DD2380 Artificial Intelligence

Lecture 10
Classical Planning

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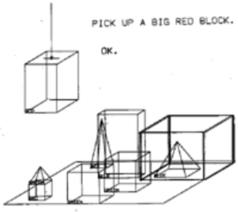
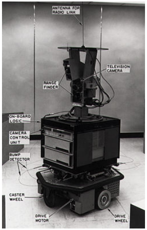
Planning

Deliberating a plan of action to achieve one's goal





Real-world planning

- Limited resources: time, cost, capacity,
- Uncertainty
- Multiple agents
- Different criteria: optimality,
- Robotics: dynamical constraints
- Integration into context, integration with other AI methods

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- Limited resources: time, cost, capacity,
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Today's lecture: only fully observable, deterministic, static, environments.

Planning problem

Planning problem:

- Initial state
- Actions available in a state $ACTIONS(s)$
- Results of applying action $RESULT(s, a)$
- Goal test

Planning vs. problem solving

- Problem solving (search and games):
  - Explicit atomic representations
  - Need good domain-specific heuristics
- Classical planning:
  - Factored representation
  - Domain-independent algorithms

Challenges

- How do we represent a planning problem?
- How do we solve a planning problem?

Challenges

- How do we represent a planning problem?
  - PDDL, STRIPS, ...
- How do we solve a planning problem?

Planning Domain Definition Language (PDDL)

A careful balance between expressivity and simplicity

States

- $At(P, SFO)$
- $At(P, Arlanda) \wedge Plane(P) \wedge Loaded(Cargo, P)$

Actions (think of them as universally quantified)

$$\begin{array}{l} Action(Fly(p, from, to), \\ \quad \textsc{Precond}: At(p, from) \wedge Plane(p) \wedge Airport(from) \wedge Airport(to) \\ \quad \textsc{Effect}: \neg At(p, from) \wedge At(p, to)) \end{array}$$

Example: Air Cargo Transport in PDDL

$$
\begin{aligned}
&Init(At(C_1,\ SFO) \land At(C_2,\ JFK) \land At(P_1,\ SFO) \land At(P_2,\ JFK) \\
&\quad \land Cargo(C_1) \land Cargo(C_2) \land Plane(P_1) \land Plane(P_2) \\
&\quad \land Airport(JFK) \land Airport(SFO)) \\
&Goal(At(C_1,\ JFK) \land At(C_2,\ SFO)) \\
&Action(Load(c,\ p,\ a), \\
&\quad \textsc{Precond}: At(c,\ a) \land At(p,\ a) \land Cargo(c) \land Plane(p) \land Airport(a) \\
&\quad \textsc{Effect}: \neg\, At(c,\ a) \land In(c,\ p)) \\
&Action(Unload(c,\ p,\ a), \\
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\end{aligned}
$$

PDDL States

- State is a conjunction of ground, functionless atomic fluents
  - $At(P, Arlanda) \wedge Plane(P) \wedge Loaded(Cargo, P)$, but
  - Not $\neg At(P, Bromma)$,
  - Not $At(x, y)$,
  - Not $At(P, TheHomeAirport(SAS))$
- Database semantics: Fluents that are not mentionad are false
- Two equivalent viewpoints:
  - Conjunction of fluents: logical inference
  - Set of fluents: set operations

PDDL Action Schemes

Actions and their results are represented through action schemes

- Action name with the list of all used variables
- Precondition: a conjunction of literals saying when an action is *applicable* in a state s, namely if s entails the precondition

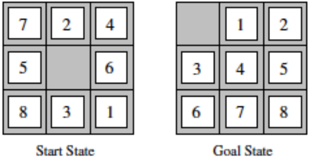
$$ACTIONS(s) = \{a \mid s \models PRECOND(a)\}.$$

- Effect: a conjunction of literals representing the literals that need to be removed and added

$$RESULT(s, a) = (s \setminus DEL(a)) \cup ADD(a),$$

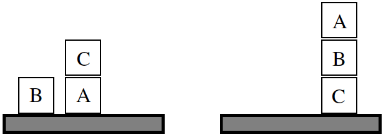
where $DEL(a)$ are the fluents that appear as negative literals in the effect and $ADD(a)$ are the fluents that appear as positive ones.

Q: What are the initial state and the goal test?

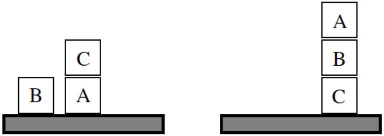


$Action(Slide(t, s_1, s_2))$
$\quad PRECOND : On(t, s_1) \wedge Tile(t) \wedge Blank(s_2) \wedge Adjacent(s_1, s_2)$
$\quad EFFECT : On(t, s_2) \wedge Blank(s_1) \wedge \neg On(t, s_1) \wedge \neg Blank(s_2)$

Block World in PDDL

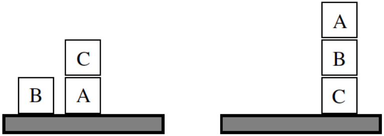


Block World in PDDL



$$Init(On(A, Table) \wedge On(B, Table) \wedge On(C, A)$$
$$\wedge\ Block(A) \wedge Block(B) \wedge Block(C) \wedge Clear(B) \wedge Clear(C))$$
$$Goal(On(A, B) \wedge On(B, C))$$
$$Action(Move(b, x, y),$$
PRECOND: $On(b, x) \wedge Clear(b) \wedge Clear(y) \wedge Block(b) \wedge Block(y) \wedge$
$(b{\neq}x) \wedge (b{\neq}y) \wedge (x{\neq}y)$,
EFFECT: $On(b, y) \wedge Clear(x) \wedge \neg On(b, x) \wedge \neg Clear(y))$
$$Action(MoveToTable(b, x),$$

Block World in PDDL



$$
\begin{array}{l}
Init(On(A, Table) \wedge On(B, Table) \wedge On(C, A) \\
\quad \wedge\ Block(A) \wedge Block(B) \wedge Block(C) \wedge Clear(B) \wedge Clear(C)) \\
Goal(On(A, B) \wedge On(B, C)) \\
Action(Move(b, x, y), \\
\quad \textsc{Precond}{:}\ On(b, x) \wedge Clear(b) \wedge Clear(y) \wedge Block(b) \wedge Block(y) \wedge \\
\qquad\qquad (b \neq x) \wedge (b \neq y) \wedge (x \neq y), \\
\quad \textsc{Effect}{:}\ On(b, y) \wedge Clear(x) \wedge \neg On(b, x) \wedge \neg Clear(y)) \\
Action(MoveToTable(b, x), \\
\quad \textsc{Precond}{:}\ On(b, x) \wedge Clear(b) \wedge Block(b) \wedge (b \neq x), \\
\quad \textsc{Effect}{:}\ On(b, Table) \wedge Clear(x) \wedge \neg On(b, x))
\end{array}
$$

Challenges

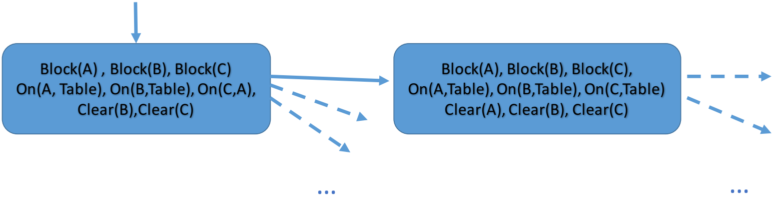
- How do we represent a planning problem?
  - PDDL, STRIPS, ...
- How do we solve a planning problem?

Challenges

- How do we represent a planning problem?
  - PDDL, STRIPS, ...
- How do we solve a planning problem?
  - Via forward search and backward search with heuristics

PDDL Planning Problem as a State Space Search

- Description of a planning problem defines a search problem
- States are truth assignments to fluents, actions and results define the transitions



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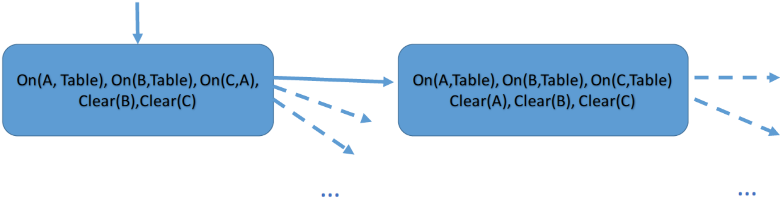

Forward (progression) search

- As expected
  - Start at the initial state
  - Explore applicable actions

- Properties
  - Large branching factor, often explores irrelevant actions
  - Needs a good heuristic, ideally domain-independent

Example: Air Cargo Transport in PDDL

$$
\begin{array}{l}
\mathit{Init}(\mathit{At}(C_1,\ \mathit{SFO}) \wedge \mathit{At}(C_2,\ \mathit{JFK}) \wedge \mathit{At}(P_1,\ \mathit{SFO}) \wedge \mathit{At}(P_2,\ \mathit{JFK}) \\
\quad \wedge\ \mathit{Cargo}(C_1) \wedge \mathit{Cargo}(C_2) \wedge \mathit{Plane}(P_1) \wedge \mathit{Plane}(P_2) \\
\quad \wedge\ \mathit{Airport}(\mathit{JFK}) \wedge \mathit{Airport}(\mathit{SFO})) \\
\mathit{Goal}(\mathit{At}(C_1,\ \mathit{JFK}) \wedge \mathit{At}(C_2,\ \mathit{SFO})) \\
\mathit{Action}(\mathit{Load}(c,\ p,\ a), \\
\quad \textsc{Precond}: \mathit{At}(c,\ a) \wedge \mathit{At}(p,\ a) \wedge \mathit{Cargo}(c) \wedge \mathit{Plane}(p) \wedge \mathit{Airport}(a) \\
\quad \textsc{Effect}: \neg\, \mathit{At}(c,\ a) \wedge \mathit{In}(c,\ p)) \\
\mathit{Action}(\mathit{Unload}(c,\ p,\ a), \\
\quad \textsc{Precond}: \mathit{In}(c,\ p) \wedge \mathit{At}(p,\ a) \wedge \mathit{Cargo}(c) \wedge \mathit{Plane}(p) \wedge \mathit{Airport}(a) \\
\quad \textsc{Effect}: \mathit{At}(c,\ a) \wedge \neg\, \mathit{In}(c,\ p)) \\
\mathit{Action}(\mathit{Fly}(p,\ \mathit{from},\ \mathit{to}), \\
\quad \textsc{Precond}: \mathit{At}(p,\ \mathit{from}) \wedge \mathit{Plane}(p) \wedge \mathit{Airport}(\mathit{from}) \wedge \mathit{Airport}(\mathit{to}) \\
\quad \textsc{Effect}: \neg\, \mathit{At}(p,\ \mathit{from}) \wedge \mathit{At}(p,\ \mathit{to}))
\end{array}
$$

Backward (regression) search

Suitable, since the predecessor function can be easily derived:

$$g' = (g \setminus ADD(a)) \cup PRECOND(a)$$

Idea: Reduce branching by considering only *relevant* (ground) actions, those that make some literal in the goal true, but don't make any literal in the goal false.

Q: What are the relevant ground actions?

$$
\begin{array}{l}
Init(At(C_1, SFO) \wedge At(C_2, JFK) \wedge At(P_1, SFO) \wedge At(P_2, JFK) \\
\quad \wedge\ Cargo(C_1) \wedge Cargo(C_2) \wedge Plane(P_1) \wedge Plane(P_2) \\
\quad \wedge\ Airport(JFK) \wedge Airport(SFO)) \\
Goal(At(C_1, JFK) \wedge At(C_2, SFO)) \\
Action(Load(c, p, a), \\
\quad \text{PRECOND: } At(c, a) \wedge At(p, a) \wedge Cargo(c) \wedge Plane(p) \wedge Airport(a) \\
\quad \text{EFFECT: } \neg At(c, a) \wedge In(c, p)) \\
Action(Unload(c, p, a), \\
\quad \text{PRECOND: } In(c, p) \wedge At(p, a) \wedge Cargo(c) \wedge Plane(p) \wedge Airport(a) \\
\quad \text{EFFECT: } At(c, a) \wedge \neg In(c, p)) \\
Action(Fly(p, from, to), \\
\quad \text{PRECOND: } At(p, from) \wedge Plane(p) \wedge Airport(from) \wedge Airport(to) \\
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\end{array}
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Q: What are the relevant ground actions?

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\begin{aligned}
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&\quad \land Cargo(C_1) \land Cargo(C_2) \land Plane(P_1) \land Plane(P_2)\\
&\quad \land Airport(JFK) \land Airport(SFO))\\
&Goal(At(C_1, JFK) \land At(C_2, SFO))\\
&Action(Load(c, p, a),\\
&\quad \text{PRECOND: } At(c, a) \land At(p, a) \land Cargo(c) \land Plane(p) \land Airport(a)\\
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&\quad \text{EFFECT: } \neg At(p, from) \land At(p, to))
\end{aligned}
$$

Relevant action $Unload(C_2, p', SFO)$

Q: What is the new goal?

$$
\begin{aligned}
&\mathit{Init}(\mathit{At}(C_1,\ \mathit{SFO}) \land \mathit{At}(C_2,\ \mathit{JFK}) \land \mathit{At}(P_1,\ \mathit{SFO}) \land \mathit{At}(P_2,\ \mathit{JFK}) \\
&\quad \land \mathit{Cargo}(C_1) \land \mathit{Cargo}(C_2) \land \mathit{Plane}(P_1) \land \mathit{Plane}(P_2) \\
&\quad \land \mathit{Airport}(\mathit{JFK}) \land \mathit{Airport}(\mathit{SFO})) \\
&\mathit{Goal}(\mathit{At}(C_1,\ \mathit{JFK}) \land \mathit{At}(C_2,\ \mathit{SFO})) \\
&\mathit{Action}(\mathit{Load}(c,\ p,\ a), \\
&\quad \text{PRECOND: } \mathit{At}(c,\ a) \land \mathit{At}(p,\ a) \land \mathit{Cargo}(c) \land \mathit{Plane}(p) \land \mathit{Airport}(a) \\
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&\mathit{Action}(\mathit{Fly}(p,\ \mathit{from},\ \mathit{to}), \\
&\quad \text{PRECOND: } \mathit{At}(p,\ \mathit{from}) \land \mathit{Plane}(p) \land \mathit{Airport}(\mathit{from}) \land \mathit{Airport}(\mathit{to}) \\
&\quad \text{EFFECT: } \neg\, \mathit{At}(p,\ \mathit{from}) \land \mathit{At}(p,\ \mathit{to}))
\end{aligned}
$$

Q: What is the new goal?

$Init(At(C_1, SFO) \land At(C_2, JFK) \land At(P_1, SFO) \land At(P_2, JFK)$
$\quad \land Cargo(C_1) \land Cargo(C_2) \land Plane(P_1) \land Plane(P_2)$
$\quad \land Airport(JFK) \land Airport(SFO))$
$Goal(At(C_1, JFK) \land At(C_2, SFO))$
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$Action(Fly(p, from, to),$
$\quad$ PRECOND: $At(p, from) \land Plane(p) \land Airport(from) \land Airport(to)$
$\quad$ EFFECT: $\neg At(p, from) \land At(p, to))$

Relevant action $Unload(C_2, p', SFO)$

$$g' = At(C_1, JFK) \land$$
$$In(C_2, p') \land At(p', C_2) \land Cargo(C_2) \land Plane(p') \land Airport(SFO)$$

Heuristics

In both progression and regression search, we need good a heuristic.

Domain-independent heuristics

- Any planning problem instance
- Define a relaxed, easier problem and a heuristic as a solution to this easier problem
- Use the internal structure of a factored representation of the state space

- Ignore preconditions
- Ignore delete lists
- State abstraction
- Decomposition
- Planning graph

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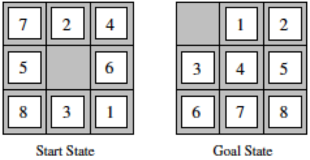
Ignore preconditions

Ignore all preconditions

- Every action becomes applicable in every state
- The number of edges in the graph increases
- The number of steps to solve the relaxed problem is almost the number of unsatisfied fluents in the goal
  - Some actions may achieve multiple goals
  - Some actions may undo the effects of others

Ignore some preconditions

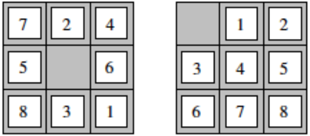
Example: Ignore preconditions



$Action(Slide(t, s_1, s_2))$
$PRECOND : On(t, s_1) \wedge Tile(t) \wedge Blank(s_2) \wedge Adjacent(s_1, s_2)$
$EFFECT : On(t, s_2) \wedge Blank(s_1) \wedge \neg On(t, s_1) \wedge \neg Blank(s_2)$

$h_1(n)$: number of the misplaced tiles

Example: Ignore preconditions



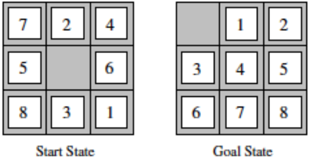
Start State   Goal State

$Action(Slide(t, s_1, s_2))$
  $PRECOND : On(t, s_1) \wedge Tile(t) \wedge Blank(s_2) \wedge Adjacent(s_1, s_2)$
  $EFFECT : On(t, s_2) \wedge Blank(s_1) \wedge \neg On(t, s_1) \wedge \neg Blank(s_2)$

$h_1(n)$: number of the misplaced tiles

- The relaxed problem assumed we can transfer any tile anywhere
- $PRECOND : On(t, s_1) \wedge Tile(t) \cancel{\wedge Blank(s_2) \wedge Adjacent(s_1, s_2)}$

Q: Match ignoring preconditions with the heuristic



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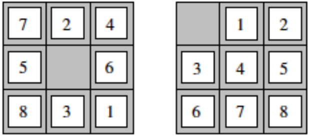
$h_2(n)$: sum of the distances of the tiles from the goal position

Q: Match ignoring preconditions with the heuristic



Start State Goal State

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$h_2(n)$: sum of the distances of the tiles from the goal position

- The relaxed problem assumed we can transfer any tile to an adjacent cell

  $PRECOND : On(t, s_1) \wedge Tile(t) \cancel{\wedge Blank(s_2)} \wedge Adjacent(s_1, s_2)$

Domain-independent heuristics

- Any planning problem instance
- Define a relaxed, easier problem and a heuristic as a solution to this easier problem
- Use the internal structure of a factored representation of the state space

- Ignore preconditions
- Ignore delete lists
- State abstraction
- Decomposition
- Planning graph

Ignore Delete Lists

- Remove all negative literals from effects
- No action will undo progress by another action towards the goal
- The number of edges in the graph increases

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State Abstraction

- Many-to-one mapping from states in the ground representation to the abstract representation
- The number of states decreases
- Ignore some fluents

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Decomposition

- $G = G_1 \wedge \ldots \wedge G_n$
- Instead of problem P, we solve problems $P_1, \ldots, P_n$
- We can use $\max_i COST(P_i)$ as a heuristic

Decomposition

- $G = G_1 \wedge \ldots \wedge G_n$
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- Q: Can we use $COST(P_1) + \ldots + COST(P_n)$ as a heuristic?

Decomposition

- $G = G_1 \wedge \ldots \wedge G_n$
- Instead of problem P, we solve problems $P_1, \ldots, P_n$
- We can use $\max_i COST(P_i)$ as a heuristic

- Q: Can we use $COST(P_1) + \ldots + COST(P_n)$ as a heuristic?

- Q: What generally happens if we use a non-admissible heuristic?

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- Ignore delete lists
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Planning Graph

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

Planning Graph

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

State level

S_0

Have(*Cake*)

$\neg$ *Eaten*(*Cake*)

Each fluent that holds initially

Planning Graph

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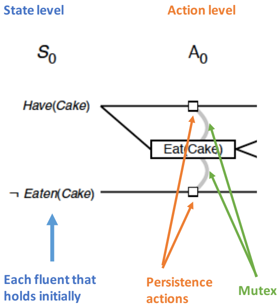
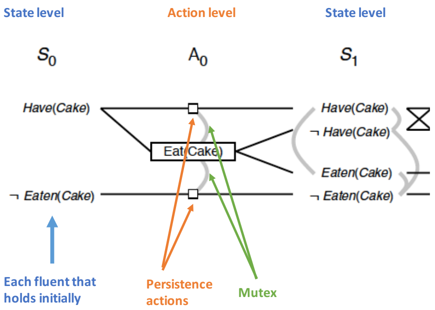


Mutex:

- Inconsistent effects: one action negates the effect of the other
- Interference: one of the effects of one action is the negation of a precondition of the other
- Competing needs: one of the preconditions of one action is the negation of a precondition of the other

Planning Graph

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

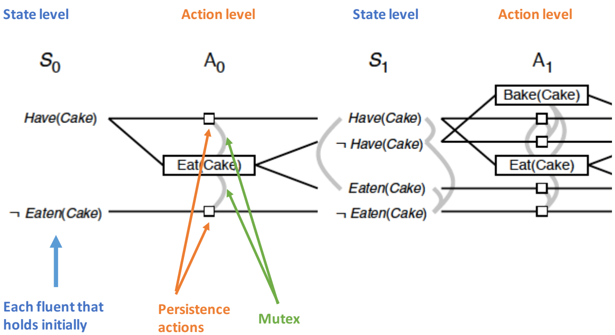


Mutex for literals:

- Negation
- If each possible pair of actions that could achieve the two literals is mutually exclusive

Planning Graph

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



Planning Graph

$Init(Have(Cake))$
$Goal(Have(Cake) \land Eaten(Cake))$
$Action(Eat(Cake)$
  PRECOND: $Have(Cake)$
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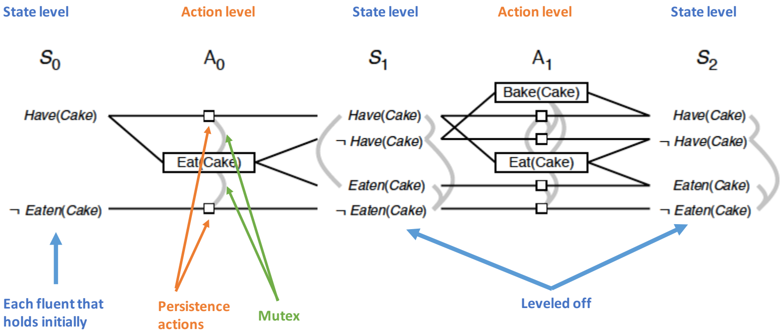


Planning Graph

- Directed graph with alternating state and action levels
- Roughly,
  - S_i level contains literals that could hold at time i
  - A_i level contains actions that could have their precoditions satisfied at time i.
- Persistence actions: a literal can persist if no action negates it
- Mutex:
  - Inconsistent effects: one action negates effect of the other
  - Interference: effect of one action negates a precondition of the other
  - Competing needs: the precondition of one action is mutually exclusive with a precondition of the other

Planning Graph Properties

- Polynomial in the size of the planning problem
- A literal never appears too late, but might appear too early
- If a goal literal does not appear in the final level of the graph, the problem is unsolvable

- We can use it for designing an independent-domain heuristic:
  - Max-level heuristic: admissible, but not always accurate
  - Level-sum heuristic: generally inadmissible, but works well in practice
  - Set-level heuristic: find the level at which all the goal literals appear without being mutually exclusive; admissible and works well

Challenges

- How do we represent a planning problem?
  - PDDL, STRIPS, ...
- How do we solve a planning problem?
  - Via forward search and backward search with heuristics

Challenges

- How do we represent a planning problem?
  - PDDL, STRIPS, ...
- How do we solve a planning problem?
  - Via forward search and backward search with heuristics
  - Via GRAPHPlan

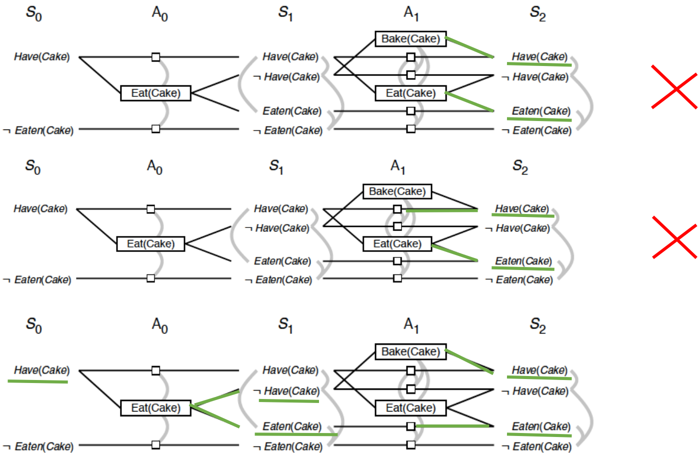
GRAPHPlan

- Using the planning graph to extract a plan directly instead of using it to design a heuristic for search
- EXTRACT-SOLUTION either through CSP or through backward search in the planning graph, not in the state space
- If EXTRACT-SOLUTION does not find a plan, we store (*level*, *goals*) in *nogoods*

function GRAPHPLAN(*problem*) **returns** solution or failure

  graph ← INITIAL-PLANNING-GRAPH(*problem*)
  goals ← CONJUNCTS(*problem*.GOAL)
  nogoods ← an empty hash table
  for $tl = 0$ **to** ∞ **do**
    if *goals* all non-mutex in S_t of *graph* **then**
      solution ← EXTRACT-SOLUTION(*graph*, *goals*, NUMLEVELS(*graph*), *nogoods*)
      if *solution* $\neq$ *failure* **then return** *solution*
    if *graph* and *nogoods* have both leveled off **then return** *failure*
    graph ← EXPAND-GRAPH(*graph*, *problem*)

GRAPHPlan



S_0
A_0
S_1
A_1
S_2
Have(Cake)
¬ Eaten(Cake)
Eat(Cake)
Have(Cake)
¬ Have(Cake)
Eaten(Cake)
¬ Eaten(Cake)
Bake(Cake)
Eat(Cake)
Have(Cake)
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Eaten(Cake)
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S_0
A_0
S_1
A_1
S_2
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Eaten(Cake)
¬ Eaten(Cake)

GRAPHPlan Properties

- Literals increase monotonically
- Actions increase monotonically
- Mutexes decrease monotonically
- No-goods decrease monotonically

- It is not enough to level-off the graph
- Termination when mutexes and no-goods have both leveled off

Challenges

- How do we represent a planning problem?
  - PDDL, STRIPS, ...
- How do we solve a planning problem?
  - Via forward search and backward search with heuristics
  - Via GRAPHPlan
  - As refinement of partially ordered plans
  - As Boolean satisfiability
  - As first-order logical deduction: situation calculus
  - As constraint satisfaction

Think-pair-share

- What is the point of using planning as opposed to problem solving?
- What are the limitations of PDDL as we saw it today?

Final remarks

Where to learn more

- Artificial Intelligence: A Modern Approach by Stuart J. Russell and Peter Norvig, chapter 10 + the udacity course Intro to AI
- Automated Planning and Acting by Dana S. Nau, Malik Ghallab, and Paolo Traverso

Tools

- http://www.fast-downward.org