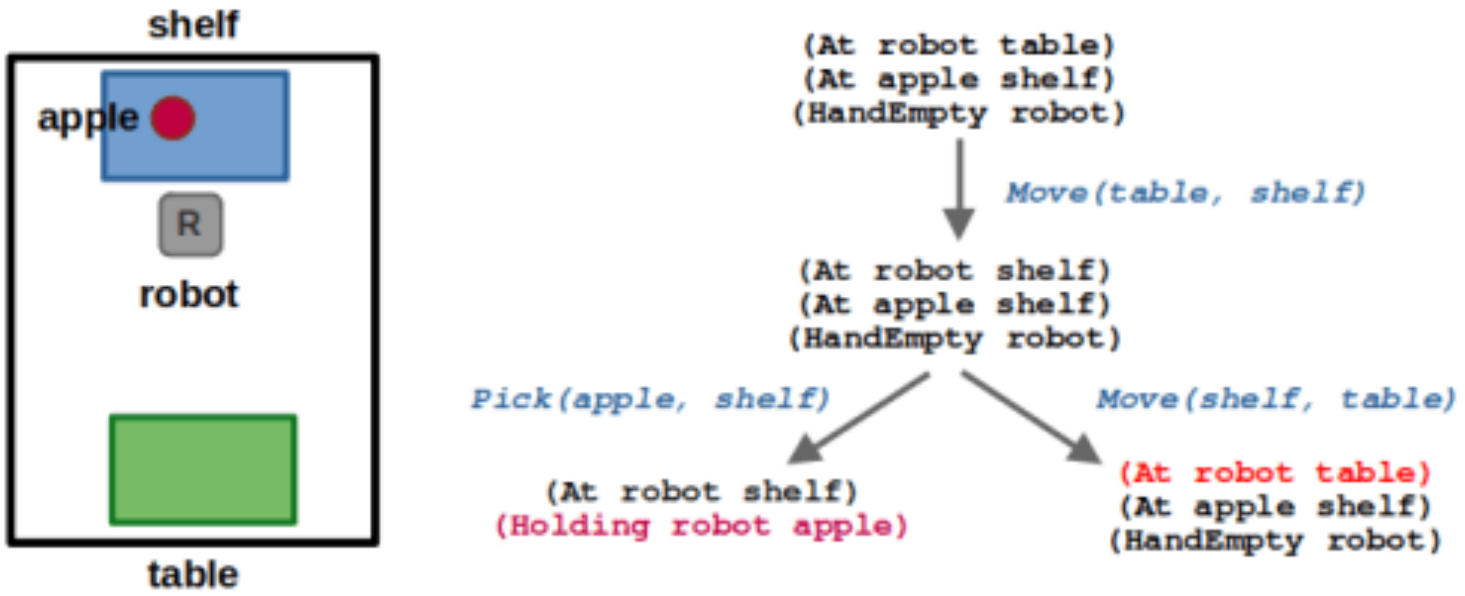
```
(:action move
    :parameters (?r ?loc1 ?loc2)
    :precondition (and (Robot ?r)
                       (Location ?loc1)
                       (Location ?loc2)
                       (At ?r ?loc1))
    :effect (and (At ?r ?loc2)
                 (not (At ?r ?loc1)))
)
```

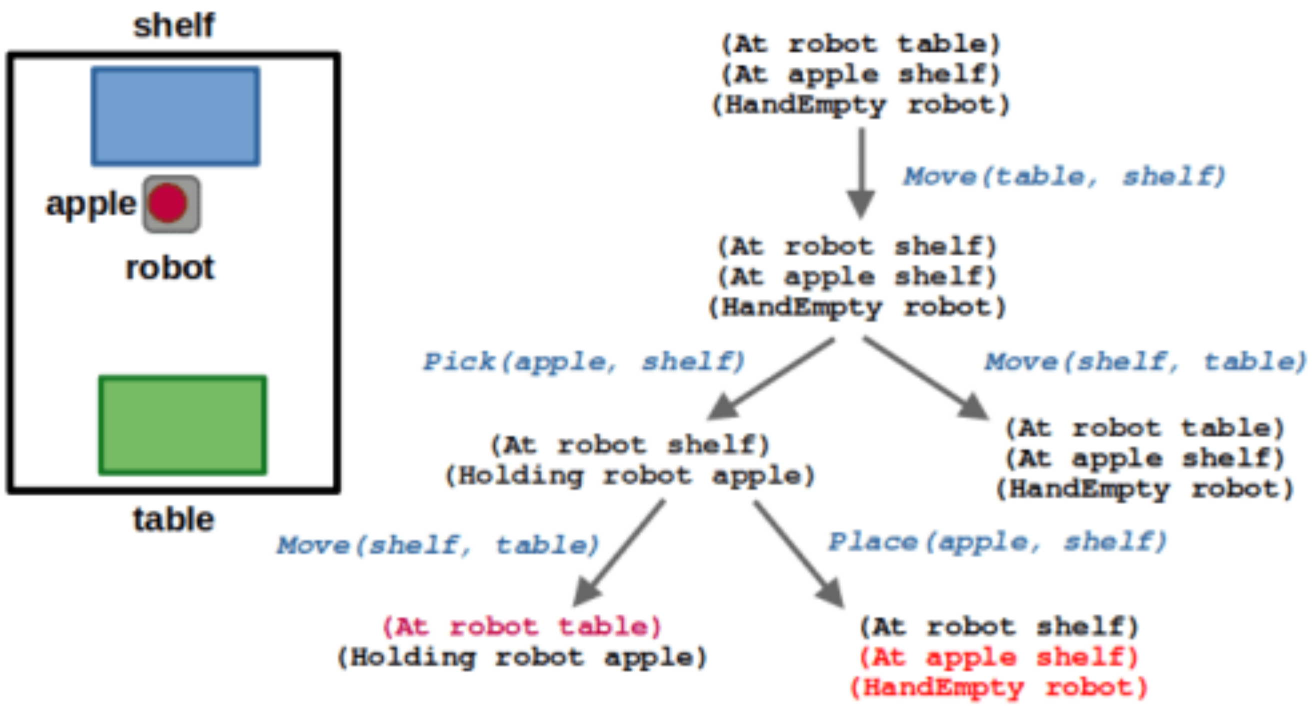
```
(:action pick
    :parameters (?r ?o ?loc)
    :precondition (and (Robot ?r)
                       (Obj ?o)
                       (Location ?loc)
                       (HandEmpty ?r)
                       (At ?r ?loc)
                       (At ?o ?loc))
    :effect (and (Holding ?r ?o)
                 (not (HandEmpty ?r))
                 (not (At ?o ?loc)))
)

(:action place
    :parameters (?r ?o ?loc)
    :precondition (and (Robot ?r)
                       (Obj ?o)
                       (Location ?loc)
                       (At ?r ?loc)
                       (not (HandEmpty ?r))
                       (Holding ?r ?o))
    :effect (and (HandEmpty ?r)
                 (At ?o ?loc)
                 (not (Holding ?r ?o)))
)
```

Example: Object Fetching

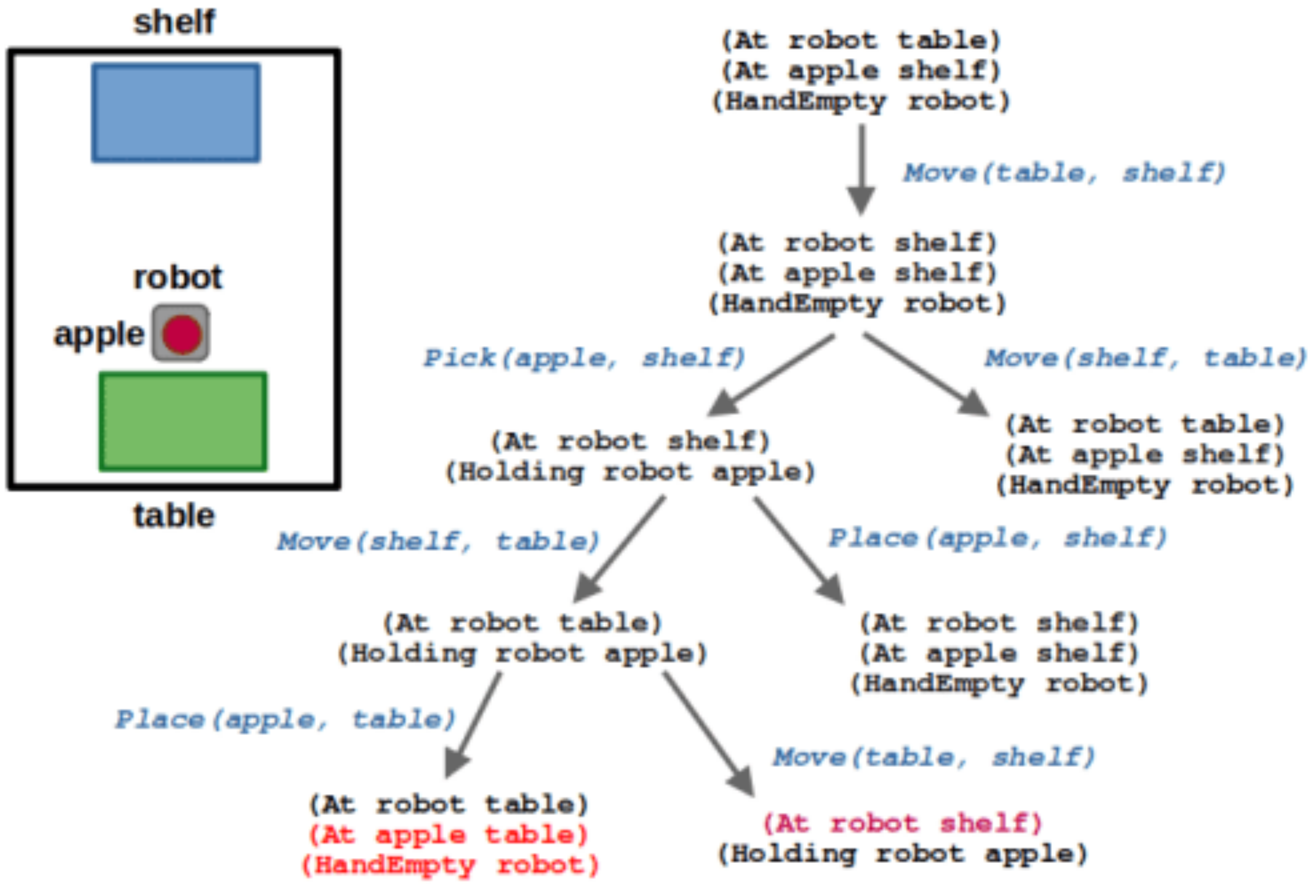



```
(At robot table)
(At apple shelf)
(HandEmpty robot)
        |
        |   Move(table, shelf)
        v
(At robot shelf)
(At apple shelf)
(HandEmpty robot)
```


shelf
apple
R
robot
table
(At robot table)
(At apple shelf)
(HandEmpty robot)
Move(table, shelf)
(At robot shelf)
(At apple shelf)
(HandEmpty robot)
Pick(apple, shelf)
Move(shelf, table)
(At robot shelf)
(Holding robot apple)
(At robot table)
(At apple shelf)
(HandEmpty robot)



shelf
apple
robot
table
(At robot table)
(At apple shelf)
(HandEmpty robot)
Move(table, shelf)
(At robot shelf)
(At apple shelf)
(HandEmpty robot)
Pick(apple, shelf)
Move(shelf, table)
(At robot shelf)
(Holding robot apple)
(At robot table)
(At apple shelf)
(HandEmpty robot)
Move(shelf, table)
Place(apple, shelf)
(At robot table)
(Holding robot apple)
(At robot shelf)
(At apple shelf)
(HandEmpty robot)


shelf
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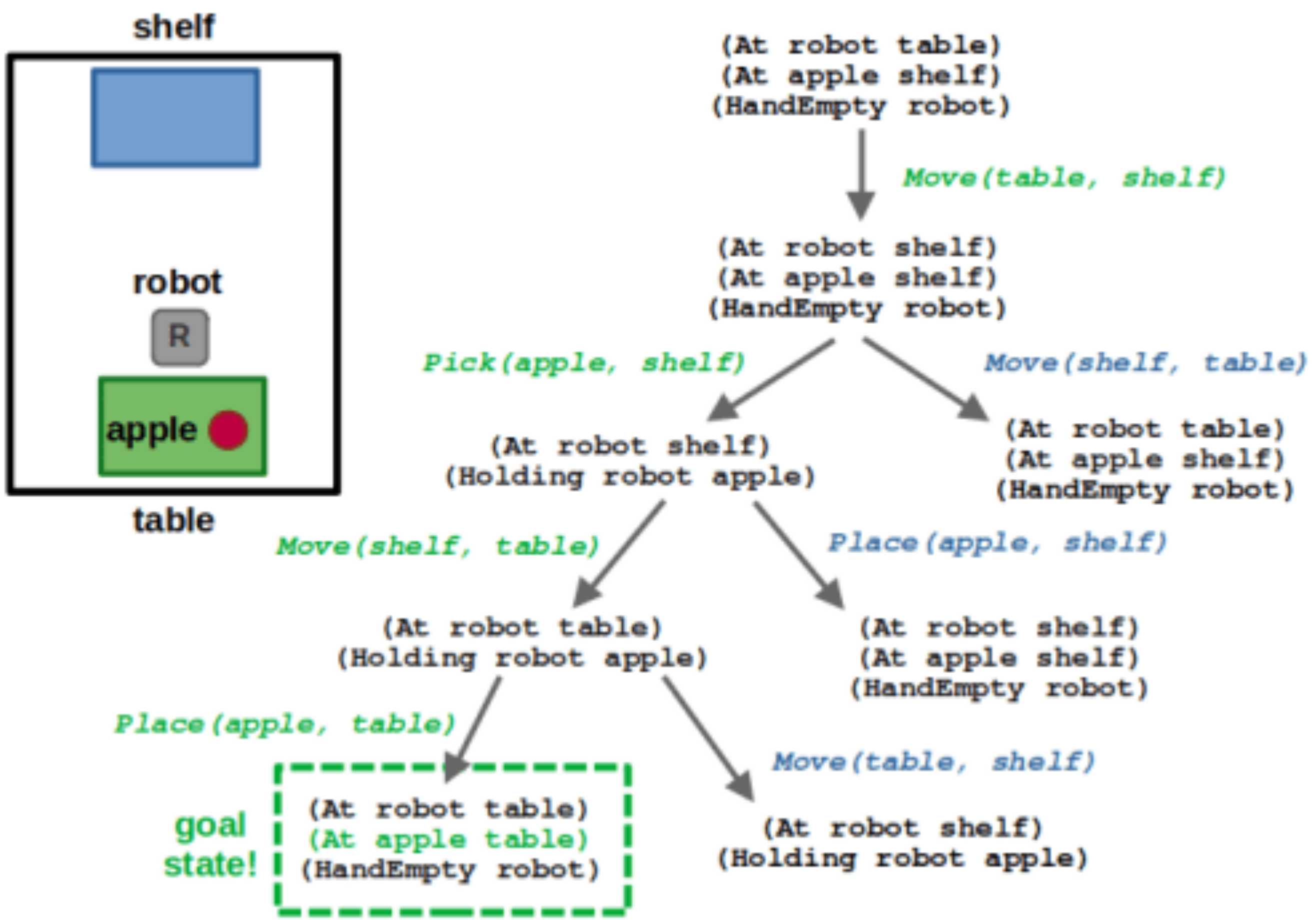
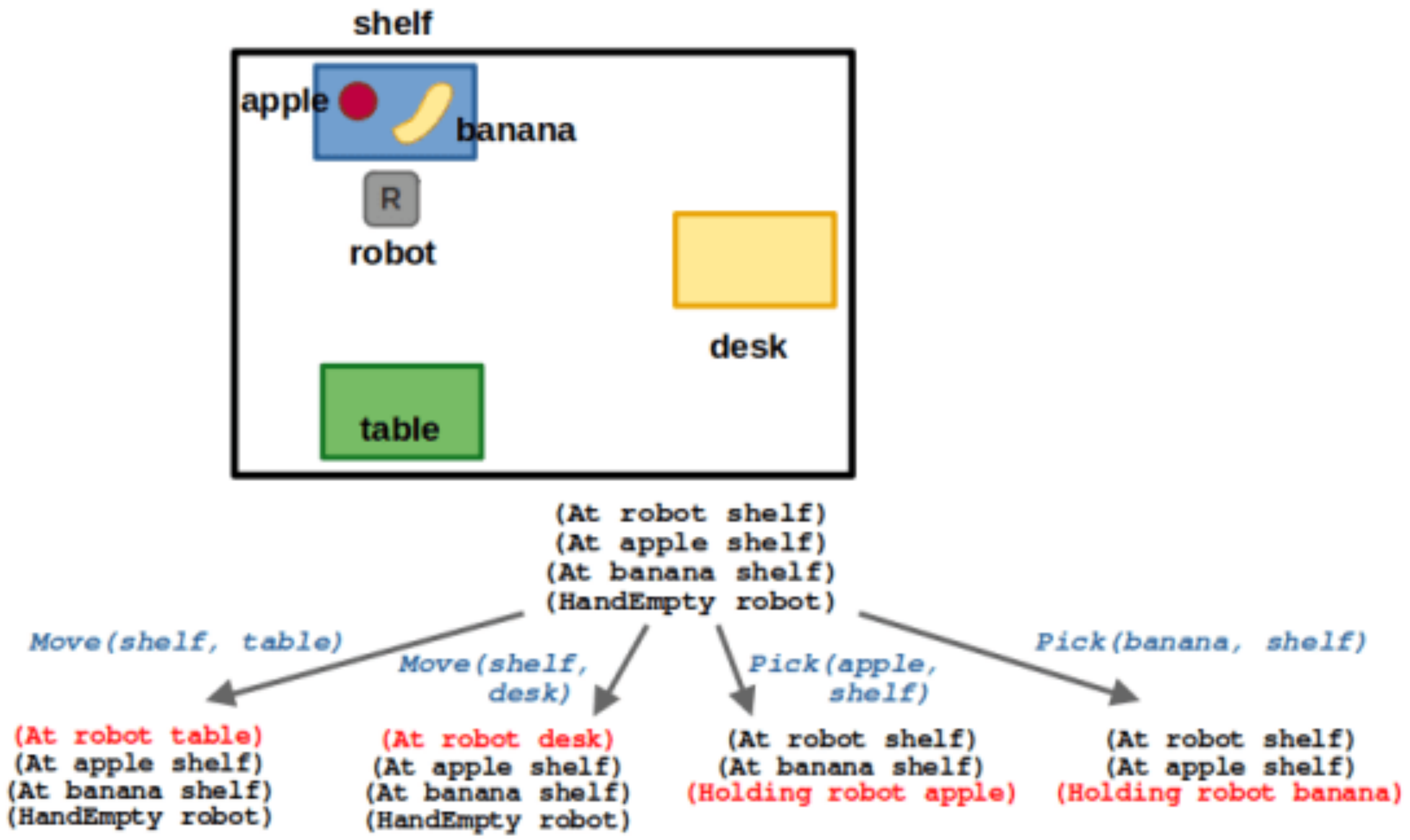
(At robot table)
(At apple shelf)
(HandEmpty robot)
Move(table, shelf)
(At robot shelf)
(At apple shelf)
(HandEmpty robot)
Pick(apple, shelf)
Move(shelf, table)
(At robot shelf)
(Holding robot apple)
(At robot table)
(At apple shelf)
(HandEmpty robot)
Move(shelf, table)
Place(apple, shelf)
(At robot table)
(Holding robot apple)
(At robot shelf)
(At apple shelf)
(HandEmpty robot)
Place(apple, table)
Move(table, shelf)
(At robot table)
(At apple table)
(HandEmpty robot)
(At robot shelf)
(Holding robot apple)



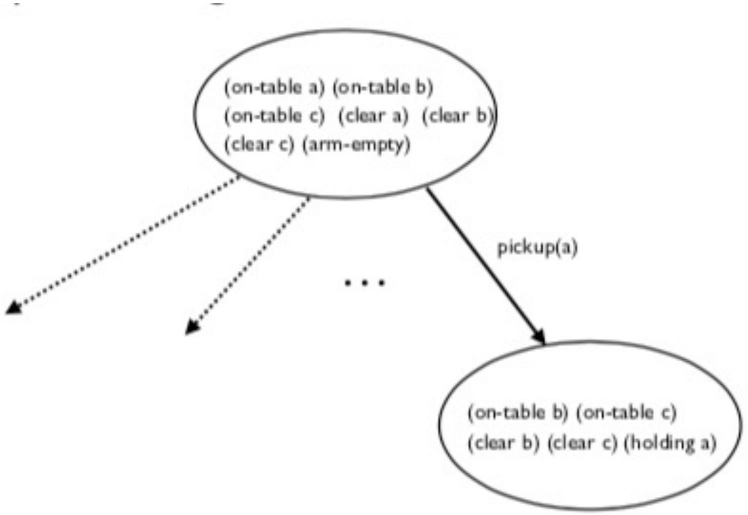
shelf
robot
R
apple
table
(At robot table)
(At apple shelf)
(HandEmpty robot)
Move(table, shelf)
(At robot shelf)
(At apple shelf)
(HandEmpty robot)
Pick(apple, shelf)
Move(shelf, table)
(At robot shelf)
(Holding robot apple)
(At robot table)
(At apple shelf)
(HandEmpty robot)
Move(shelf, table)
Place(apple, shelf)
(At robot table)
(Holding robot apple)
(At robot shelf)
(At apple shelf)
(HandEmpty robot)
Place(apple, table)
Move(table, shelf)
goal state!
(At robot table)
(At apple table)
(HandEmpty robot)
(At robot shelf)
(Holding robot apple)


shelf
apple
banana
R
robot
desk
table
(At robot shelf)
(At apple shelf)
(At banana shelf)
(HandEmpty robot)
Move(shelf, table)
Move(shelf, desk)
Pick(apple, shelf)
Pick(banana, shelf)
(At robot table)
(At apple shelf)
(At banana shelf)
(HandEmpty robot)
(At robot desk)
(At apple shelf)
(At banana shelf)
(HandEmpty robot)
(At robot shelf)
(At banana shelf)
(Holding robot apple)
(At robot shelf)
(At apple shelf)
(Holding robot banana)

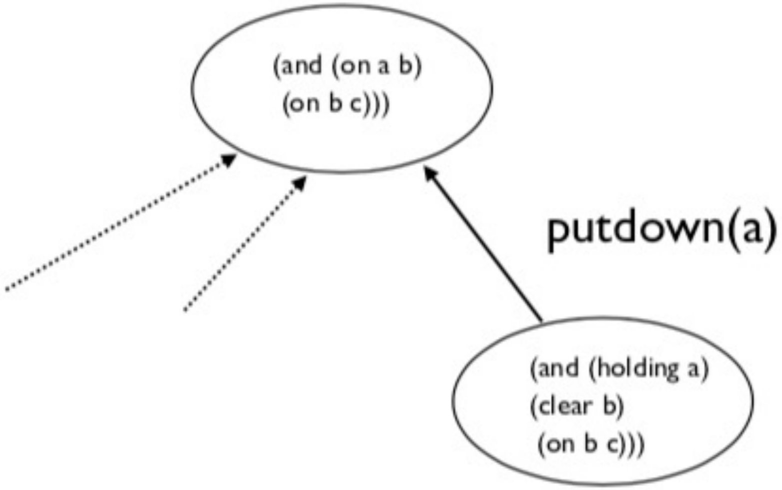
Searching for a Plan

- Forward planning
  - Begin from the initial state and examine the effects of all actions applicable on that state.
  - Determine *successor* states and continue the process till you reach the goal state.
  - Often the branching factor is large.
- Backward or regression search
  - Start at the goal state, apply actions backward until we find the sequence of actions that reaches the initial state.
  - Computes the *predecessor* state s' for a final state s reached by action a.
  - Check for only those actions that are relevant for the goal
    - At least one of the action's effects (positive or negative) should unify with the goal.
  - Often the branching factor is low.

Forward search

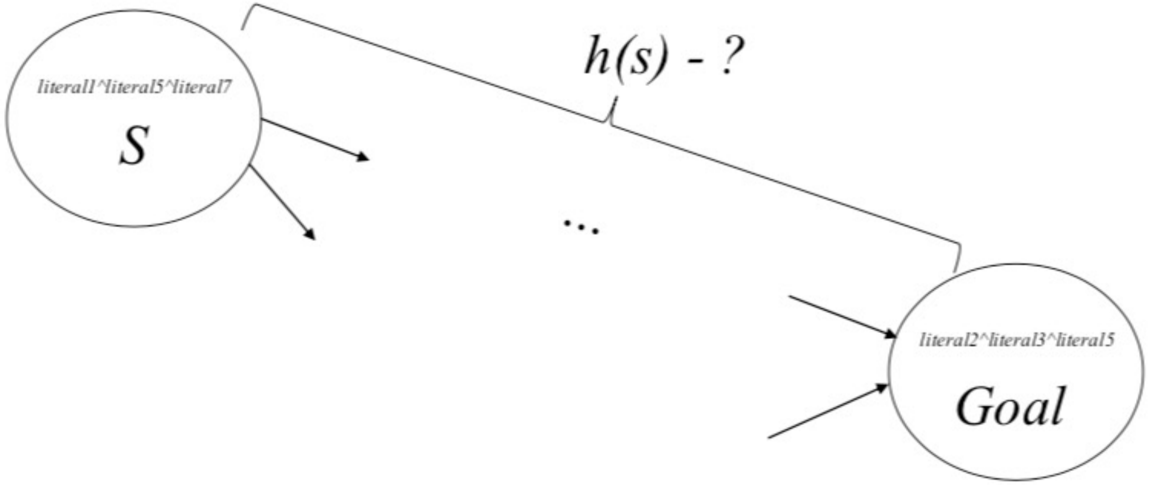


Backward search



Heuristics for Planning

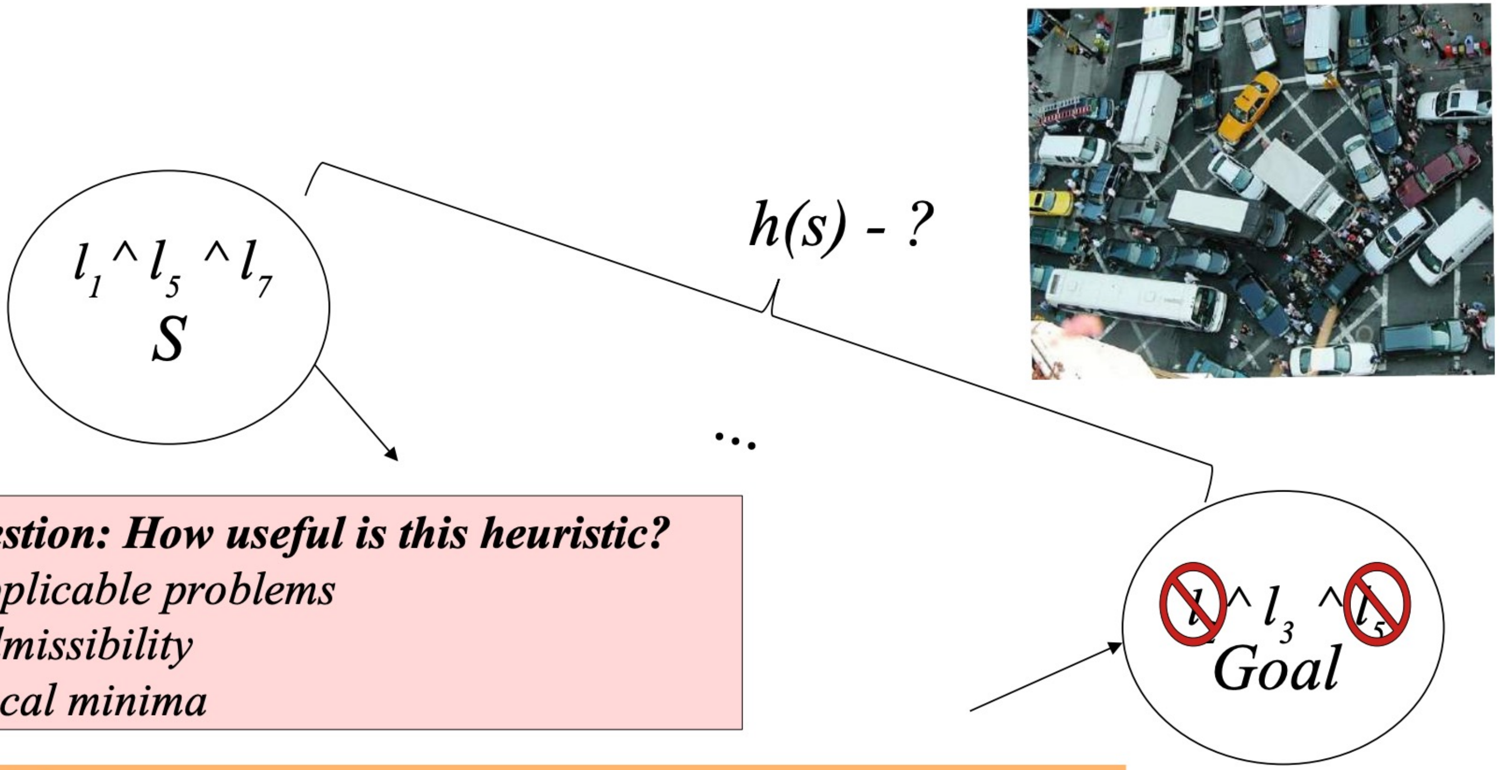
- Informed Search
  - Can try to search with A* by constructing a heuristic.
  - *Domain-specific heuristics* can be derived from the problem structure.
  - Requires careful engineering.
- *Domain-independent* heuristics
  - Once a planning problem is encoded in the PDDL form then can the search be independent of the domain.
    - The number of literals that are NOT yet satisfied.
  - The heuristic should work for any problem encoded in PDDL.



Heuristics for Planning

Heuristic I: Number of unsatisfied goals.

Is this admissible in general? No. One action may generate more than one goals. Hence, the estimate may not be a lower bound.



Question: How useful is this heuristic?
- *Applicable problems*
- *Admissibility*
- *Local minima*

Key idea:
$h(s)$ = # of literals in goal not satisfied in s

i.e., $h(s)$ = # *of literals* l_i *such that* $l_i(s)$=*false and* $l_i(goal)$ = *true*

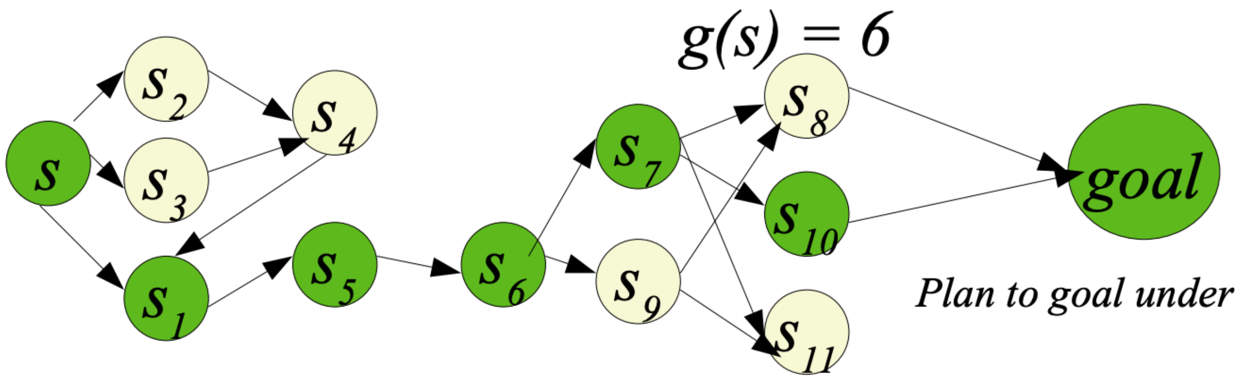
Heuristics for Planning

Alternatively, create a relaxation of the problem.

Solve the simplified problem optimally.

Key idea:
*1) Compute h(s) by solving a **relaxed** (simpler) problem*
*2) **empty-delete-list:** assume actions do not have any <u>negative</u> effects*

<u>MoveToTable(b,x)</u>
Precond: On(b,x)^Clear(b)^Block(b)
Effect: On(b,Table)^Clear(x)^~On(b,x)



Plan to goal under relaxed problem

Heuristics by Solving Relaxed Problems

- Recap: Notion of a relaxed problem
  - Make simplifying assumption on the original planning problem i.e., address a relaxed problem.
  - Solve the relaxed problem optimally. Use the optimal plan in the relaxed problem as a heuristic for the original problem which is hard to solve.
- Heuristic Search Planner (HSP) and Fast Forward (FF) Planner use this idea
  - Relax the problem by deleting the negative effects of actions.
  - Solve the relaxed problem using a planner.

```
(:action pickup
  :parameters (?ob)
  :precondition (and (clear ?ob) (on-table ?ob) (arm-empty))
  :effect (and (holding ?ob) ~~(not (clear ?ob)) (not (on-table ?ob))
          (not (arm-empty))~~))
```

Create problem relaxations by ignoring the delete list.

Heuristic Search Planning

- Deleting negative effects of actions leads to a relaxation of the problem.
- Setup
  - Goal: conjunction of positive literals.
  - Actions
    - Precondition (conjunction of positive literals)
    - Effects (adds and deletes)
- *Monotonic* progress towards the goal
  - Each action execution monotonically adds the applicable actions.
    - Once a literal is made true, it is not deleted. Progress made is not undone.
  - When the delete effects are ignored then some of the the complex interactions between actions is ignored
    - Intuitively, If there is an action that deletes the preconditions for another action then the plan length will be longer as effort is needed to set the deleted predicate as true.
    - By ignoring delete effects, the problem gets relaxed as the actual plan is going to be at least as long.
- Heuristic Search Planning System
  - Core idea: Search for a plan making use of the “heuristic” computed from solving the “relaxed” problem. In essence, convert a planning problem to a search problem guided by a heuristic.
  - Domain independent, i.e., when the problem is expressed in PDDL format, the heuristic can be constructed automatically.

Heuristic Search Planning

- Problem: Even the relaxed problem may be hard to solve
    - Still NP hard to compute the optimal solution in the relaxed problem
    - Solution: Approximate solution can be found via hill climbing.
- Figure
    - Visualizes state space for two problems using the ignore delete list heuristic.
    - Dots (states), edges (actions) and height (heuristic cost).
    - Lower the heuristic cost, the closer we are to the goal.
    - Hill climbing search will provide an approximate solution.
- HSP Planner (Bonet and Geffner) build on this idea.
- https://bonetblai.github.io/reports/hsp-aij.pdf

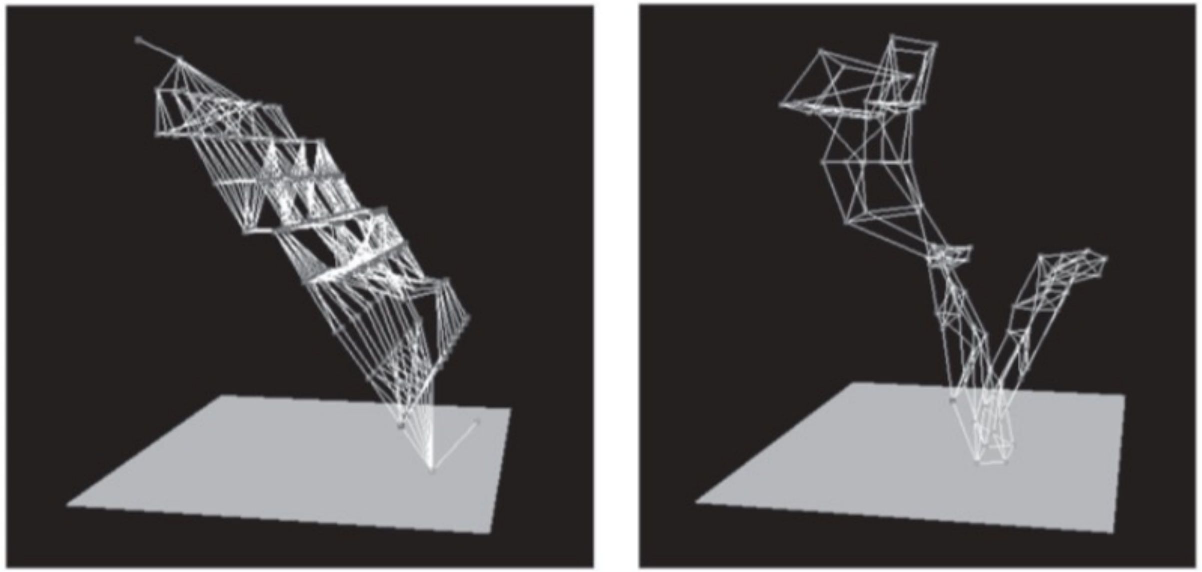


Figure 10.6 Two state spaces from planning problems with the ignore-delete-lists heuristic. The height above the bottom plane is the heuristic score of a state; states on the bottom plane are goals. There are no local minima, so search for the goal is straightforward. From Hoffmann (2005).

AIMA Ch 10

Planning Graphs

- A planning problem asks if we can reach a goal state from the initial state.
- If we have a tree of all possible actions from the initial state to successor states and so on.
- We can determine if there is a plan from start to the goal.
- ***Problem: this tree is exponential in size.***

AIMA Ch 10 Sec 10.3

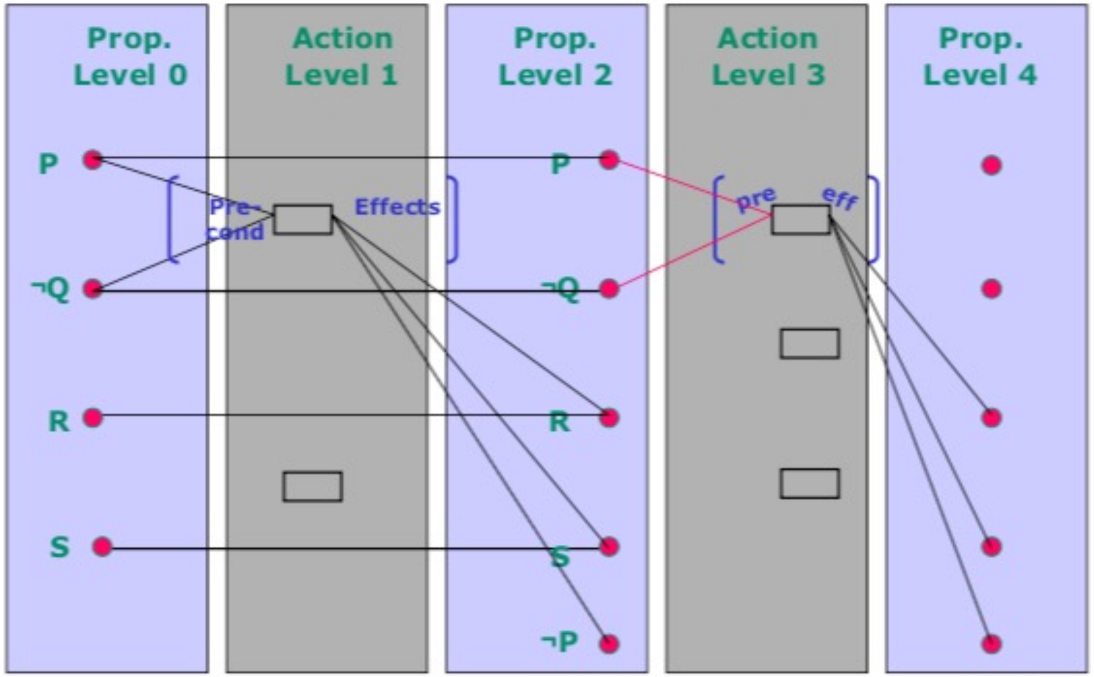
Planning Graphs

- Planning graph is a polynomial-size approximation to this tree.
  - Trade off is that the planning graph indicates states that can ***possibly*** be reached.
- **It cannot definitively answer if the goal G is attainable from s_0**
  - ***But, it can estimate how may steps it takes to reach G.***
- The estimate is always correct when it reports the goal is not reachable.
  - It never overestimates the number of steps (hence an admissible heuristic)
- Where are planning graphs used?
  - Used for obtaining heuristic values (estimating the cost of obtaining a goal)
  - Used for determining a plan (GraphPlan)

AIMA Ch 10 Sec 10.3

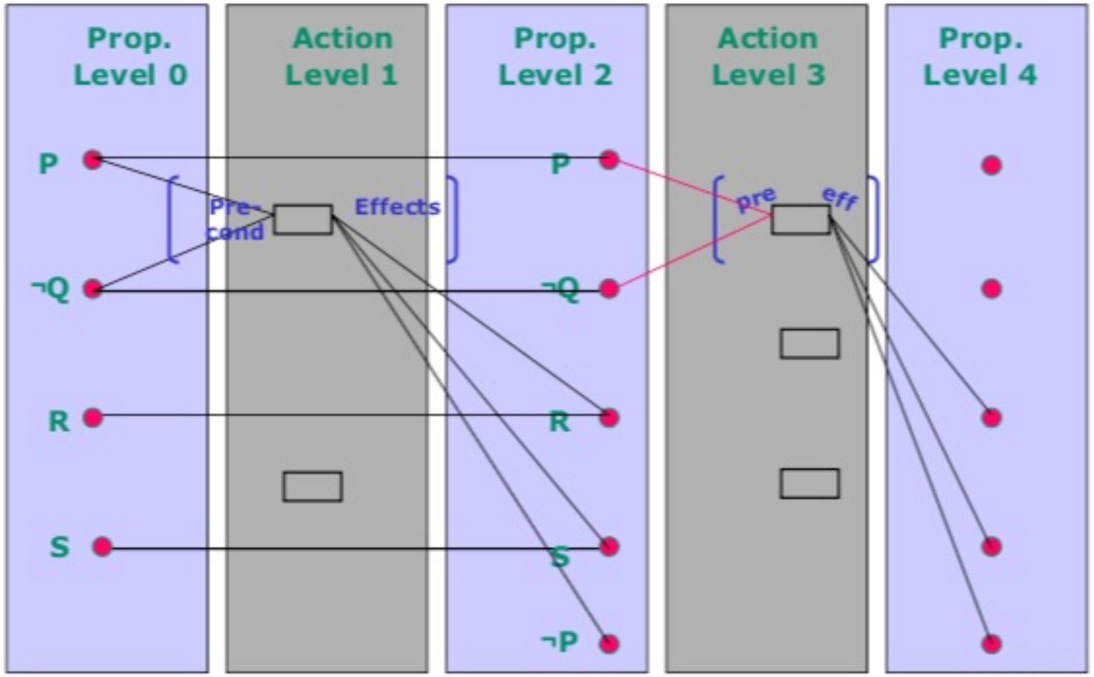
Planning Graphs

- Construction
  - Layered Graph: states and actions
  - S_i contains all the literals that ”could” hold at time i.
  - A_i contains all the actions that “could” have their pre-conditions satisfied at time i.
  - No variables.
    - All grounded literals and grounded actions.



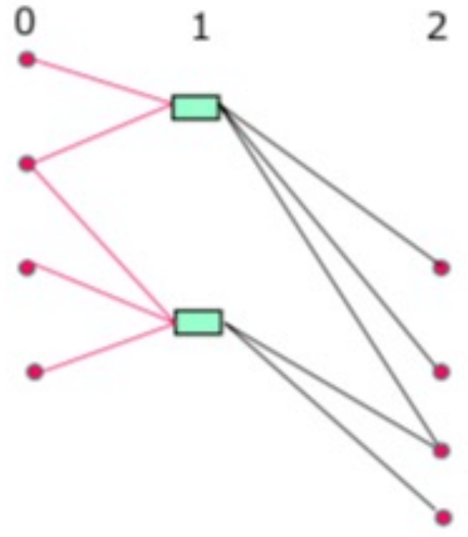
Planning Graphs

- What does a planning graph encode?
  - A planning graph only records a restricted subset of negative interactions between actions.
  - Allows **"quick" elimination** of some impossible alternatives in the search process.
    - Not all inconsistencies are recorded. Only obvious flaws.
  - The level at which a literal **appears** is a good estimate of how difficult it is to attain a literal from the initial state.

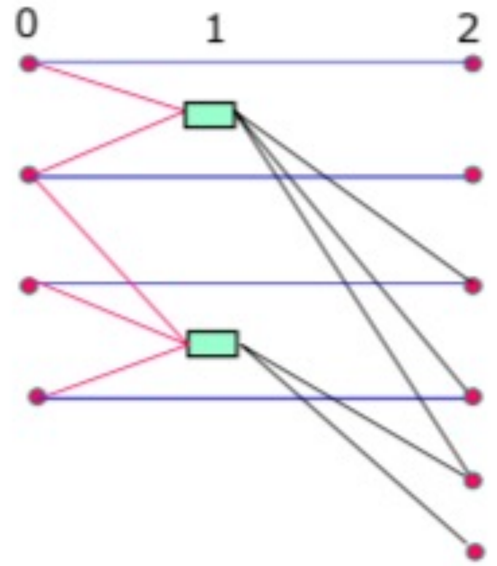


Planning graph: Construction

- Start with the initial state (given)
- Add applicable actions and effects
  - Add actions with satisfied pre-conditions
  - Add all effects of actions at previous levels
  - The action layer will contain all actions whose pre-conditions are satisfied.
- Add maintenance actions
  - Ensures that once a literal is reached it is "maintained" in the planning graph for every subsequence layer.



Add actions with satisfied pre-conditions

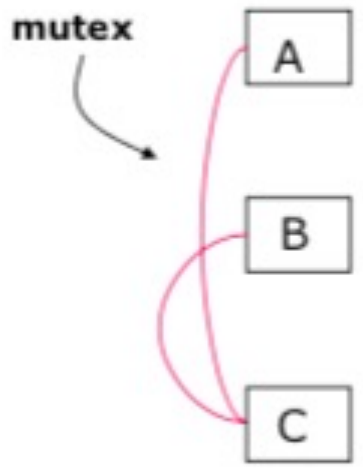


Add maintenance operations.

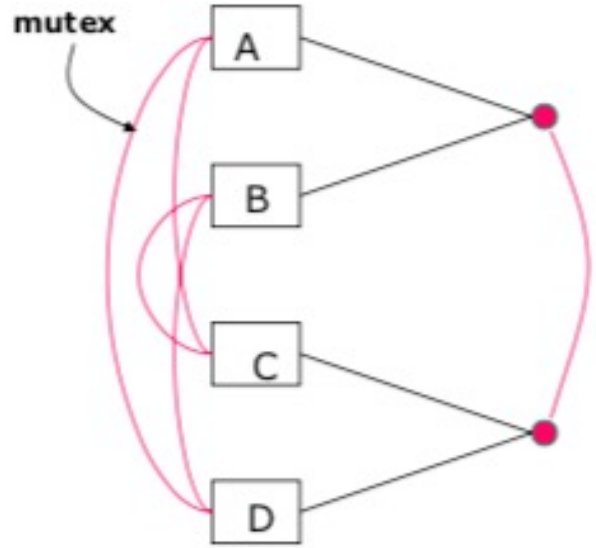
Mutually Exclusive Actions

- Two action instances at level i are mutex if:
  - Inconsistent effects
    - The effect of one action is negation of another.
  - Interference
    - One action deletes the precondition of another.
  - Competing needs
    - The actions have preconditions that are mutex at level i-1
- What do the mutexes model?
  - Some conditions under which two actions cannot be performed together (i.e., only one of them must be selected)
  - Detection of certain obvious flaws (there may be other conflicts that are not encoded by the planning graph)

Actions considered as mutex



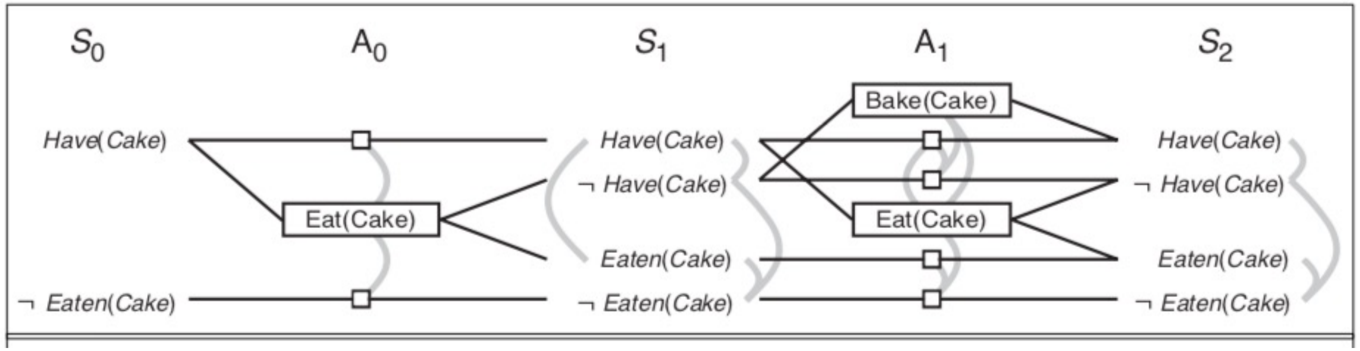
Inconsistent support



Mutually Exclusive Actions

- Inconsistent effects
  - Eat(Cake) and the persistence of Have(cake) have inconsistent effects.
- Interference
  - Eat(Cake) interferes with the persistence of Have(Cake) by negating its pre-conditions.
  - Eat(Cake) and persistence of not Eaten(Cake) are mutex.
- Competing needs
  - Bake(Cake) and Eat(Cake) are mutex because they compete on the value of the Have(Cake) precondition.

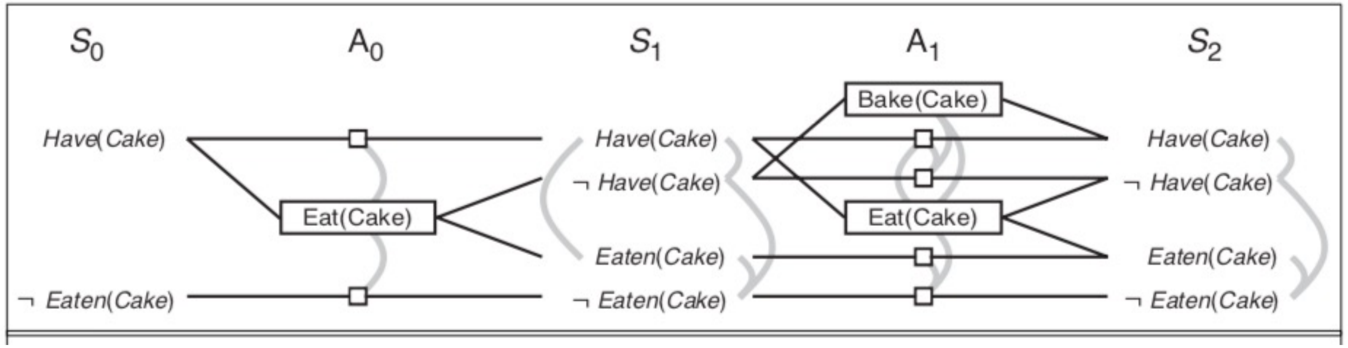
$Init(Have(Cake))$
$Goal(Have(Cake) \wedge Eaten(Cake))$
$Action(Eat(Cake)$
  PRECOND: $Have(Cake)$
  EFFECT: $\neg Have(Cake) \wedge Eaten(Cake))$
$Action(Bake(Cake)$
  PRECOND: $\neg Have(Cake)$
  EFFECT: $Have(Cake))$



Mutually Exclusive Propositions

- Two propositions at level i are mutex if:
  - Negation of each other
    - They are negations of one another
  - Inconsistent support
    - All ways of achieving the propositions at level i-1 are pairwise mutex. All pairs of actions that can lead to these literals cannot occur together.
- Example
  - Inconsistent support
    - Have(Cake) and Eaten(Cake) are mutex in S1 because the only way of attaining Have(Cake) which is maintenance action is mutex with the only way of achieving Eaten(Cake) which is Eat(Cake)

Init(*Have*(*Cake*))
Goal(*Have*(*Cake*) ∧ *Eaten*(*Cake*))
Action(*Eat*(*Cake*)
  PRECOND: *Have*(*Cake*)
  EFFECT: ¬ *Have*(*Cake*) ∧ *Eaten*(*Cake*))
Action(*Bake*(*Cake*)
  PRECOND: ¬ *Have*(*Cake*)
  EFFECT: *Have*(*Cake*))



Planning Graphs for Heuristic Estimation

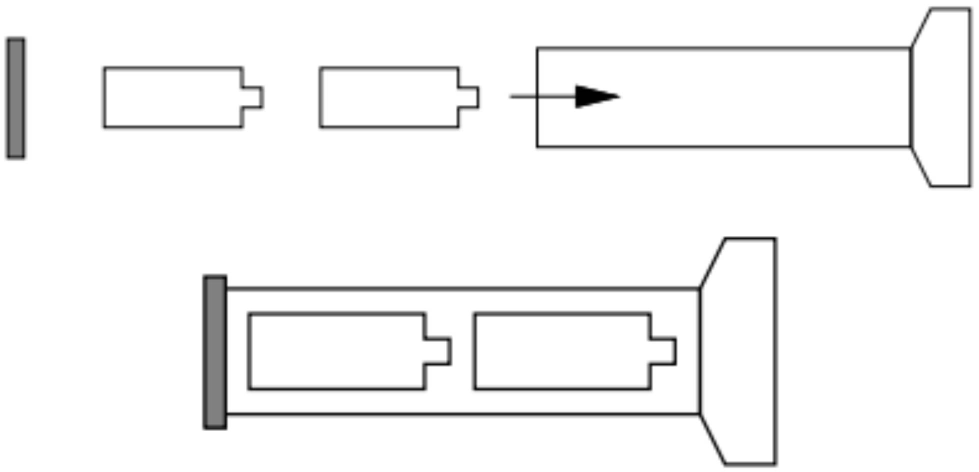
- Level-cost of a goal literal (atom)
  - Cost of attaining any goal g_i from a state s as the level at which g_i first appears in the planning graph constructed from the initial state s.
  - Encodes the difficulty to making a literal true. This estimate can be used to estimate the *"cost to go"* from a current state s to the goal, serving as a heuristic.
  - If any goal literal fails to appear in the final level of the planning graph, then the problem is unsolvable.
  - The planning graph is polynomial in size (hence tractable to compute)

Heuristic Cost of Attaining Conjunctive Goals

- **Max-level** heuristic
  - Maximum level cost of any of the goals (admissible but not accurate)
- **Level-sum** heuristic
  - Sum of the level costs of the goals
- **Set-level** heuristics
  - Level at which all the literals in the conjunctive goal appear in the planning graph without any pair of them being mutually exclusive.
- The Fast Forward (FF) Planning System (Hoffman et al.) uses the planning graph to provide a heuristic estimate while searching for a plan.
  - http://www.cs.toronto.edu/~sheila/2542/w06/readings/ffplan01.pdf
  - The idea is similar to HSP planning system. The idea is still one of converting the planning problem to a heuristic-guided search. But the heuristic comes from the planning graph instead of computing via the HSP approach.

Example: flashlight domain

- Problem involves putting batteries into a torchlight.



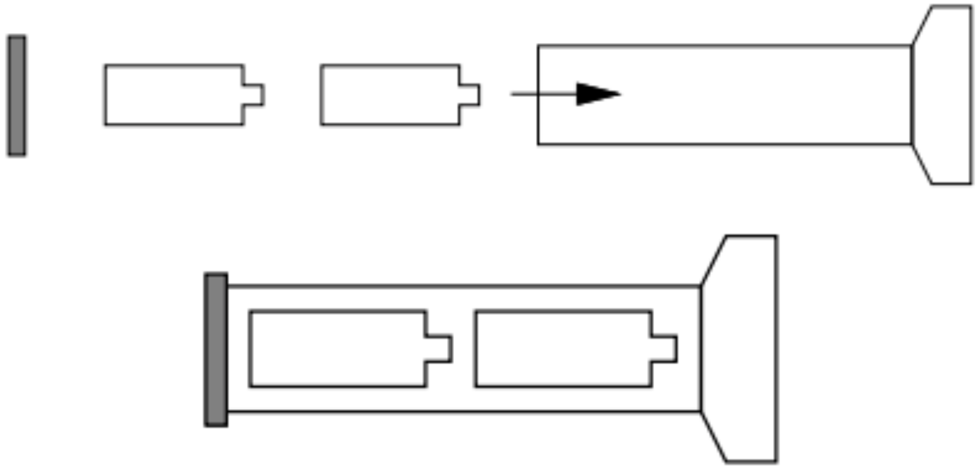
Object Instances

$$I = \{Battery1, Battery2, Cap, Flashlight\}$$

Actions

Name	Preconditions	Effects
$PlaceCap$	$\{\neg On(Cap, Flashlight)\}$	$\{On(Cap, Flashlight)\}$
$RemoveCap$	$\{On(Cap, Flashlight)\}$	$\{\neg On(Cap, Flashlight)\}$
$Insert(i)$	$\{\neg On(Cap, Flashlight), \neg In(i, Flashlight)\}$	$\{In(i, Flashlight)\}$

Example: flashlight domain



Initial State $S = (On(Cap, Flashlight), \neg In(Battery1, Flashlight1)\ \neg In(Battery2, Flashlight))$

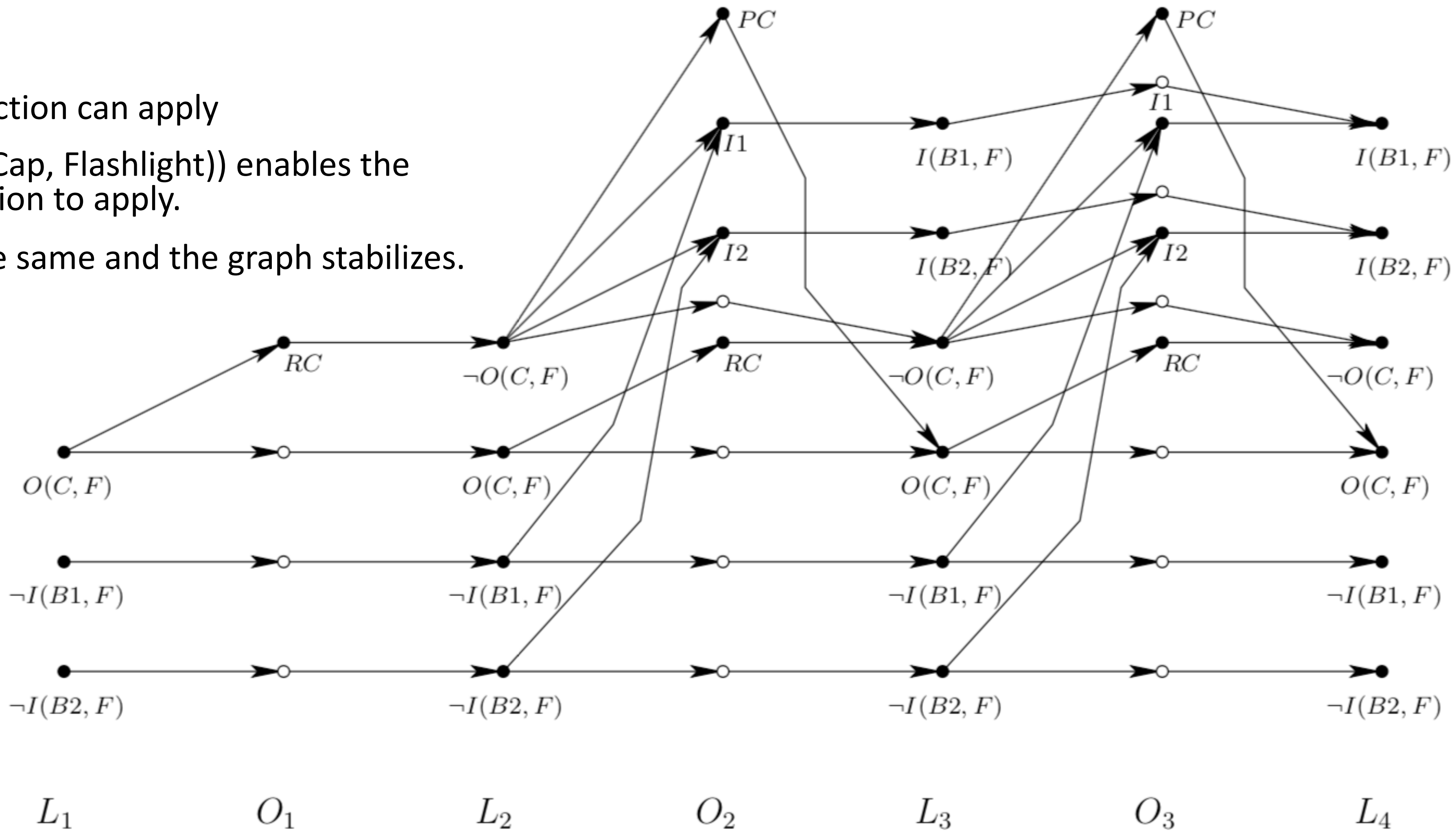
Goal $G = \{On(Cap, Flashlight), In(Battery1, Flashlight), In(Battery2, Flashlight)\},$

Plan $(RemoveCap, Insert(Battery1), Insert(Battery2), PlaceCap)$

Example: flashlight domain

Planning graph

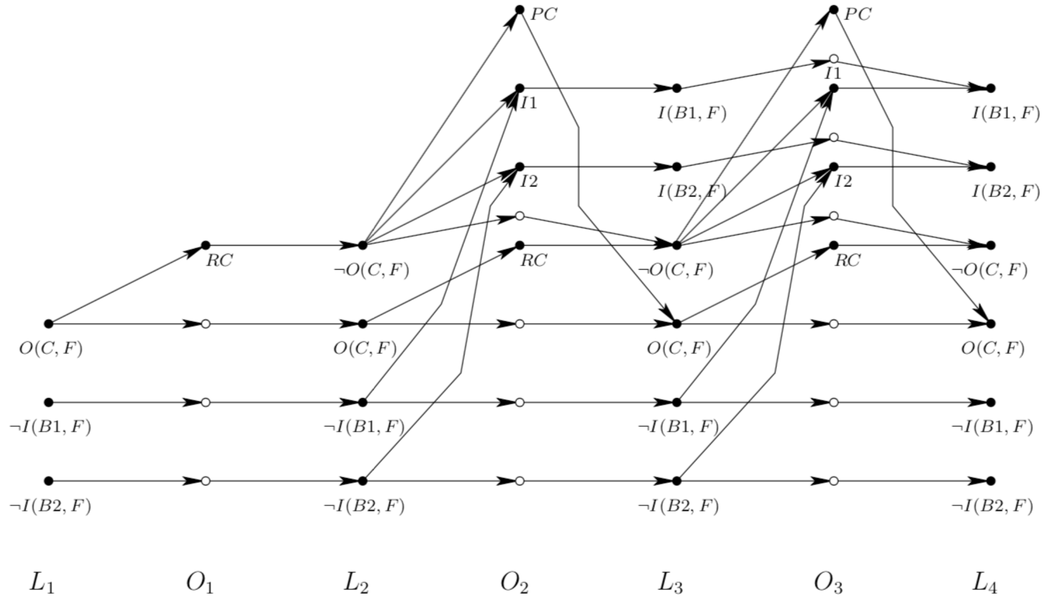
- In L1 only remove cap action can apply
- Appearance of Not(On(Cap, Flashlight)) enables the battery insertion operation to apply.
- Finally, L3 and L4 are the same and the graph stabilizes.



Graph Plan: Using Planning Graphs for Obtaining the Plan

- Central Idea
  - Use the planning graph to extract a plan
  - Instead of using the graph for providing a heuristic.

- Graph Plan
  - Look for a plan of depth K.
  - Then search for a solution.
  - If you succeed return a plan, else increase the plan depth to K+1



- Interleaves graph extension and plan search
- Once all the goals appear as non-mutex in the graph then call a plan search.

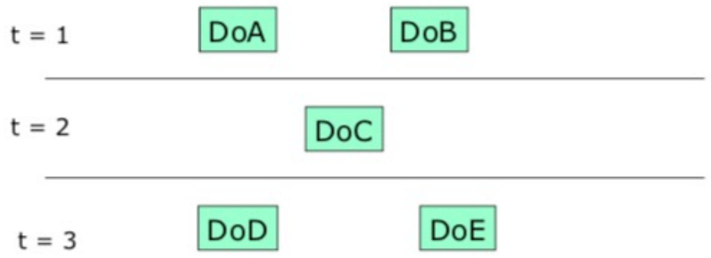
Extracting the Plan

- There can be several actions in an action layer.

- How to extract the plan?
  - Start from layer k and search backwards.
  - Perform an And/Or search.
  - All literals in the target state are to be satisfied (AND part)
  - Try the possible operators under mutex constraints (OR part). Note: mutex says that some actions cannot take place together, we need to select between them.

Planning graph has multiple actions at a level.

A plan of depth k
- has k times steps
- may have multiple parallel actions per time step



Procedure for plan extraction

- If all the literals in the goal appear at the deepest level and not mutex, then search for a solution for each subgoal at level i
  - For each subgoal at level i
    - Choose an action to achieve it
    - If it’s mutex with another action, Fail
  - Repeat for preconditions at level i-2

Lots more to planning! Hierarchical Planning

There is whole lot more to planning!

Complex tasks may be decomposed hierarchically and then refined.

Key idea:
Not every action needs to be fully planned out from the beginning!

1. Plan at a high level
2. Work out details as needed