CS440/ECE448: Intro to Artificial Intelligence

Lecture 12: Planning algorithms

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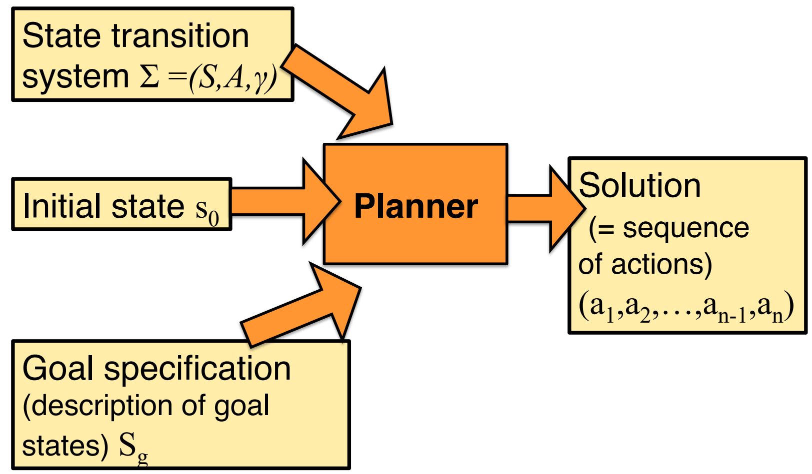
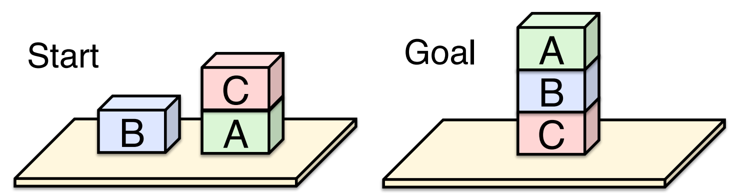
Classical Planning



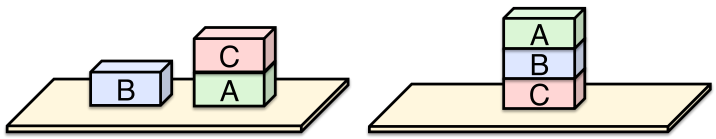
Review: representations for planning

Situation Calculus	Strips
Specify fluents	Specify fluents
Add-set	*Add*-set
Persist-set	*Delete*-set
By default fluents are deleted	By default fluents persist

Sussman anomaly

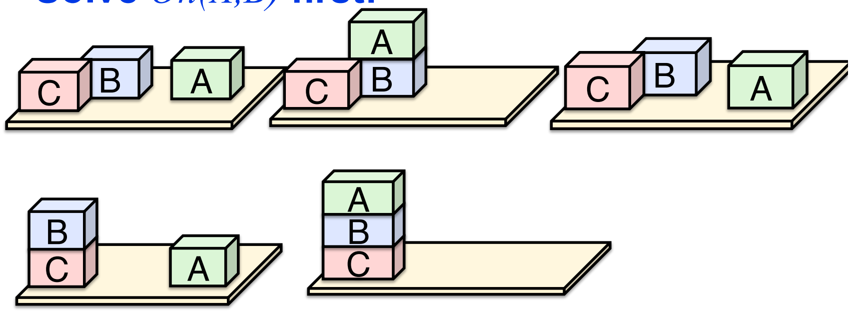


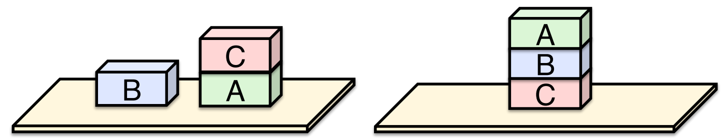
Start: $On(C,A)$
Goal: $On(A,B) \wedge On(B,C)$



Start: $On(C,A)$ Goal: $On(A,B) \wedge On(B,C)$

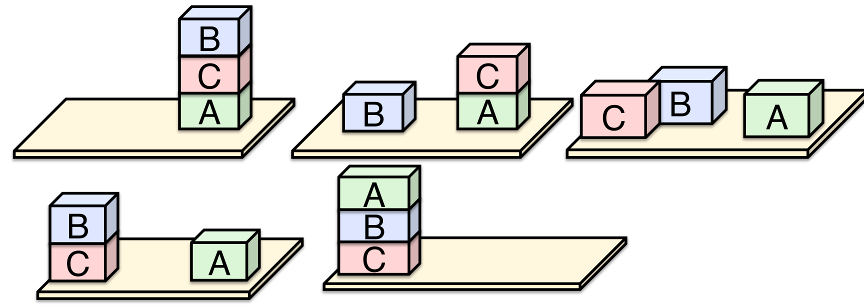
Solve $On(A,B)$ **first:**

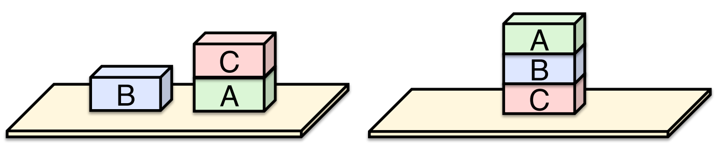




Start: $On(C,A)$ Goal: $On(A,B) \wedge On(B,C)$

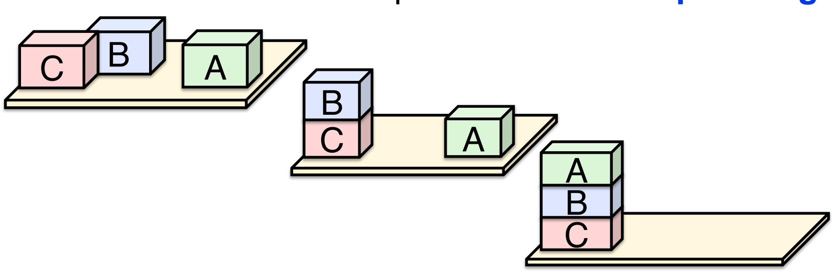
Solve $On(B,C)$ **first:**





Start: $On(C,A)$ Goal: $On(A,B) \wedge On(B,C)$

Most efficient solution requires **interleaved planning:**



Planning algorithms

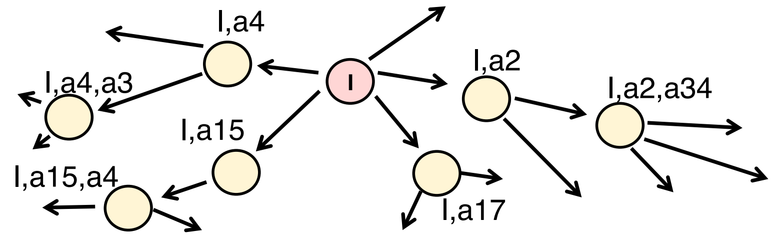
State space search (DFS, BFS, etc.)
Nodes = states; edges = actions;
Heuristics (make search more efficient)
Compute h() using relaxed version of the problem
Plan space search (refinement of partial plans)
Nodes = partial plans; edges: fix flaws in plan
SATplan (encode plan in propositional logic)
Solution = *true* variables in a model for the plan
Graphplan (reduce search space to planning graph)
Planning graph: levels = literals and actions

State space search

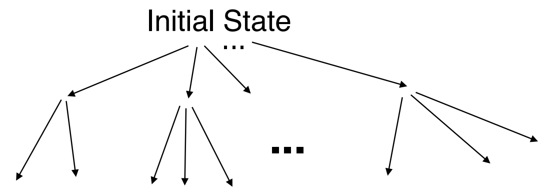
Planning as state space search

Search tree:

- Nodes: states
- Root: initial state
- Edges: actions (ground instances of operators
- Solutions: paths from initial state to goal.



Forward search



Breadth-first forward search is sound and complete, but may require lots of memory

Depth-first forward search can be better in practice (needs graph-search to be complete)

Problem: branching factor is very large (need good heuristic: which actions may lead to goal?)

DFS and loops: iterative deepening

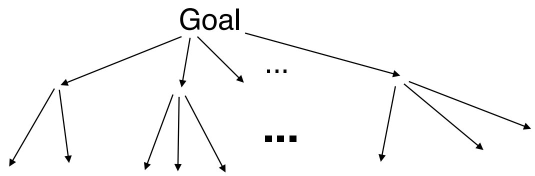
Loops ($s_i \rightarrow \ldots \rightarrow s_i$) in the search graph lead to infinite branches in the search tree.

The tree-search variant of DFS never terminates if it goes down an infinite branch

Remedy (iterative deepening):

- Try to find solution of length l with DFS
- If this fails, $l := l + \Delta$; try again.

Backward search



Start with goal; ‘undo’ actions until initial state

Edges = inverse actions a^{-1}:

$Result(a^{-1},s) = s \setminus effects(a) \cup precond(a)$

Large branching factor: many possible actions; not every $Result(a^{-1}, s)$ leads back to initial state

State space search is inefficient

Observation 1: many actions are independent.

e.g.: *move(A,B,C)* and *move(D,E,F)*

We don’t want to have to commit to specific order.

Observation 2: naïve backward search requires fully instantiated actions. We often don’t know/care how to instantiate variables.

move(A,B,?C) is prerequisite for *move(B,D,E)*, but we don’t care which C A moves to.

Plan-space search

Searching plan-space

States in plan-space are partial plans: = sets of partially instantiated actions with constraints on precedence and variable (in)equality

$move(A,B,x) < move(B,y,z); \; z \neq A$

Solution is (partially ordered) complete plan with fully instantiated actions

Searching plan-space

1. Start with the empty plan
   = *{start state, goal state}*

2. Iteratively refine current plan to resolve flaws
   (refine = add new actions and constraints)

3. Solution = a plan without flaws

Flaws: open goals

Open goal: a precondition that is not yet met
move(A,B,x) requires *clear(x)*

Solution*:*
add new action and precedence constraint:
move(A,B,x) needs to be preceded by
some new action *A* with effect *clear(x).*

Flaws: threats

C is a threat if *A* is a precondition for *B*
and *C* undoes the effect of *A.*

move(A,B,x) establishes precondition *clear(B)* for *move (C,D,B). move(E,F,B)* undoes *clear(B)*

Solution: add new precedence constraint: *move(E,F,B)*
has to precede *move(A,B,x)*, or follow *move(C,D,B)*.

SATplan

SATplan: basic idea

We can encode a plan of fixed length *n* (*n* time steps required for solution) as a formula in propositional logic.

There is a solution if this formula is satisfiable. Use existing tools (SAT solvers)

If there is no solution of length *n,* try *n+1.*

From plans to propositional logic

– **Fluents** are ground literals:
$clear(B)^t$: block *B* is clear at time *t*

– **Actions** are ground implications:
$(preconditions^t \land action^t) \rightarrow effect^{t+1}$

Operator *move(x,y,z):*
PRE: on(x,y), clr(z) EFFECT: on(x,z),clr(y)
Action $move(A,B,C)^{23}$
$(on(A,B)^{23} \land clr(C)^{23} \land move(A,B,C)^{23}) \rightarrow on(A,C)^{24} \land clr(B)^{24}$

Graphplan

Basic idea

1. Create an easier, relaxed problem P':
   – can be solved in polynomial time
   – relax = remove some restrictions
   – Solutions to P' ⊃ solutions to P
2. Solve this relaxed problem P'
3. Search among solutions to P' for solutions to P

Iterative deepening: try to solve P' in 1,…,n steps

Basic idea

Relaxed problem P': can we satisfy some necessary precondition for the goal of P in *k* steps? (N.B.: this only solves P if *all* necessary preconditions can be achieved in *k* steps)

Solve P': build a planning graph of depth *(2)k*

Solve P: do backward search on the planning graph to extract solution to P. If this fails, set k to k+1.

Planning graph: nodes

Two kinds of levels alternate:

State level S_i:

Node at level S_i: a ground fluent (pos. or neg. literal) which may hold *i* actions after S_0

Action level A_i:

Node at level A_i: a ground action (incl. *noop*) whose preconditions might be satisfied at S_i

Have your cake and eat it too!

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

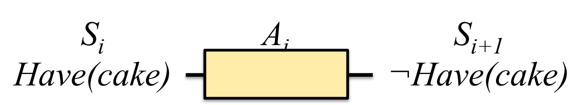
Action *Eat(Cake):*
PRECOND: *Have(Cake)*
EFFECT: ¬*Have(Cake)* ∧ *Eaten(Cake)*

Action *Bake(Cake):*
PRECOND: ¬*Have(Cake)*
EFFECT: *Have(Cake)*

Preconditions/effects: edges *between* levels

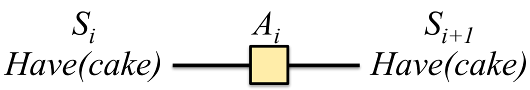
From state level S_i to action level A_i:
the node (fluent) at level S_i is a precondition for the node (action) at level A_i

From action level A_i to state level S_{i+1}
the node (fluent) at level S_{i+1} is an effect of the node (action) at level A_i



Persistence (no-op) actions

For each literal C_i at state level S_i:

- add a **persistence action $Noop_C$** at action level A_i
- Link from **C_i to $Noop_C$**
- Also add **$C_{(i+1)}$** to state level S_{i+1}
- Link from **$Noop_C$ to C_{i+1}**
- 

Mutually exclusive actions: *mutex* links *within* action levels

–Inconsistent effects:
effect of A_1 negates effect of A_2
eat(cake) negates *bake(cake)*

–Interference:
effect of A_1 negates precondition of A_2
eat(cake) interferes with no-op for *have(cake)*

–Competing needs:
preconditions of A_1, A_2 are *mutex*
eat(cake) competes with *bake(cake)*

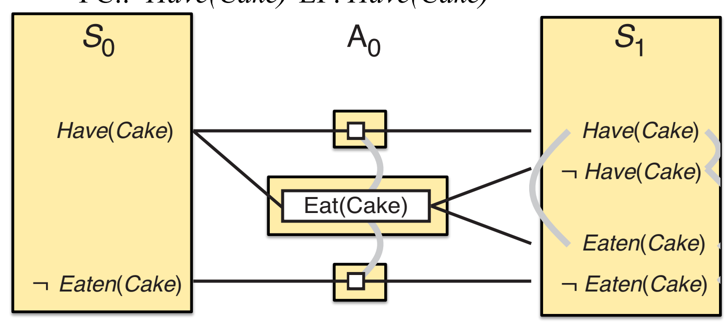
Mutually exclusive fluents: edges *within* state levels

Mutex within **state level S_i:** *F1* and F2 cannot hold at the same time.

- Negation:
  have(Cake) negates ¬*have(Cake)*
- Inconsistent support:
  all actions a1 to achieve F1 are mutex with any action a2 that achieves F2.
  have(Cake) and *eaten(Cake)*

The initial planning graph

Action ***Eat(Cake)***
PC: *Have(Cake)* EF: ¬*Have(Cake)* ∧ *Eaten(Cake)*
Action ***Bake(Cake)***
PC.:¬*Have(Cake)* EF: *Have(Cake)*



The size of the planning graph

The original planning problem P has *l* literals and *a* actions

Size of planning graph with *n levels*: polynomial in *l* and *a*

- State levels: at most *l* nodes and l^2 *mutex* links
- Action levels: at most *a+l* nodes, $(a+l)^2$ *mutex;*

Solution extraction

If all literals in *goal(P)* hold at S_n and are not *mutex* with each other, we may be able to find a solution by backward search:

- States in backward search tree: conjunction of (a subset of the) literals at S_i
- Actions in backward search tree: conflict-free subset of actions at A_{i-1}
- Goals of S_n: all literals in *goal(P)*
- At each state level S_i, select

The search tree for solution extraction

- **State**: conjunction of (subset of the) literals at S_i
- **Initial state:** all literals in *goal(P)*
- **Goal state:** all literals in *init(P)*

- **Actions**: a conflict-free subset **a** of actions at A_{i-1}
- **Result of a set of actions from** A_{i-1}: the conjunction of all literals in S_{i-1} that are preconditions for some action in **a**

Heuristics for planning

Using the planning graph to estimate heuristics

What is the cost of a goal literal *g*?
Minimum cost (level cost)
= minimum number of steps required to achieve *g*
= first state level at which *g*

What is the cost of a conjunction of goal literals?
Max level cost: max. of level costs of each literal
Level sum: sum of level costs (inadmissible)
Set level cost: level at which all are true and each pair of literals is non *mutex*

Today's key concepts

State space search (DFS, BFS, etc.)
Nodes = states; edges = actions;
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