AI: Representation and Problem Solving

Classical Planning

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Slide credits: Reid Simmons, Manuela Veloso

Announcements

- P3 out!
  - Sorry it is late. Due 3/7.
  - Can submit 3/8 without penalty
  - Can submit 3/9 with 1 late day
  - No submissions later than 3/9
- HW6 out soon!

Planning, Thus Far

Goal States
completely specified

Goal Statements
partially specified

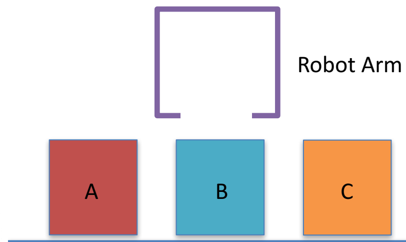
Preference models
objective function

Increasing Generality

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

Goal States
completely specified

Goal Statements
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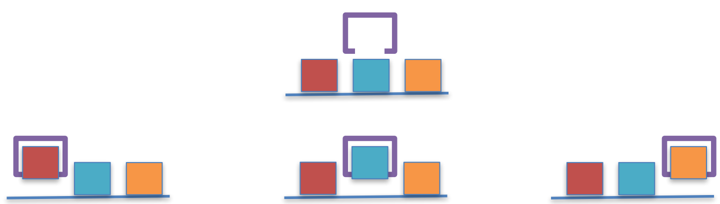
Preference models
objective function

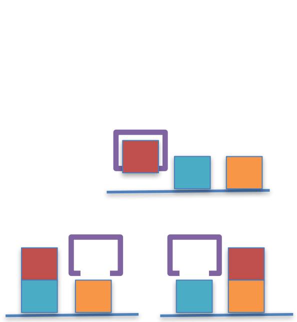
Increasing Generality

Block Stacking States

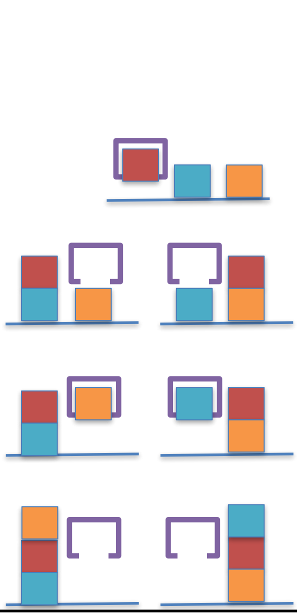
Block Stacking States



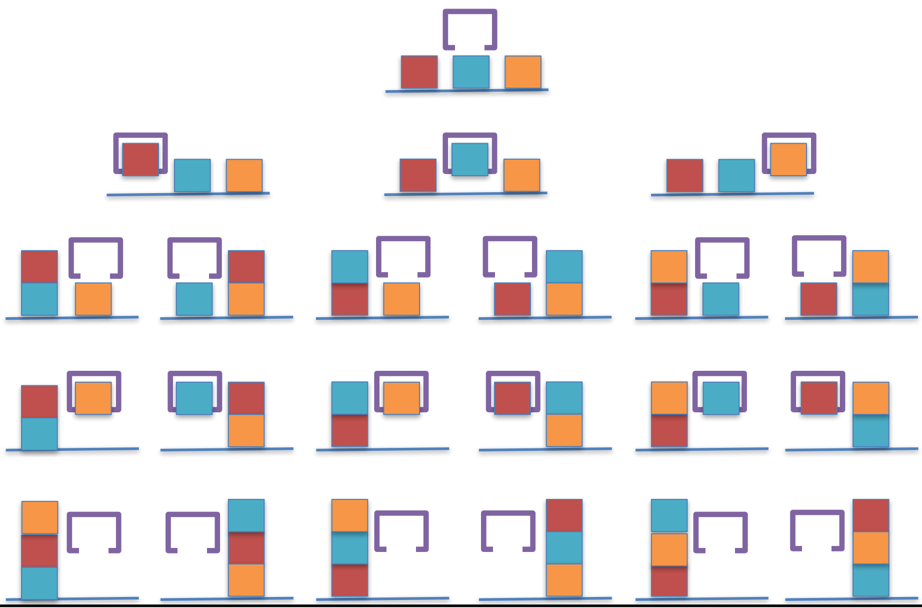
Block Stacking States



Block Stacking States

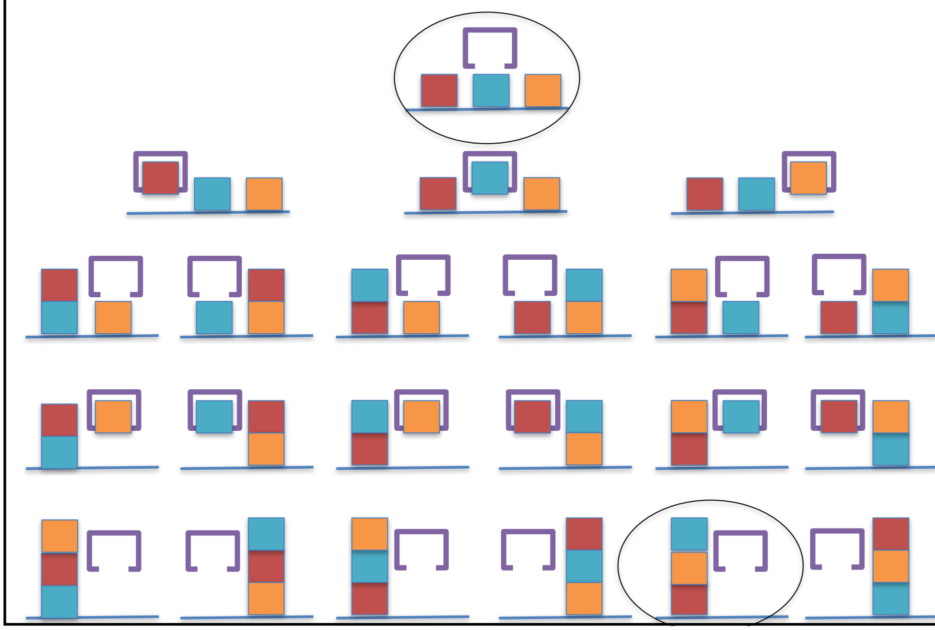


Block Stacking States

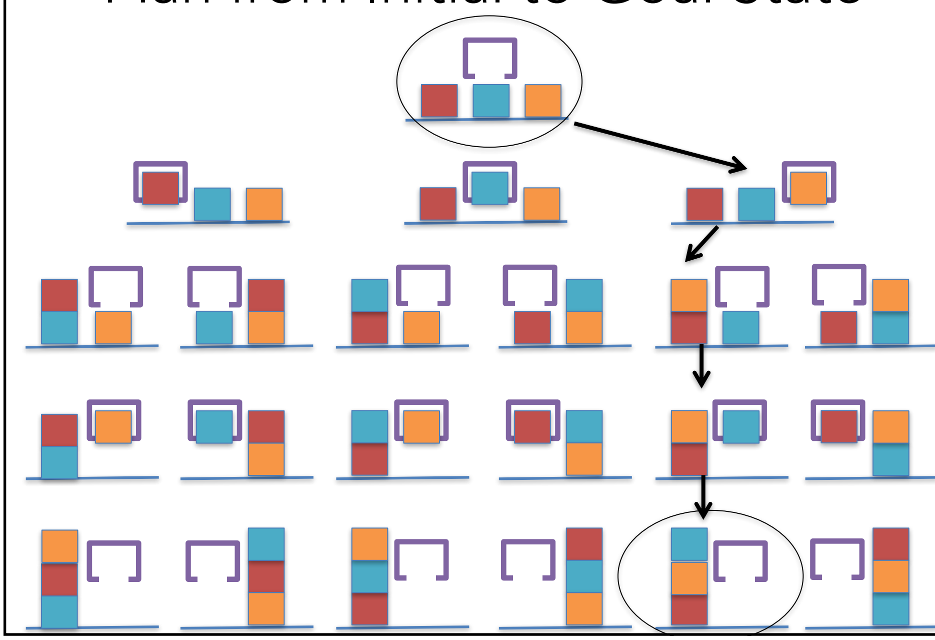


States are Informationless

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

Increasing Generality

BFS, DFS, A*

Goals in the World

Goal States
completely specified

Goal Statements
partially specified

Preference models
objective function

Increasing Generality

BFS, DFS, A*

Goals in the World

	Increasing Generality ↓	
Goal States completely specified		BFS, DFS, A*
Goal Statements partially specified		
Preference models objective function		CSP, LP, IP

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

Goal Statements
partially specified

Preference models
objective function

Increasing Generality

BFS, DFS, A*

CSP, LP, IP

Goals in the World

Goal States
completely specified

Goal Statements
partially specified

Preference models
objective function

Increasing Generality

BFS, DFS, A*

CSP, LP, IP

Goals in the World

	Increasing Generality ↓
Goal States completely specified	BFS, DFS, A*
Goal Statements partially specified	Logic
Preference models objective function	CSP, LP, IP

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

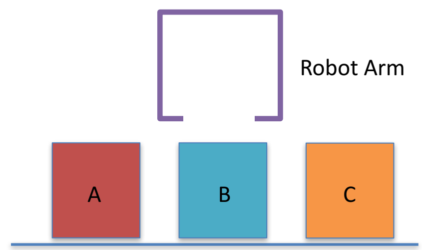
Properties and relationships of those objects change (i.e., locations)

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

Logical Agents

Create a Knowledge Base

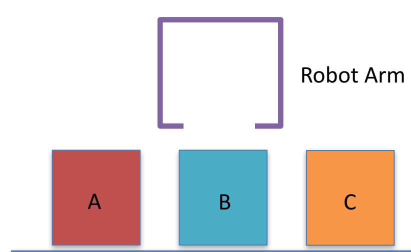
Symbols



Logical Agents

Create a Knowledge Base

Symbols



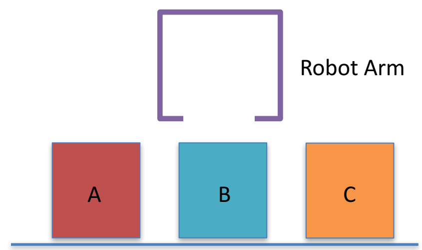
A-on-Table
B-on-Table
C-on-Table
A-In-Hand
B-In-Hand
C-In-Hand
Hand-Empty
A-on-B
A-on-C
B-on-C
B-on-A
C-on-A
C-on-B

Logical Agents

Create a Knowledge Base

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

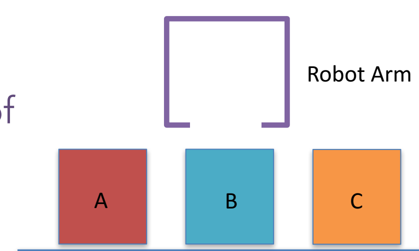


Logical Agents

Create a Knowledge Base

Implications

What are the implications of A-on-Table[t]?



Logical Agents

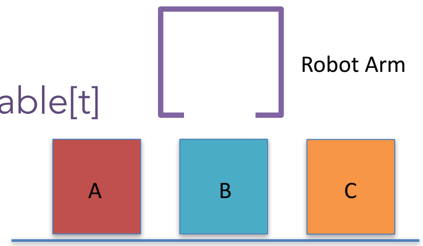
Create a Knowledge Base

Implications

Hand-Empty[t] AND A-on-Table[t]

↔

A-In-Hand[t-1] AND
Hand-Empty[t-2] AND
(A-on-B[t-2] OR A-on-C[t-2])



Logical Agents

Create a Knowledge Base

Implications

Hand-Empty[t] AND A-on-Table[t]

↔

A-In-Hand[t-1] AND
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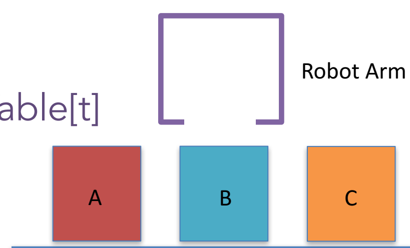
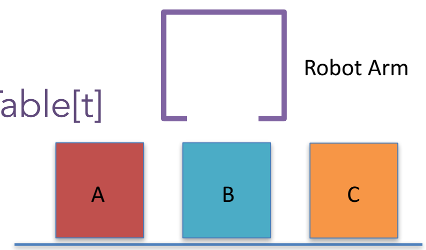


Is this enough?

Logical Agents

Create a Knowledge Base

Implications



Hand-Empty[t] AND A-on-Table[t]

$\leftrightarrow$

A-In-Hand[t-1] AND
Hand-Empty[t-2] AND
(A-on-B[t-2] OR A-on-C[t-2])

Is this enough? Need to specify !Hand-Empty[t-1]…

Logical Agents

Create a Knowledge Base

Symbols

Implications

Check whether the KB entails a query

Query – a subset of symbols in model

Logical Agents

Create a Knowledge Base
- Symbols
- Implications

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

The actions (e.g., picking a block) are implicitly represented as the implications

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?

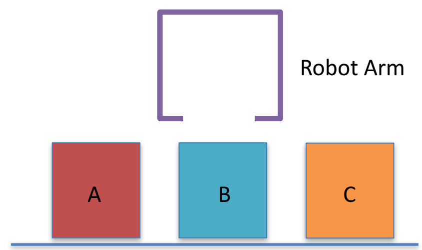
Predicates

Are there other functions that we could use?

YES!!
Your challenge is finding a representation
that works for your environment

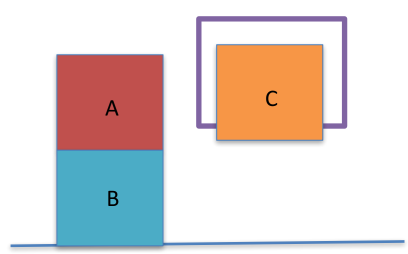
Piazza Poll – Check all that apply

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()



Piazza Poll – Check all that apply

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()



Classical Planning

Also partially-specified

Create a Knowledge Base
- ~~Symbols~~ Predicates
- ~~Implications~~ Operators

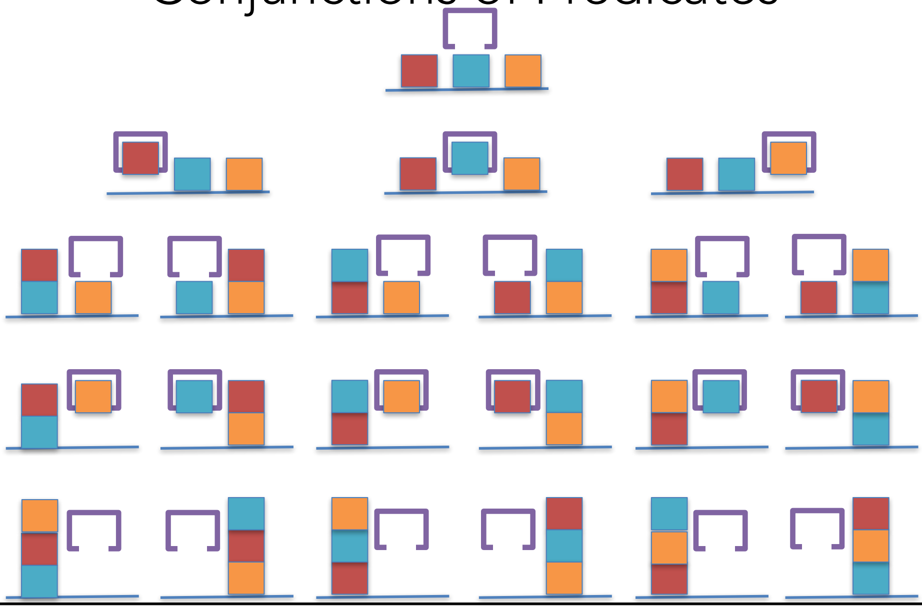
Check whether the KB entails a query
- A goal state (conjunction of predicates)

Models of Operators (Actions)

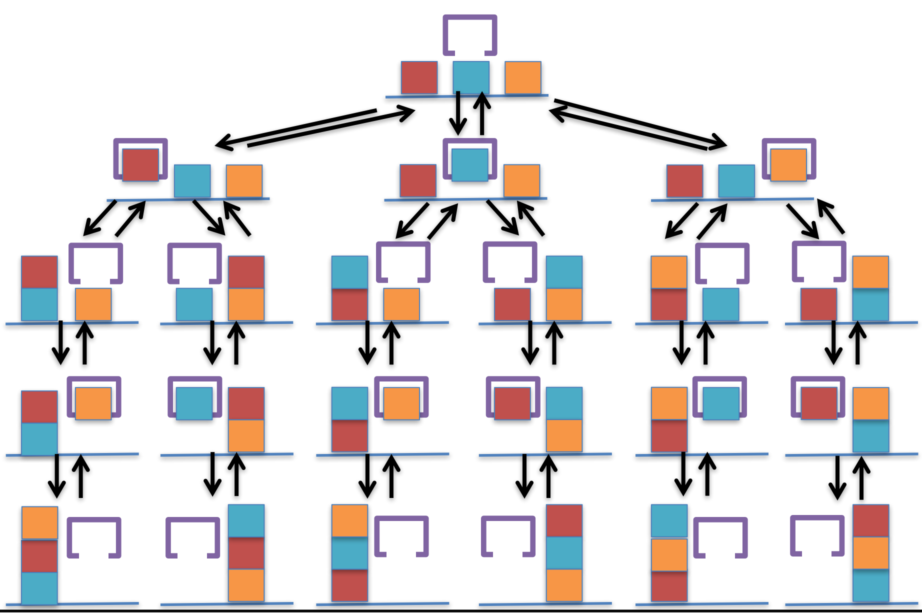
Actions can be applied only if all conditions are met
Actions change the state of the world
- Represented as effects that add/delete predicates

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

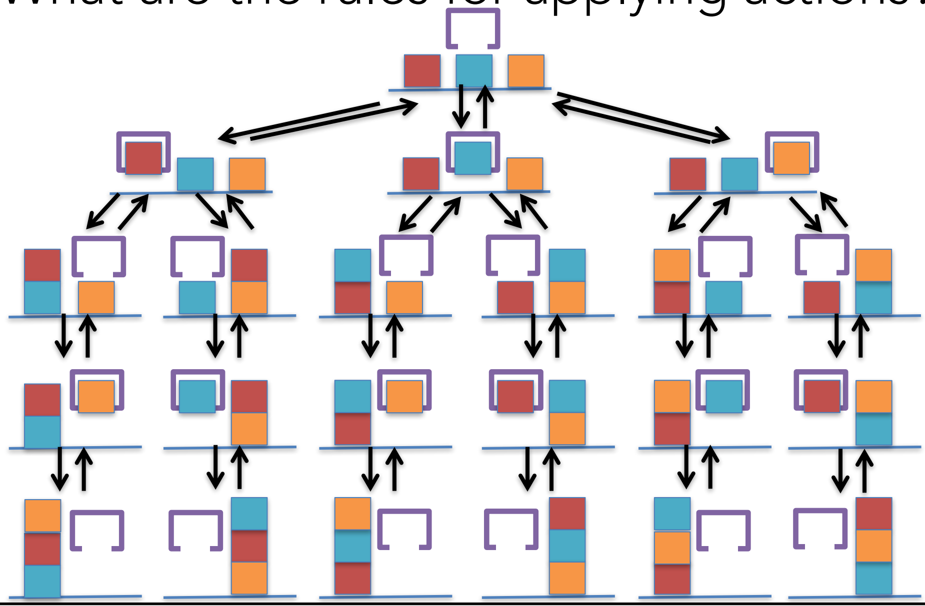
Block Stacking States – Conjunctions of Predicates



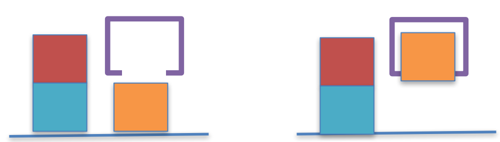
Block Stacking Operators (Actions)



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

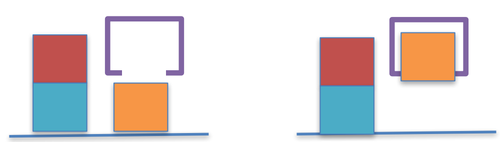
Preconditions
HandEmpty
On-Table(b)
Clear(b)

Pick Up Block from Table Example

Preconditions
- HandEmpty
- On-Table(b)
- Clear(b)

Effects?

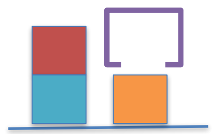
Pick Up Block from Table Example



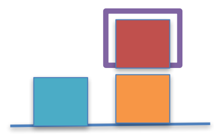
Preconditions
- HandEmpty
- On-Table(b)
- Clear(b)

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

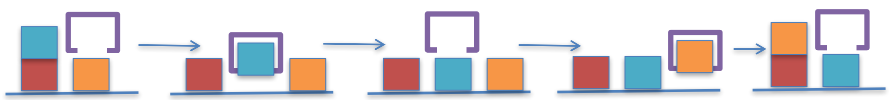
HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

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)

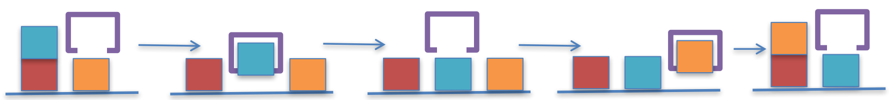
Pickup_from_Table(b):
Pre: HandEmpty, Clear(b), On-Table(b)
Add: Holding(b)
Delete: HandEmpty, On-Table(b)

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)

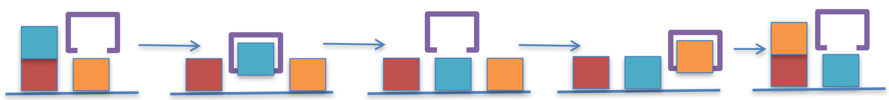
On-Table(R) & Clear(T) & On-Table(O) & Clear(O)

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

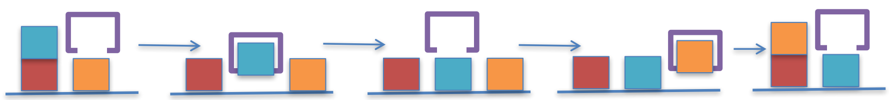
HandEmpty & On-Table(R) & On(T,R) & Clear(T) & On-Table(O) & Clear(O)

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):
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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)
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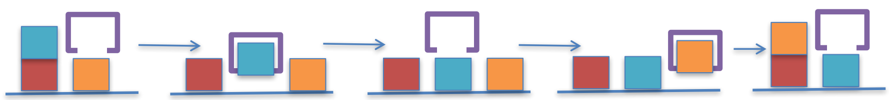


Example Plan of Actions

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)

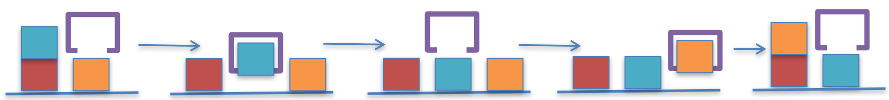
On-Table(R) & Clear(T) & On-Table(O) & Clear(O) & Holding(T) & Clear(R)

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)

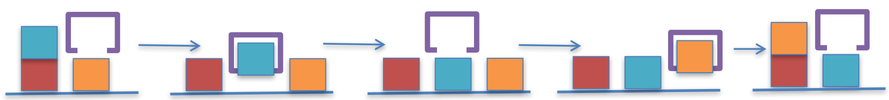
Pickup_from_Table(O)

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)

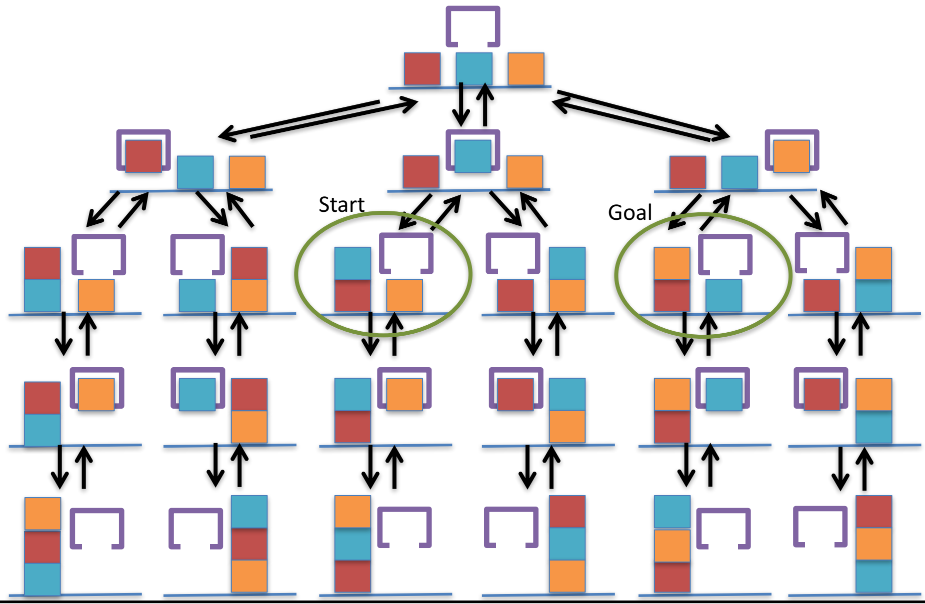
Completeness

- 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

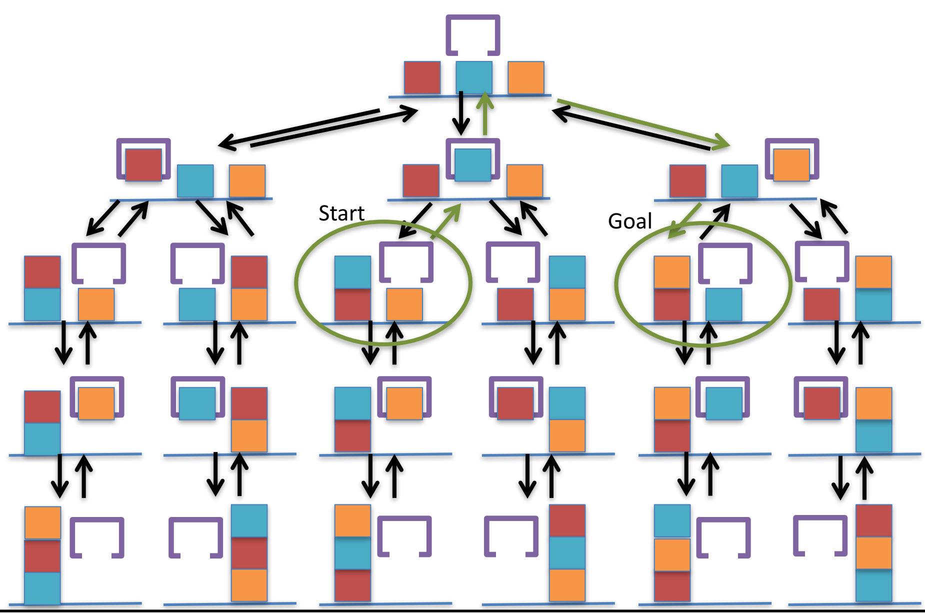
Optimality

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

Techniques for Planning

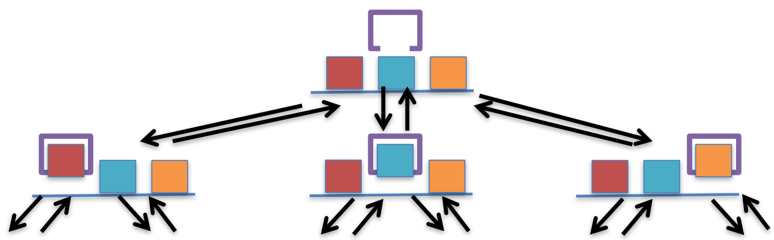


BFS – Find shortest action sequence



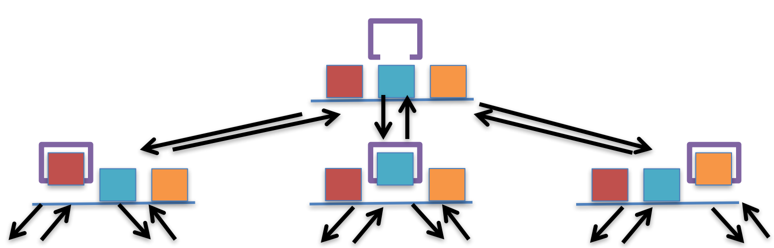
Reachability Graph Representation

States: Conjunctions of Predicates
Arrows = Actions
Every state in level K is *reachable* in K actions
Space complexity in terms of # predicates p?

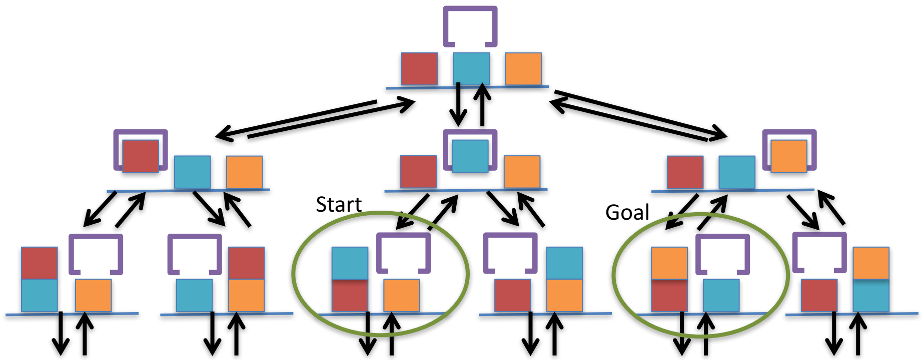


Reachability Graph Representation

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

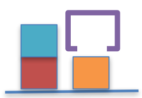
Idea: Since we have a conjunction of goal predicates, let's try to solve one at a time

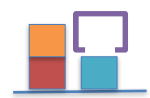
- Maintain a stack of achievable goals
- Use BFS (or anything else) to find a plan to achieve that single goal
- Add a goal back on the stack if a later change makes it violated

Linear Planning Example

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

Action Plan:

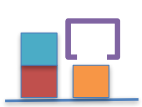


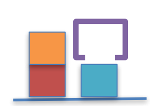


Linear Planning Example

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

Action Plan:

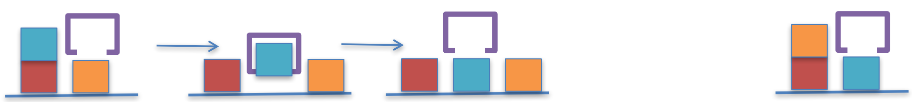




Linear Planning Example

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

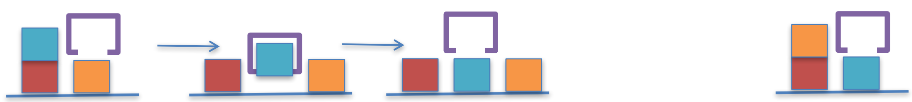
Goal Stack:
On-Table(R)
On(O,R)
Clear(O)
Clear(T)

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

Linear Planning Example

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

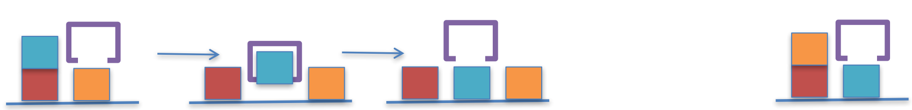
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)
On-Table(R)



Linear Planning Example

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

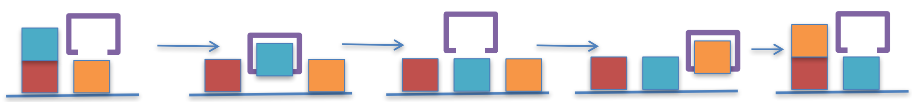
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)
On-Table(R)



Linear Planning Example

Goal Stack:
Clear(O)
Clear(T)

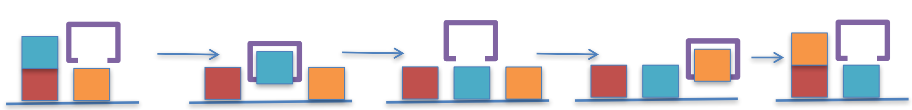
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)
On-Table(R)
On(O,R)
    Pickup(O)
    Put(O,R)



Linear Planning Example

Goal Stack:
Clear(O)
Clear(T)

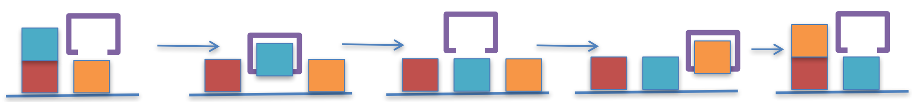
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)
On-Table(R)
On(O,R)
    Pickup(O)
    Put(O,R)



Linear Planning Example

Goal Stack:

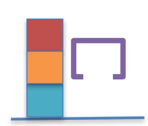
Action Plan:
On-Table(T)
    Pickup(T)
    Put-Table(T)
On-Table(R)
On(O,R)
    Pickup(O)
    Put(O,R)
Clear(O)
Clear(T)



Linear Planning Example 2

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

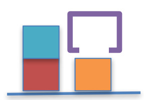
Action Plan:

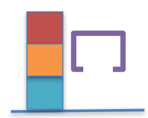


Linear Planning Example 2

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

Action Plan:

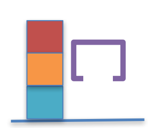




Linear Planning Example 2

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

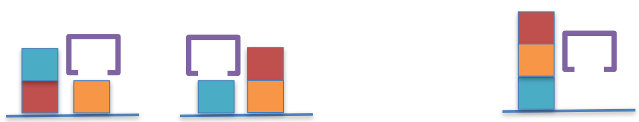
Action Plan:
On(R,O)
- Pickup(T)
- Put-Table(T)
- Pickup(R)
- Put(R,O)



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)

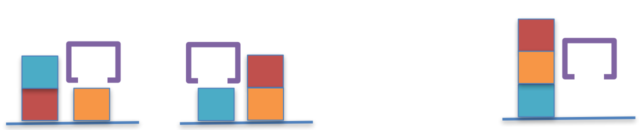


Linear Planning Example 2

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

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

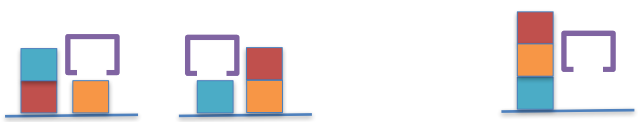
On-Table(T)



Linear Planning Example 2

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

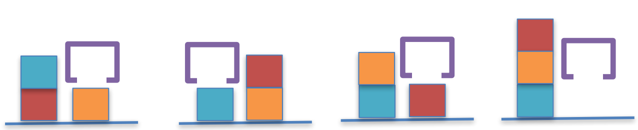
Action Plan:
On(R,O)
  Pickup(T)
  Put-Table(T)
  Pickup(R)
  Put(R,O)
On-Table(T)



Linear Planning Example 2

Goal Stack:
Clear(R)

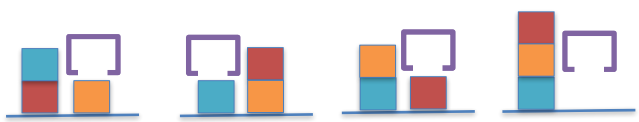
Action Plan:
On(R,O)
  Pickup(T)
  Put-Table(T)
  Pickup(R)
  Put(R,O)
On-Table(T)
On(O,T)
  Pickup(R)
  Put-Table(R)
  Pickup(O)
  Put(O,T)



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)

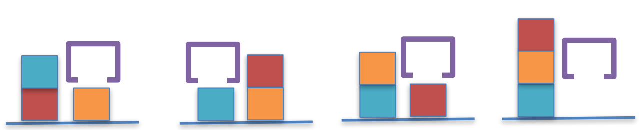


Linear Planning Example 2

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

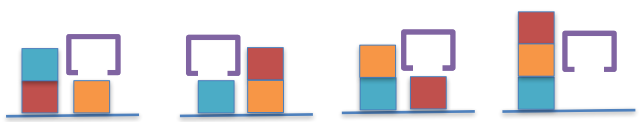
Goal Stack:

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)

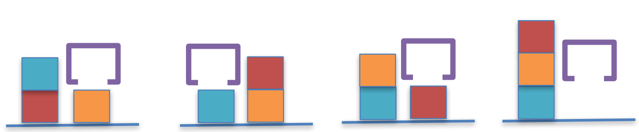
On-Table(T)
On(O,T)
- Pickup(R)
- Put-Table(R)
- Pickup(O)
- Put(O,T)

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)

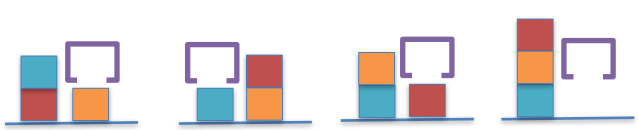
On-Table(T)
On(O,T)
- Pickup(R)
- Put-Table(R)
- Pickup(O)
- Put(O,T)

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

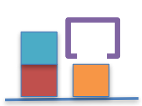
Idea: Interleave goals to achieve plans

- 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)

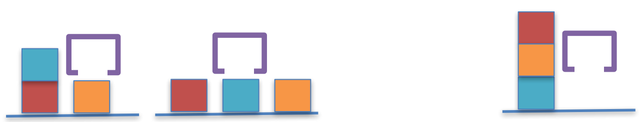
Action Plan:



Non-Linear Planning (Example 2)

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

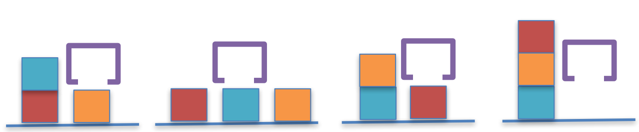
Action Plan:
On(R,O)
    Pickup(T)
    Put-Table(T)
  STOP-SWITCH-GOALS



Non-Linear Planning (Example 2)

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

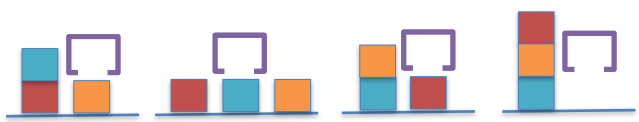
Action Plan:
On(R,O)
    Pickup(T)
    Put-Table(T)
  STOP-SWITCH-GOALS
On(O,T)
    Pickup(O)
    Put(O,T)



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)

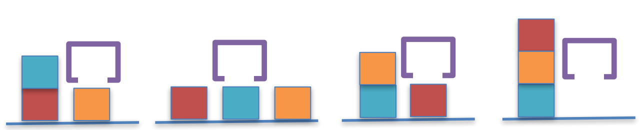


Non-Linear Planning (Example 2)

Goal Set:
On(R,O)
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)

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

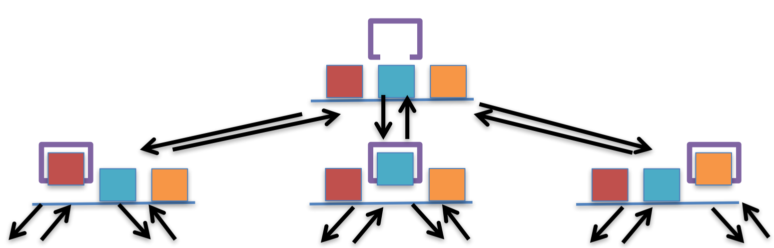
Reachability Graph Representation

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

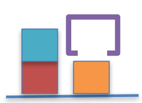
Two alternating stages:

- 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)

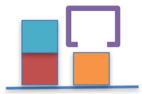
On-Table(O)

On(T,R)

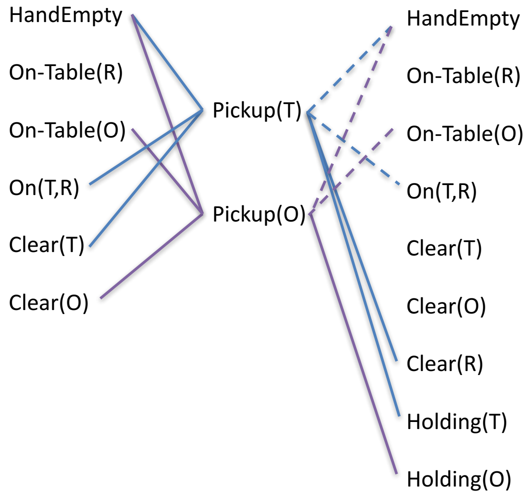
Clear(T)

Clear(O)

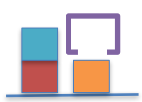
Building a Planning Graph



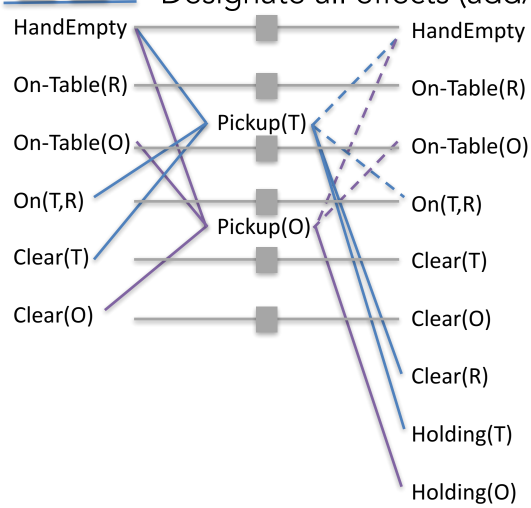
Extend the graph with all applicable actions
Designate all effects (add/delete)



Building a Planning Graph

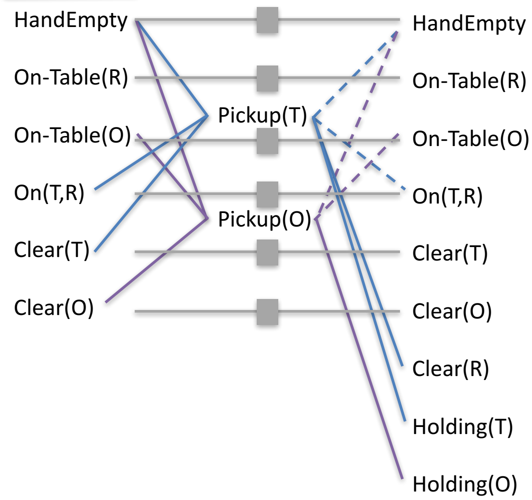


Extend the graph with all applicable actions, noops
Designate all effects (add/delete)



Building a Planning Graph

Extend the graph
Determine exclusive actions

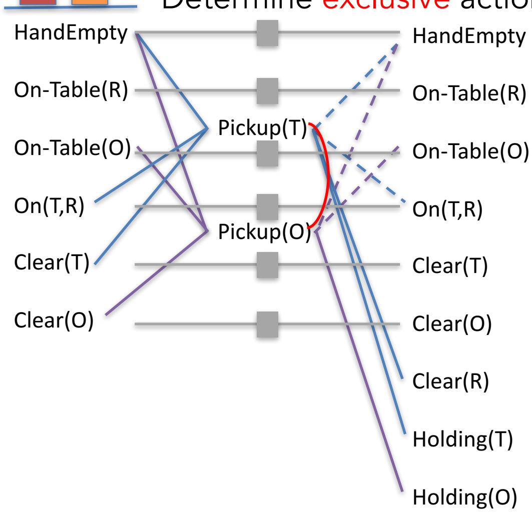


Actions A and B are *exclusive (mutex)* at action-level *i*, if:

- 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



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

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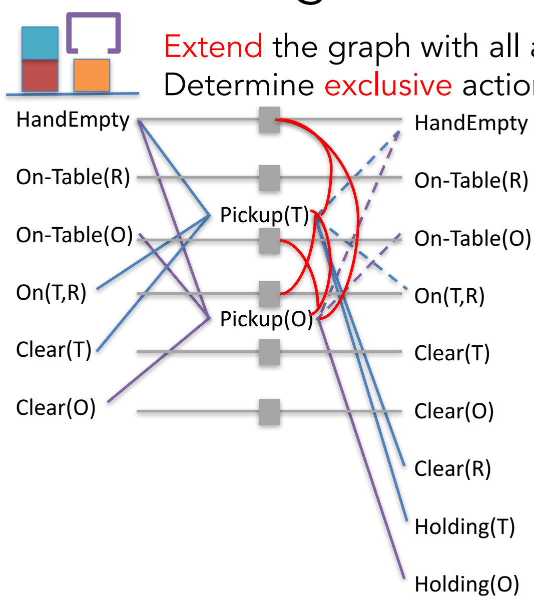
- Inconsistency: one action is the negation of the other
- Competing Needs: *p* is a precondition of A and *q* is a precondition of B, and *p* and *q* are exclusive in proposition-level *i* – 1

Building a Planning Graph

Extend the graph with all applicable actions, noops
Determine exclusive actions



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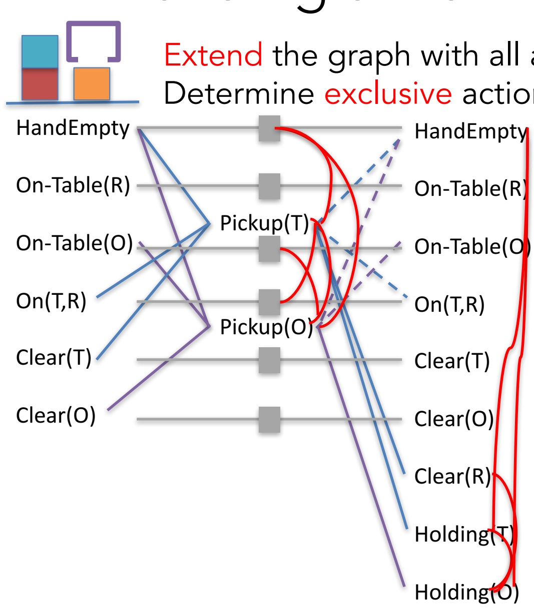
- Inconsistency: one action is the negation of the other
- Competing Needs: *p* is a precondition of A and *q* is a precondition of B, and *p* and *q* are exclusive in proposition-level *i* – 1

Building a Planning Graph

Extend the graph with all applicable actions, noops
Determine exclusive actions, 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

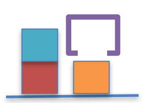
- May not be a solution, at that level

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

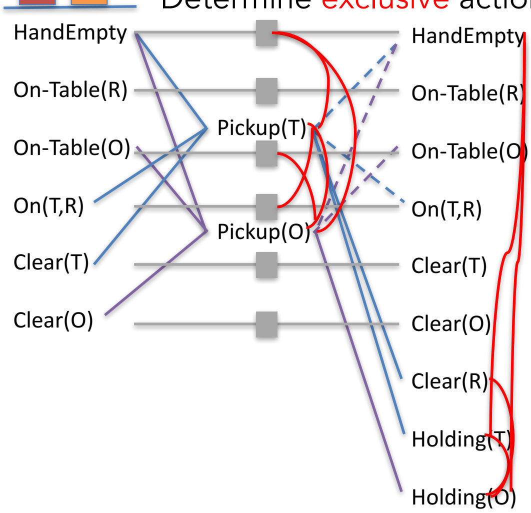
If search is exhausted, extend planning graph one more proposition level

Extend a Level

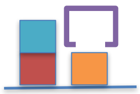


Extend the graph with all applicable actions, noops

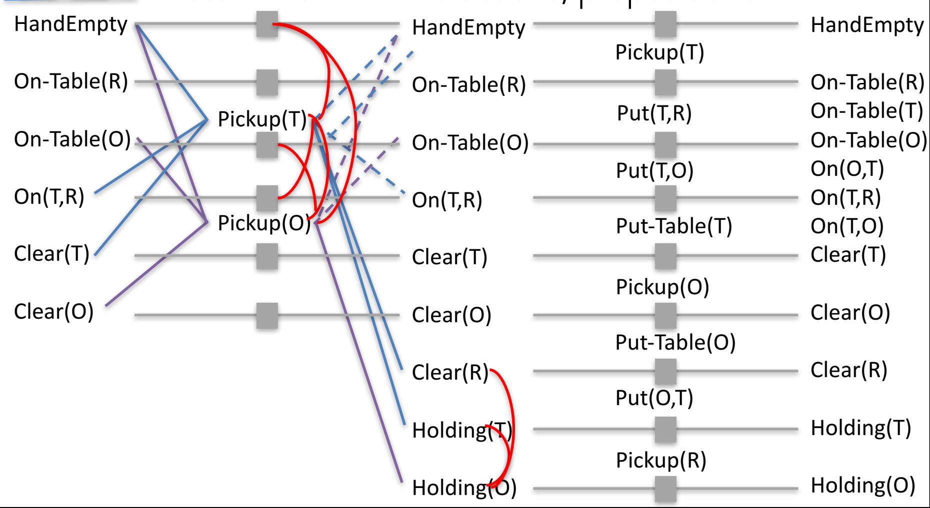
Determine exclusive actions, propositions



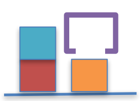
Building a Planning Graph



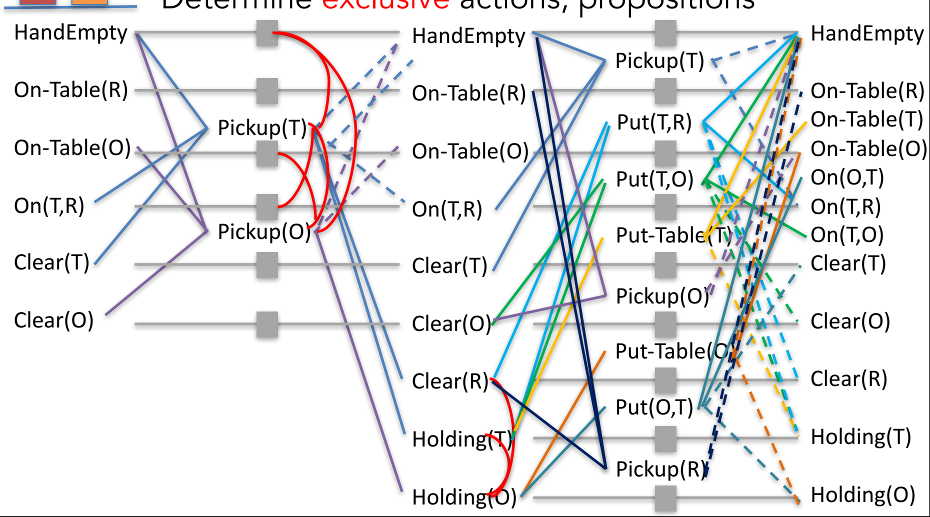
Extend the graph with all applicable actions, noops
Determine exclusive actions, propositions



Building a Planning Graph

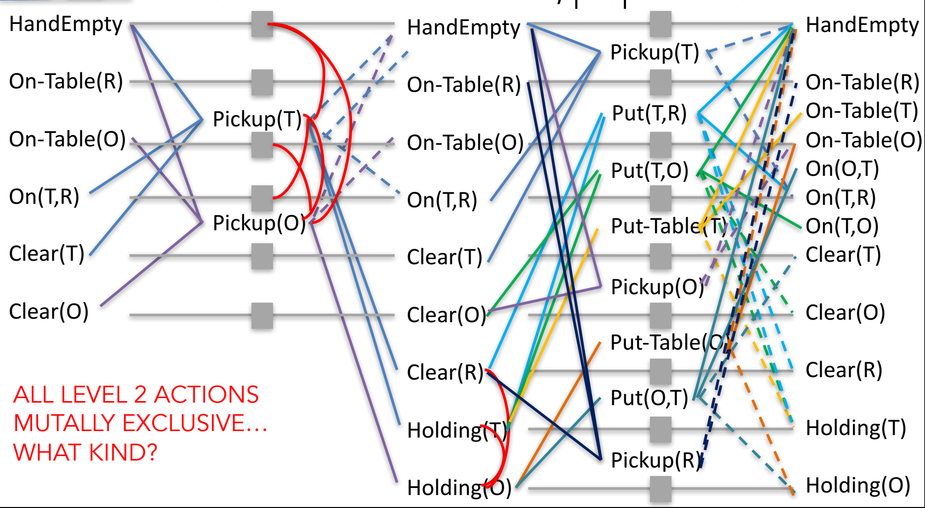


Extend the graph with all applicable actions, noops
Determine exclusive actions, propositions



Building a Planning Graph

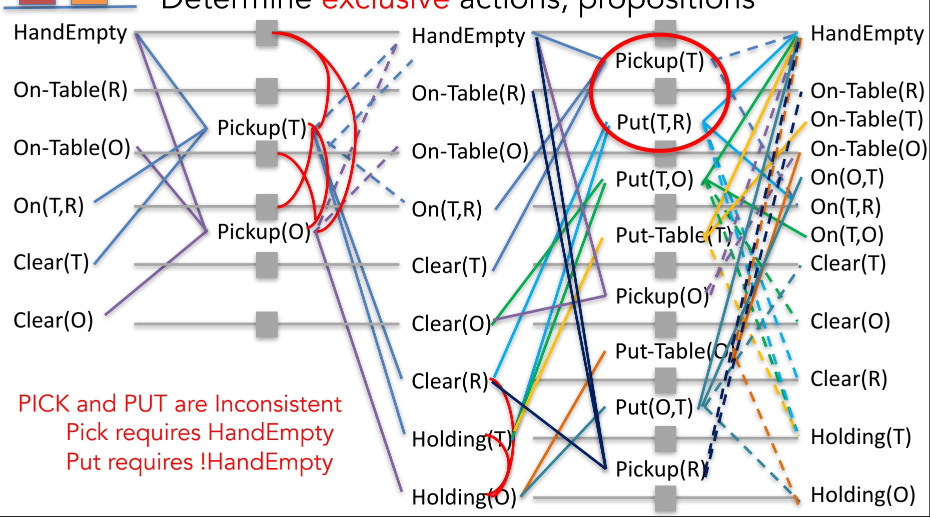
Extend the graph with all applicable actions, noops
Determine exclusive actions, propositions



ALL LEVEL 2 ACTIONS
MUTALLY EXCLUSIVE…
WHAT KIND?

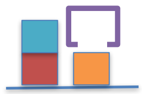
Building a Planning Graph

Extend the graph with all applicable actions, noops
Determine exclusive actions, propositions

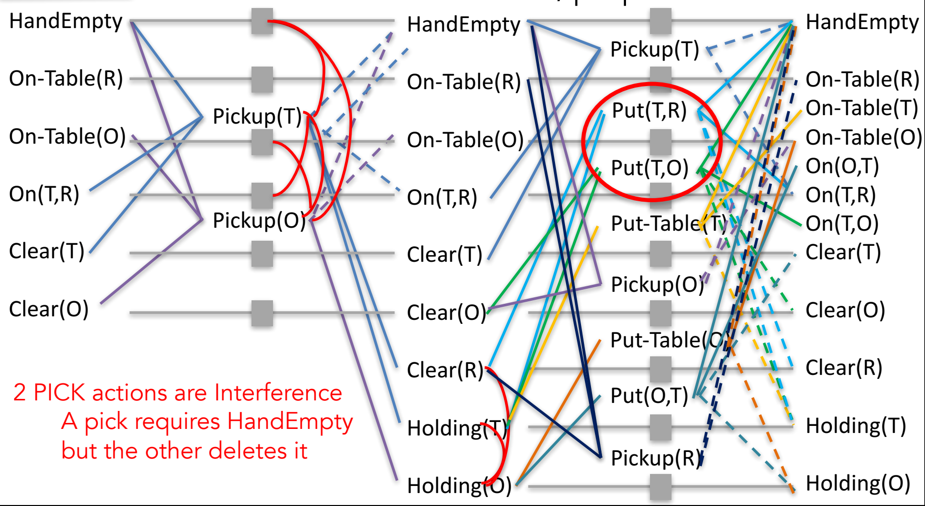


PICK and PUT are Inconsistent
Pick requires HandEmpty
Put requires !HandEmpty

Building a Planning Graph



Extend the graph with all applicable actions, noops
Determine exclusive actions, propositions



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)

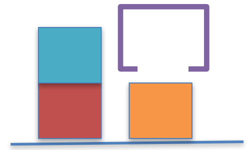
Variables: Can take on any TYPE thing

v_a = Variable(“v_name”,TYPE)

Propositions: Relationships

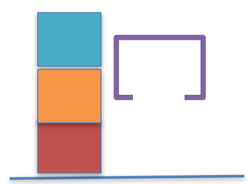
Proposition(“relation”, v_a)
Proposition(“relation”, i)
Proposition(“relation2”, v, i)
Proposition(“relation2”, v_a, v_b)

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)

Piazza Poll – Select All



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

Lists are conjunctions

Lists are conjunctions

Lists are conjunctions

```
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

Variable with matching name must match subsequent propositions

```
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

Variable with matching name must match subsequent propositions

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

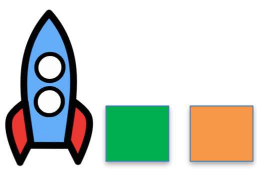
```
pickup_table = Operator("pick_table",
            [Proposition("Handempty",True),
             Proposition("clear", v_block),
             Proposition("on-table", v_block2)],
            [Proposition("holding", v_block)],
            [Proposition("Handempty",True),
             Proposition("on-table",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

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

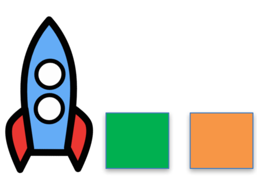
Suppose we have a rocket ship that can only be used once. It has to carry two payloads.



Another Example - Rocket Ship

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

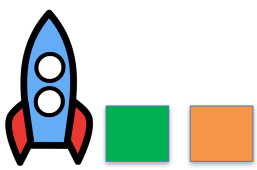
Literals?



Another Example - Rocket Ship

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

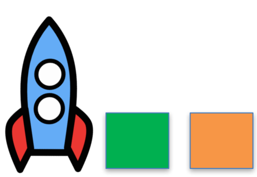
Literals: Rocket, G, O, LocA, LocB



Another Example - Rocket Ship

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

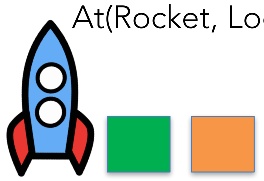
Literals: Rocket, G, O, LocA, LocB
Start state:
    At(Rocket, LocA), Has-Fuel(),
    Unloaded(G,LocA), Unloaded(O,LocA)



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)
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

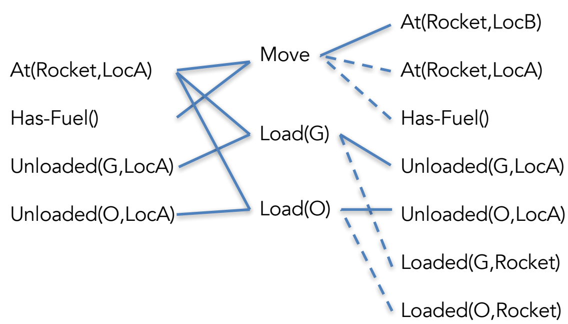
Load:
P: At(Rocket,L), Unloaded(Pkg,L)
A: Loaded(Pkg,Rocket)
D: Unloaded(Pkg,L)

Another Example - Rocket Ship

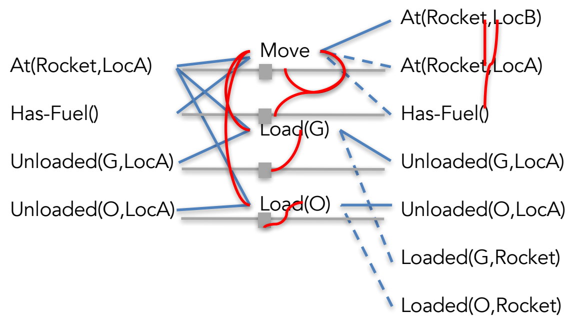
Literals: Rocket, G, O, LocA, LocB
Start state:
At(Rocket, LocA), Has-Fuel(),
Unloaded(G,LocA), Unloaded(O,LocA)
Goal state:
At(Rocket, LocB), Unloaded(G,LocB), Unloaded(O,LocB)
Variables: L, Dest, Pkg

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

Rocket Ship Planning Graph



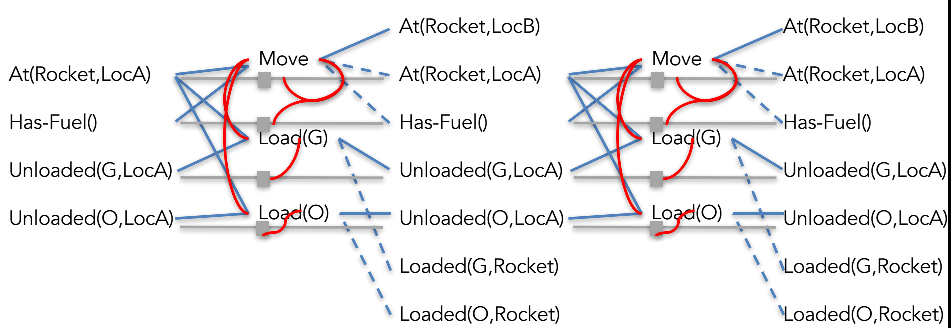
Rocket Ship Planning Graph



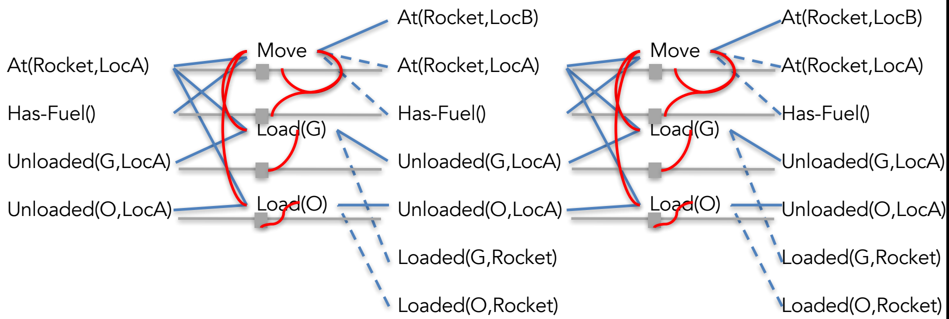
Mutex Propositions:
- At(Rocket,LocB) and At(Rocket,LocA) because Move and noop are mutex actions
- What else?

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

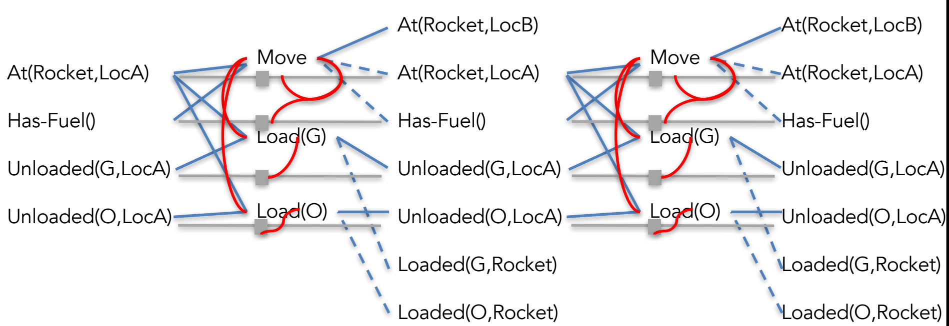


Rocket Ship Planning Graph



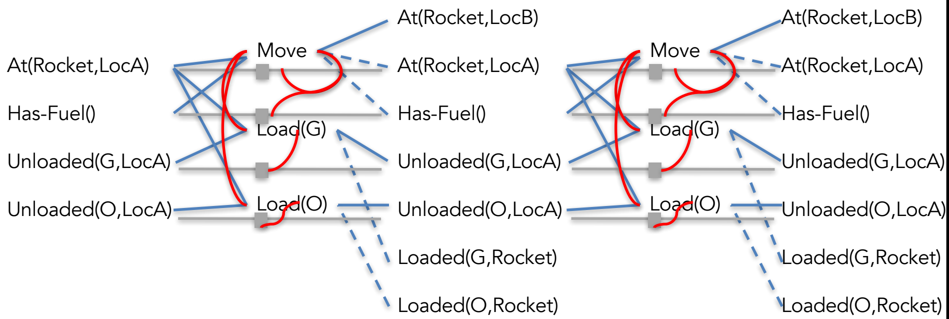
At time 1: Move can be performed OR both Load actions
At time 2: Possible plans include:
- Load(G), Load(O), Move(LocB)
- Load(G), Move(LocB)
- Load(O), Move(LocB)

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

Increasing Generality

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?

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?

How do these different algorithms fit together?

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

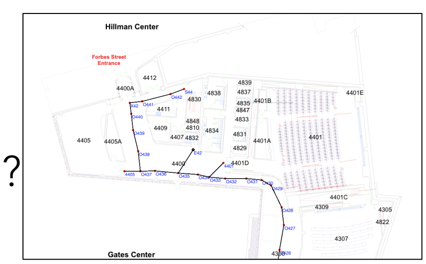
How can I plan the robot's tasks? Where should it go, and it what order?

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?

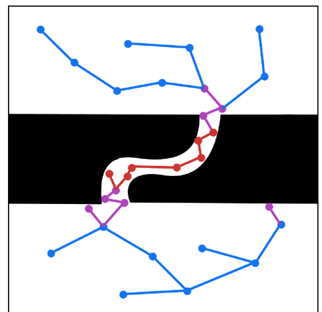


BFS

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

Increasing Generality

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

Another Example: Getting Dressed

States?

Actions?

Goal?

Another Example: Robot Navigation

States?

Actions?

Goal?