Announcements

Midterm 1 Exam

- Tue 10/1, in class

Assignments:

- HW4
  - Due tonight, 10 pm
- P2: Logic and Planning
  - Due Sat 10/5, 10 pm

AI: Representation and Problem Solving

Classical Planning

Instructors: Pat Virtue & Fei Fang

Slide credits: CMU AI

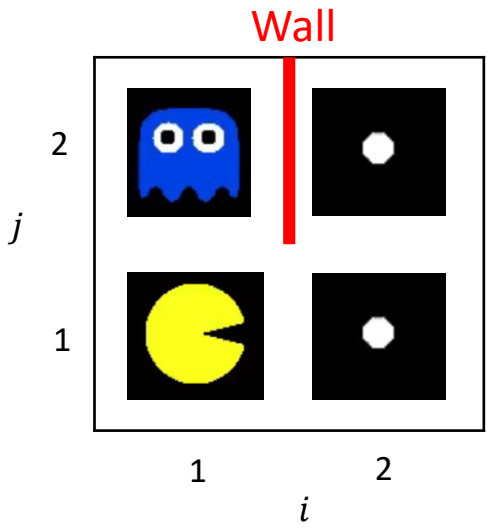
Planning as Satisfiability (SATPlan)

How to set up the KB? KB often includes sentences describing

- Transition model sentences up to time T

Write down how each *fluent* at each time gets its value based on successor-state axiom:

$$F^{t+1} \Leftrightarrow ActionCausesF^t \vee (F^t \wedge \neg ActionCausesNotF^t)$$



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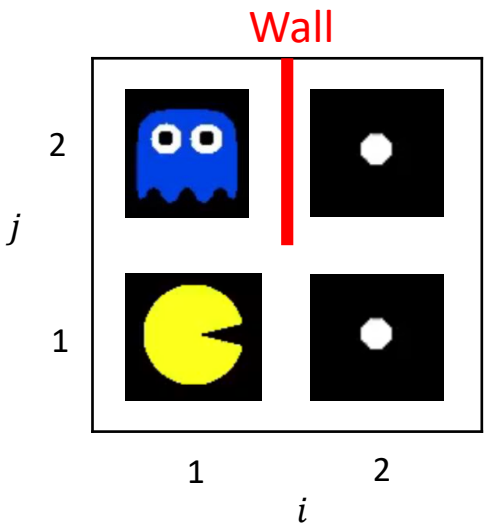
e.g., If "Stop" action is allowed, for L_{12}^1, Pacman was at an adjacent square at time 0 and moved to (1,2) or was at (1,2) and nothing causes to change its location

$$L_{12}^1 \Leftrightarrow \left(\left(L_{11}^0 \wedge N^0 \wedge \neg Wall_{12}^S \wedge \cdots \right) \vee \cdots \right)$$
$$\vee \left(L_{12}^0 \wedge \neg \left(\left(S^0 \wedge \neg Wall_{12}^S \right) \vee \cdots \right) \right)$$



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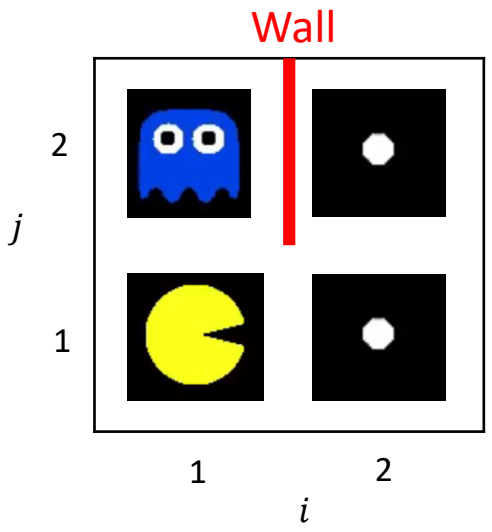


Planning, Thus Far

Goal States

completely specified

Goal Statements

partially specified

Preference models

objective function

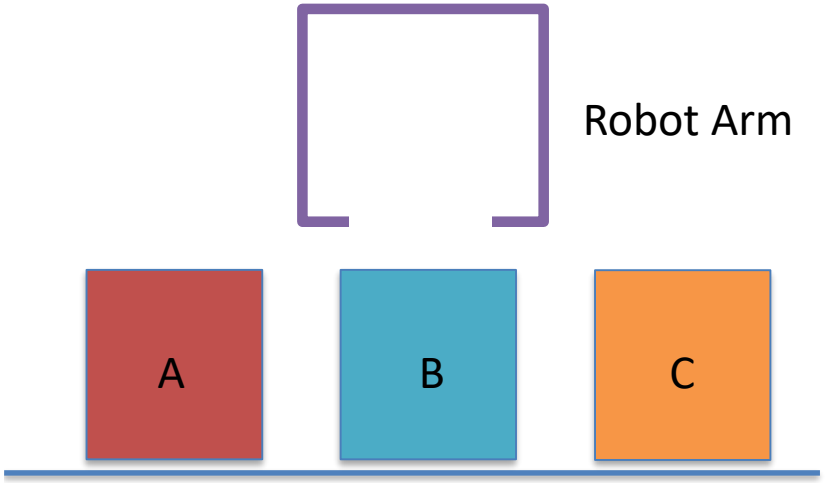
Robot Block Stacking

Start state: A, B, C on table

Goal: Block B on C and C on A

Actions: ?

Modeling Block Stacking States



Start state: A, B, C on table

Goal: Block B on C and C on A

Actions: ?

Goals in the World

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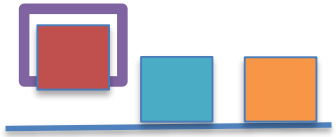
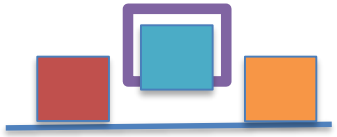
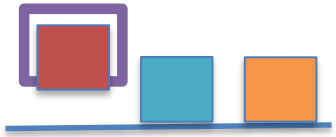
Block Stacking States

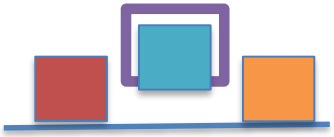
Block Stacking States

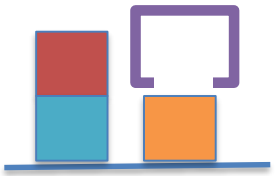




Block Stacking States







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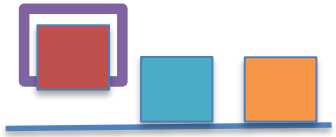
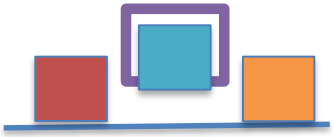
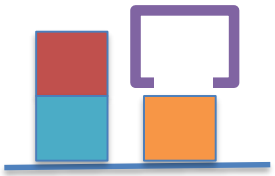
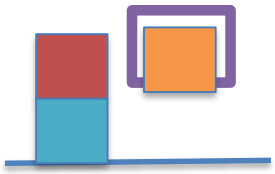
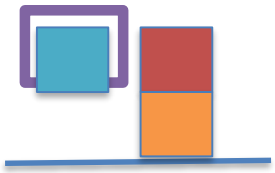
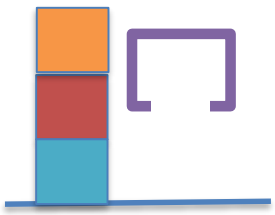




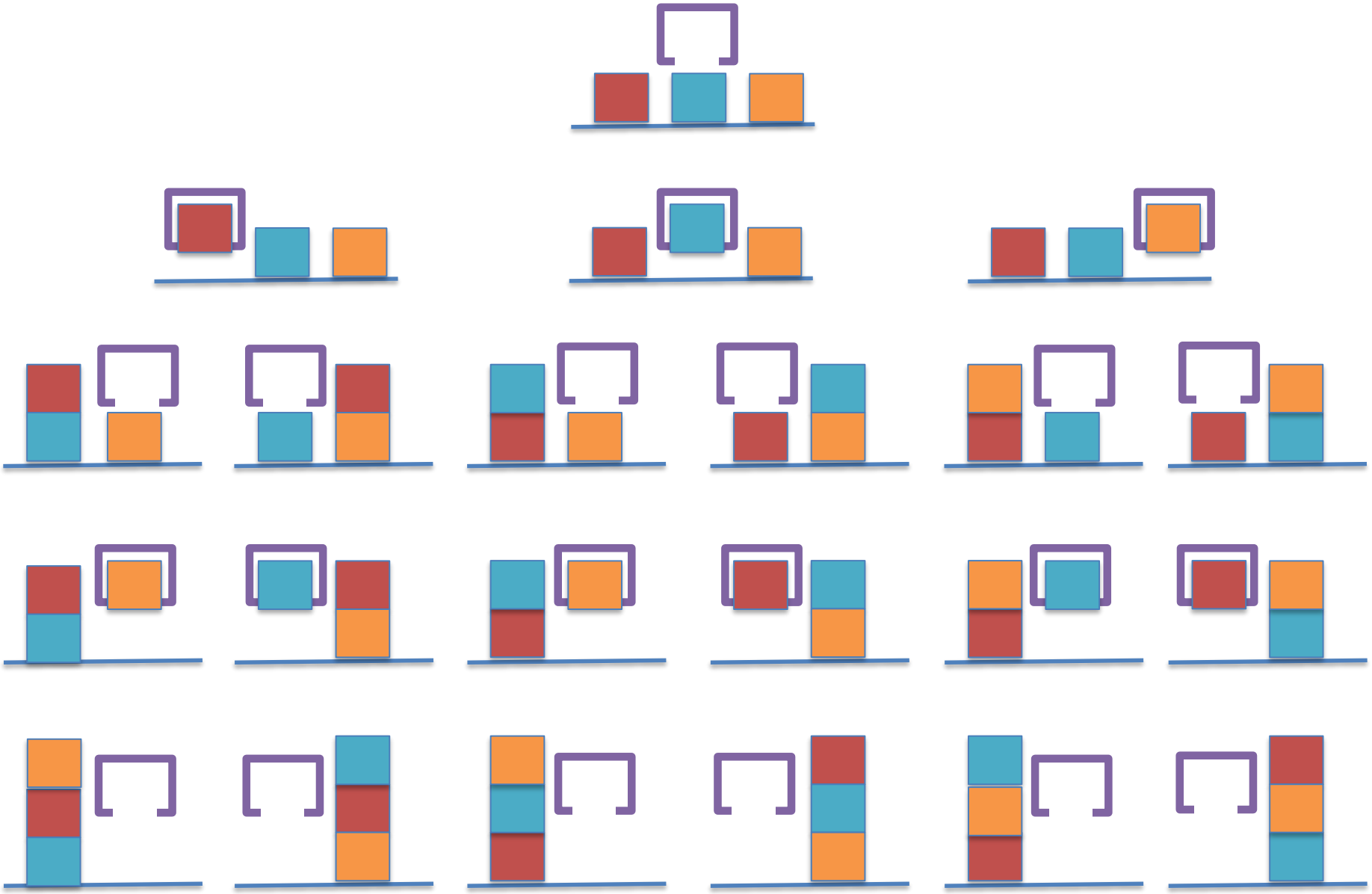




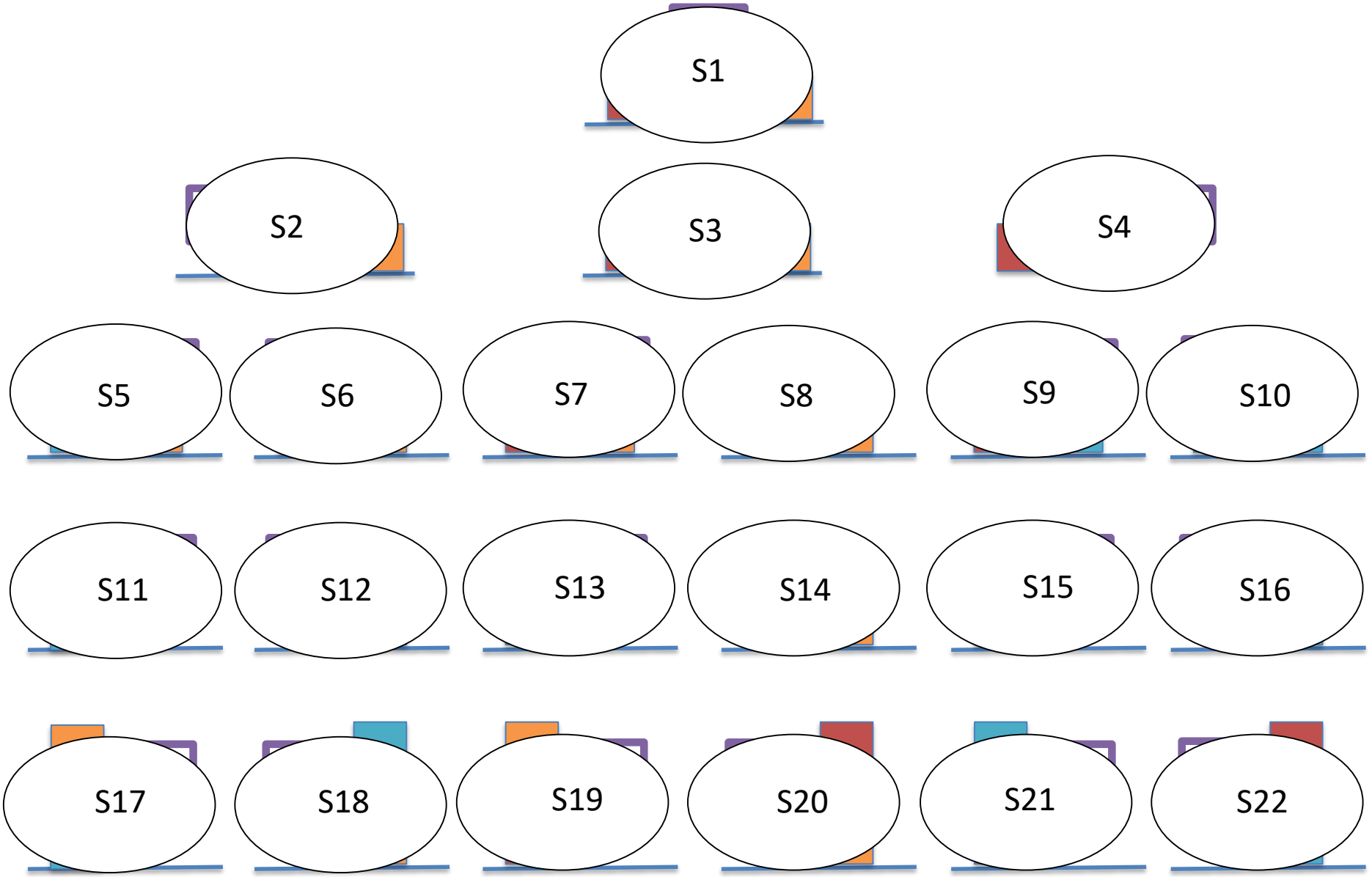




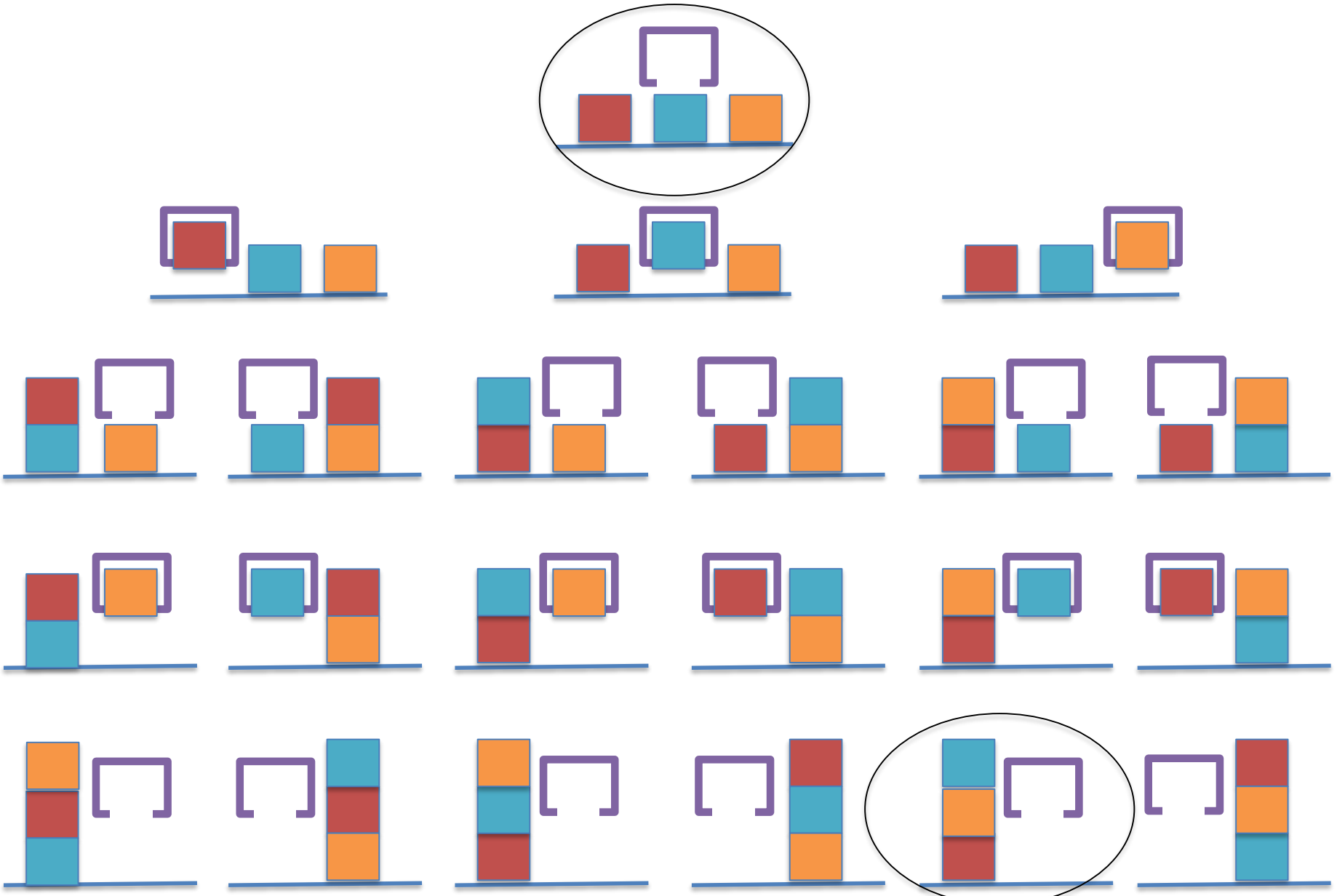
Block Stacking States



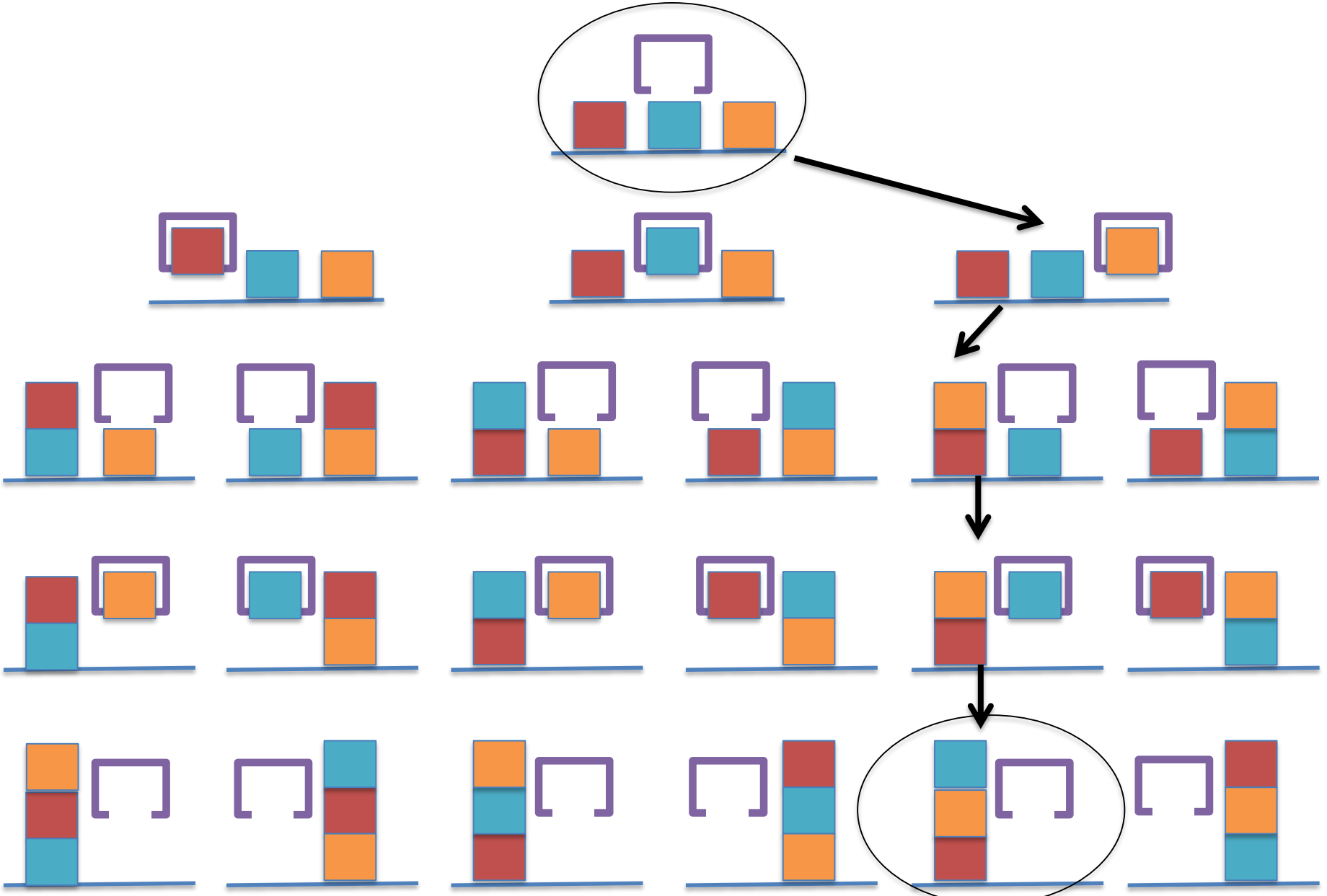
States are Informationless



Initial and Goal States



Plan from Initial to Goal State



Goals in the World

Goal States

completely specified

Goal Statements

partially specified

Preference models

objective function

BFS, DFS, A*

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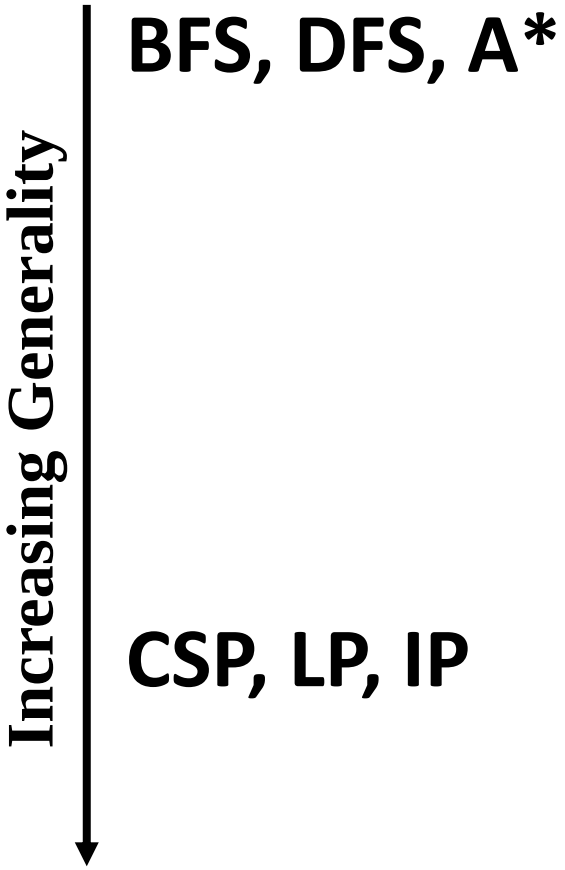

CSP for Blocks World

Goal: Block B on C and C on A

Constraint Satisfaction Problem:

Height(B) > Height(C)

Height(C) > Height(A)

Goals in the World

Goal States

completely specified

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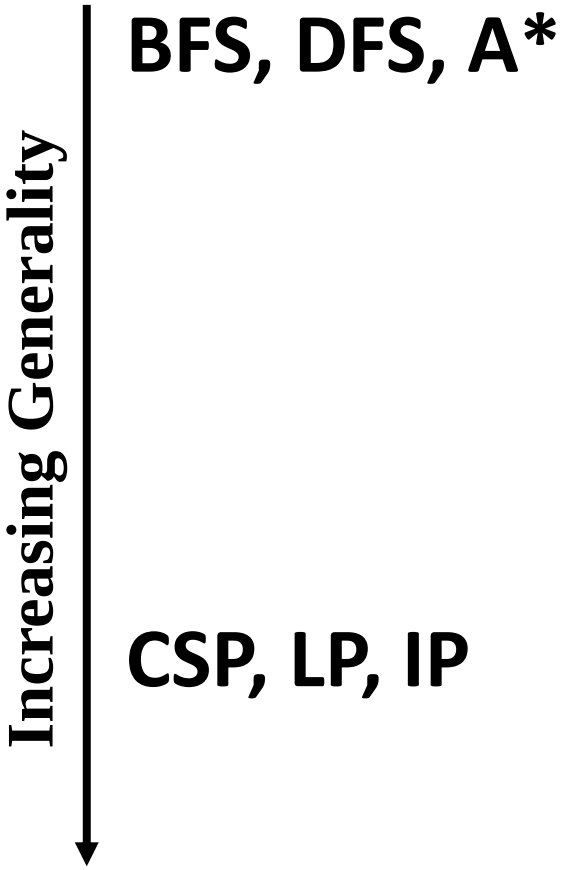
Preference models

objective function



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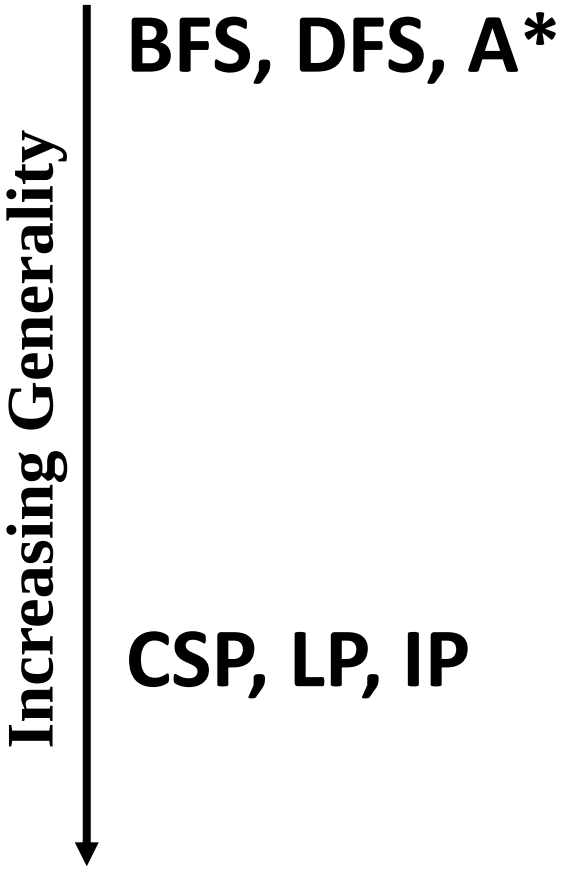

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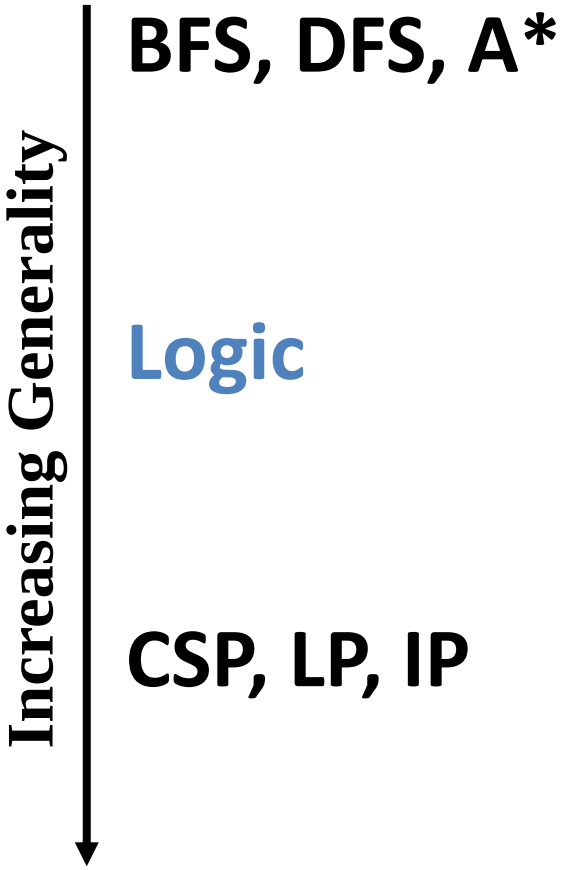


Logical Agents

Create a Knowledge Base

- Symbols
- Implications

Logical Agents

Create a Knowledge Base

- Symbols – each is true or false
- Implications – conjunctions imply new info

Symbolic Descriptions

Every state has the same objects

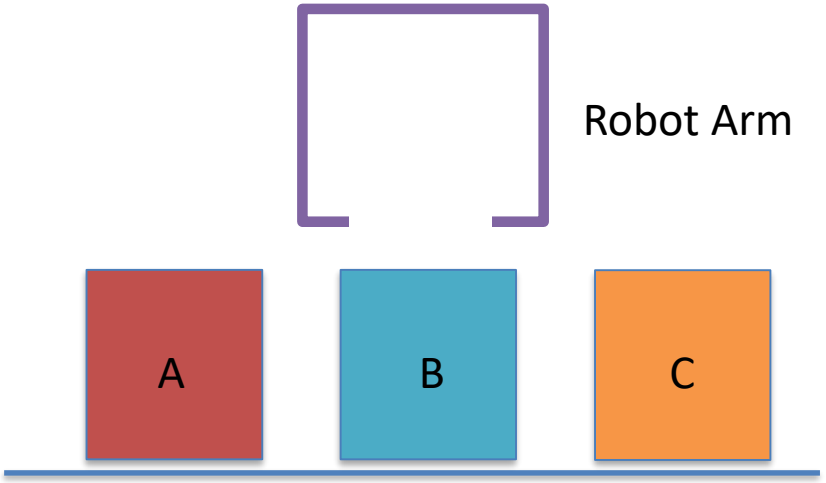
Properties and relationships of those objects change (i.e., locations)

Define states as set of symbols that represent whether those properties are true

Logical Agents

Create a Knowledge Base

Symbols



Logical Agents

Create a Knowledge Base

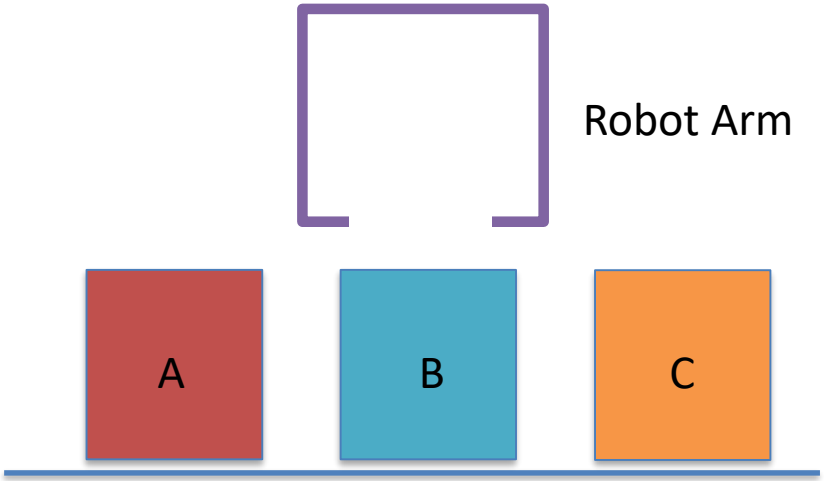
Symbols

A-on-Table
B-on-Table
C-on-Table
Hand-Empty

A-In-Hand
B-In-Hand
C-In-Hand

A-on-B
A-on-C
B-on-C

B-on-A
C-on-A
C-on-B



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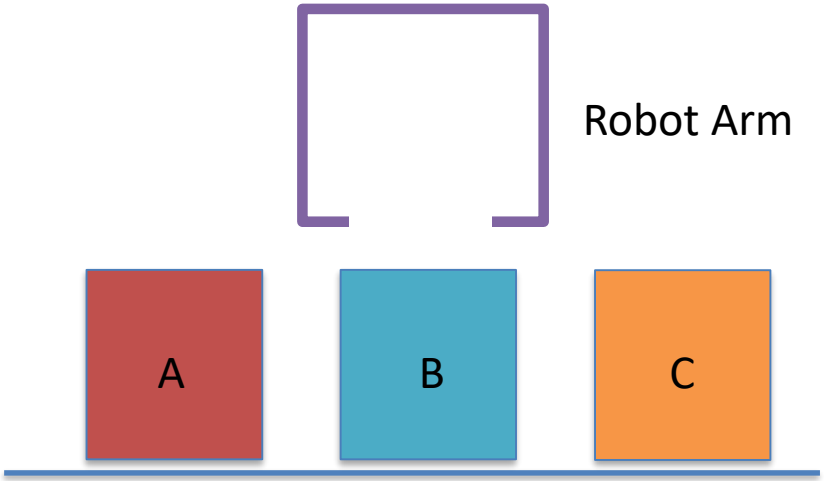
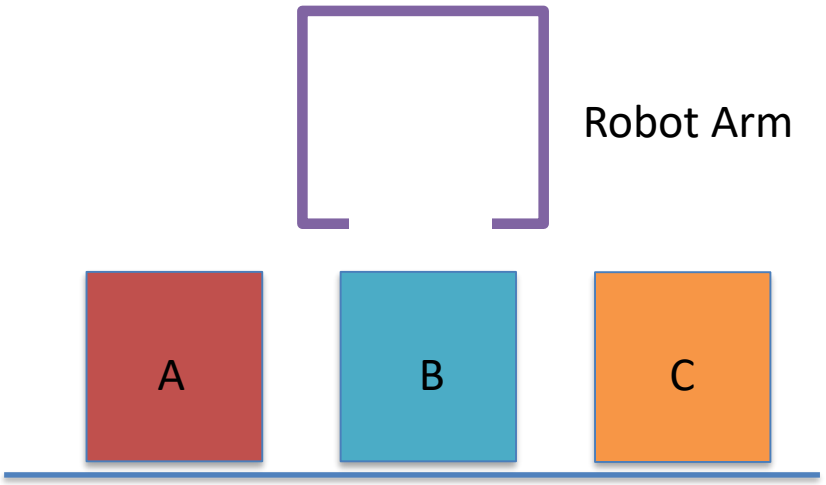


Logical Agents

Create a Knowledge Base

Implications

What are the successor state axioms for A-on-Table[t]?



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Check whether the KB entails a query

- Query – a subset of symbols in model

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Create a Knowledge Base

- Symbols
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Check whether the KB entails a query

- Query – a subset of symbols in model

B-on-C[t] AND C-on-A[t] AND HandEmpty[t]?

Partially-Specified

We didn't tell you what all goal symbols needed to be, only some

There are potentially many goal states that could satisfy this goal

We only need to search for one satisfying assignment of variables

Challenges of Logic Planning

We need symbols for each time step

Easy to incorrectly specify an implication

So many symbols means it is hard to debug

Classical Planning

Also partially-specified

Create a Knowledge Base

~~Symbols~~ Predicates

~~Implications~~ Operators

Check whether the KB entails a query

A goal state (conjunction of predicates)

Predicates

Can be symbols

A-on-Table, A-In-Hand,
B-on-Table, B-In-Hand,
C-on-Table, C-In-Hand,
Hand-Empty,
A-on-B, B-on-A,
A-on-C, C-on-A,
B-on-C, C-on-B
Clear-A, Clear-B,
Clear-C

Predicates

Can be symbols

A-on-Table, A-In-Hand,
B-on-Table, B-In-Hand,
C-on-Table, C-In-Hand,
Hand-Empty,
A-on-B, B-on-A,
A-on-C, C-on-A,
B-on-C, C-on-B
Clear-A, Clear-B,
Clear-C

Can be functional

Instances: A, B, C
Propositions:

- In-Hand(A)
- On-Table(B)
- On-Block(B,C)
- HandEmpty()
- Clear(A)

Predicates

Are there other functions that we could use?

Predicates

Are there other functions that we could use?

YES!!

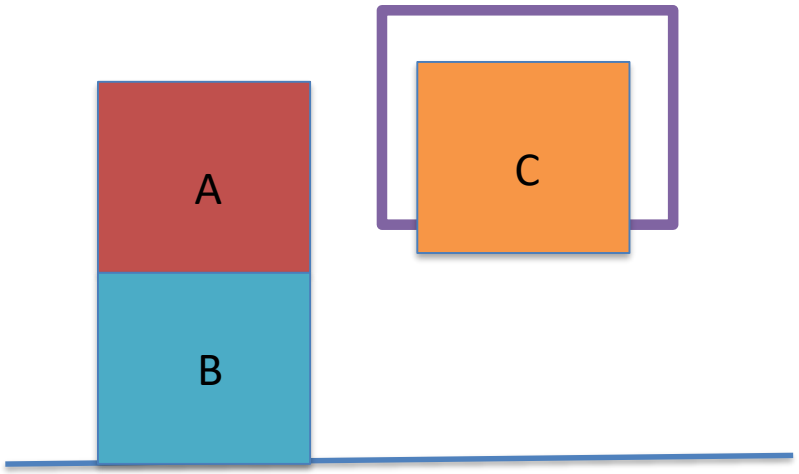
Your challenge is finding a representation that works for your environment

Piazza Poll: Which propositions apply to this state?

Instances: A, B, C

Propositions:

1) In-Hand(A)
2) In-Hand(B)
3) In-Hand(C)
4) On-Table(A)
5) On-Table(B)
6) On-Table(C)
7) On-Block(B,C)
8) On-Block(A,B)
9) HandEmpty()



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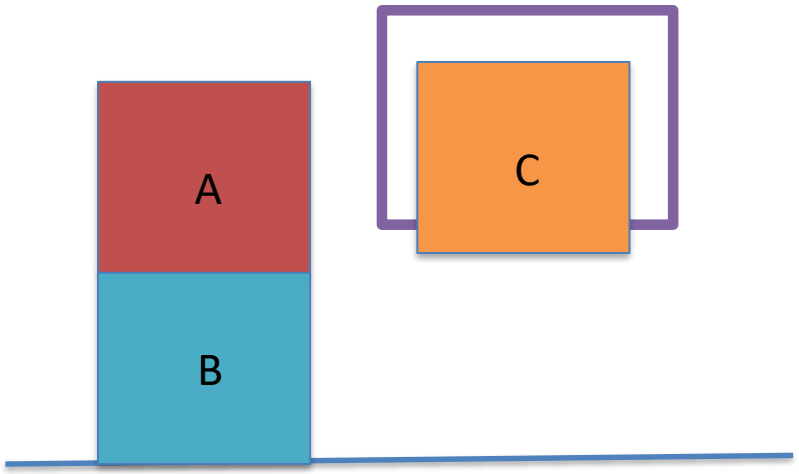
5) On-Table(B)
6) On-Table(C)
7) On-Block(B,C)
8) On-Block(A,B)
9) HandEmpty()



Classical Planning

Also partially-specified

Create a Knowledge Base

~~Symbols~~ Predicates

~~Implications~~ Operators

Check whether the KB entails a query

A goal state (conjunction of predicates)

Models of Operators (Actions)

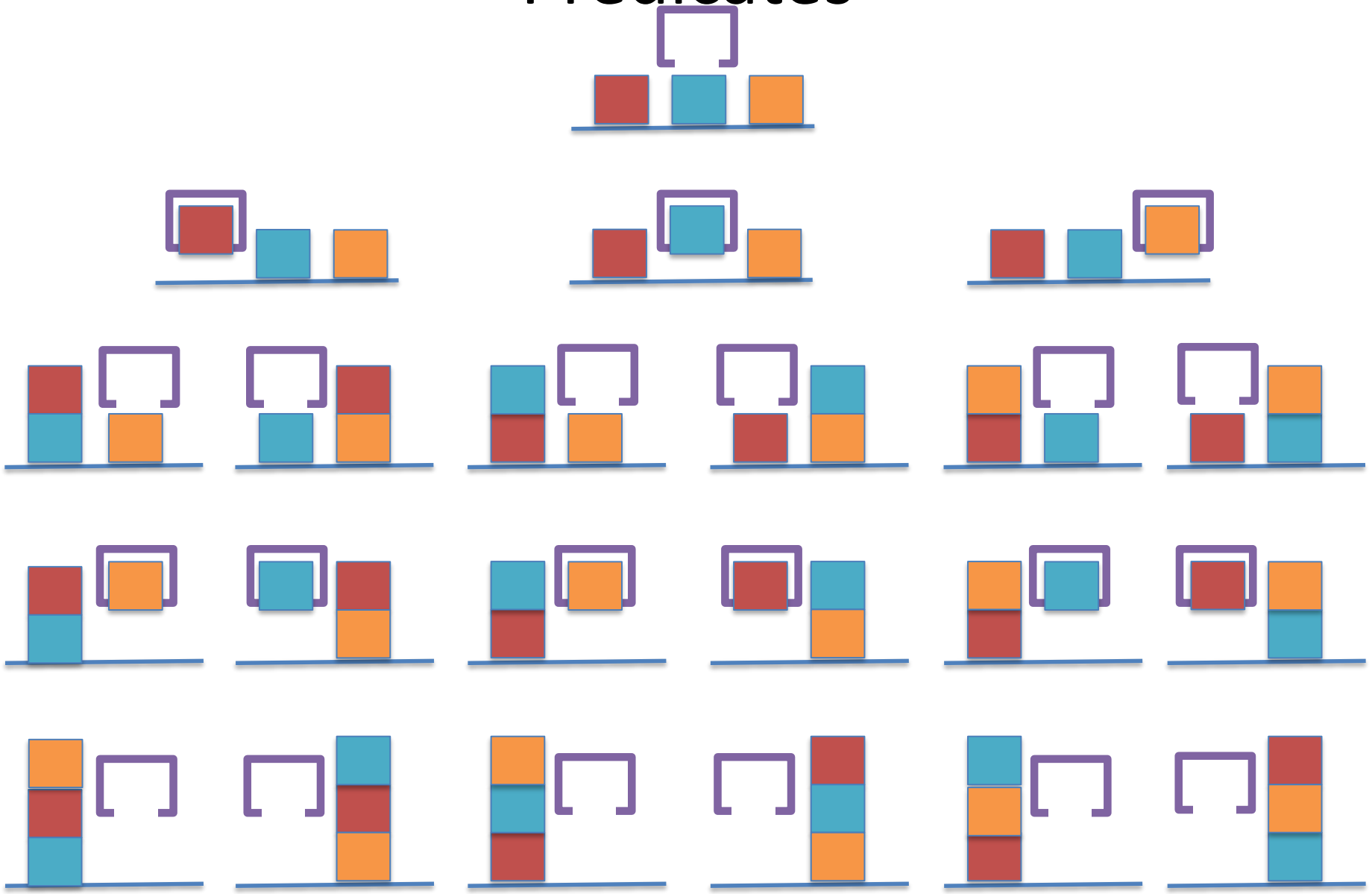
Actions can be applied only if all conditions are met

Actions change the state of the world

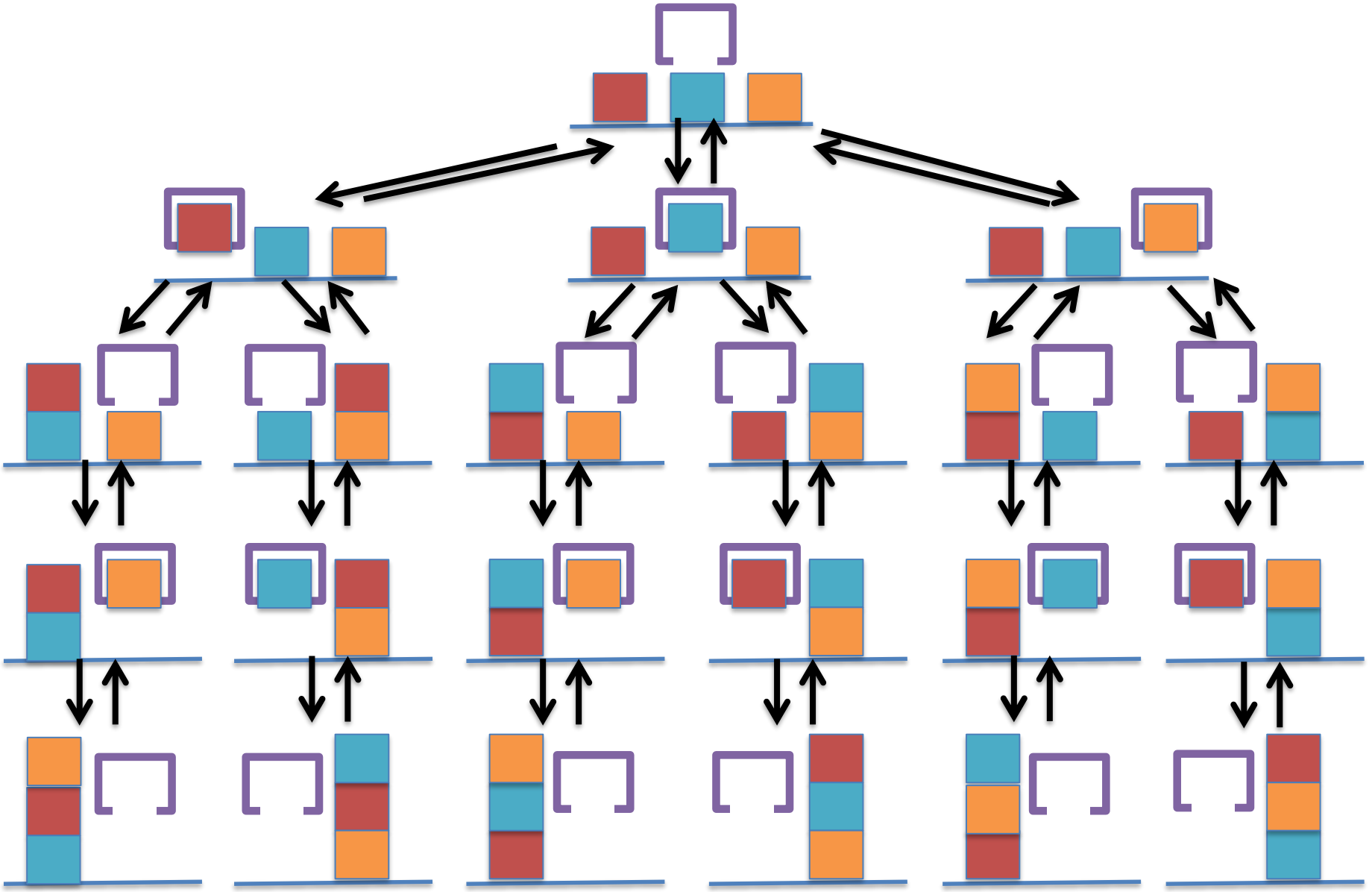
Represented as effects that add/delete predicates

Unlike the implications, we can represent actions with symbolic descriptions (e.g., pick-up, put-down)

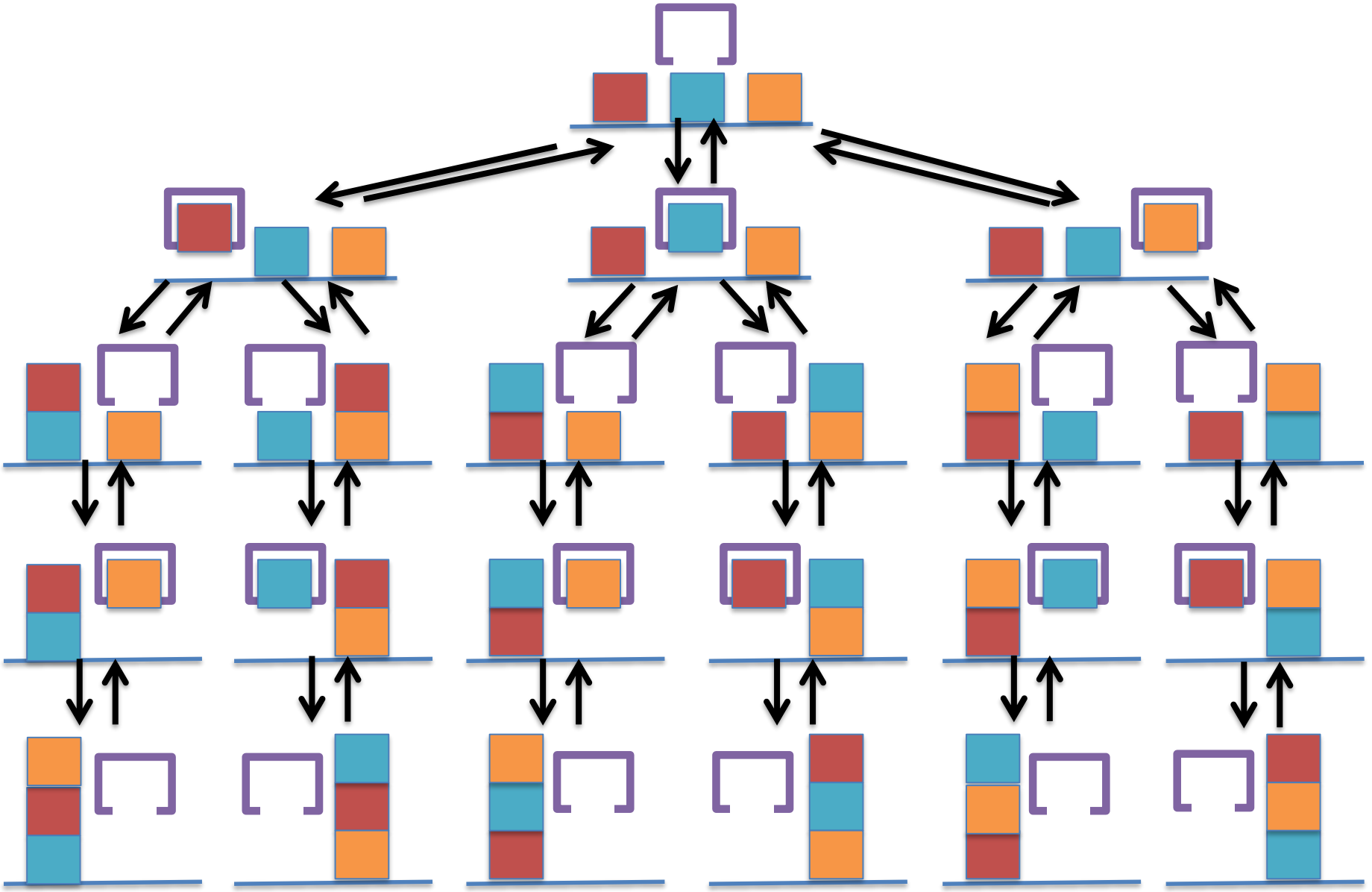
Block Stacking States – Conjunctions of Predicates



Block Stacking Operators (Actions)



What actions are represented?
What are the rules for applying actions?



Actions for Block Stacking

Blocks are picked up and put down by the hand

Blocks can be picked up only if they are clear

Hand can pick up a block only if the hand is empty

Hand can put down blocks on blocks or on the table

Pick Up Block from Table Example

Preconditions

Pick Up Block from Table Example

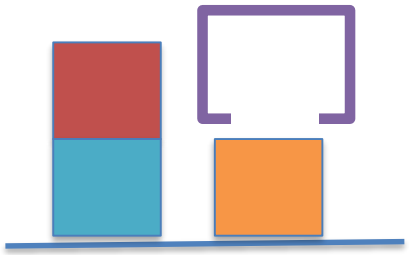
Preconditions

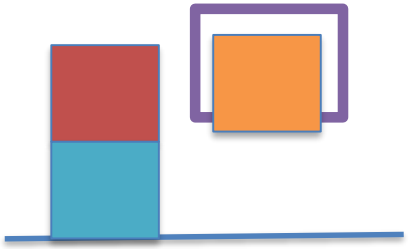
HandEmpty

On-Table(b)

Clear(b)

Pick Up Block from Table Example





Preconditions

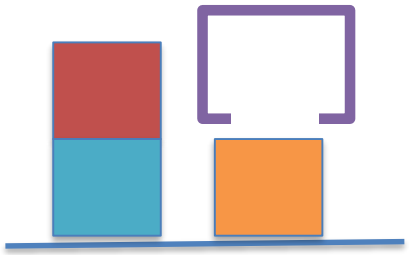
HandEmpty

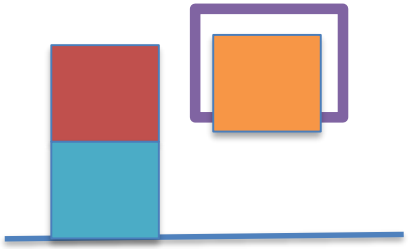
On-Table(b)

Clear(b)

Effects?

Pick Up Block from Table Example





Preconditions

HandEmpty

On-Table(b)

Clear(b)

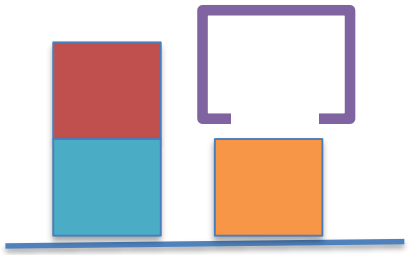
Effects

Add: Holding(b)

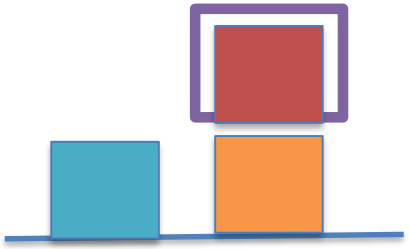
Delete: On-Table(b)

HandEmpty

Pick Block from Block Example



Preconditions



Effects

Operators for Block Stacking

Pickup_from_Table(b):

Pre: HandEmpty, Clear(b),
On-Table(b)

Add: Holding(b)

Delete: HandEmpty, On-Table(b)

Pickup_from_Block(b,c):

Pre: HandEmpty, On(b,c), b!=c

Add: Holding(b), Clear(c)

Delete: HandEmpty, On(b,c)

Operators for Block Stacking

Pickup_from_Table(b):

Pre: HandEmpty, Clear(b), On-Table(b)

Add: Holding(b)

Delete: HandEmpty, On-Table(b)

Putdown_on_Table(b):

Pre: Holding(b)

Add: HandEmpty, On-Table(b)

Delete: Holding(b)

Pickup_from_Block(b,c):

Pre: HandEmpty, On(b,c), b!=c

Add: Holding(b), Clear(c)

Delete: HandEmpty, On(b,c)

Putdown_on_Block(b,c):

Pre: Holding(b), Clear(c)

Add: HandEmpty, On(b,c)

Delete: Clear(c), Holding(b)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(b,c):

Pre: HandEmpty, On(b,c), b!=c

Add: Holding(b), Clear(c)

Delete: HandEmpty, On(b,c)

Pickup_from_Table(b):

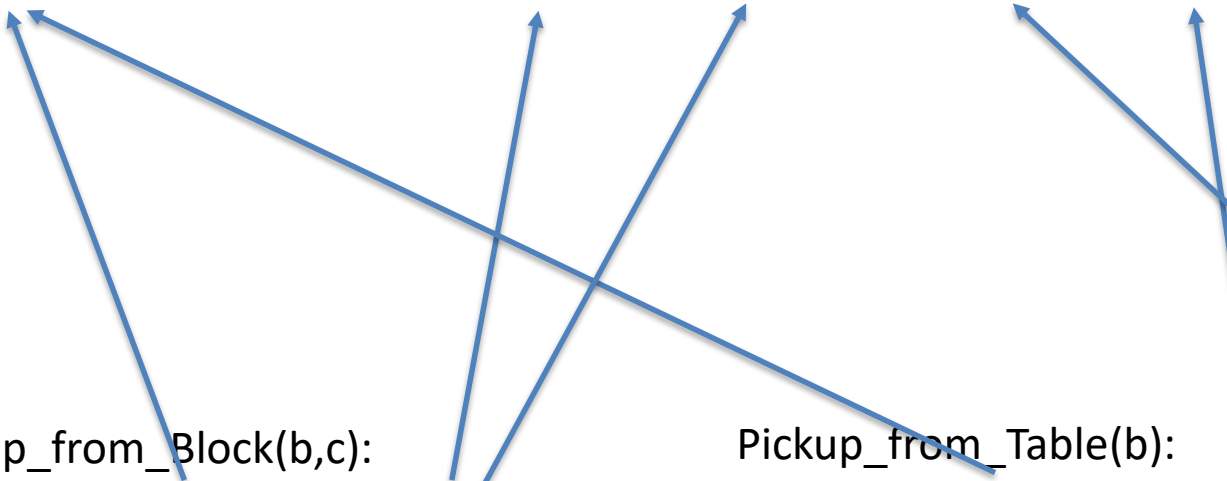
Pre: HandEmpty, Clear(b), On-Table(b)

Add: Holding(b)

Delete: HandEmpty, On-Table(b)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)



Pickup_from_Block(b,c):

Pre: HandEmpty, On(b,c), b!=c

Add: Holding(b), Clear(c)

Delete: HandEmpty, On(b,c)

Pickup_from_Table(b):

Pre: HandEmpty, Clear(b), On-Table(b)

Add: Holding(b)

Delete: HandEmpty, On-Table(b)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(T,R)

Pickup_from_Block(b,c):

Pre: HandEmpty, On(b,c), Clear(c), b!=c

Add: Holding(b), Clear(c)

Delete: HandEmpty, On(b,c)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(T,R)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(b,c):

Pre: HandEmpty, On(b,c), Clear(c), b!=c

Add: Holding(b), Clear(c)

Delete: HandEmpty, On(b,c)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(T,R)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Holding(T) & Clear(R)

Pickup_from_Block(b,c):

Pre: HandEmpty, On(b,c), Clear(c), b!=c

Add: Holding(b), Clear(c)

Delete: HandEmpty, On(b,c)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(T,R)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Holding(T) & Clear(R)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(T,R)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Holding(T) & Clear(R)

Putdown_on_Table(T)

Putdown_on_Table(b):

Pre: Holding(b)

Add: HandEmpty, On-Table(b)

Delete: Holding(b)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(T,R)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Holding(T) & Clear(R)

Putdown_on_Table(T)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Clear(R)

Putdown_on_Table(b):

Pre: Holding(b)

Add: HandEmpty, On-Table(b)

Delete: Holding(b)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(T,R)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Holding(T) & Clear(R)

Putdown_on_Table(T)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Clear(R) & HandEmpty & On-Table(T)

Putdown_on_Table(b):

Pre: Holding(b)

Add: HandEmpty, On-Table(b)

Delete: Holding(b)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(T,R)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Holding(T) & Clear(R)

Putdown_on_Table(T)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Clear(R) & HandEmpty & On-Table(T)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(T,R)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Holding(T) & Clear(R)

Putdown_on_Table(T)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Clear(R) & HandEmpty & On-Table(T)

Pickup_from_Table(O)

Pickup_from_Table(b):

Pre: HandEmpty, Clear(b), On-Table(b)

Add: Holding(b)

Delete: HandEmpty, On-Table(b)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(T,R)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Holding(T) & Clear(R)

Putdown_on_Table(T)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Clear(R) & HandEmpty & On-Table(T)

Pickup_from_Table(O)

On-Table(R) & Clear(T) & Clear(O) & Clear(R) & On-Table(T) & Holding(O)

Pickup_from_Table(b):

Pre: HandEmpty, Clear(b), On-Table(b)

Add: Holding(b)

Delete: HandEmpty, On-Table(b)

Example Plan of Actions

HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

Pickup_from_Block(T,R)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Holding(T) & Clear(R)

Putdown_on_Table(T)

On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Clear(R) & HandEmpty & On-Table(T)

Pickup_from_Table(O)

On-Table(R) & Clear(T) & Clear(O) & Clear(R) & On-Table(T) & Holding(O)

Putdown_on_Block(O,R)

On-Table(R) & Clear(T) & Clear(O) & On-Table(T) & On(O,R) & HandEmpty

Properties of Planners

Soundness

- A planning algorithm is ***sound*** if all solutions found are legal plans
  - All preconditions and goals are satisfied
  - No constraints are violated (temporal, variable binding)

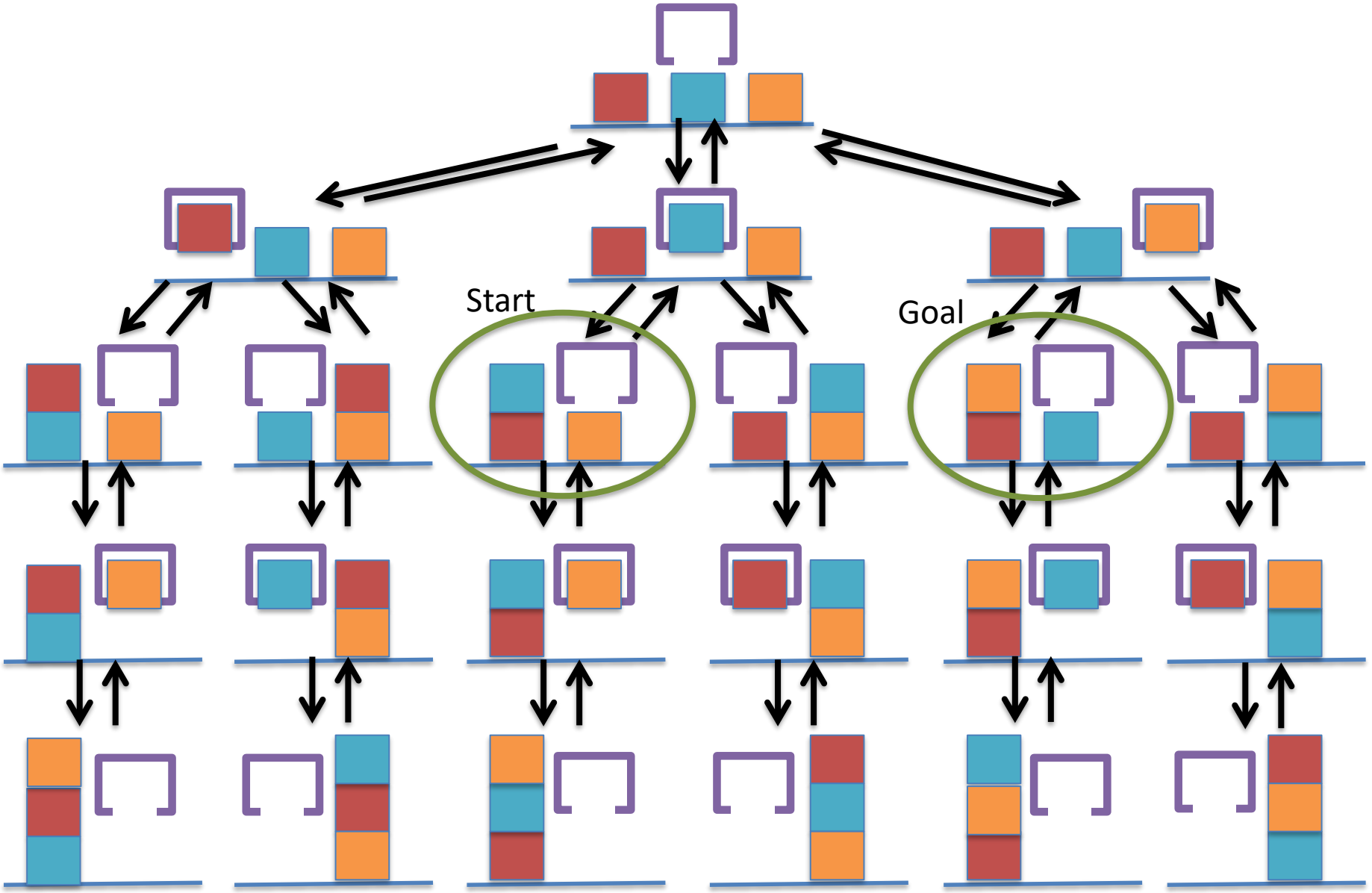
Completeness

- A planning algorithm is ***complete*** if a solution can be found whenever one actually exists
- A planning algorithm is ***strictly complete*** if all solutions are included in the search space

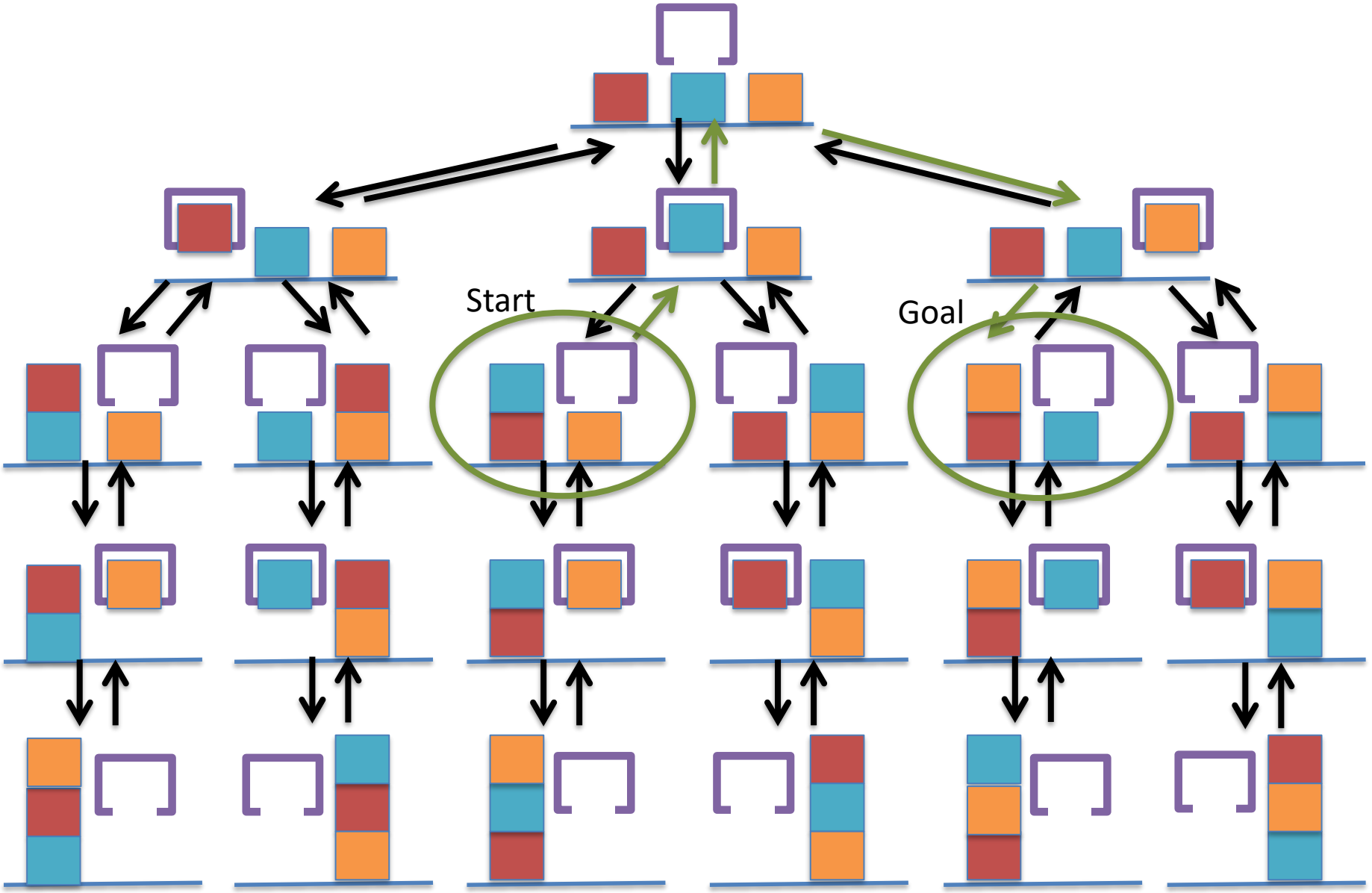
Optimality

- A planning algorithm is ***optimal*** if the order in which solutions are found is consistent with some measure of plan quality

Techniques for Planning



BFS – Find shortest action sequence



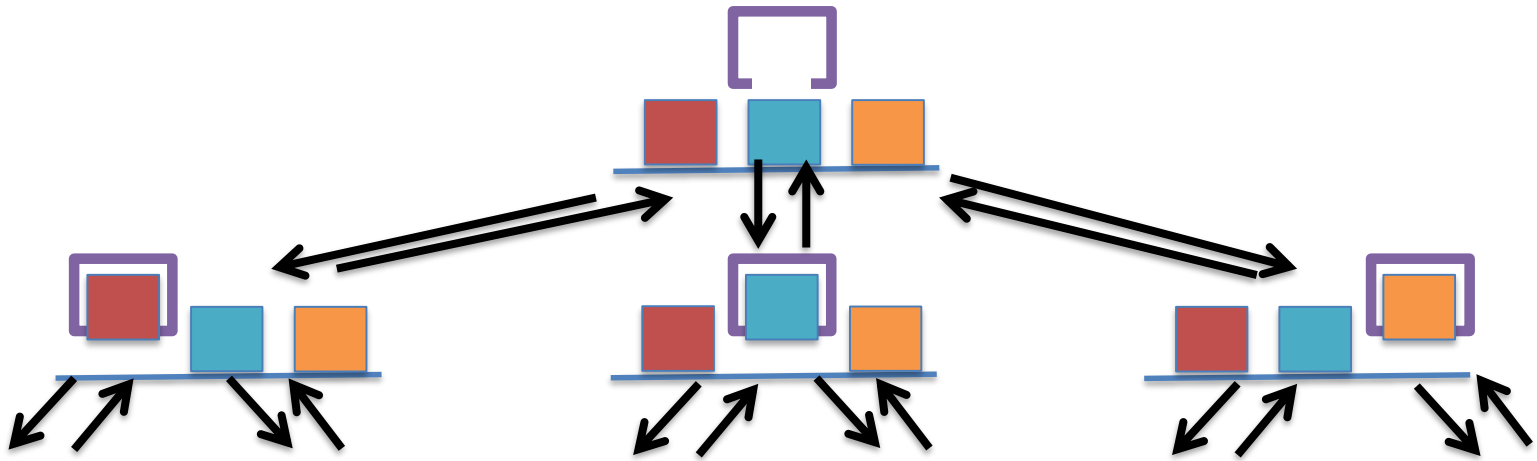
Reachability Graph Representation

States: Conjunctions of Predicates

Arrows = Actions

Every state in level K is *reachable* in K actions

Space complexity in terms of # predicates p?



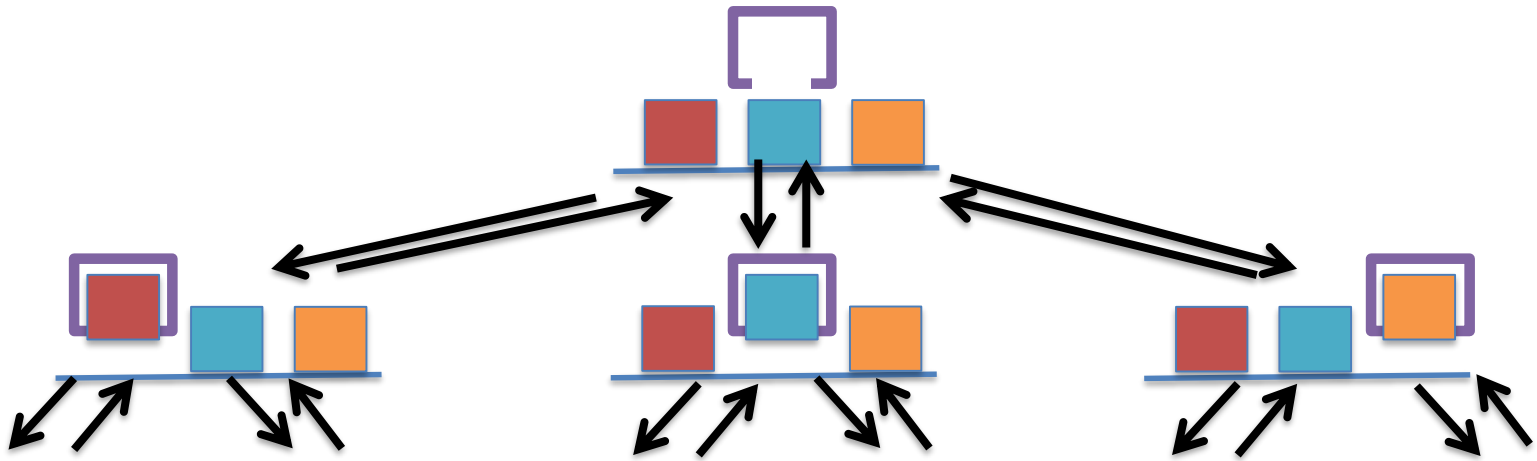
Reachability Graph Representation

States: Conjunctions of Predicates

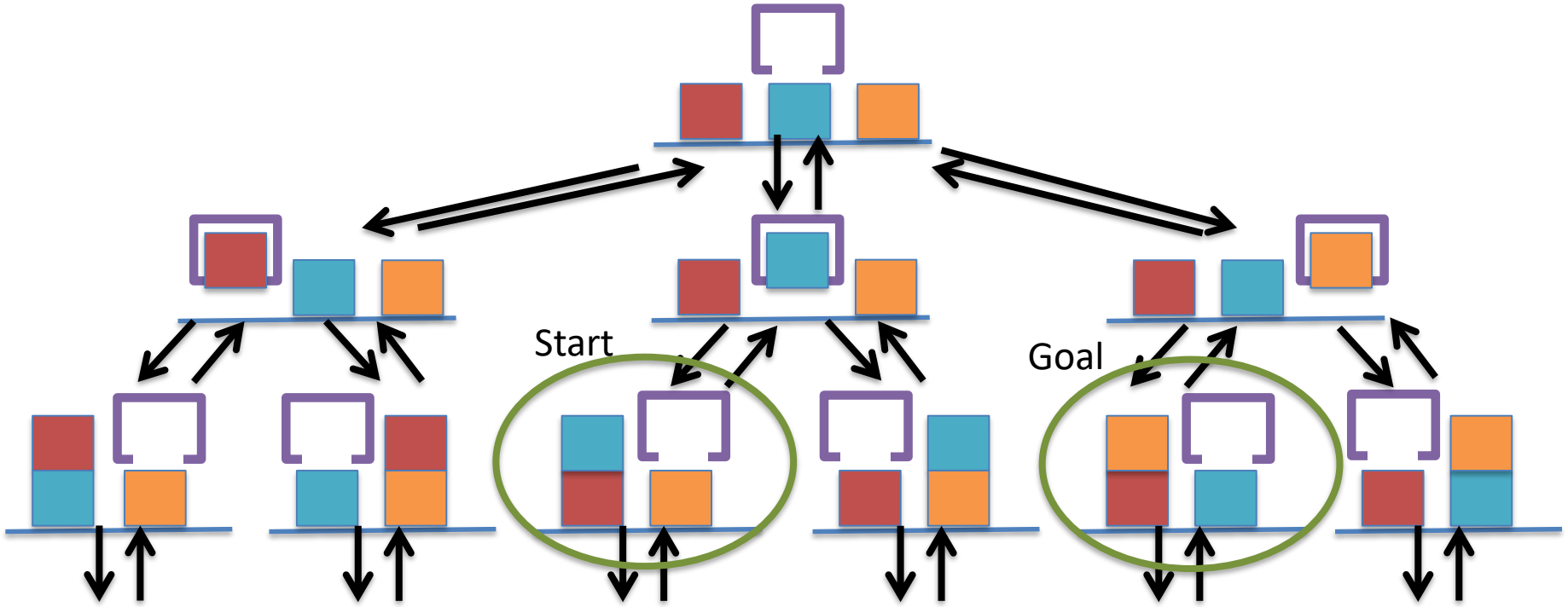
Arrows = Actions

Every state in level K is *reachable* in K actions

Space complexity in terms of # predicates? 2^p



Poll: Is BFS sound, complete, optimal?



Soundness - all solutions found are legal plans

Completeness - a solution can be found whenever one actually exists

Optimality - the order in which solutions are found is consistent with some measure of plan quality

Linear Planning

Idea: Since we have a conjunction of goal predicates, let's try to solve one at a time

- Maintain a stack of achievable goals
- Use BFS (or anything else) to find a plan to achieve that single goal
- Add a goal back on the stack if a later change makes it violated

Linear Planning Example

Goal Stack:
On-Table(T)
On-Table(R)
On(O,R)
Clear(O)
Clear(T)

Action Plan:

Linear Planning Example

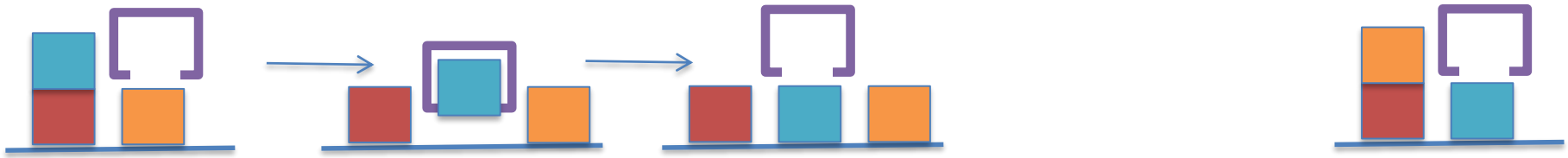
Goal Stack:
On-Table(T)
On-Table(R)
On(O,R)
Clear(O)
Clear(T)

Action Plan:

Linear Planning Example

Goal Stack:
On-Table(R)
On(O,R)
Clear(O)
Clear(T)

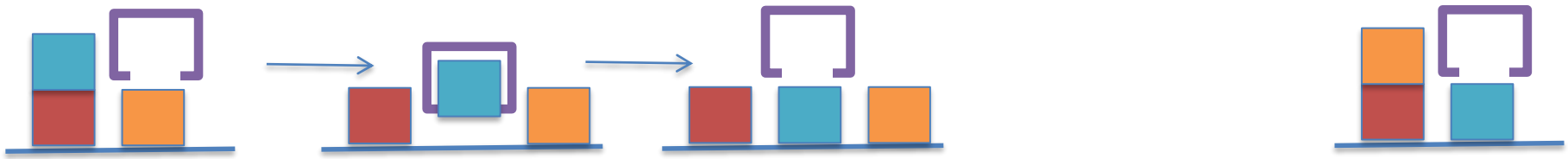
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)



Linear Planning Example

Goal Stack:
On-Table(R)
On(O,R)
Clear(O)
Clear(T)

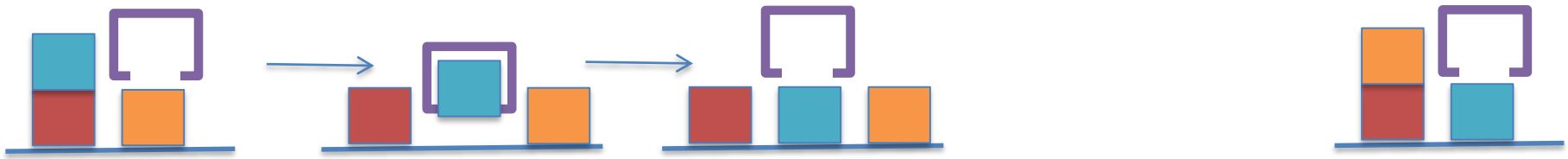
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)



Linear Planning Example

Goal Stack:
On(O,R)
Clear(O)
Clear(T)

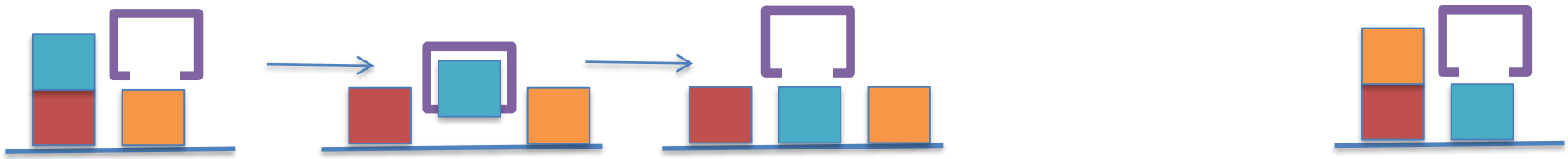
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)
On-Table(R)



Linear Planning Example

Goal Stack:
On(O,R)
Clear(O)
Clear(T)

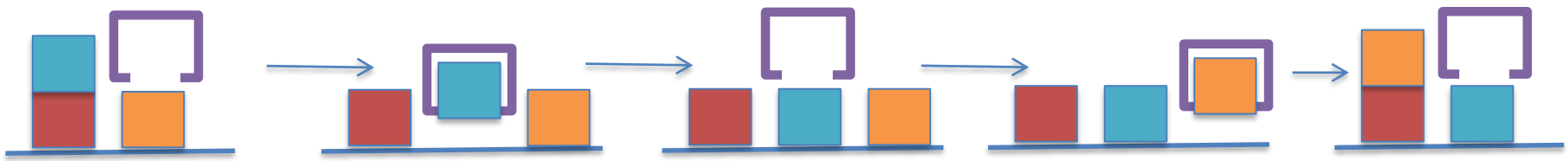
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)
On-Table(R)



Linear Planning Example

Goal Stack:
Clear(O)
Clear(T)

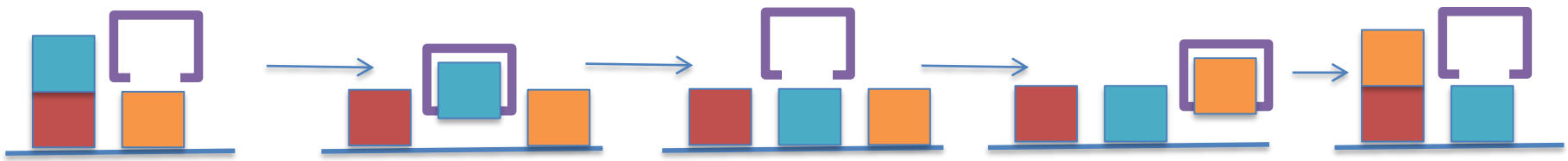
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)
On-Table(R)
On(O,R)
    Pickup(O)
    Put(O,R)



Linear Planning Example

Goal Stack:
Clear(O)
Clear(T)

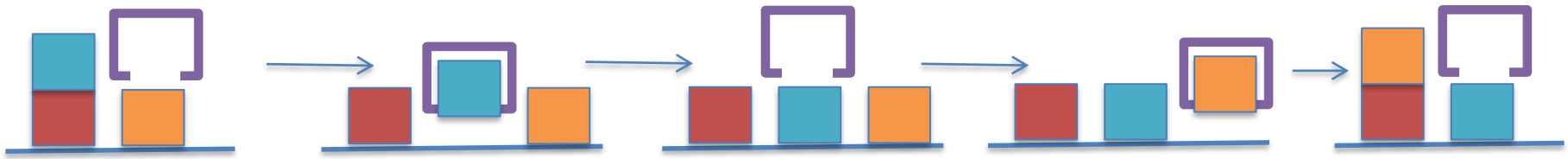
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)
On-Table(R)
On(O,R)
    Pickup(O)
    Put(O,R)



Linear Planning Example

Goal Stack:

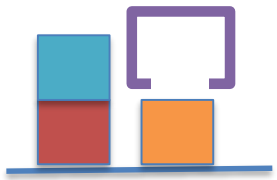
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)
On-Table(R)
On(O,R)
    Pickup(O)
    Put(O,R)
Clear(O)
Clear(T)

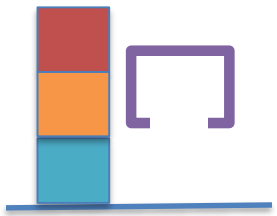


Linear Planning Example 2

Goal Stack:
On(R,O)
On-Table(T)
On(O,T)
Clear(R)

Action Plan:

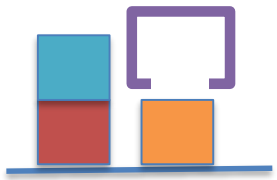




Linear Planning Example 2

Goal Stack:
On(R,O)
On-Table(T)
On(O,T)
Clear(R)

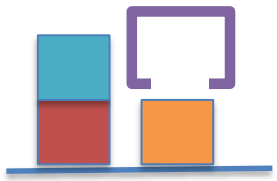
Action Plan:

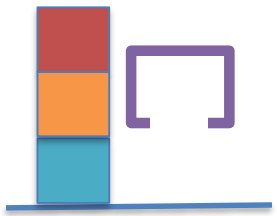


Linear Planning Example 2

Goal Stack:
On-Table(T)
On(O,T)
Clear(R)

Action Plan:
On(R,O)
- Pickup(T)
- Put-Table(T)
- Pickup(R)
- Put(R,O)

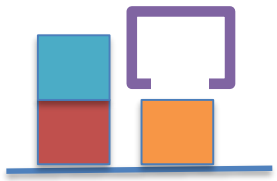




Linear Planning Example 2

Goal Stack:
On-Table(T)
On(O,T)
Clear(R)

Action Plan:
On(R,O)
- Pickup(T)
- Put-Table(T)
- Pickup(R)
- Put(R,O)

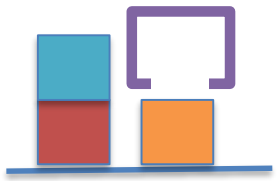


Linear Planning Example 2

Goal Stack:
On(O,T)
Clear(R)

Action Plan:
On(R,O)
- Pickup(T)
- Put-Table(T)
- Pickup(R)
- Put(R,O)

On-Table(T)

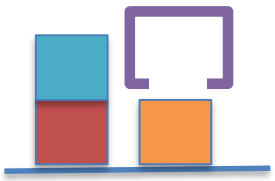


Linear Planning Example 2

Goal Stack:
On(O,T)
Clear(R)

Action Plan:
On(R,O)
- Pickup(T)
- Put-Table(T)
- Pickup(R)
- Put(R,O)

On-Table(T)

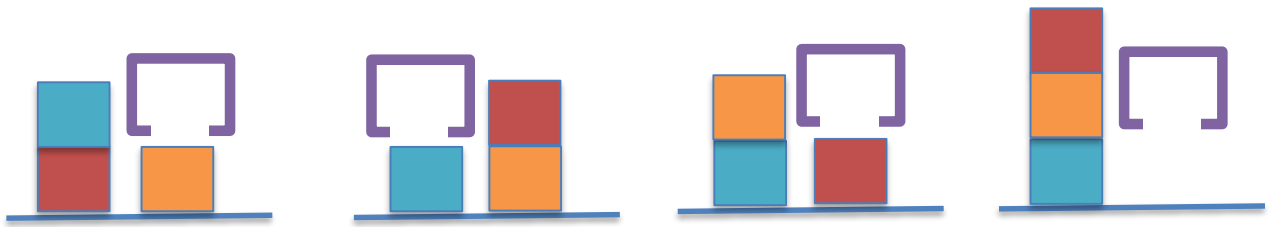


Linear Planning Example 2

Goal Stack:
Clear(R)

Action Plan:
On(R,O)
- Pickup(T)
- Put-Table(T)
- Pickup(R)
- Put(R,O)

On-Table(T)
On(O,T)
- Pickup(R)
- Put-Table(R)
- Pickup(O)
- Put(O,T)

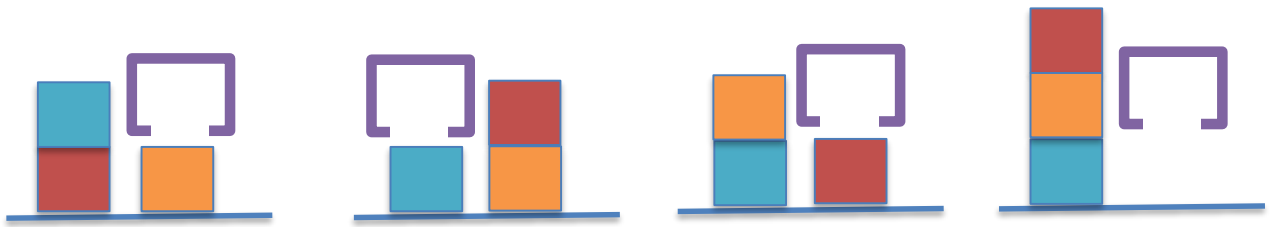


Linear Planning Example 2

Goal Stack:
On(R,O)
Clear(R)

Action Plan:
On(R,O)
- Pickup(T)
- Put-Table(T)
- Pickup(R)
- Put(R,O)

On-Table(T)
On(O,T)
- Pickup(R)
- Put-Table(R)
- Pickup(O)
- Put(O,T)



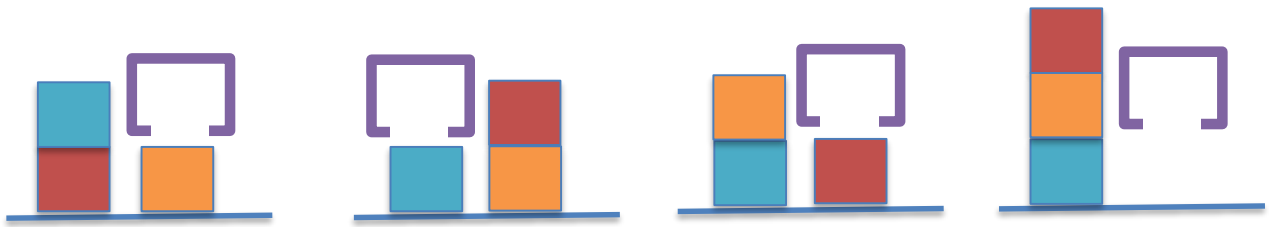
Linear Planning Example 2

Goal Stack:
Clear(R)

Action Plan:
On(R,O)
- Pickup(T)
- Put-Table(T)
- Pickup(R)
- Put(R,O)

On-Table(T)
On(O,T)
- Pickup(R)
- Put-Table(R)
- Pickup(O)
- Put(O,T)

Action Plan (cont'd):
On(R,O)
- Pickup(R)
- Put(R,O)



Linear Planning Example 2

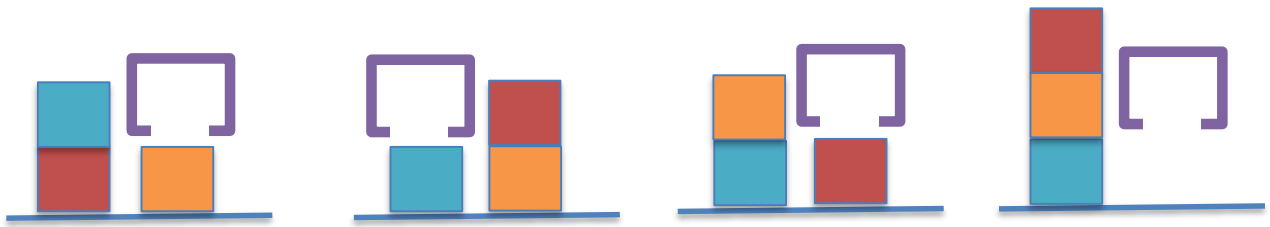
Goal Stack:

Action Plan:
On(R,O)
- Pickup(T)
- Put-Table(T)
- Pickup(R)
- Put(R,O)

On-Table(T)
On(O,T)
- Pickup(R)
- Put-Table(R)
- Pickup(O)
- Put(O,T)

Action Plan (cont'd):
On(R,O)
- Pickup(R)
- Put(R,O)

Clear(R)



Linear Planning Example 2

Goal Stack:

Action Plan:
On(R,O)
- Pickup(T)
- Put-Table(T)
- Pickup(R)
- Put(R,O)

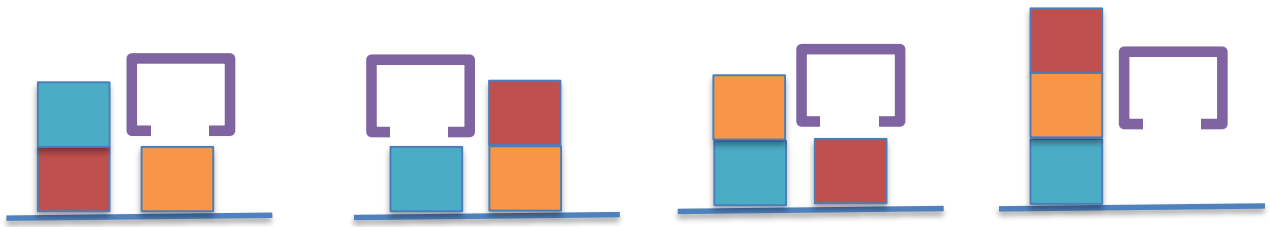
On-Table(T)
On(O,T)
- Pickup(R)
- Put-Table(R)
- Pickup(O)
- Put(O,T)

Action Plan (cont'd):
On(R,O)
- Pickup(R)
- Put(R,O)

Clear(R)

What happened?

Is linear planning sound?
Is linear planning complete?
Is linear planning optimal?



Sussman's Anomaly

A weakness of linear planning is that sometimes you get really long plans

One goal can be achieved

The second goal immediately undoes it

Note: This isn't just a choice of goals. The anomaly happens no matter which goal is first

Linear Planning Example 2

Goal Stack:

Action Plan:
On(R,O)
- Pickup(T)
- Put-Table(T)
- Pickup(R)
- Put(R,O)

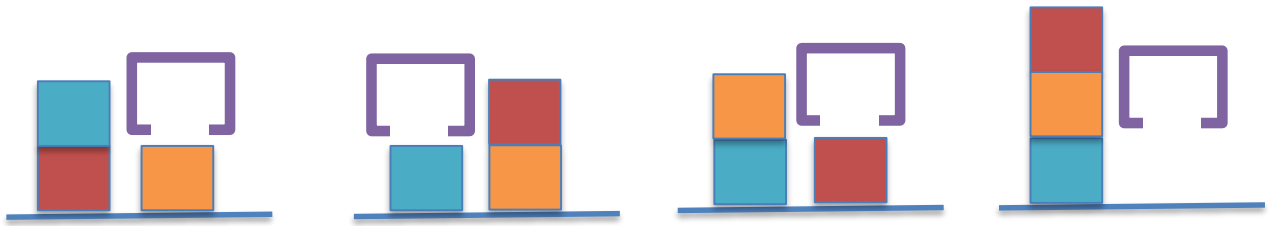
On-Table(T)
On(O,T)
- Pickup(R)
- Put-Table(R)
- Pickup(O)
- Put(O,T)

Action Plan (cont'd):
On(R,O)
- Pickup(R)
- Put(R,O)

Clear(R)

What happened?

Is linear planning sound? Yes
Is linear planning complete? No
Is linear planning optimal? No



Non-Linear Planning

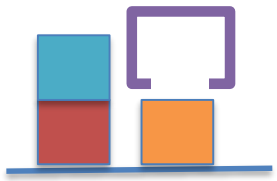
Idea: Interleave goals to achieve plans

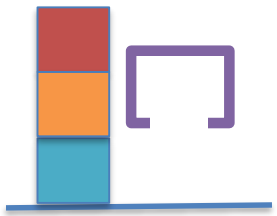
- Maintain a set of unachieved goals
- Search all interleavings of goals
- Add a goal back to the set if a later change makes it violated

Non-Linear Planning (Example 2)

Goal Set:
On(R,O)
On-Table(T)
On(O,T)
Clear(R)

Action Plan:

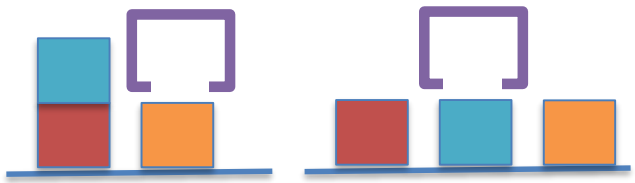




Non-Linear Planning (Example 2)

Goal Set:
On(R,O)
On-Table(T)
On(O,T)
Clear(R)

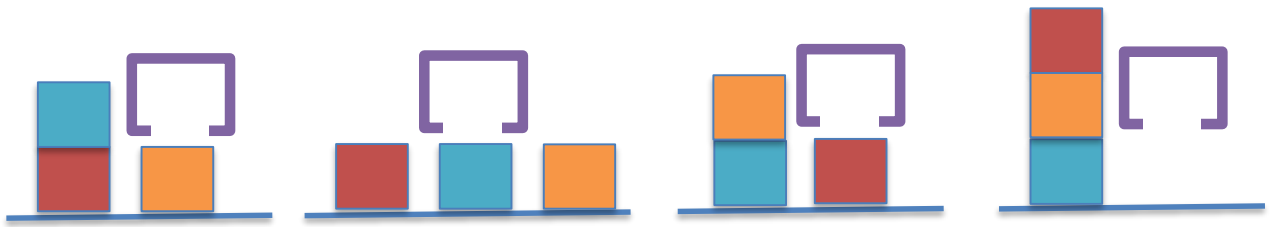
Action Plan:
On(R,O)
Pickup(T)
Put-Table(T)
STOP-SWITCH-GOALS



Non-Linear Planning (Example 2)

Goal Set:
On(R,O)
On-Table(T)
On(O,T)
Clear(R)

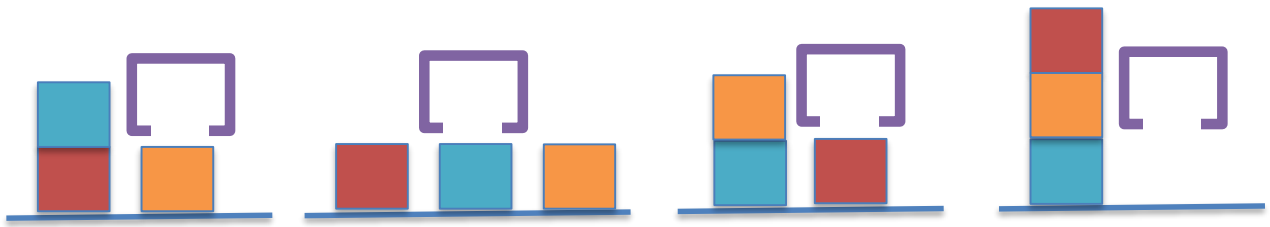
Action Plan:
On(R,O)
    Pickup(T)
    Put-Table(T)
  STOP-SWITCH-GOALS
On(O,T)
    Pickup(O)
    Put(O,T)



Non-Linear Planning (Example 2)

Goal Set:
On(R,O)
On-Table(T)
On(O,T)
Clear(R)

Action Plan:
On(R,O)
    Pickup(T)
    Put-Table(T)
  STOP-SWITCH-GOALS
On(O,T)
    Pickup(O)
    Put(O,T)
On(R,O)
    Pickup(R)
    Put(R,O)



Non-Linear Planning (Example 2)

Goal Set:
On(R,O)
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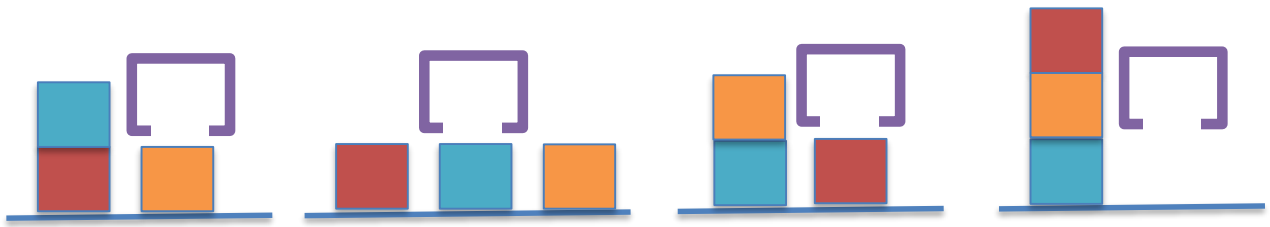
Action Plan:
On(R,O)
    Pickup(T)
    Put-Table(T)
  STOP-SWITCH-GOALS
On(O,T)
    Pickup(O)
    Put(O,T)
On(R,O)
    Pickup(R)
    Put(R,O)

6 vs 10 actions



Non-Linear Planning

Idea: Interleave goals to achieve plans

- Maintain a set of unachieved goals
- Search all interleavings of goals
- Add a goal back to the set if a later change makes it violated
- It is complete, but takes longer to search
- It can produce shorter plans
  - Optimal plans if all interleavings are searched

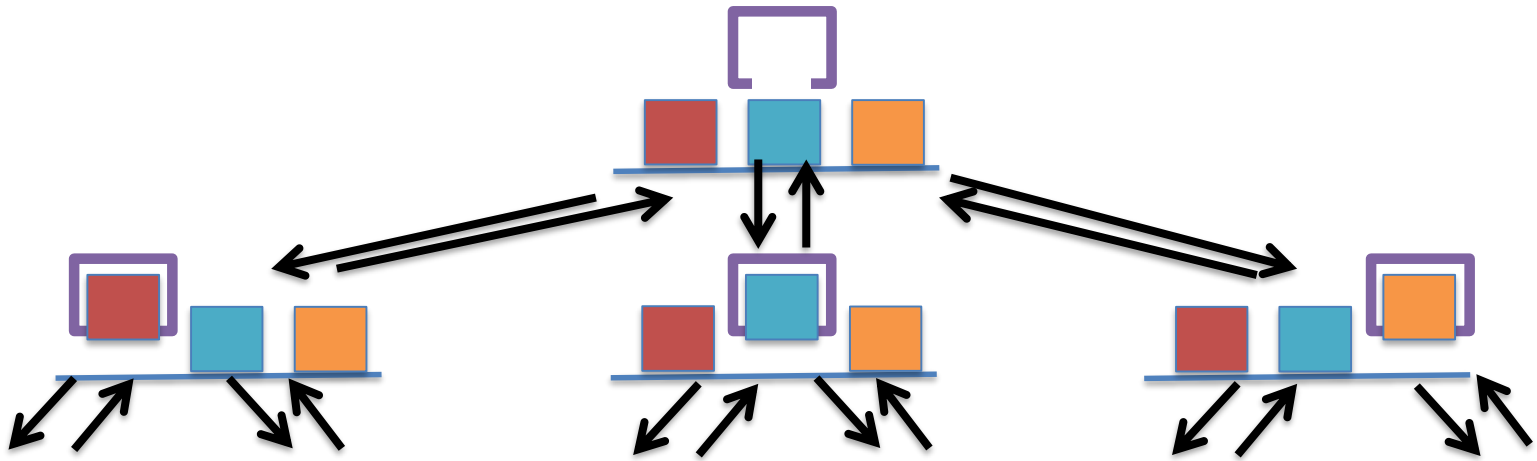
Reachability Graph Representation

States: Conjunctions of Predicates

Arrows = Actions

Every state in level K is *reachable* in K actions

Space complexity in terms of # predicates p?



Planning Graph Representation

Key idea: Construct an approximation of the reachability graph in polynomial space

- The planning graph computes the **possibly reachable** states although they aren't necessarily **feasible**

Planning Graph Representation

Key idea: Construct an approximation of the reachability graph in polynomial space

- The planning graph computes the **possibly reachable** states although they aren't necessarily **feasible**

Planning graphs contain two types of layers

Proposition layers – all reachable predicates

Action layers – actions that could be taken

Both layers represent one time step

GraphPlan

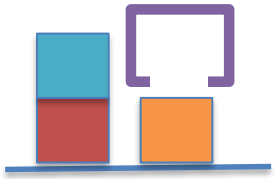
Two alternating stages:

- **Extend**: One time step (two layers) in the planning graph
- **Search**: Find a valid plan in the planning graph

GraphPlan finds a plan or proves that no plan has fewer time steps

- Each time step can contain multiple actions

Building a Planning Graph



Start the planning graph with all starting predicates

HandEmpty

On-Table(R)

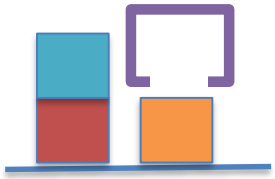
On-Table(O)

On(T,R)

Clear(T)

Clear(O)

Building a Planning Graph



Extend the graph with all applicable actions

Designate all effects (add/delete)

HandEmpty

On-Table(R)

On-Table(O)

On(T,R)

Clear(T)

Clear(O)

Pickup(T)

Pickup(O)

HandEmpty

On-Table(R)

On-Table(O)

On(T,R)

Clear(T)

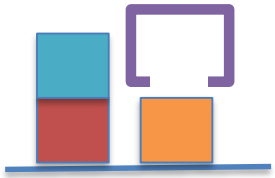
Clear(O)

Clear(R)

Holding(T)

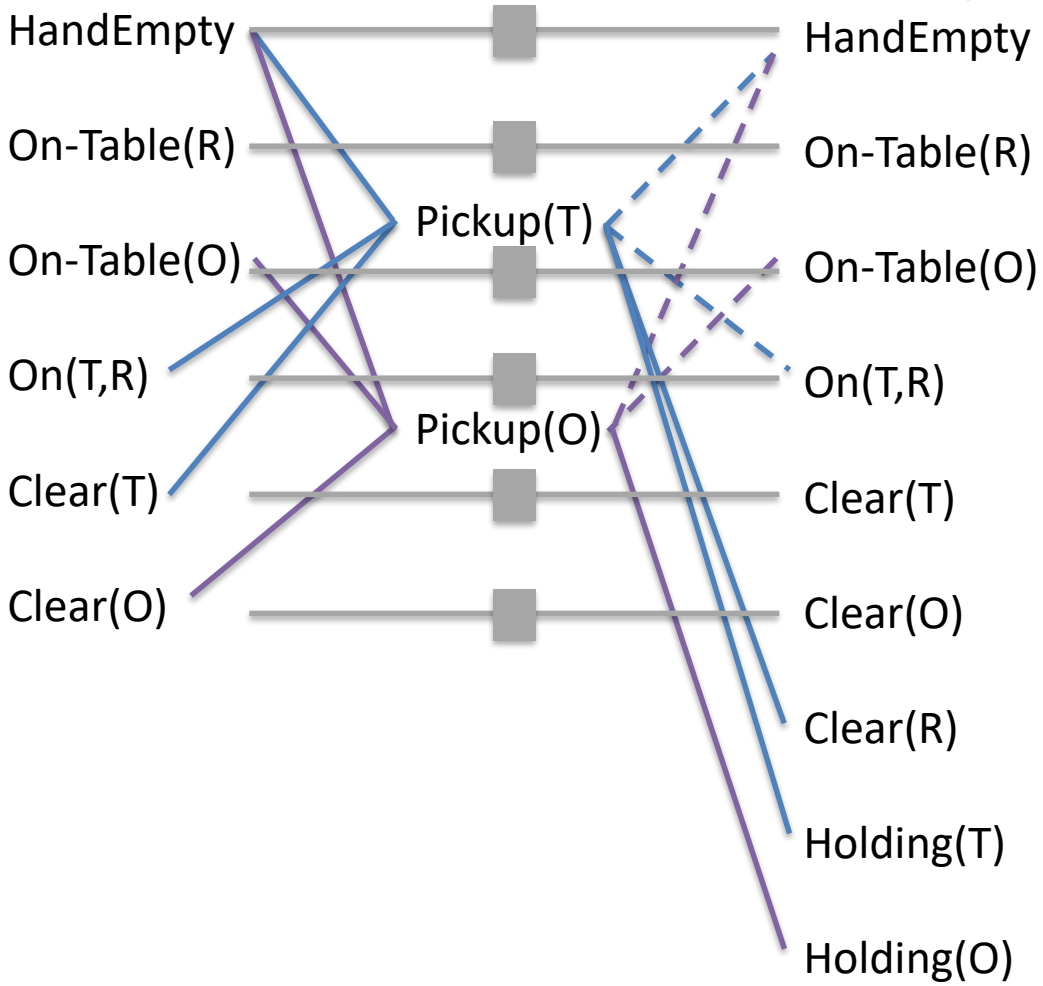
Holding(O)

Building a Planning Graph



Extend the graph with all applicable actions, noops

Designate all effects (add/delete)



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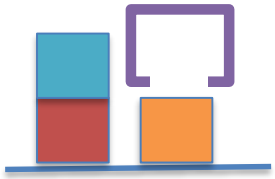
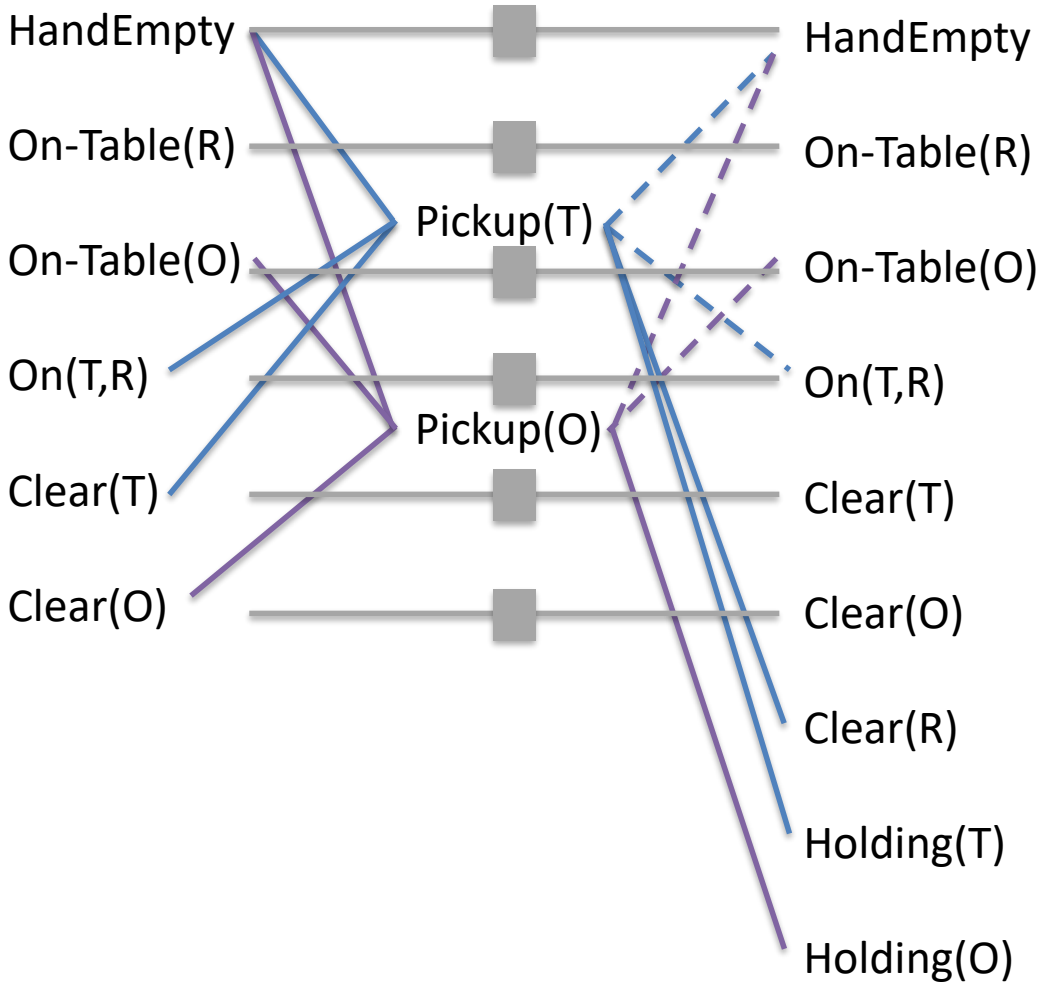


Extend the graph

Determine exclusive actions



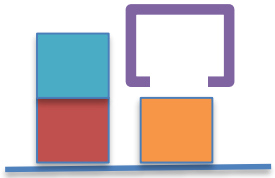
Actions A and B are ***exclusive (mutex)*** at action-level *i*, if:

Interference: one action deletes a precondition of the other

Inconsistency: one action is the negation of the other

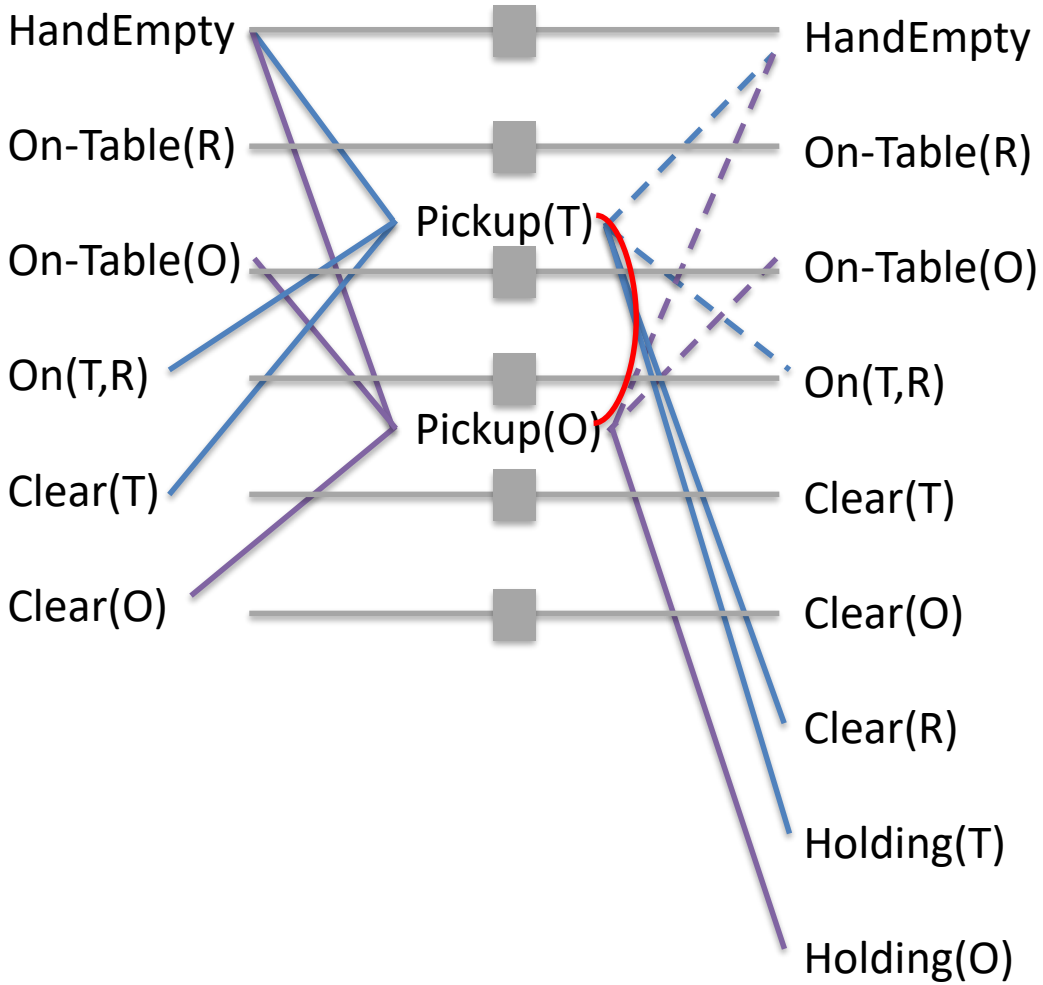
Competing Needs: *p* is a precondition of A and *q* is a precondition of B, and *p* and *q* are exclusive in proposition-level *i* – 1

Building a Planning Graph



Extend the graph with all applicable actions, noops

Determine exclusive actions



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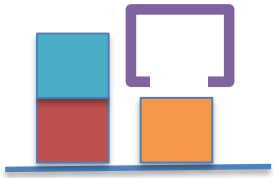
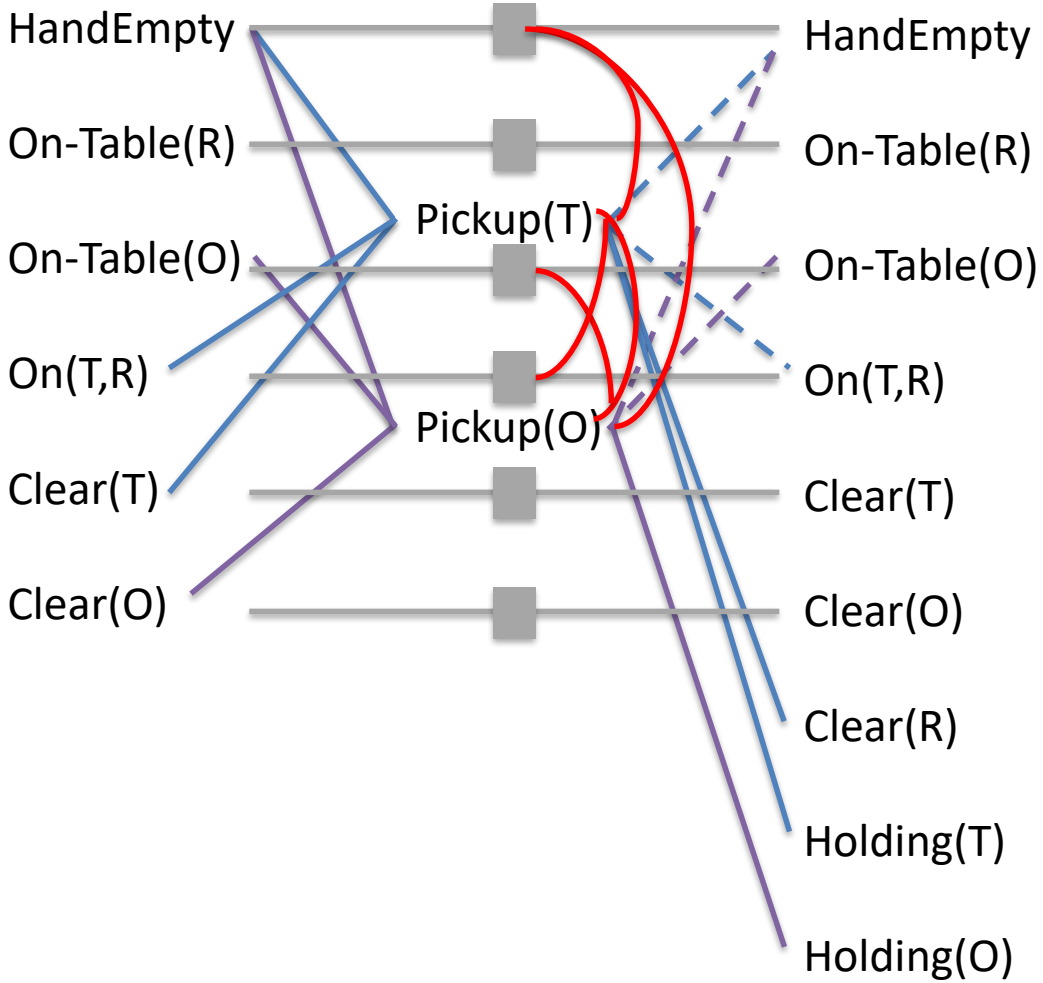
Building a Planning Graph



Extend the graph with all applicable actions, noops

Determine exclusive actions



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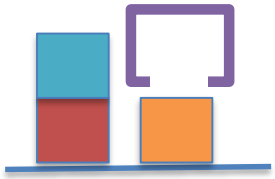
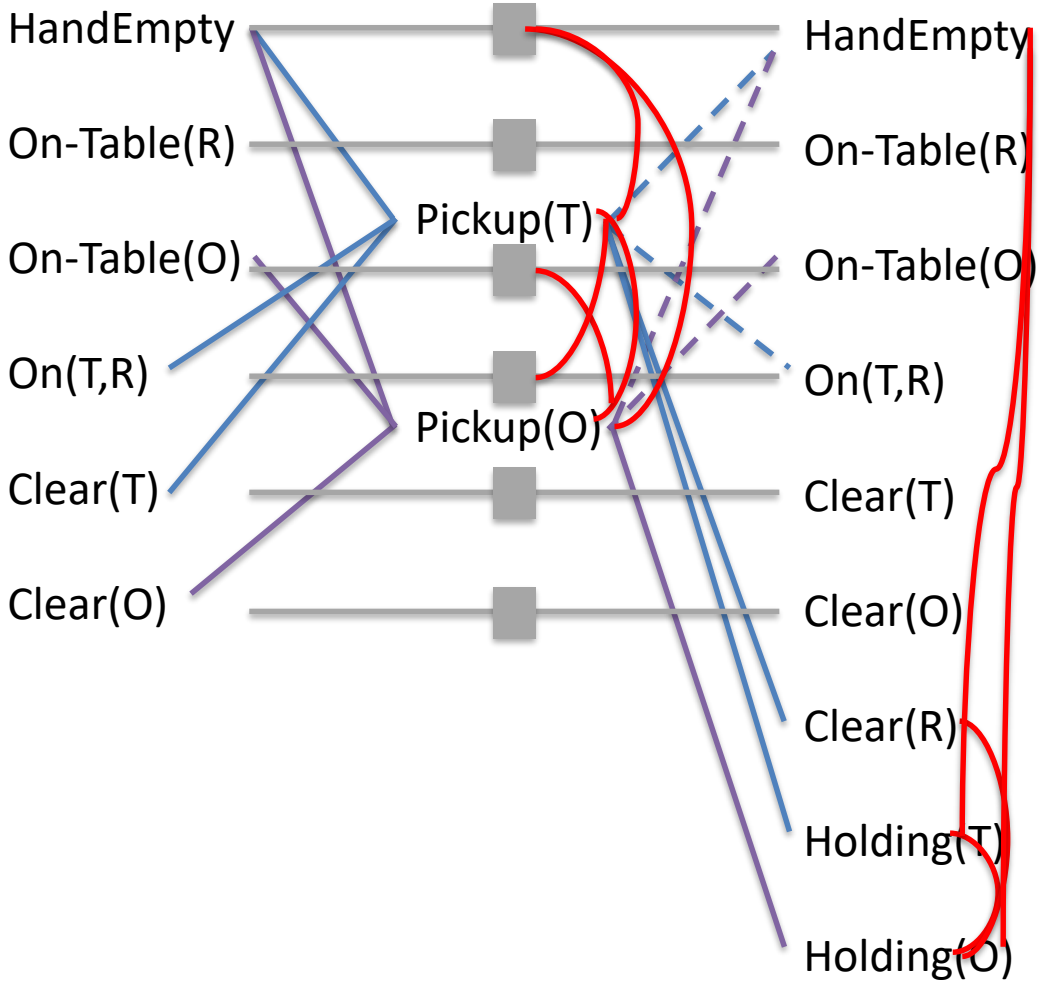
Building a Planning Graph



Extend the graph with all applicable actions, noops

Determine exclusive actions, propositions



Two propositions *p* and *q* are **exclusive (mutex)** at a proposition-level if ALL actions (including no-ops) that add *p* are exclusive of ALL actions that add *q*

Search the Planning Graph

Extend until first time all goals are present at a proposition level

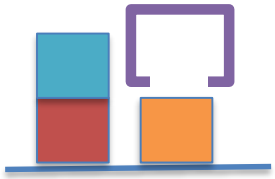
- May not be a solution, at that level

For each goal at level *i* (in some arbitrary order)

- Select an action at level *i*-1 that achieves that goal and is not exclusive with any other action already selected at that level
- Add all its preconditions to the set of goals at level *i-2*
- Do this for all the goals at level *i*
  - Use already selected actions, when possible
- Backtrack if no non-exclusive action exists

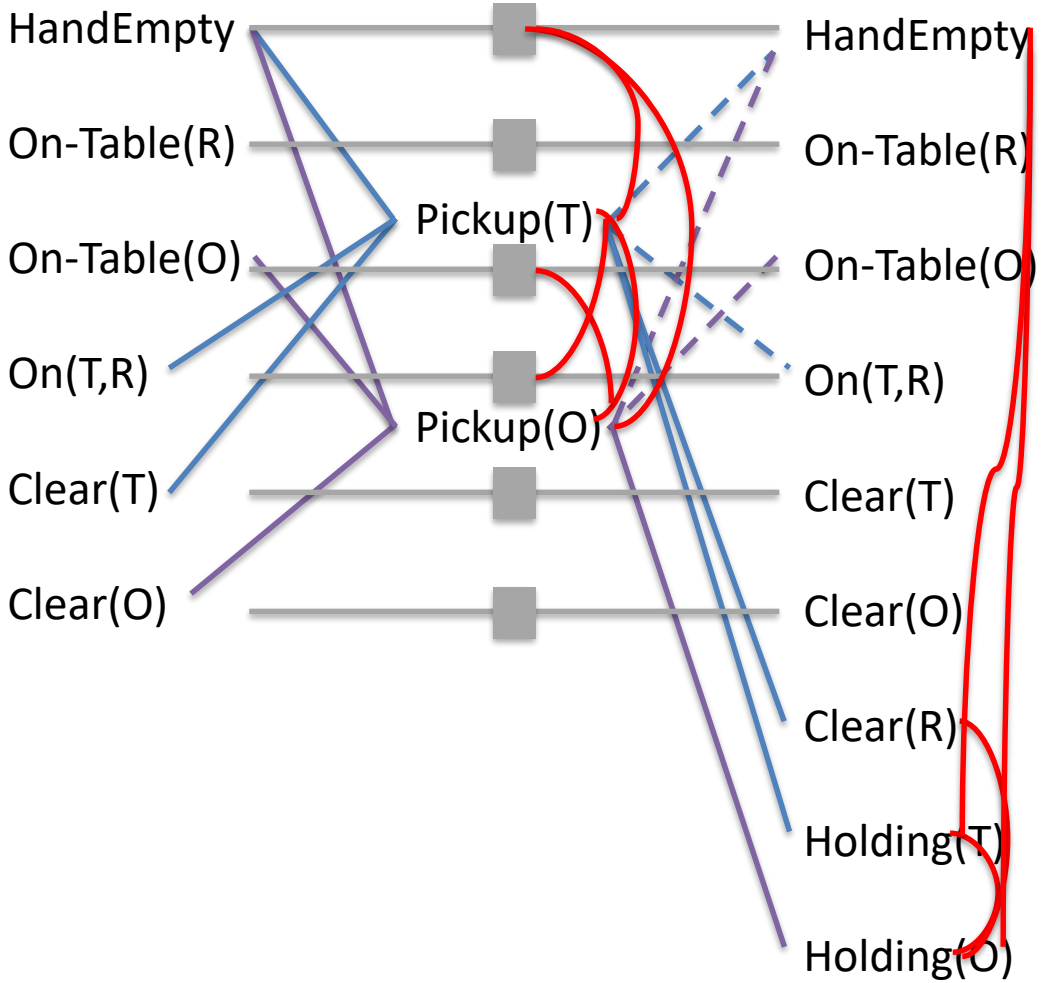
If search is exhausted, extend planning graph one more proposition level

Extend a Level

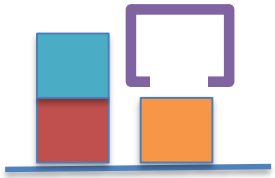


Extend the graph with all applicable actions, noops

Determine exclusive actions, propositions

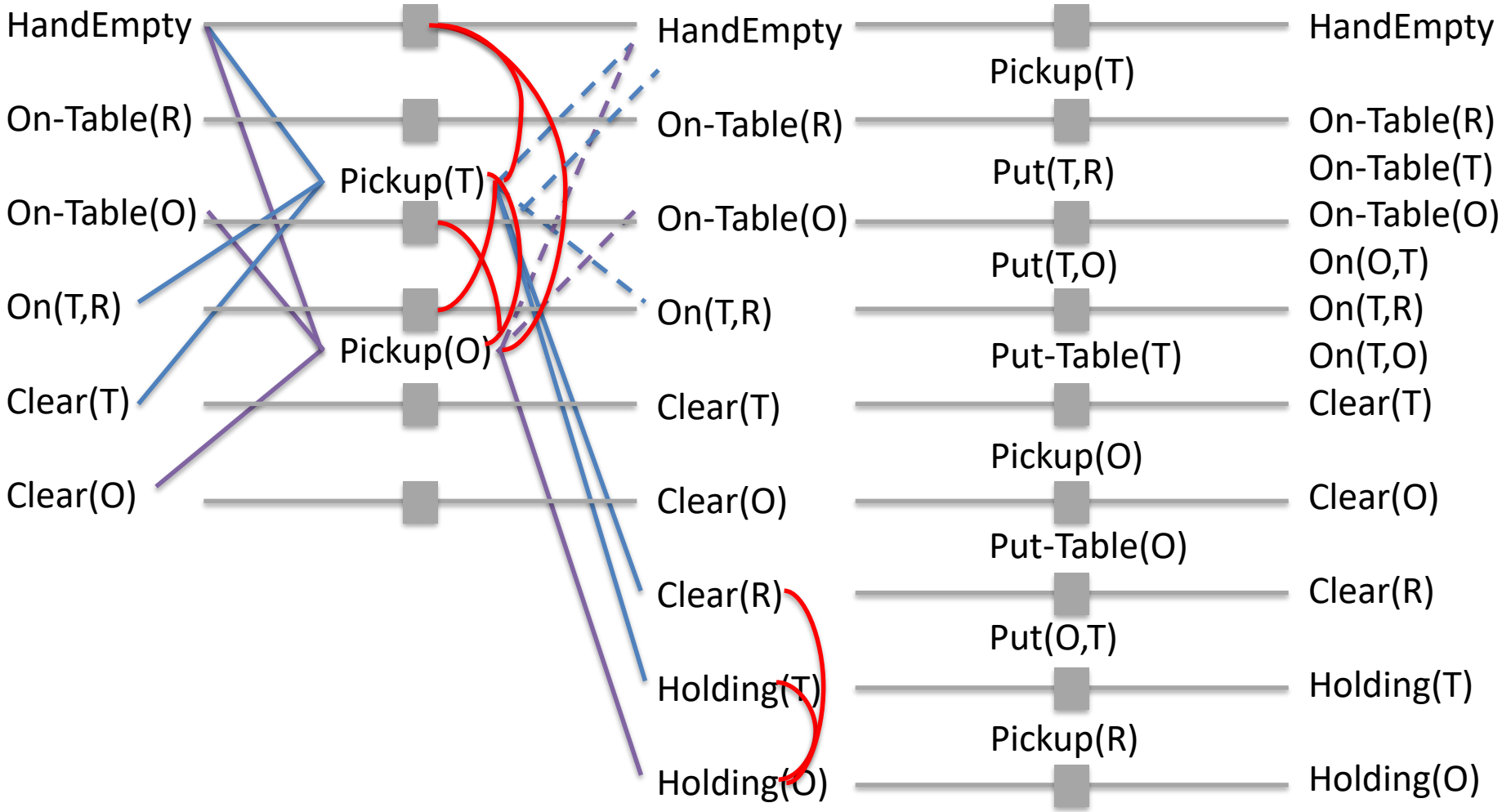


Building a Planning Graph



Extend the graph with all applicable actions, noops

Determine exclusive actions, propositions



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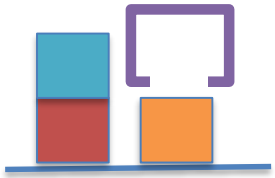

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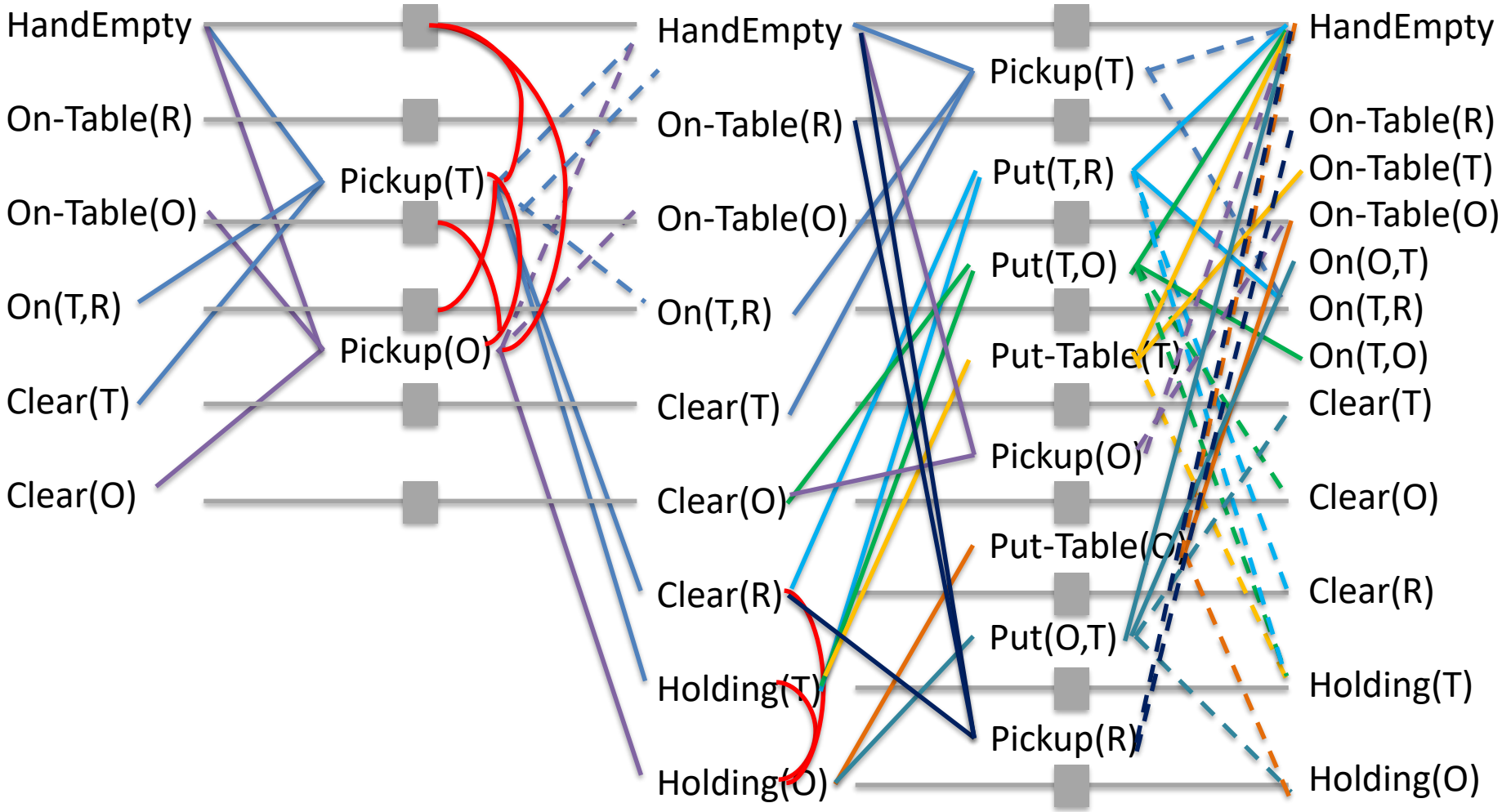
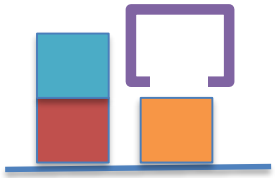
Determine exclusive actions, propositions

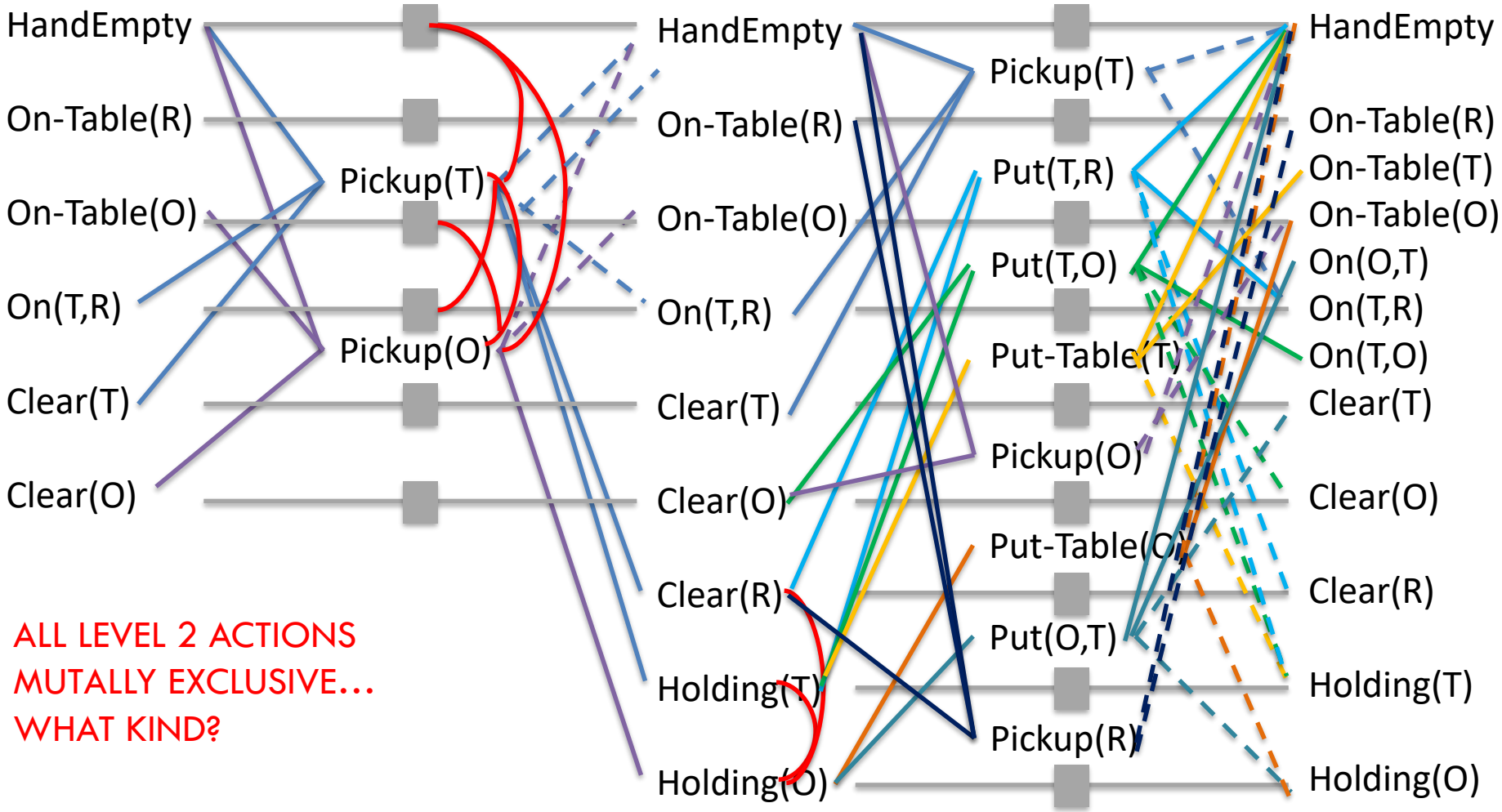


Building a Planning Graph



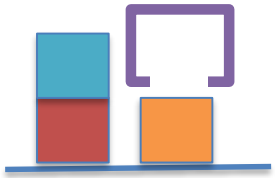
Extend the graph with all applicable actions, noops

Determine exclusive actions, propositions



ALL LEVEL 2 ACTIONS MUTALLY EXCLUSIVE… WHAT KIND?

Building a Planning Graph



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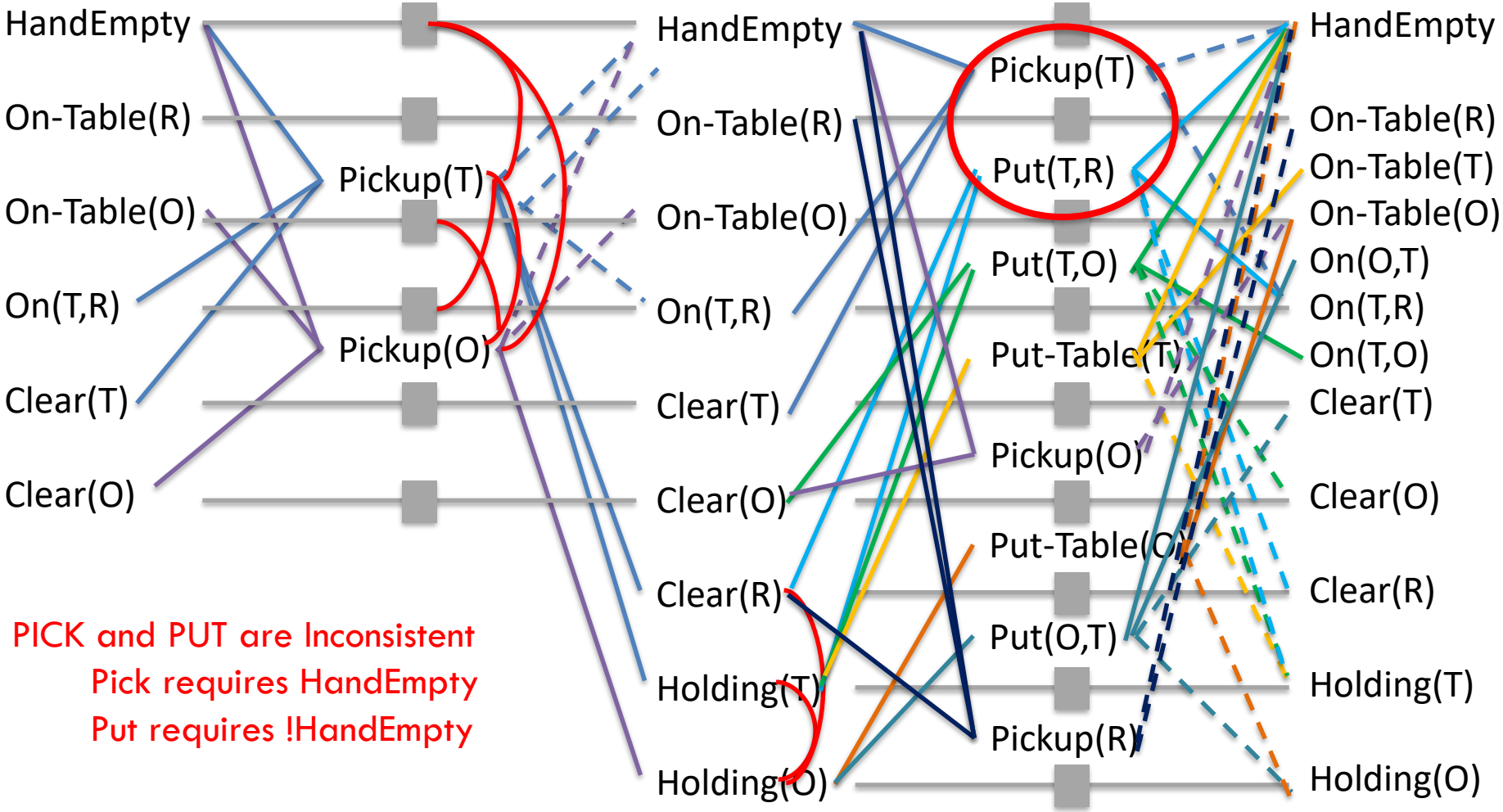
Determine exclusive actions, propositions

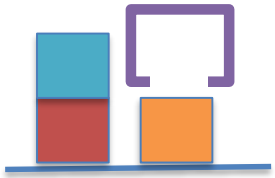


PICK and PUT are Inconsistent

Pick requires HandEmpty

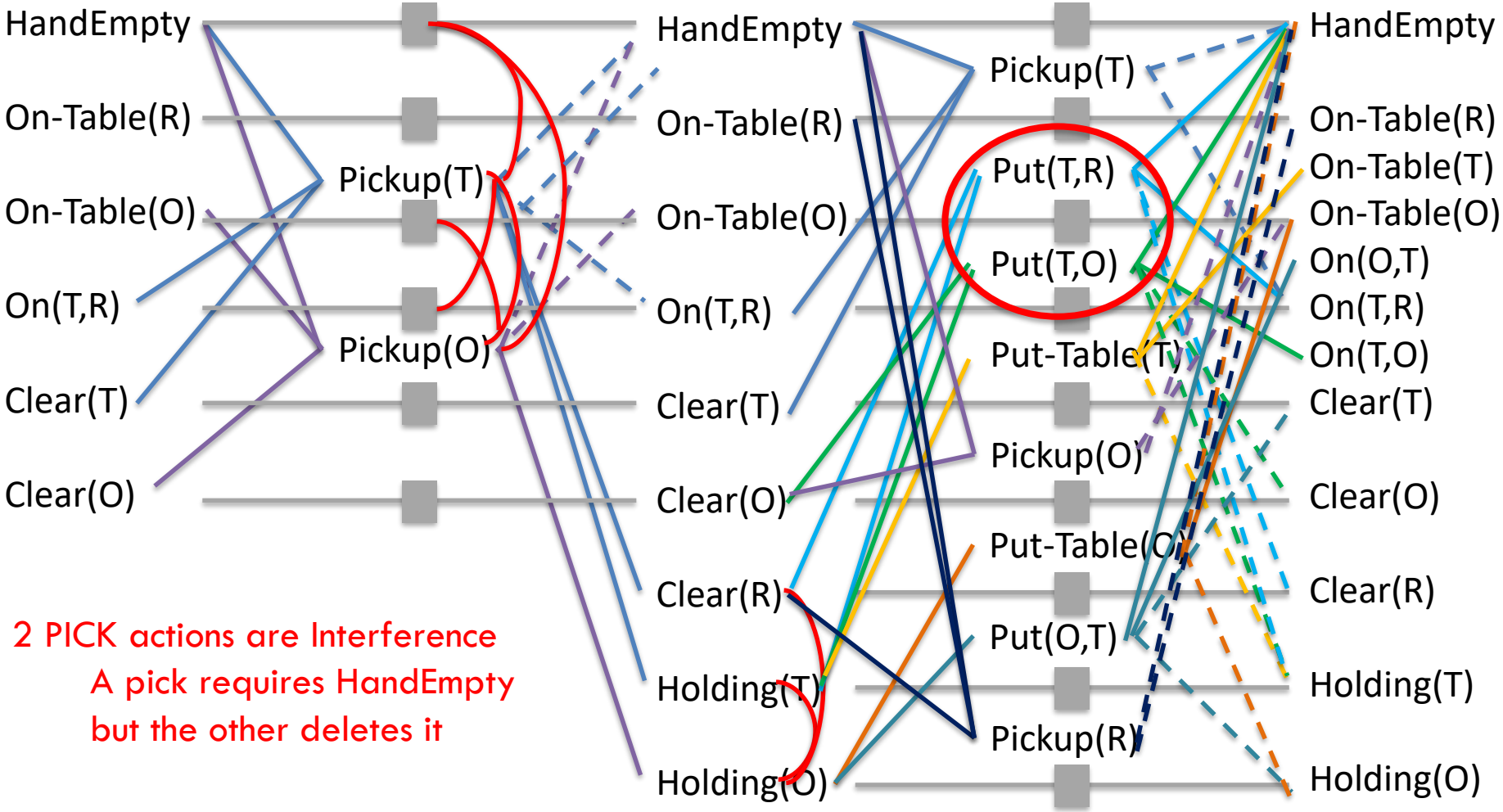
Put requires !HandEmpty

Building a Planning Graph



Extend the graph with all applicable actions, noops

Determine exclusive actions, propositions



2 PICK actions are Interference

A pick requires HandEmpty

but the other deletes it

Planning Graph Heuristics

Key idea: Construct an approximation of the reachability graph in polynomial space

- The planning graph computes the **possibly reachable** states although they aren't necessarily **feasible**

What kinds of heuristics could we apply to the planning graph?

Is the solution GraphPlan finds admissible?

How can we program GraphPlan?

How can we program GraphPlan?

Literals: Each thing in our model

i = Instance(“name”,TYPE)

Variables: Can take on any TYPE thing

v_a = Variable(“v_name”,TYPE)

Propositions: Relationships

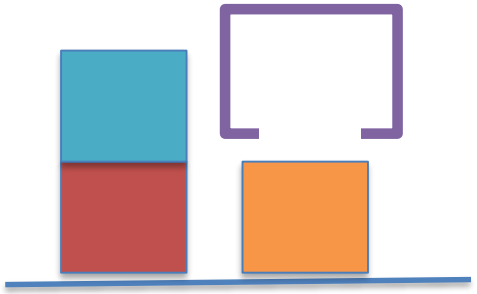
Proposition(“relation”, v_a)

Proposition(“relation”, i)

Proposition(“relation2”, v, i)

Proposition(“relation2”, v_a, v_b)

Example



A = Instance(“blockA”, BLOCK)

B = Instance(“blockB”, BLOCK)

C = Instance(“blockC”, BLOCK)

Proposition(”on”, B, A)

Proposition(”on-table”, A)

Proposition(”on-table”, C)

Proposition(”clear”, B)

Proposition(”clear”, C)

Proposition(“handempty”, True)

Example

A = Instance(“blockA”, BLOCK)

B = Instance(“blockB”, BLOCK)

C = Instance(“blockC”, BLOCK)

a. Proposition(”on”, B, A)

b. Proposition(“on”, B, C)

c. Proposition(”on-table”, A)

d. Proposition(”on-table”, C)

e. Proposition(”clear”, B)

f. Proposition(”clear”, C)

How can we program operators?

Operators: the actions we take change state

```
o = Operator("name",
             [], #preconditions
             [], #add effects
             []) # delete effects
```

How can we program operators?

Operators: the actions we take change state

```
pickup_table = Operator("pick_table",
        [Proposition("Handempty",True),
         Proposition("clear", v_block),
         Proposition("on-table", v_block)],
        [Proposition("holding", v_block)],
        [Proposition("Handempty",True),
         Proposition("on-table", v_block]
    )
```

How can we program operators?

Operators: the actions we take change state

```
pickup_table = Operator("pick_table",
    [Proposition("Handempty",True),
     Proposition("clear", v_block),
     Proposition("on-table", v_block)],
    [Proposition("holding", v_block)],
    [Proposition("Handempty",True),
     Proposition("on-table", v_block]
)
```

Lists are conjunctions

Lists are conjunctions

Lists are conjunctions

How can we program operators?

Operators: the actions we take change state

```
pickup_table = Operator("pick_table",
        [Proposition("Handempty",True),
         Proposition("clear", v_block),
         Proposition("on-table", v_block)],
        [Proposition("holding", v_block)],
        [Proposition("Handempty",True),
         Proposition("on-table", v_block]
    )
```

Variable with matching name must match subsequent propositions

How can we program operators?

Operators: the actions we take change state

```
pickup_table = Operator("pick_table",
        [Proposition("Handempty",True),
         Proposition("clear", v_block),
         Proposition("on-table", v_block2)],
        [Proposition("holding", v_block)],
        [Proposition("Handempty",True),
         Proposition("on-table", v_block]
    )
```

Variable with matching name must match subsequent propositions

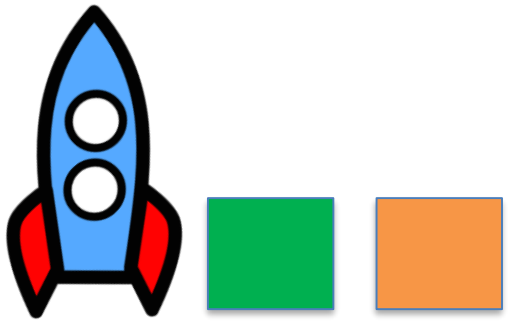
Variables that don't match name don't have to be the same

We will give you a GraphPlan Solver

Solver takes all instances, all operators, the start state and the goal state and produces a plan

Another Example - Rocket Ship

Suppose we have a rocket ship that can only be used once. It has to carry two payloads.



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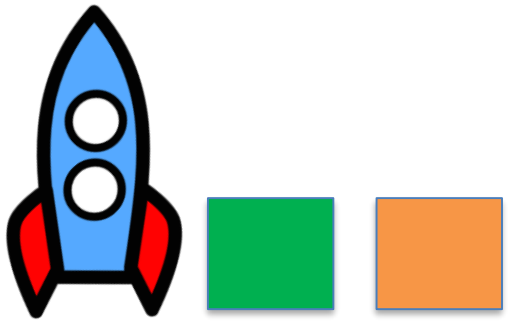
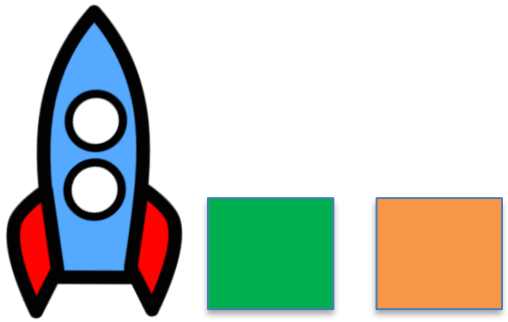
Literals?



Another Example - Rocket Ship

Suppose we have a rocket ship that can only be used once. It has to carry two payloads.

Literals: Rocket, G, O, LocA, LocB

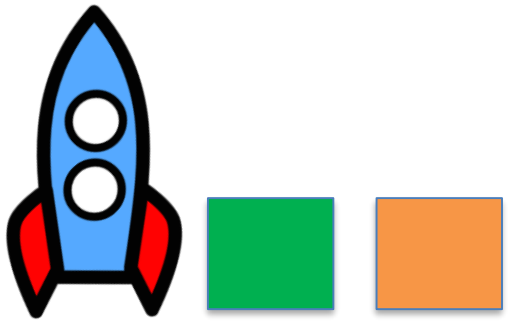


Another Example - Rocket Ship

Suppose we have a rocket ship that can only be used once. It has to carry two payloads.

Literals: Rocket, G, O, LocA, LocB
Start state:

At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)



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Literals: Rocket, G, O, LocA, LocB
Start state:
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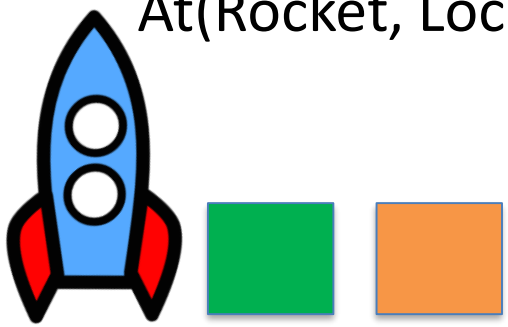
Unloaded(G,LocA), Unloaded(O,LocA)
Goal state:
At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)



Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB

Start state:

At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)

Goal state:

At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)

Move: Load: Unload:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB

Start state:

At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)

Goal state:

At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)

Move:

P:

A:

D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB

Start state:

At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)

Goal state:

At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)

Move:

P: At(Rocket,L)

A:

D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB

Start state:

At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)

Goal state:

At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)

Move:

P: At(Rocket,L)

A:

D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB

Start state:

At(Rocket, LocA), Has-Fuel(),

Unloaded(G,LocA), Unloaded(O,LocA)

Goal state:

At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)

Variables: L

Move:

P: At(Rocket,L)

A:

D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB

Start state:

At(Rocket, LocA), Has-Fuel(),

Unloaded(G,LocA), Unloaded(O,LocA)

Goal state:

At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)

Variables: L

Move:

P: At(Rocket,L), Has-Fuel()

A:

D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB

Start state:

At(Rocket, LocA), Has-Fuel(),

Unloaded(G,LocA), Unloaded(O,LocA)

Goal state:

At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)

Variables: L

Move:

P: At(Rocket,L), Has-Fuel()

A: At(Rocket,Dest)

D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB

Start state:

At(Rocket, LocA), Has-Fuel(),

Unloaded(G,LocA), Unloaded(O,LocA)

Goal state:

At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)

Variables: L, Dest

Move:

P: At(Rocket,L), Has-Fuel()

A: At(Rocket,Dest)

D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB
Start state:
At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)
Goal state:
At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)
Variables: L, Dest

Move:
P: At(Rocket,L), Has-Fuel(), L!=Dest
A: At(Rocket,Dest)
D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB
Start state:
At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)
Goal state:
At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)
Variables: L, Dest

Move:
P: At(Rocket,L), Has-Fuel(), L!=Dest
A: At(Rocket,Dest)
D: Has-Fuel(),At(Rocket,L)

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB

Start state:

At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)

Goal state:

At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)

Variables: L, Dest

Load:

P:

A:

D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB
Start state:
At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)
Goal state:
At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)
Variables: L, Dest

Load:
P: At(Rocket,L), Unloaded(Pkg,L)
A:
D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB

Start state:

At(Rocket, LocA), Has-Fuel(),

Unloaded(G,LocA), Unloaded(O,LocA)

Goal state:

At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)

Variables: L, Dest

Load:

P: At(Rocket,L), Unloaded(Pkg,L)

A:

D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB

Start state:

At(Rocket, LocA), Has-Fuel(),

Unloaded(G,LocA), Unloaded(O,LocA)

Goal state:

At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)

Variables: L, Dest, Pkg

Load:

P: At(Rocket,L), Unloaded(Pkg,L)

A:

D:

Another Example - Rocket Ship

Literals: Rocket, G, O, LocA, LocB
Start state:
At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)
Goal state:
At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)
Variables: L, Dest, Pkg

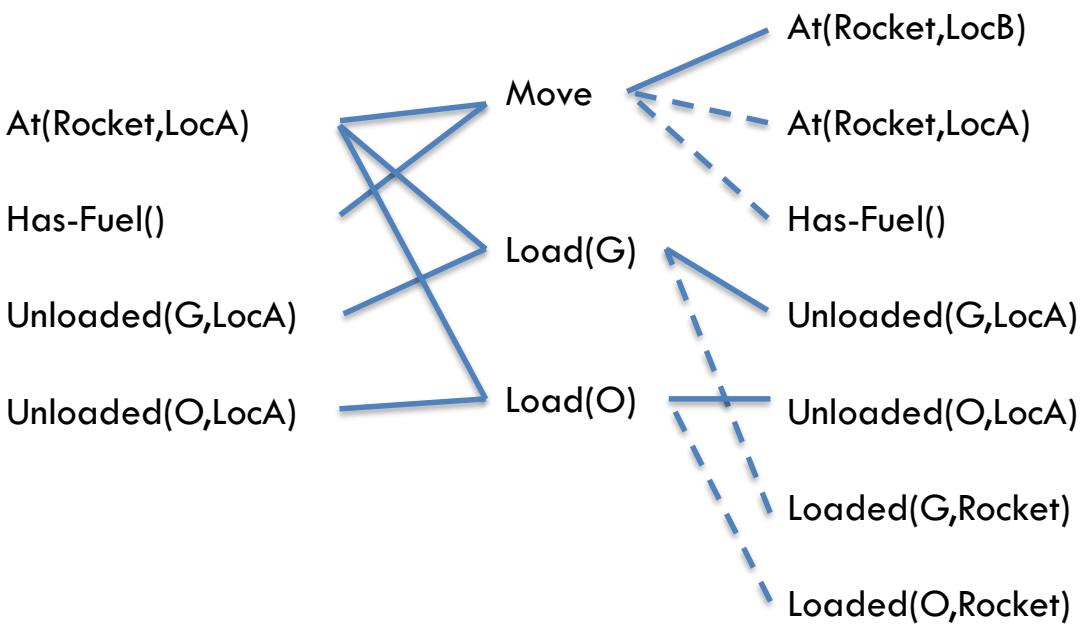
Load:
P: At(Rocket,L), Unloaded(Pkg,L)
A: Loaded(Pkg,Rocket)
D: Unloaded(Pkg,L)

Another Example - Rocket Ship

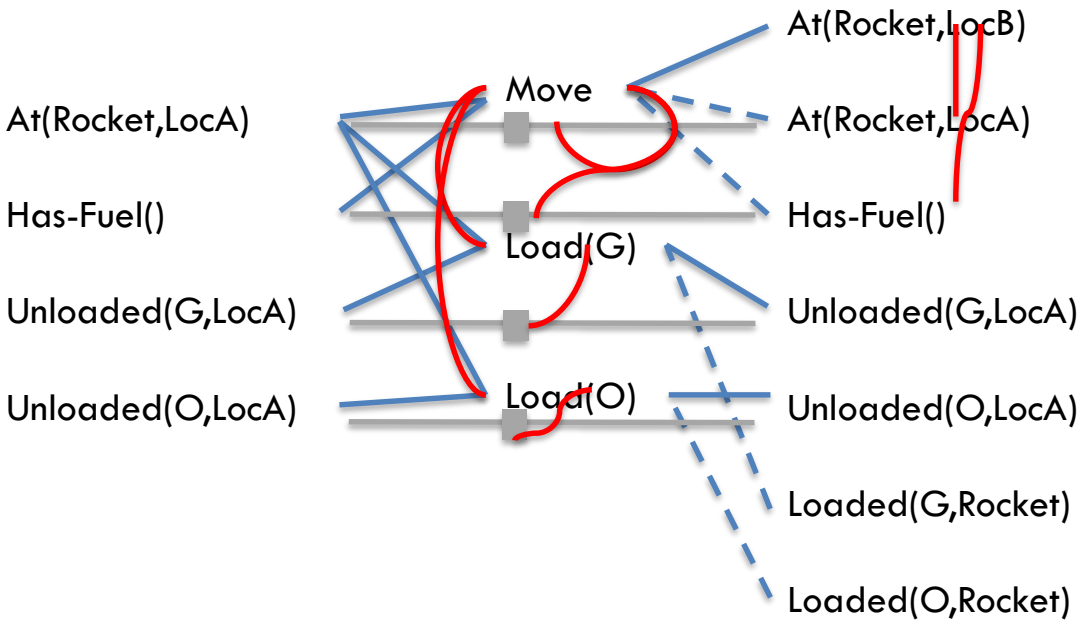
Literals: Rocket, G, O, LocA, LocB
Start state:
At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)
Goal state:
At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)
Variables: L, Dest, Pkg

Unload:
P: At(Rocket,Dest), Loaded(Pkg,Rocket)
A: Unloaded(Pkg,Dest)
D: Loaded(Pkg,Rocket)

Rocket Ship Planning Graph



Rocket Ship Planning Graph



Mutex Propositions:
- At(Rocket,LocB) and At(Rocket,LocA) because Move and noop are mutex actions
- What else?

Mutex Actions

Interference:

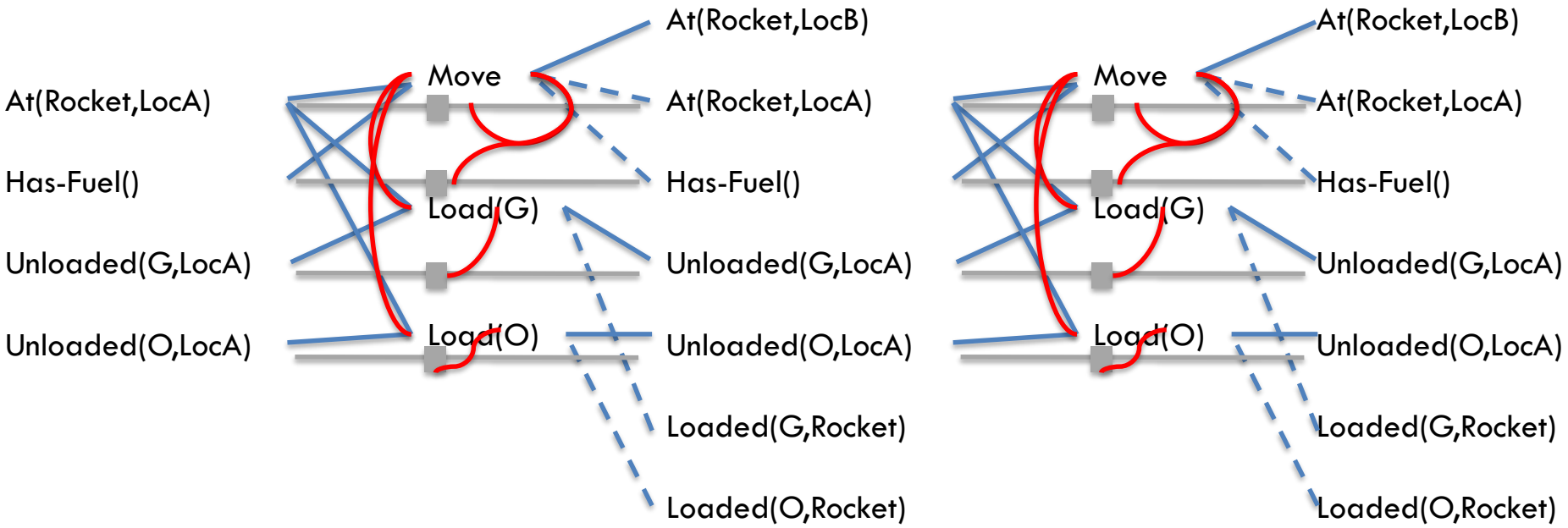
Move deletes At which is a precondition of Load

Inconsistent:

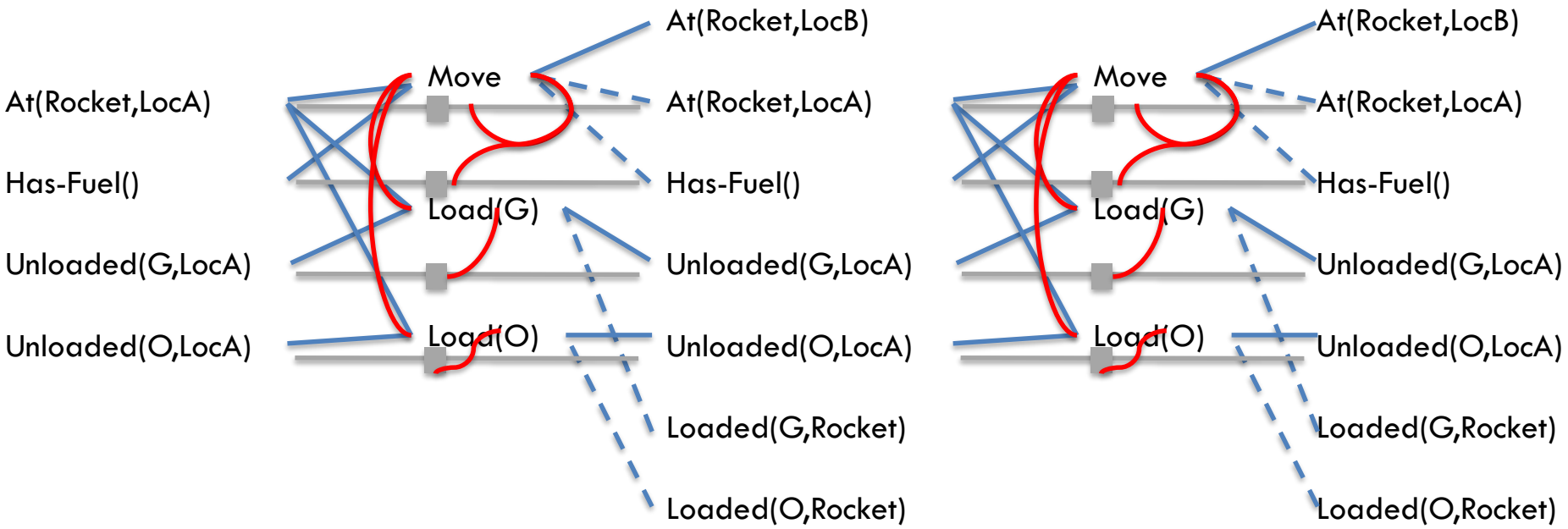
Move deletes At but noop adds it

Move deletes Has-Fuel but noop adds it

Rocket Ship Planning Graph



Rocket Ship Planning Graph



At time 1: Move can be performed OR both Load actions

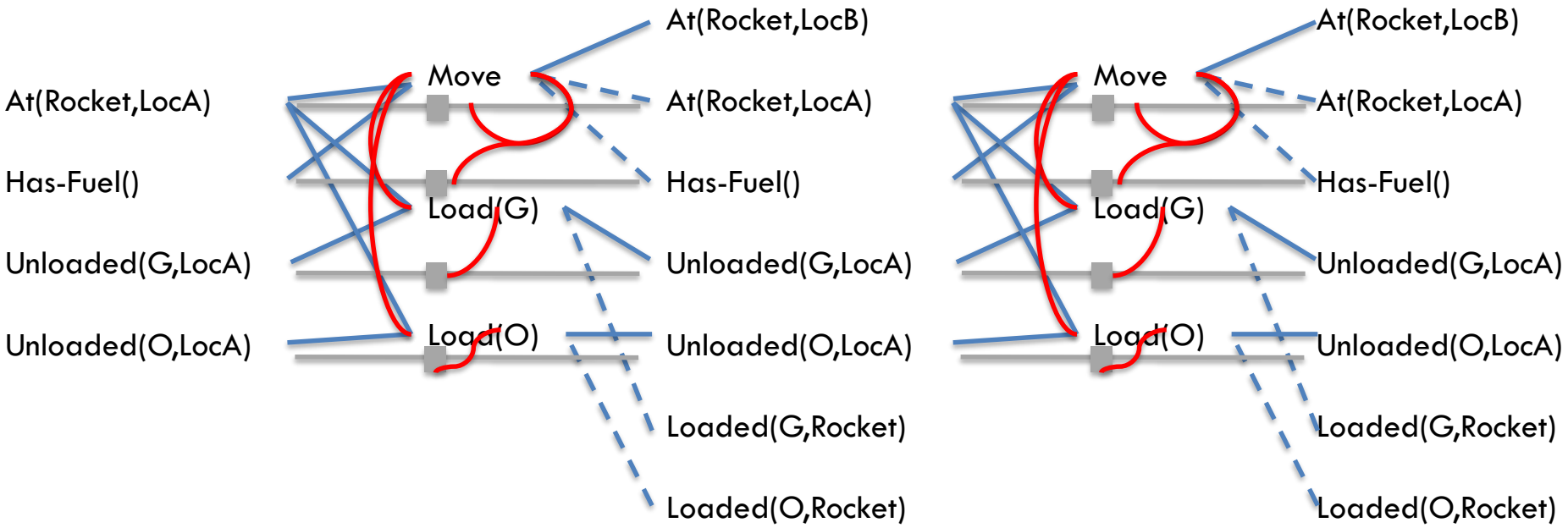
At time 2: Possible plans include:

Load(G), Load(O), Move(LocB)

Load(G), Move(LocB)

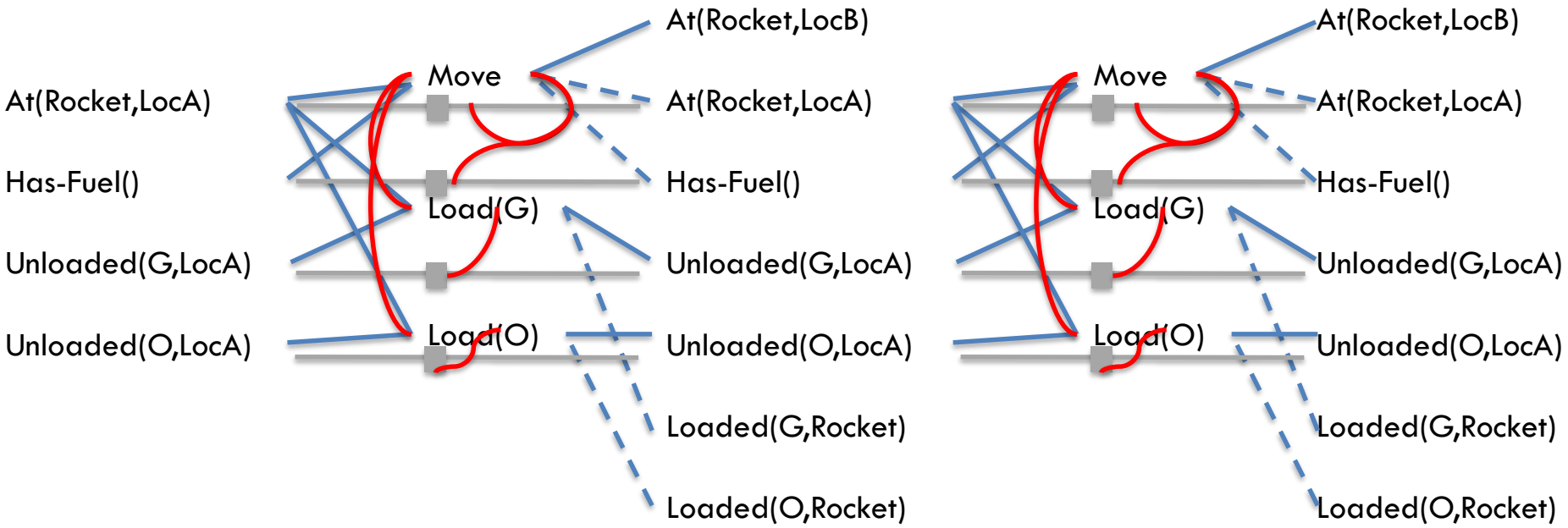
Load(O), Move(LocB)

Rocket Ship Planning Graph



At time 3: What will happen?

Rocket Ship Planning Graph



At time 3: What will happen?

Is the planning graph estimate of 3 timesteps admissible?

Are there other admissible heuristics that could use the planning graph?

Planning, Thus Far

Goal States

completely specified

Goal Statements

partially specified

Preference models

objective function

How do these different algorithms fit together?

Suppose I have a robot that can take items to different people, deliver messages, etc.

How do these different algorithms fit together?

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How can I plan the robot's tasks? Where should it go, and it what order?

How do these different algorithms fit together?

Suppose I have a robot that can take items to different people, deliver messages, etc.

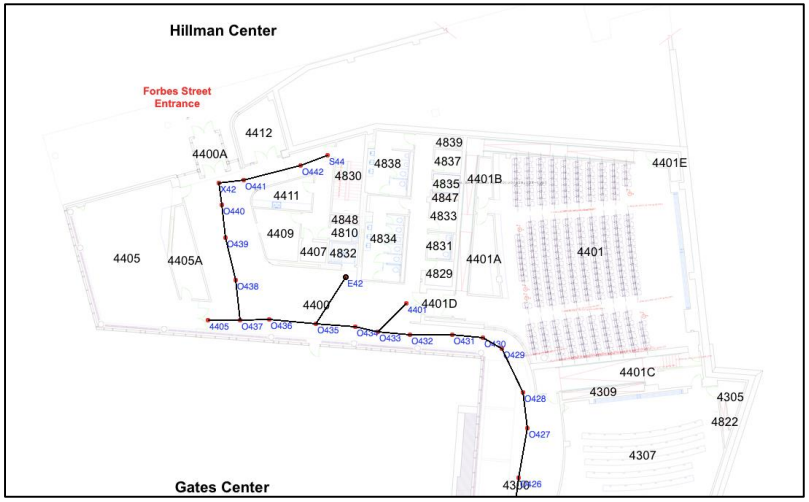
How can I plan the robot's tasks? Where should it go, and it what order?

Classical Planning

How do these different algorithms fit together?

Suppose I have a robot that can take items to different people, deliver messages, etc.

Once you have the sequence of locations, how does it plan a path to each destination?

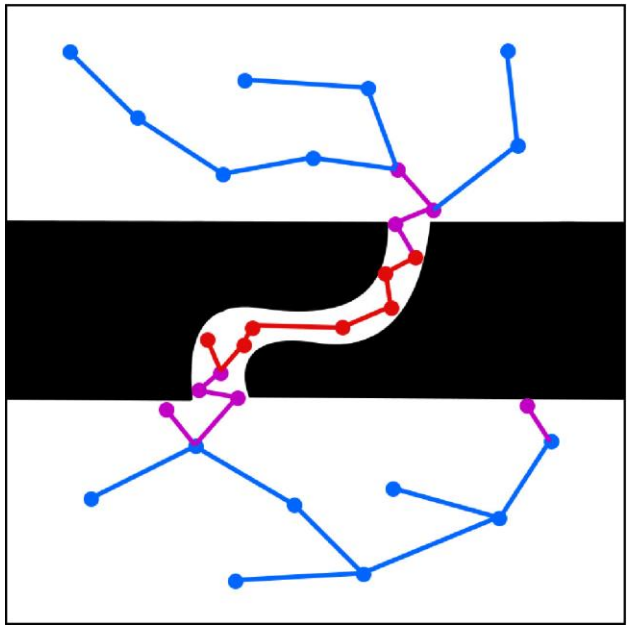


BFS

How do these different algorithms fit together?

Suppose I have a robot that can take items to different people, deliver messages, etc.

Once the robot has a list of locations to navigate, how does it get there?



Motor motion control

Rapidly-exploring Random Trees (obstacles)

How do these different algorithms fit together?

Suppose I have a robot that can take items to different people, deliver messages, etc.

Hierarchical Planning:
High-level: classical
Mid-level: BFS
Low-level: motors

Planning, Thus Far

Goal States

completely specified

Goal Statements

partially specified

Preference models

objective function

Probabilistic States and Actions

Summary

Informationless states and actions

- Easy to program
- Can take a lot of memory
- Hard to change the problem (e.g., adding a block)

Predicates and Properties

- Potentially avoids the memory issues
- Many alternate definitions
- Need separate actions for different conditions

Other concerns like uncertainty unmodeled