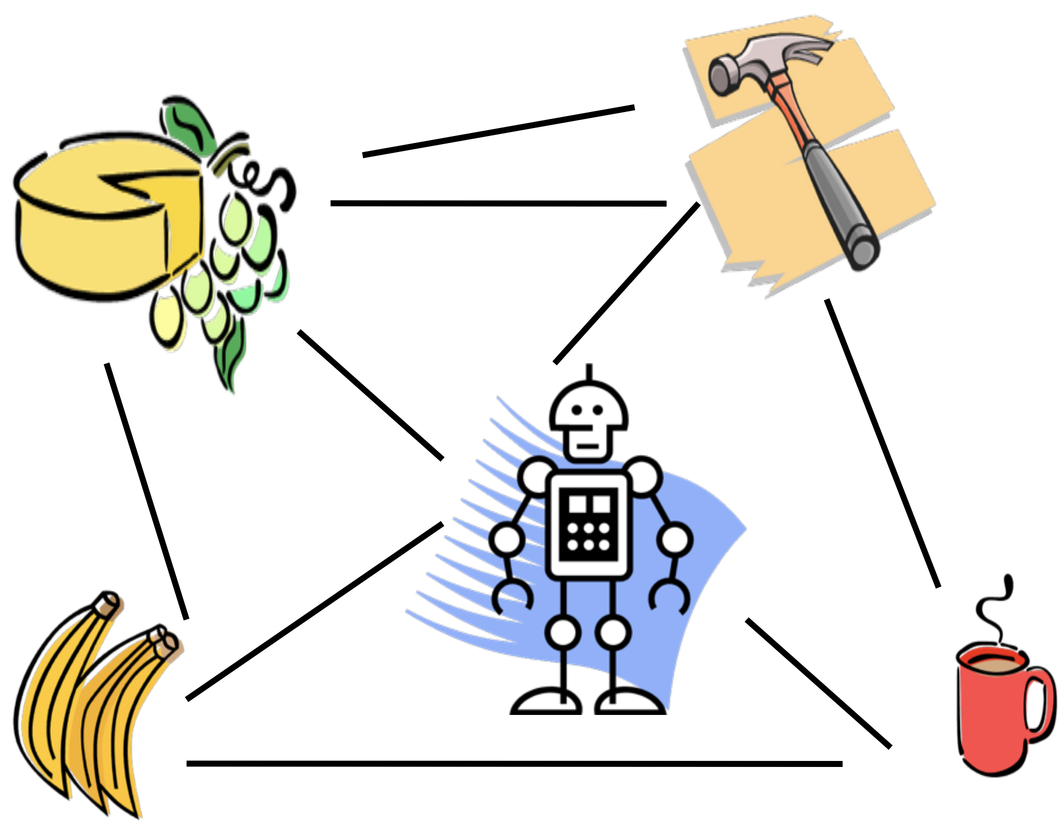
Classical Planning

CS 486/686: Introduction to Artificial Intelligence
Winter 2016

Classical Planning

A plan is a collection of actions for performing some task (reaching some goal)



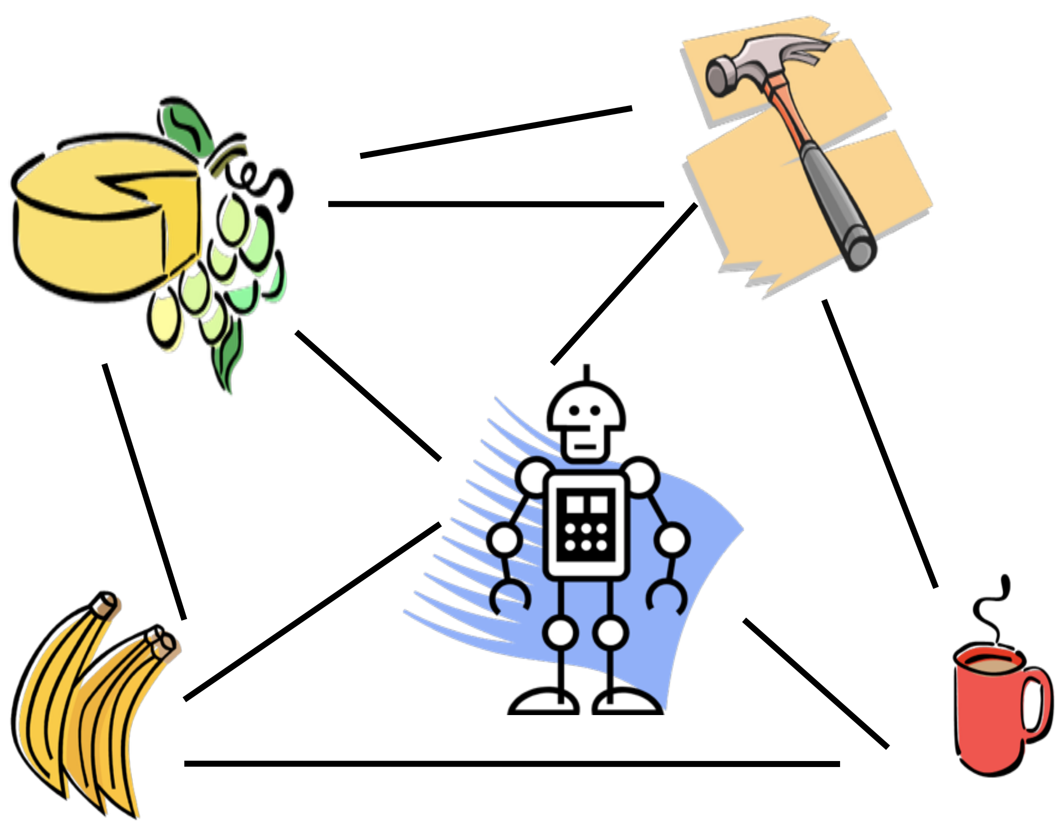
If we have a robot we want the robot to

1. Decide what to do, and
2. Figure out what actions it needs to do in order to accomplish its goals

Classical Planning

We want to change the world to suit our needs.

Problem: Need to reason about what the world will be like after taking certain actions



Goal: Kate has coffee and has food in the fridge and the bookshelf is fixed

Currently: Robot is at home, has no coffee, coffee is not made, no food in the fridge, …

To Do: Go to the kitchen, make coffee, bring it to Kate, go to the store,…

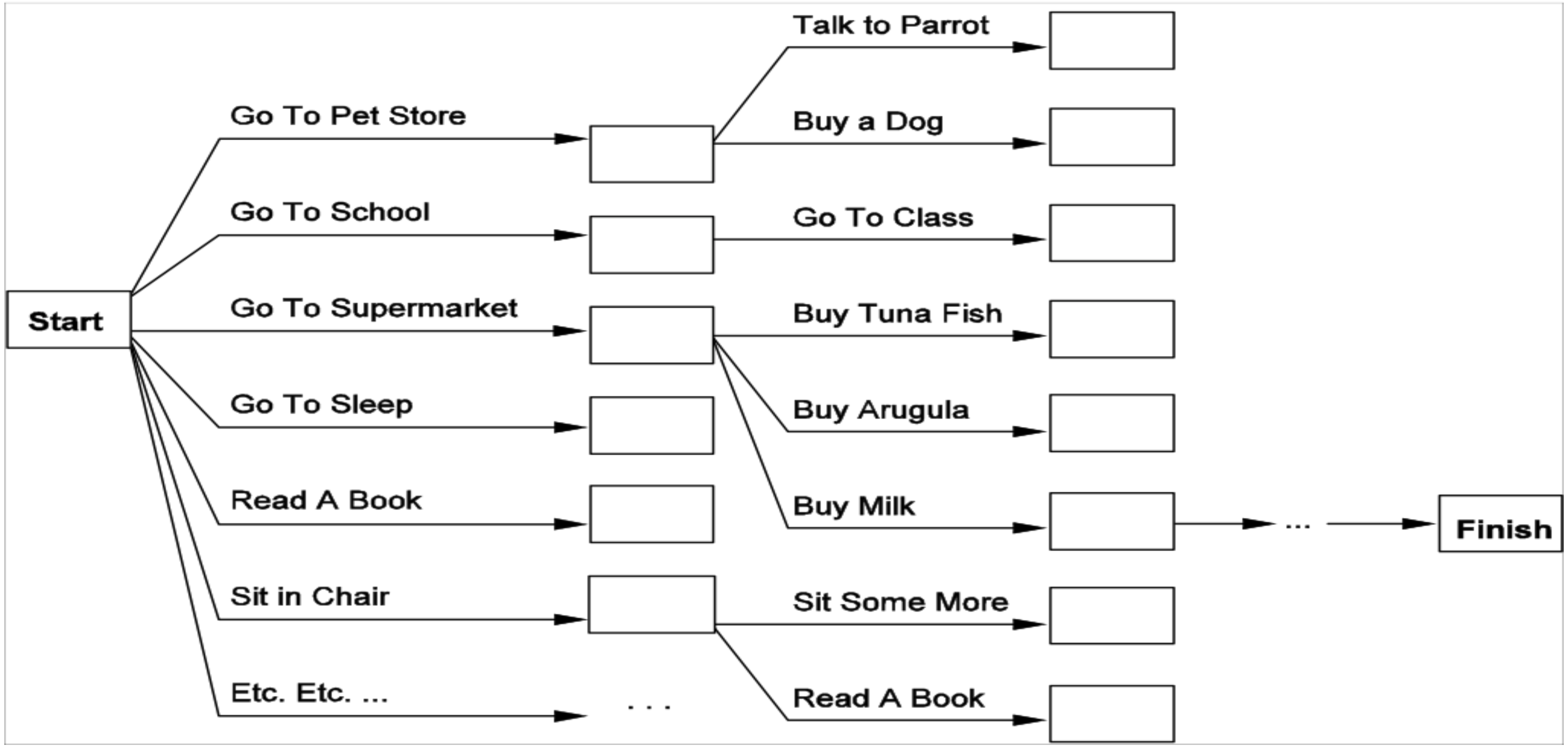
Planning

- Planning is basically searching over sets of states while also reasoning over the effects of actions
- Optimal plan will be the one with smallest number of actions
- This is a lot like search BUT
  - Representation is extremely important

Planning vs Search

Consider the task get milk, bananas, and a hammer.

Standard search fails miserably



Planning Languages

- By using a structured and restricted planning language we can do better than standard search algorithms
  - Connect state and action descriptions
  - Allow the adding of actions in any order
  - Establish independent subproblems and solve the separately

STRIPS

Stanford Research Institute Problem Solver

Domain

- Set of typed objects (usually represented as propositions)
- B and Shakey are OK, but x and Robot(x) are not

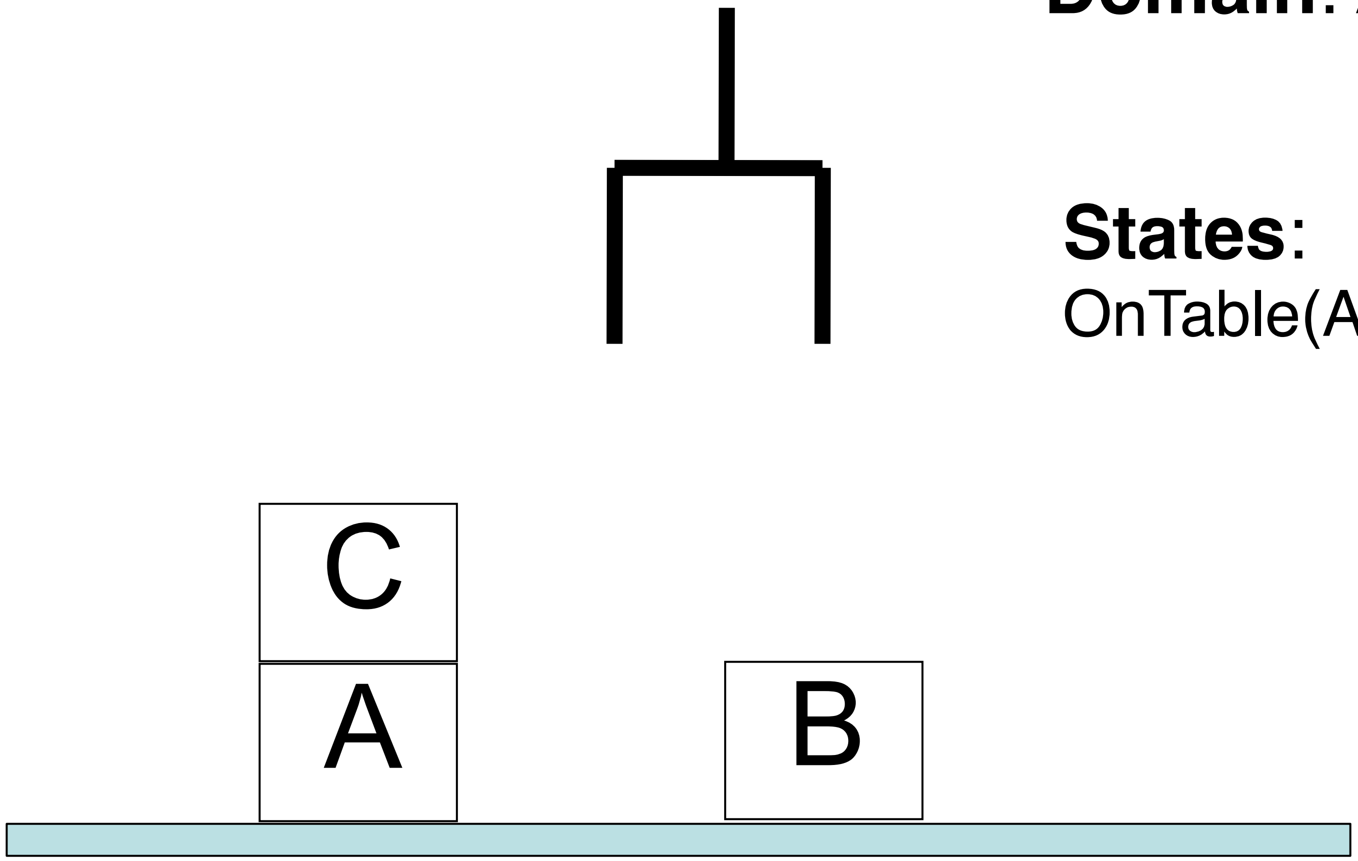
States

- Conjunctions of first-order predicates over objects
- On(A,B)$\wedge$On(B,C) is allowed but not On(x,y)$\wedge$On(y,z)

Closed-World Assumption

- Any conditions not mentioned in a state are assumed to be false
- This is required to overcome the *Frame Problem*

Block World



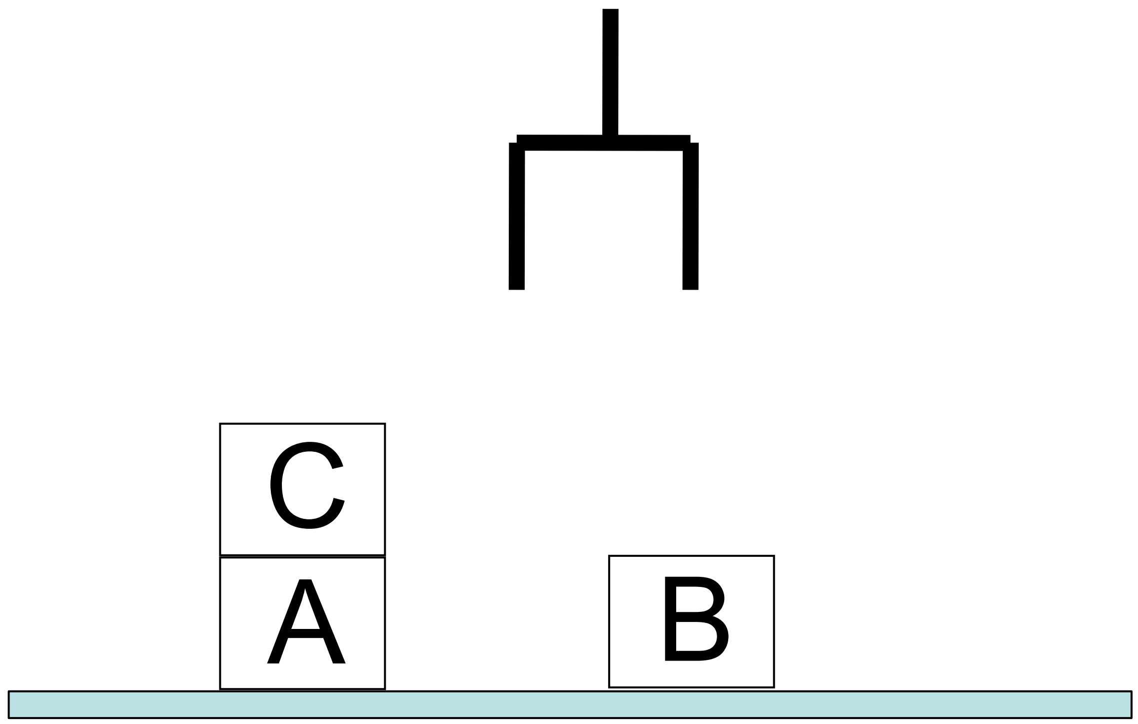
Domain: A, B and C

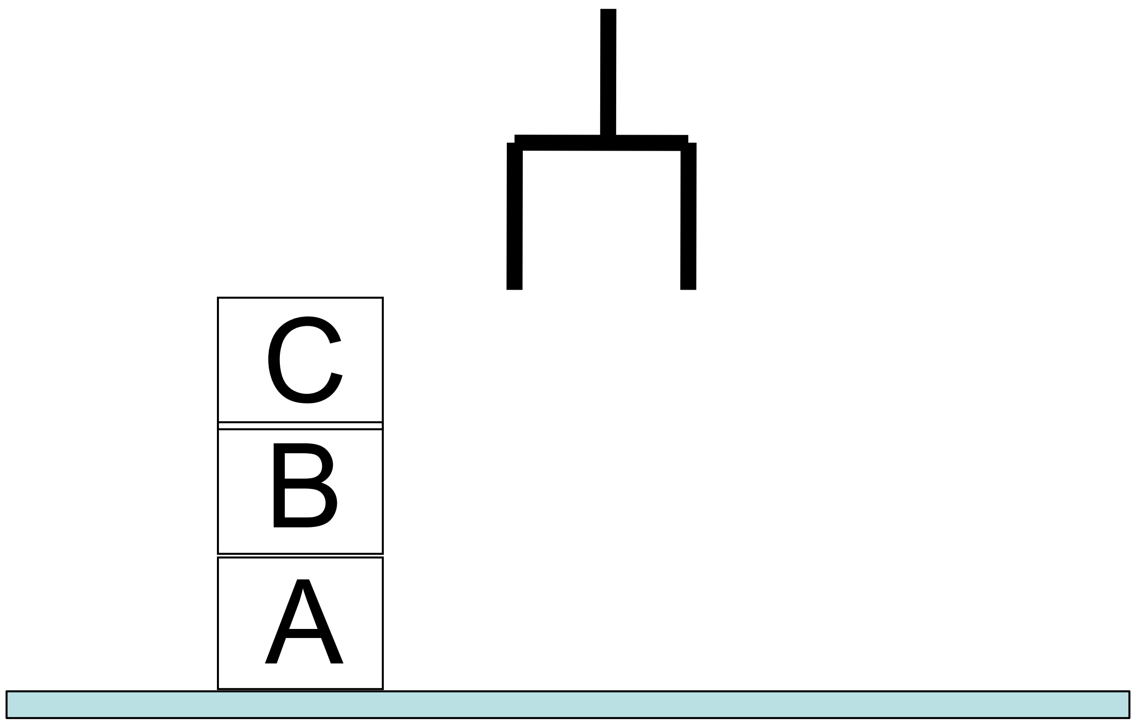
States:
OnTable(A)∧OnTable(B)∧On(C,A)∧HandEmpty()

STRIPS

Goals

- Conjunctions of positive ground literals
- OnTable(A)∧On(B,A)∧On(B,C)∧HandEmpty()





STRIPS

Actions are specified by their **preconditions** and their **effects**

Name and parameter list

Fly(p, from , to)

PRECOND: At(p, from)∧Plane(p)∧Airport(from)∧Airport(to)

EFFECT: ~At(p,from)∧At(p,to)

Description of what must be true in order for the action to be executed. (Conjunction of function-free positive literals)

Description of how the state changes when the action is executed. Variables in the effect must be included in the original parameter list.

Effects are sometimes represented as *Add-lists* and *Delete-lists.*
Add-list: propositions that become true
Delete-list: propositions that become false

STRIPS

Semantics:

- If the precondition is false in a world state then the action changes nothing (it can not be applied)
- If the precondition is true
  - Delete items from the Delete-list
  - Add items in the Add-list
  - Order of operations is important

Strips Assumption
Every literal not mentioned in an effect stays the same

Solution:

- Action sequence that when executed in the start state results in a state that satisfies the goal

Example

- Init(At(Flat,Axle)^ At(Spare,Trunk))

- Goal(At(Spare, Axle))

- Action(Remove(Spare, Trunk),
  - PRECOND: At(Spare, Trunk)
  - EFFECT: ~At(Spare,Trunk)^ At(Spare, Ground))

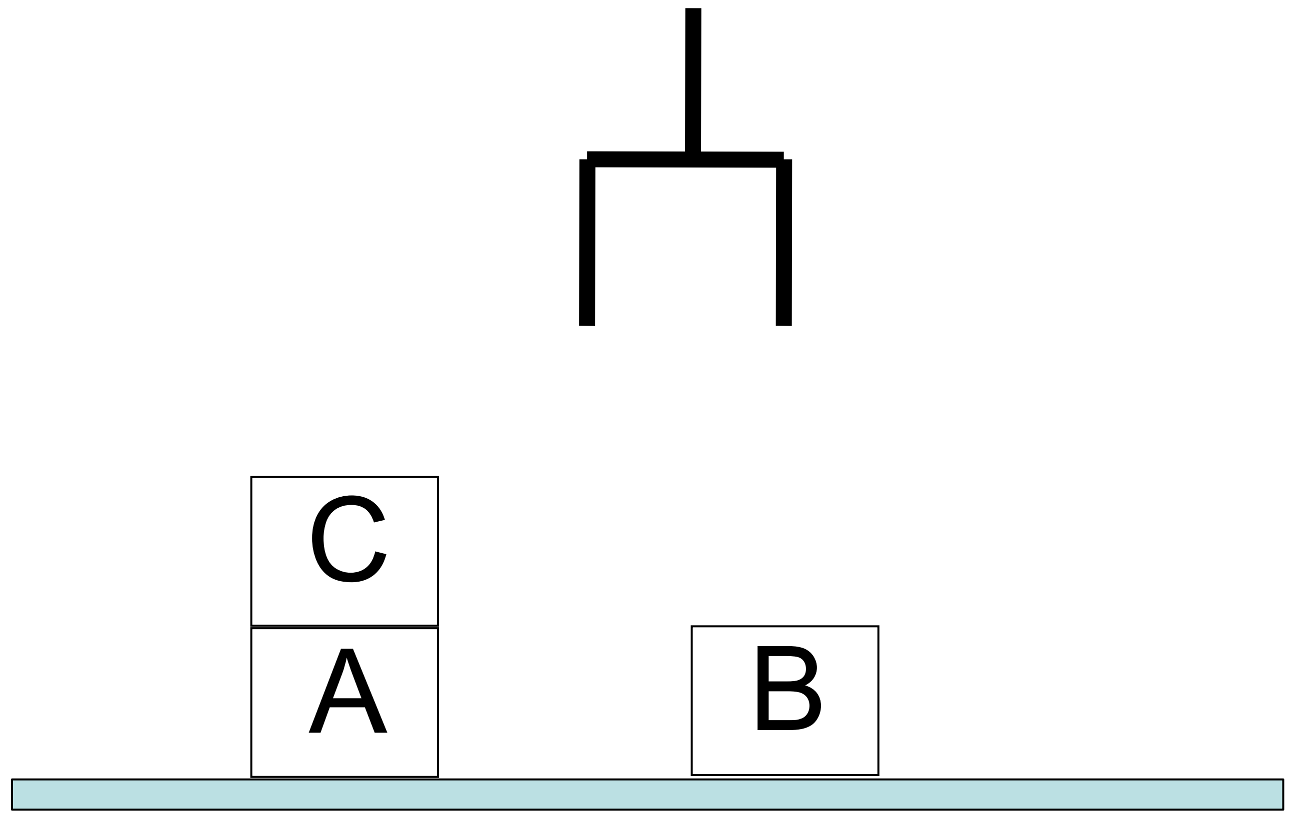
- Action(Remove(Flat, Axle),
  - PRECOND: At(Flat, Axle)
  - EFFECT: ~At(Flat, Axle)^ At(Flat,Ground)^ Clear(Axle)

- Action(PutOn(Spare, Axle),
  - PRECOND: At(Spare,Ground)^ Clear(Axle)
  - EFFECT: ~At(Spare, Ground)^ At(Spare, Axle))

- Action(LeaveOverNight,
  - PRECOND:
  - EFFECT: ~At(Spare, Ground)^ ~At(Spare,Axle)^ ~At(Spare, Trunk)^~At(Flat, Ground)^ ~At(Flat, Axle)

Example

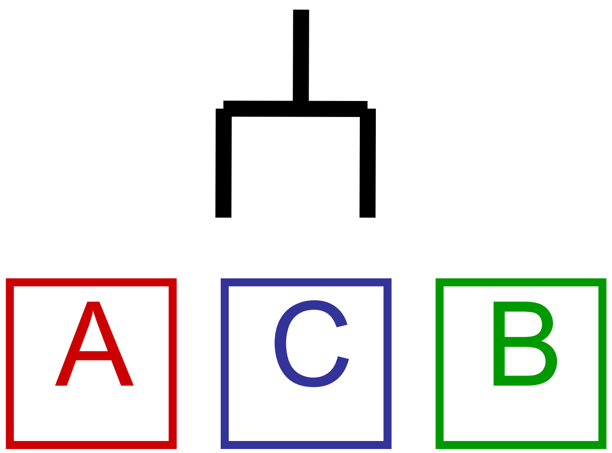
Define the action *Move* object from someplace to another place



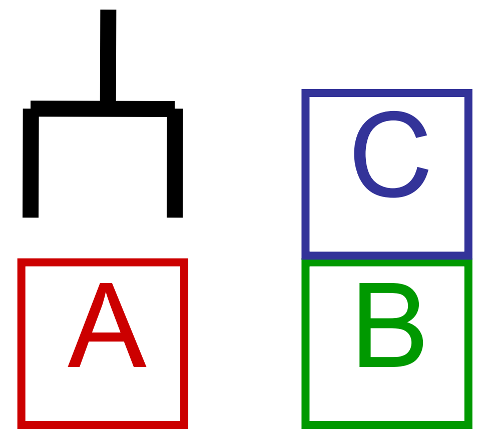
Planning as Search

- Progression Planning (Forward Planning)
  - This is precisely search like we saw earlier in the course
  - You need good heuristics but these can be domain independent
- Regression Planning (Backward Planning)
  - Start from the goal state
  - Find consistent, relevant actions
    - Consistent: it can not undo any desired literals
    - Relevant: it must achieve one of the conjuncts of the goal

Example



Initial State:
Clear(c)
Clear(a)
Clear(b)
OnTable(b)
OnTable(a)
OnTable(c)
HandEmpty()



Goal:
Clear(a)
Clear(c)
On(b,c)

Pickup(x)
P: OnTable(x), Clear(x), HandEmpty
E: Holding(x), ~OnTable(x), ~HandEmpty

PutDown(x)
P: Holding(x)
E: OnTable(x), Clear(x), HandEmpty, ~Holding(x)

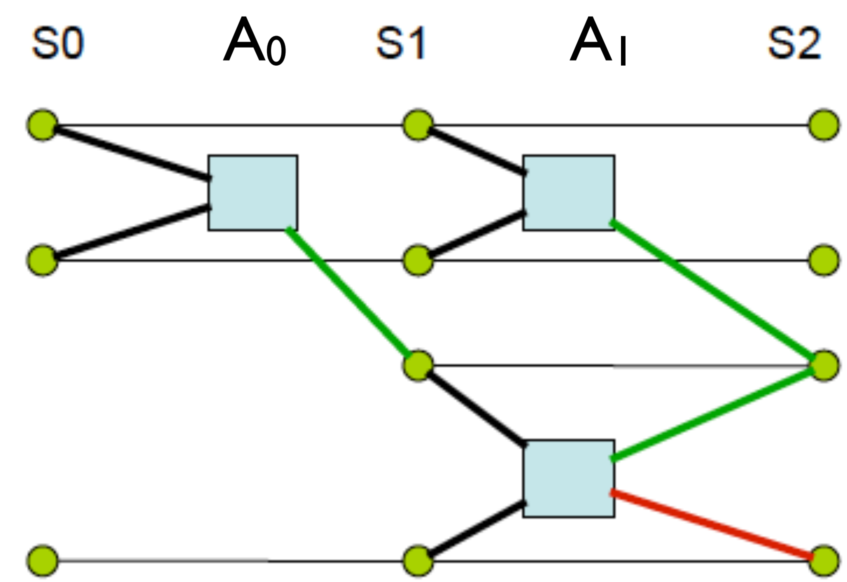
Stack(x,y)
P: Holding(x), Clear(y)
E: On(x,y), Clear(x), HandEmpty, ~Clear(y), ~Holding(x)

UnStack(x,y)
P: Clear(x), On(x,y), HandEmpty
E: Clear(y), Holding(x), ~Clear(x), ~On(x,y), ~HandEmpty

Planning Graphs

It can be useful to represent planning problems as planning graphs

- For deriving heuristics
- For running particular algorithms



Planning graphs consist of **levels**

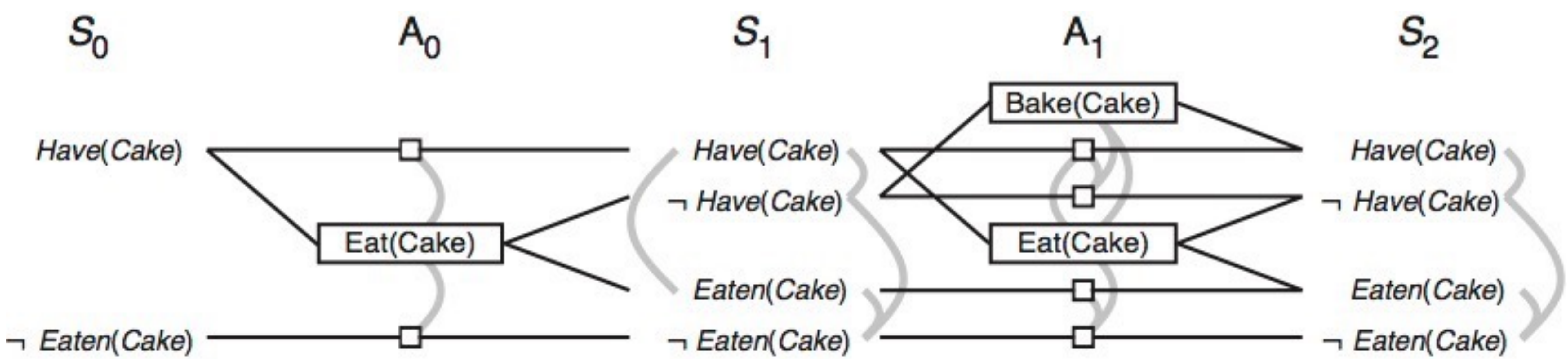
- S_0 has a node for each literal that holds in the initial state
- A_0 has nodes for each action that could be taken in S0
- S_i contains all literals that could hold given the actions taken in level A_{i-1}
- A_i contains all actions who's preconditions could hold in S_i

Planning Graphs

Init: Have (Cake)
Goal: Have(Cake)∧Eaten(Cake)

Action: Eat(Cake)
PRECOND: Have(Cake)
EFFECT: ~Have(Cake)∧Eaten(Cake)

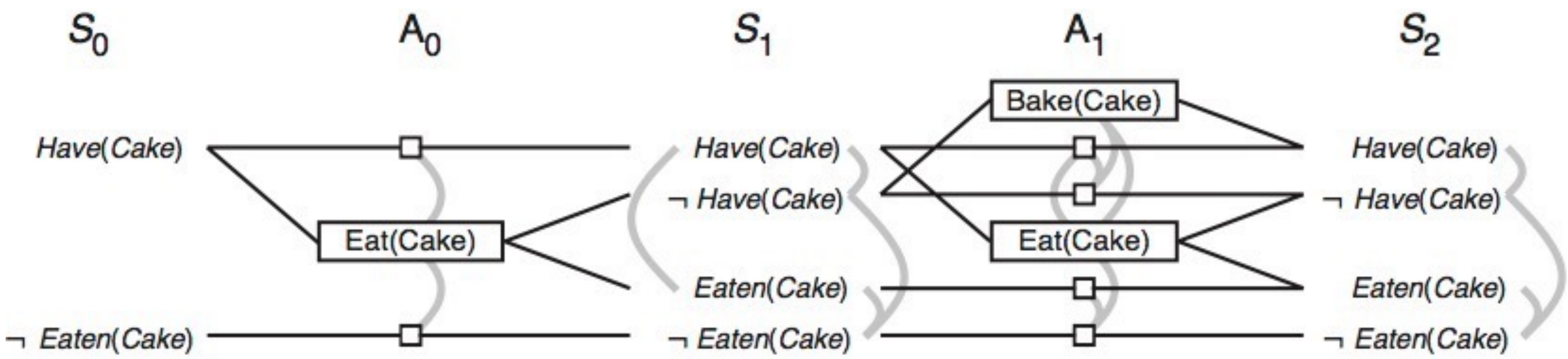
Action: Bake(Cake)
PRECOND: ~Have(Cake)
EFFECT: Have(Cake)



Planning Graphs

Persistence Actions: Once a literal appears, then it can persist if no action negates it (no-op)

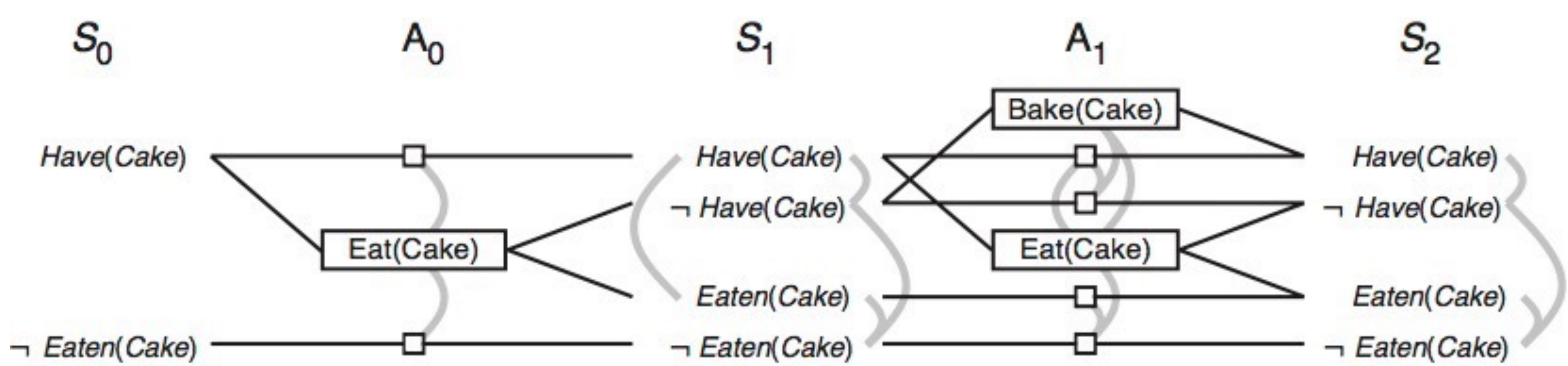
Mutual Exclusion Links (Mutex): Record conflicts between actions that can not occur together



Planning Graphs

Mutual Exclusion Links (Mutex): Record conflicts between actions that can not occur together

- **Inconsistent Effects:** (actions) An effect of one negates the effect of another
- **Interference:** (actions) One deletes a precondition of another
- **Competing Needs:** (actions) Mutually inconsistent preconditions
- **Inconsistent Support:** (states) One is a negation of another OR all ways of achieving them are mutually exclusive



Using Planning Graphs

Observations

- Graph is polynomial in the size of the planning problem.
- If any goal literal does not appear in the final level then the problem is unsolvable.

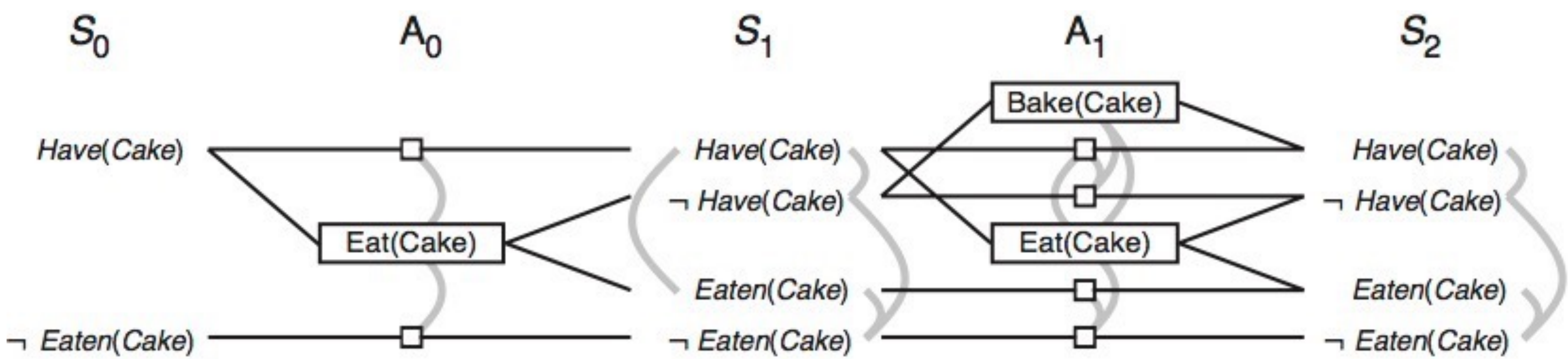
Using Planning Graphs

Heuristics

- For a single goal literal g, the level in which it first appears is an admissible heuristic (level-cost(g))
- For multiple goal literals ($g_1 \wedge g_2 \wedge \ldots$)
  - Max-level heuristic: Max level-cost(g_i) (admissible)
  - Level-sum heuristic: ∑ level-cost(g_i) (may be inadmissible)
  - Set-level heuristic: Level where all goal literals appear and are not mutex (admissible and dominates max-level)

Example: Planning Graphs

Level-cost?
Max-level?
Level-sum?
Set-level?



GraphPlan

- Start with an empty graph
- Iterate until you find a solution
  - Graph expansion
  - Analyze graph for mutex
  - Check if there is a possible solution
  - If yes, extract-solution

GraphPlan

Solution extraction is backward search through the planning graph

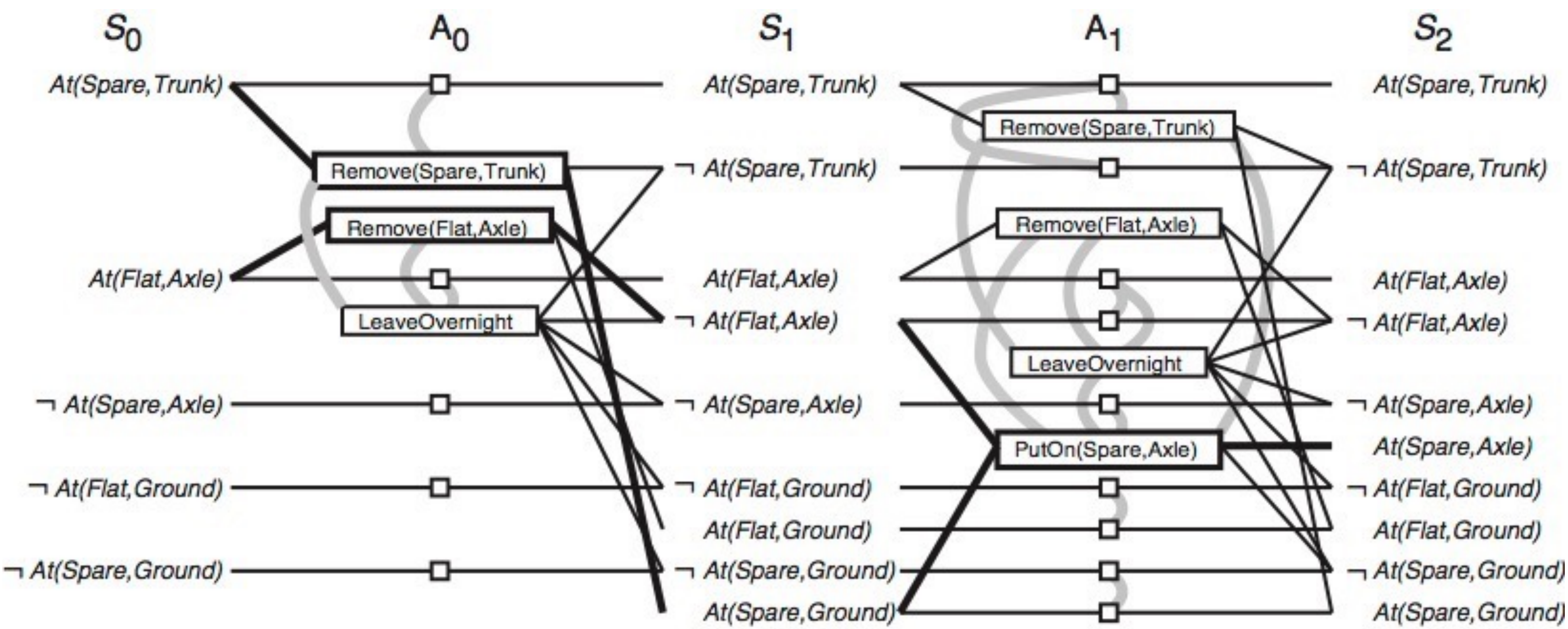
Extract-Solution(S_G,t)

- If t=0 return solution
- For each proposition s in S_G
  - Choose an action in A_{t-1} to achieves s
- If any pair of actions chosen are mutex then backtrack
- $S_{G'}$ = set of preconditions for chosen actions
- Extract-Solution($S_{G'}$, t-1)

Example

- Init(At(Flat,Axle)^ At(Spare,Trunk))
- Goal(At(Spare, Axle))
- Action(Remove(Spare, Trunk),
  - PRECOND: At(Spare, Trunk)
  - EFFECT: ~At(Spare,Trunk)^ At(Spare, Ground))
- Action(Remove(Flat, Axle),
  - PRECOND: At(Flat, Axle)
  - EFFECT: ~At(Flat, Axle)^ At(Flat,Ground)^ Clear(Axle)
- Action(PutOn(Spare, Axle),
  - PRECOND: At(Spare,Ground)^ Clear(Axle)
  - EFFECT: ~At(Spare, Ground)^ At(Spare, Axle))
- Action(LeaveOverNight,
  - PRECOND:
  - EFFECT: ~At(Spare, Ground)^ ~At(Spare,Axle)^ ~At(Spare, Trunk)^~At(Flat, Ground)^ ~At(Flat, Axle)

Example



S0
A0
S1
A1
S2
At(Spare,Trunk)
Remove(Spare,Trunk)
Remove(Flat,Axle)
At(Flat,Axle)
LeaveOvernight
¬ At(Spare,Axle)
¬ At(Flat,Ground)
¬ At(Spare,Ground)
At(Spare,Trunk)
¬ At(Spare,Trunk)
At(Flat,Axle)
¬ At(Flat,Axle)
¬ At(Spare,Axle)
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At(Flat,Axle)
¬ At(Flat,Axle)
¬ At(Spare,Axle)
At(Spare,Axle)
¬ At(Flat,Ground)
At(Flat,Ground)
¬ At(Spare,Ground)
At(Spare,Ground)

GraphPlan Properties

- Sound and complete
  - Search must terminate
  - Any plan found is a sound plan
- Optimal
  - Finds shortest length plan assuming that multiple actions may occur at the same time
- Time complexity
  - Polynomial time to construct the planning graph
  - However planning is PSPACE-complete. Thus, extraction may be intractable