CSE537

AIMA CHAPTER 10.3: PLANNING GRAPHS

Resource: based on material & slide
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SEARCH AND PLANNING

- Planning: generate seq. of actions to achieve one's goals
- We have seen two examples of planning agents so far:
  - search-based problem-solving agent of Ch.3
    - can find sequences of actions that result in a goal state.
    - but deals with atomic states (needs good domain-specific heuristics)
  - hybrid logical agent of Chapter 7.
    - can find plans without domain-specific heuristics

      (uses domain-independent heuristics based on the logical structure of the problem)
    - but relies on ground (variable-free) propositional inference

      (it may be over worked when there are many actions and states.)
- We want representation for **planning problems**
  - that **scales up** to problems unable to be handled by earlier approach es.

CLASSICAL PLANNING ENVIRONMENT

The assumptions for classical planning problems

- Fully observable
  - we see everything that matters
- Deterministic
  - the effects of actions are known exactly
- Static
  - no changes to environment other than those caused by agent actions
- Discrete
  - changes in time and space occur in quantum amounts
- Single agent
  - no competition or cooperation to account for

FACTORED REPRESENTATION IN PLANNING LANGUAGE

- What is a good representation?
  - Expressive enough to describe a wide variety of problems
  - Restrictive enough for efficient algorithms to operate on it
  - Planning algorithm should be able to take advantage
    - of the *logical structure* of the problem
- Historical AI planning languages
  - STRIPS was used in classical planners
    - Stanford Research Institute Problem Solver
  - ADL addresses expressive limitations of STRIPS
    - Action Description Language
    - Adds features not in STRIPS
      - negative literals, quantified variables, conditional effects, equality
  - We'll look at a simpler version of de facto standard language called PDDL

PDDL

- PDDL and most of the planning language use *factored* representation for states
  - Each state is represented as a collection of variables
- Planning Domain Definition Language
  - To see its expressive power, recall propositional agent in the Wumpus World, which requires $4Tn^2$ actions to describe a m ovement of 1 square
  - PDDL captures this with a single Action Schema

PDDL: STATE

- Each **state** is represented as a conjunction of fluents: groun d, functionless atoms.
  - Ex> *Poor* ∧ *Unknown* might represent the state of a hapless agent,
  - Ex> a state in a package delivery problem might be *At(Truck1,Melb ourne)* ∧ *At(Truck2,Sydney)*
- **Database semantics** is used
  - the **closed-world assumption**: any fluents that are not mentioned ar e false,
  - the **unique names assumption**: ex>*Truck1* and *Truck2* are distinct
  - fluents *not* allowed: *At(x, y)* (because it is non-ground), ¬*Poor* (beca use it is a negation), and *At (Father (Fred), Sydney)* (because it use s a function symbol).
- This state representation allows alternative algorithms
  - it can be manipulated either by *logical inference* techniques or by
  - *set operations* (sets may be easier to deal with)

PDDL: ACTION SCHEMAS

- **Actions** are defined by a set of *action schemas*
  - These implicitly define the ACTIONS(s) & RESULT(s, a) functi ons required to apply search techniques
- Classical planning concentrates on problems where m ost actions leave most things unchanged.
  - PDDL specify the result of an action in terms of what change s;

    everything that stays the same is left unmentioned.

PDDL: ACTION SCHEMAS

- Ground (variable-free) action are represented by single **action schema** - a *lifted* representation
  - lifts from propositional logic to a restricted subset of First-or der logic
- Consists of
  - the schema name,
  - list of variables used,
    - Consider variables as universally quantified, choose any values we w ant to instantiate them
  - a **precondition**
    - PRECOND: defines states in which an action can be executed
  - an effect
    - EFFECT: defines the result of executing the action

EXAMPLE ACTION SCHEMA

- Each represents a set of variable-free actions
  - Form: Action Schema = predicate + preconditions + effects
  - Example action schema for flying a plane from one location t o another :

    Action(Fly(p, from, to),

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

    EFFECT: ¬AT(p, from) ∧ At(p, to))

  - Action that results from substituting values for all the variabl es:

    Action(Fly(P1,SFO,JFK),

    PRECOND:At(P1,SFO) ∧ Plane(P1) ∧ Airport(SFO) ∧ Airport(JFK)

    EFFECT:¬At(P1,SFO) ∧ At(P1,JFK))

APPLYING ACTION SCHEMA

- Action *a* is *applicable* in state *s*
  - *s entails the* precondition of *a*
    - If *a*'s preconditions are satisfied in *s* *("a is* ***applicable*** *in s")*

      a $\in$ *ACTIONS(s))* $\Leftrightarrow$ *s* |= *PRECOND(a)*
  - Given variables in *a*, there can be multiple applicable instant iations
    - For *v* variables in a domain with *k* unique object names, worst case ti me to find applicable ground actions is $O(v^k)$
  - Leads to one approach for solving PDDL planning problems
    - **Propositionalize** by replacing action schemas with sets of ground acti ons

      then applying a propositional solver like SATPlan
    - Impractical for large v & k

PDDL: RESULT

- Result of executing action *a* in state s is state s'

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

  - Start with s
  - Remove negative literal in the action's effect
    (the *delete list*, DEL(a))
  - Add positive literals in action's EFFECTs
    (the *add list*, ADD(a))
  - For example, with the action Fly(P1,SFO,JFK),
    - we would remove At(P1,SFO) and
    - add At(P1,JFK).
- Any variable in the effect must also appear in the precondi tion.
  - When the precondition is matched against the state s, all the vari ables will be bound, and RESULT(s,a) will therefore have only grou nd atoms.

PDDL: ACTION SCHEMAS

1. Variables & ground terms
   - Variables in effects must also be in precondition
     - so matching to state s yields results with all variables bound
       i.e. that contain only ground terms
     - Ground states are closed under the RESULT operation.
2. Handling of time
   - No explicit time terms
   - Instead time is implicitly represented in PDDL schemas
     - Preconditions always refer to time: t
     - Effects always refer to time: t + 1
3. A set of schemas defines a *planning domain*
   - A specific *problem* within the domain is defined with the addition of an initial state and a goal.

PDDL: INITIAL STATES, GOALS, SOLUTIONS

- Initial state
  - Conjunction of ground terms
- Goal
  - Conjunction of positive and negative literals that contain variable.
    - Both ground terms & those containing variables
    - EX> At (p, SFO) ∧ Plane (p).
  - Variables are treated as existentially quantified
    - EX> so this goal is to have *any* plane at SFO
- Solution
  - A sequence of actions ending in *s* that entails the goal
  - EX> state *Rich ∧ Famous ∧ Miserable* entails the goal *Rich ∧ Famous*,
  - EX> *state Plane(P1) ∧ At (P1, SFO)* entails *At(p, SFO) ∧ Plane (p)*
- We have defined planning as a search problem:
  - have an initial state, an ACTIONS function, a RESULT function, and a goal test

WHY PLANNING GRAPHS

- All of the heuristics we have suggested can suffer from inaccuracies.
- A special data structure called a **planning graph** can be used to give better heuristic estimates.
- We can search for a solution over the space formed by the planning graph, using an algorithm called GRAPH PLAN.
  - These heuristics can be applied to any of the search techniques we have seen so far.

PLANNING GRAPHS

- Graphplan was developed in 1995 by Avrim Blum and Merrick Furst, at CMU.
- Constructs compact constraint encoding of state space from operators and initial state, which prunes many invalid plans.
- A planning graph compactly encodes the space of consistent plans, while pruning . . .
  - Partial states and actions at each time i
    that are not reachable from the initial state.
  - Pairs of actions and propositions
    that are mutually inconsistent at time i.
  - Plans that cannot reach the goals.

PLANNING GRAPHS PROPERTIES

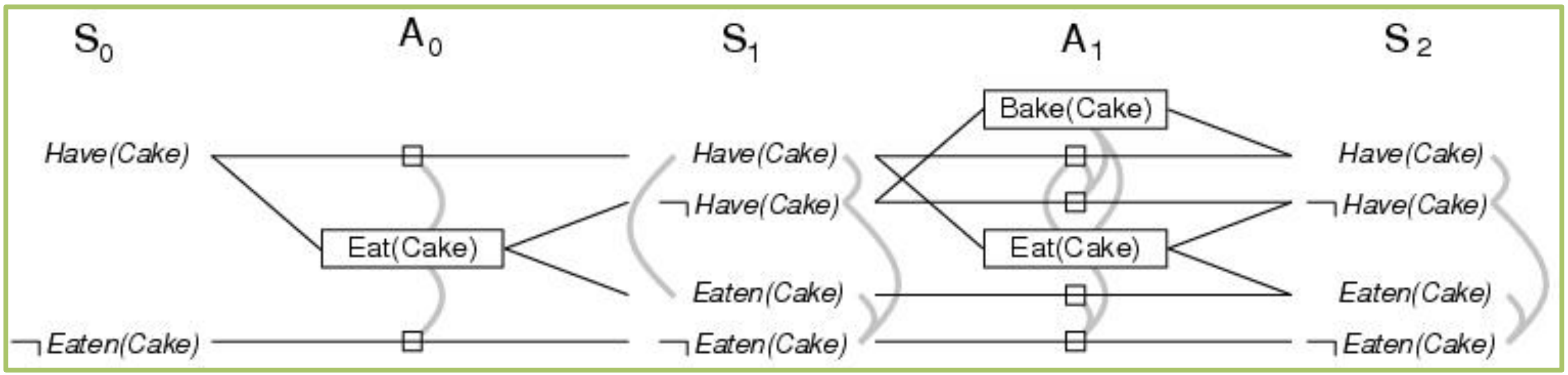
- A **polynomial-size approximation** to tree-based state space searching that can be constructed quickly
- The plan graph does not eliminate all infeasible plans.
- Planning graph cannot answer definitely whether goal G is reachable form initial state S0, but it can estimate how ma ny steps it takes to reach the goal.
  - Always correct when it reports the goal is not reachable
  - Never overestimate the number of steps (admissible heuristic)
- Planning graphs
  - Provide a possible basis for better search heuristics
  - Can be use directly, for extracting a solution to a planning proble m, by applying the GRAPHPLAN algorithm

Problem "Have cake and eat cake too"

PDDL Problem Description

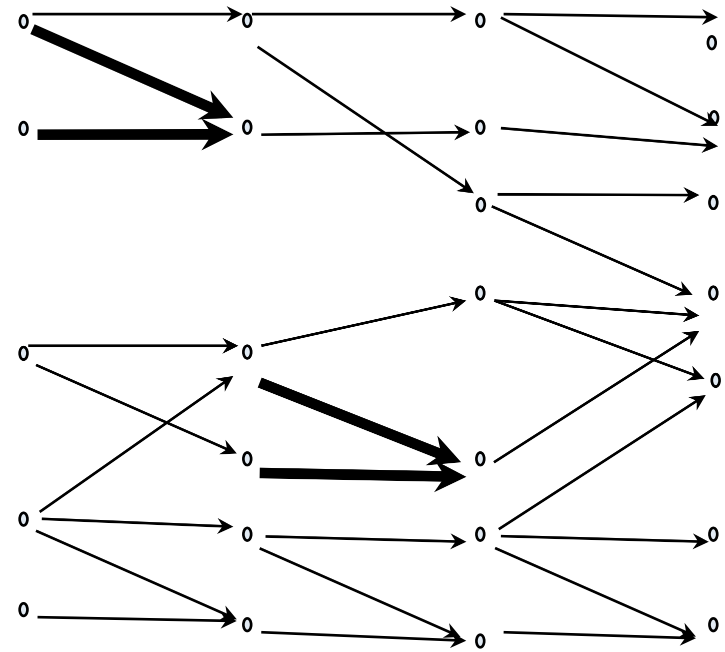
Init(Have(Cake))
Goal(Have(Cake) ∧ Eaten(Cake))
Action(Eat(Cake)
    PRECOND: Have(Cake)
    EFFECT: ¬Have(Cake) ∧ Eaten(Cake))
Action(Bake(Cake)
    PRECOND: ¬ Have(Cake)
    EFFECT: Have(Cake))

corresponding planning graph



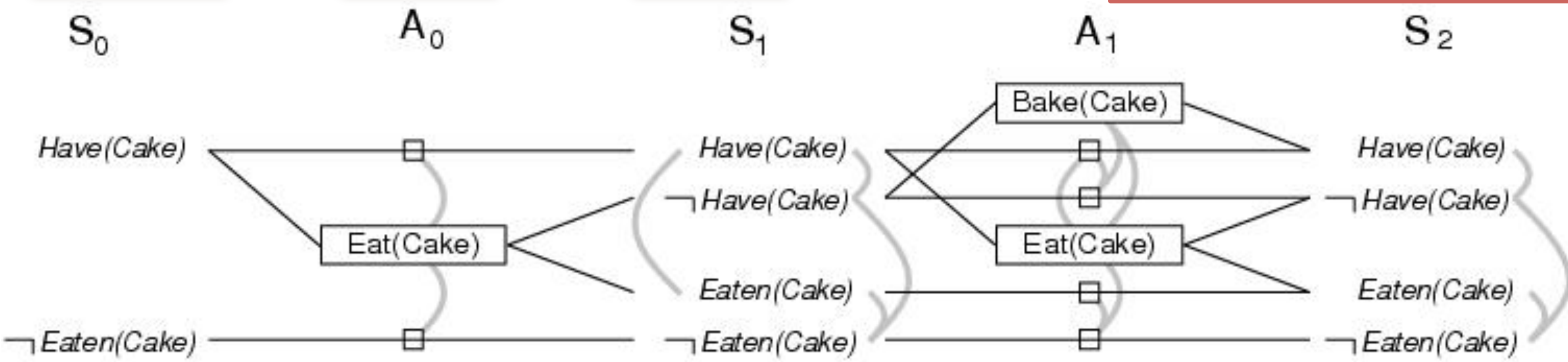
PLANNING GRAPH DESCRIPTION

- Planning graph
  - Is a directed graph organize d in time steps **levels**
  - Consist of alternating
    - S_i level: contains all the literal s that could result from any p ossible choice of action in A_{i-1}
    - A_i level: contains all the action s that are applicable in S_i.
    - Precondition link
    - Effects link
    - Mutual exclusion (mutex) link s: links joining nodes that can not persist simultaneously



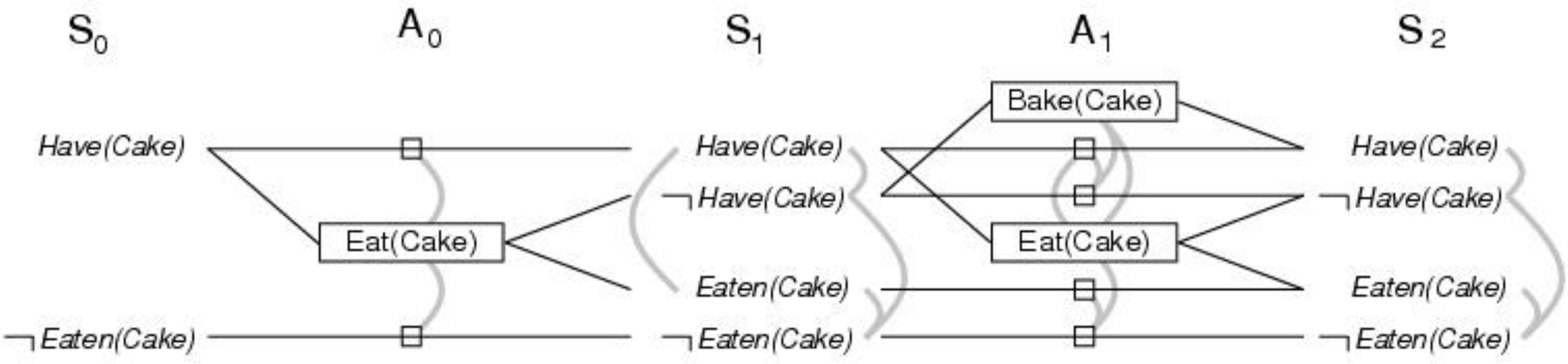
PLANNING GRAPH CAKE EXAMPLE

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))



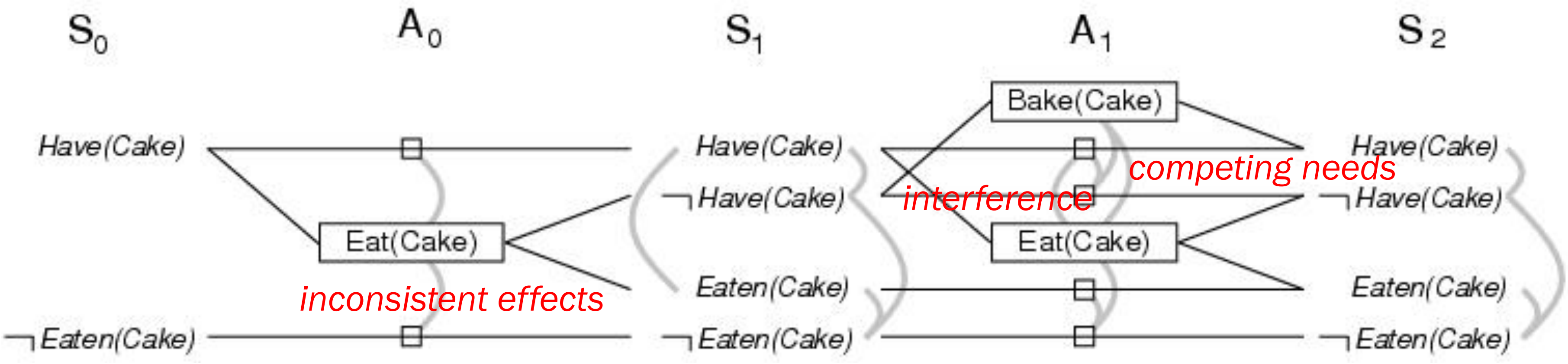
- Start at level S_0, determine action level A_0 & next level S_1
  - A_0: all actions whose preconditions are satisfied in the previous level (i nitial state)
    - Lines connect PRECONDs at S_0 to EFFECTs at S_1
  - Also, for each literal in S_i, there's a *persistence action* (square box) & li ne to it in the next level S_{i+1}
- Level A_0 contains the actions that *could* occur
  - Conflicts between actions are represented by arcs: mutual exclusion or *mutex links*

PLANNING GRAPH CAKE EXAMPLE



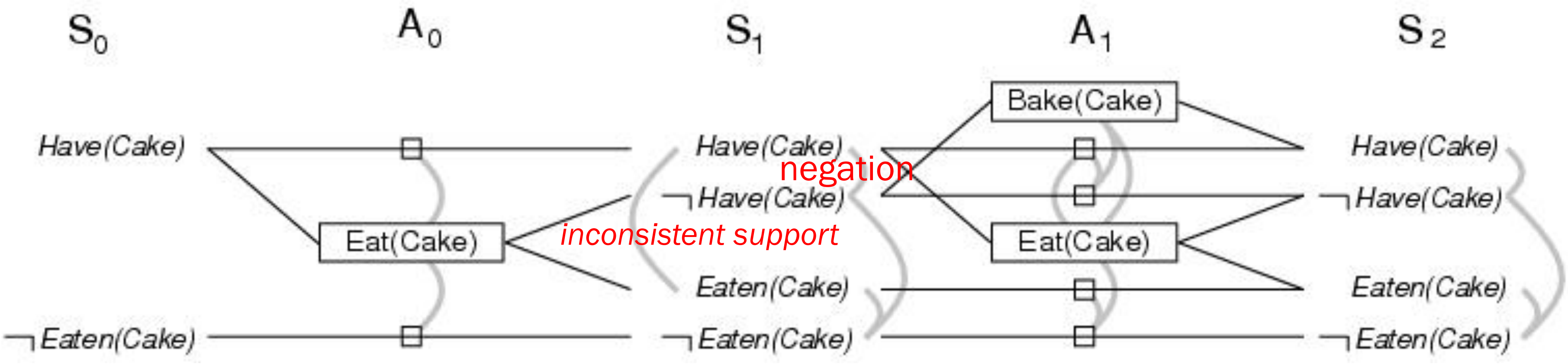
- Level S_1 contains all the literals that could result
  - From picking any subset of actions in A_0
  - So S_1 is a belief state consisting of the set of all possible states
    - Each is a subset of literals with no mutex links between members
  - Conflicts between literals that cannot occur together are represented by the mu tex links.
- The level generation process is repeated
- Termination condition (*leveling off*):
  - When consecutive levels are identical

MUTEX LINKS – ACTION



- Mutex relation holds between 2 actions at a level when
  - 1. *Inconsistent effects*
    - One action negates the effect of another
    - Eat(Cake) and Have(Cake) have inconsistent effects because they disagree on the effect Have(Ca ke).
  - 2. *Interference*
    - An effect of one action negates a precondition of the other;
    - Ex> Eat(Cake) interferes with the persistence of Have(Cake) by negating its precondition.
  - 3. *Competing needs*
    - A precondition of one action is mutex with a precondition of the other
    - Ex> Bake(cake) & Eat(cate) <- compete on the value of Have(cake)

MUTEX LINKS - LITERALS



- Mutex relation holds between 2 literals at a level when
  - 1. One is the negation of the other
  - 2. *Inconsistent support*
    - If each possible action pair that could achieve the literals is mutex
    - Ex> Have(Cake) & Eaten(Cake) at S_1
    - (the only way of achieving Have(Cake), the persistence action, is mutex with the only way of achieving Eaten (Cake),)

PLANNING GRAPHS COMPLEXITY

- Construction has complexity polynomial in the size of t he planning problem:

  $O(n(a + l)^2)$

  - Given l literals and a actions,
  - each S_i has no more than
    - l nodes and
    - l^2 mutex links, and
  - each A_i has no more than
    - $a + l$ nodes (including the no-ops),
    - $(a + l)^2$ mutex links, and
    - $2(al + l)$ precondition and effect links.
  - entire graph with n levels has a size of $O(n(a + l)^2)$

PROPERTIES OF COMPLETED PLANNING GRAPH

- Provides information about the problem & candidate heuristics
- A goal literal g that does not appear in the final level cannot be achieved by any plan
- The level cost, the level at which a goal literal first appears, is useful as a cost estimate of achieving that goal literal
- Note that level cost is admissible, though possibly inaccurate since it counts levels, not actions
  - Planning graphs allow several actions at each level, whereas the heuristic counts just the level and not the number of actions.
  - We could find a better alternative level cost by using a *serial planning graph* variation, restricted to one action per level
    - Add mutex links between every pair of nonpersistence actions

PLANNING GRAPHS & HEURISTICS

- Planning Graph provides
  - Possible heuristics for the cost of a *conjunction of goals*
  - 1. *Max-level* heuristic : highest level of any conjunct in the goal
    - Admissible, possibly not accurate
  - 2. *Level sum* heuristic: the sum of level costs of conjuncts in the g oal
    - Incorporates the subgoal independence assumption
      - So may be inadmissible to degree the assumption does not hold
      - Works well in practice for problems that are largely decomposable
  - 3. *Set-level* heuristic: level where all goal conjuncts are present wi thout mutex links
    - Admissible,
    - Dominates the max-level heuristic
    - Works well on tasks with good deal of interaction among subplans.
    - However, ignores interactions among three or more literals.

PLANNING GRAPHS & HEURISTICS

- A Planning Graph is a relaxed version of the problem
  - If a goal literal *g* does not appear, no plan can achieve it,
  - If it does appear, is not guaranteed to be achievable
  - Why?
    - The PG only captures pairwise conflicts & there could be higher orde r conflicts likely not worth the computational expense of checking for them
      - Similar to Constraint Satisfaction Problems where arc consistency was a valuable pruning tool
    - 3-consistency or even higher order consistency would have made fin ding solutions easier but was not worth the additional work
  - Example where PG fails to detect unsolvable problem
    - Blocks world problem with goal of A on B, B on C, C on A
      - Any pair of subgoals are achievable, so no mutexes
      - Problem only fails at stage of searching the PG

THE GRAPHPLAN ALGORITHM

- GRAPHPLAN algorithm
  - Generates the Planning Graph & extracts a solution directly

function GRAPHPLAN(*problem*) **return** 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* ≠ failure **then return** *solution*
        if *graph* and *nogoods* have both leveled off **then return** failure
        graph ← EXPAND-GRAPH(*graph, problem*)

EXTRACT-SOLUTION: search for a plan that solves the problem.
EXPAND-GRAPH: adds a new level

EXAMPLE: SPARE TIRE PROBLEM

- PDDL of spare tire problem (problem of changing a flat tire)

Goal is to have a good spare tire properly mounted onto the car's axle,

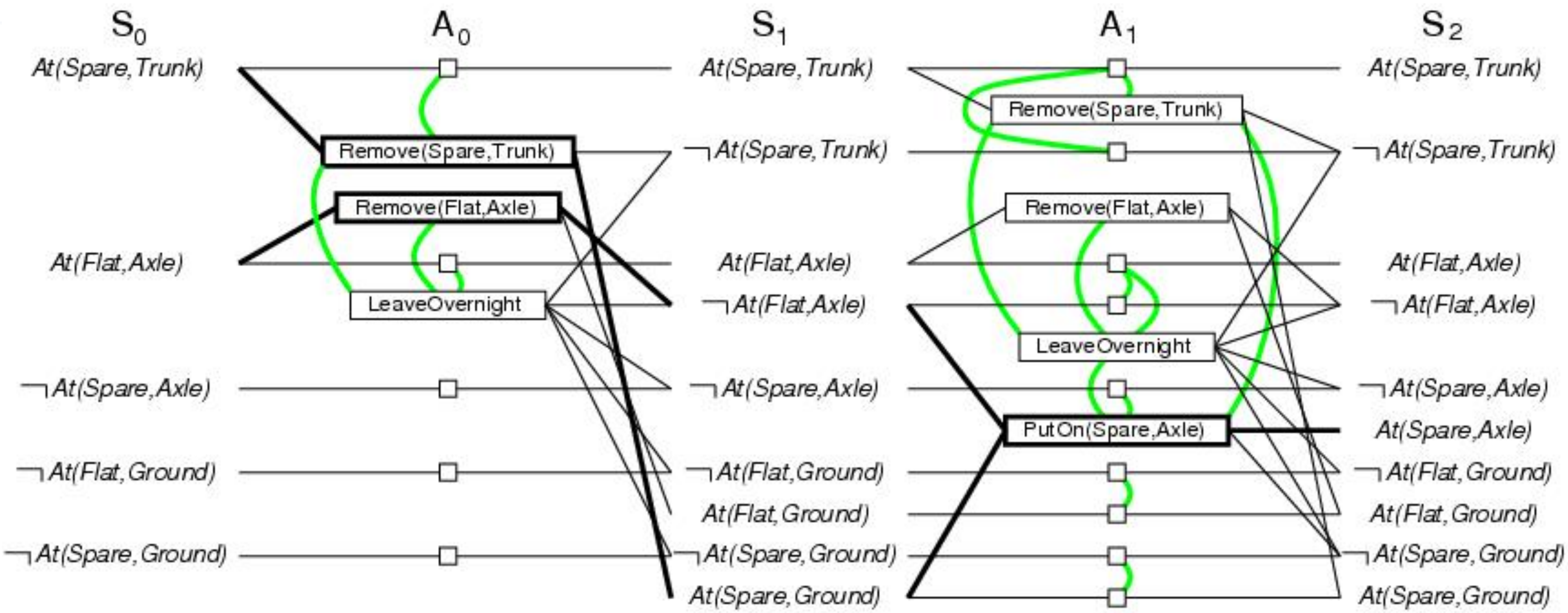
Initial state has a flat tire on the axle and a good spare tire in the trunk.

Init(At(Flat, Axle) ∧ At(Spare, Trunk))

Goal(At(Spare, Axle))

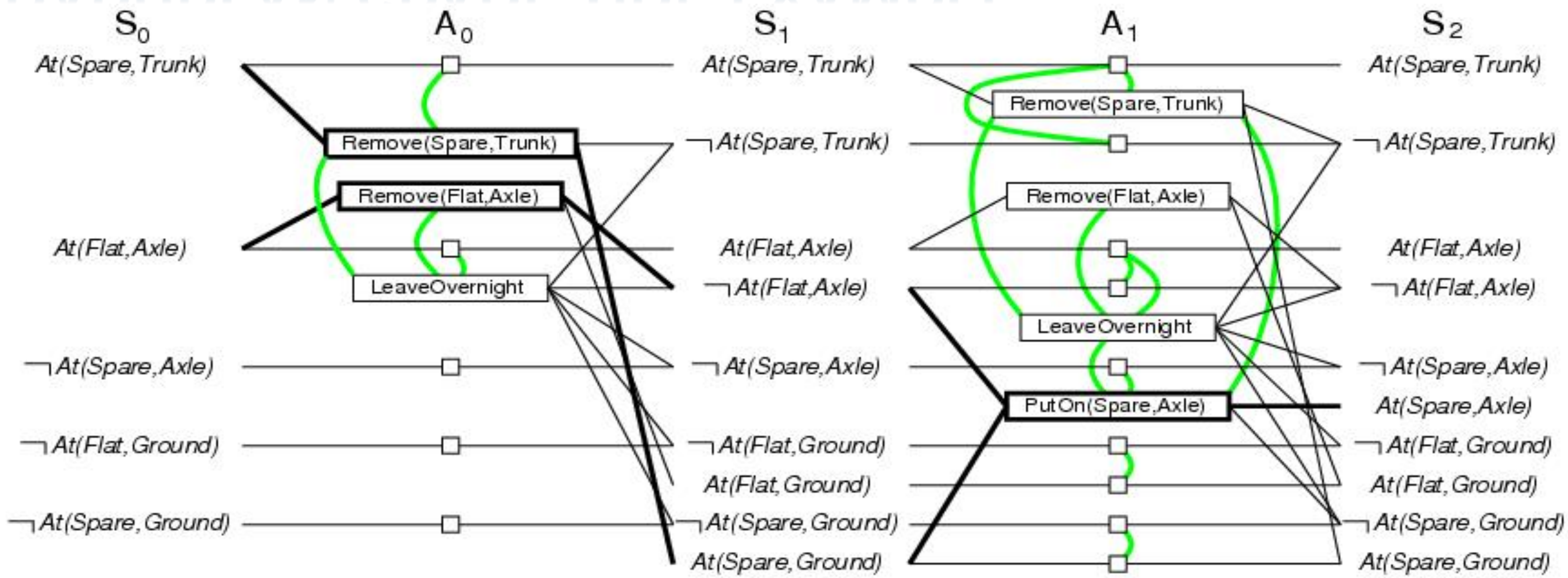
Action(Remove(Spare, Trunk)
    PRECOND: At(Spare, Trunk)
    EFFECT: ¬At(Spare, Trunk) ∧ At(Spare, Ground))
Action(Remove(Flat, Axle)
    PRECOND: At(Flat, Axle)
    EFFECT: ¬At(Flat, Axle) ∧ At(Flat, Ground))
Action(PutOn(Spare, Axle)
    PRECOND: At(Spare, Ground) ∧¬At(Flat, Axle)
    EFFECT: At(Spare, Axle) ∧ ¬At(Spare, Ground))
Action(LeaveOvernight
    PRECOND:
    EFFECT: ¬ At(Spare, Ground) ∧ ¬ At(Spare, Axle)
        ∧ ¬ At(Spare, Trunk) ∧ ¬ At(Flat, Ground) ∧ ¬ At(Flat, Axle))

GRAPHPLAN SPARE TIRE EXAMPLE



- Notes:
  - This figure shows the *complete* Planning Graph for the problem
  - Arcs show mutex relations (arcs between literals are *omitted* to avoid clutter)
  - Omits unchanging positive literals (for example, Tire(Spare))
  - Omits irrelevant negative literals
  - **Bold boxes & links** indicate the solution plan

GRAPHPLAN SPARE TIRE EXAMPLE



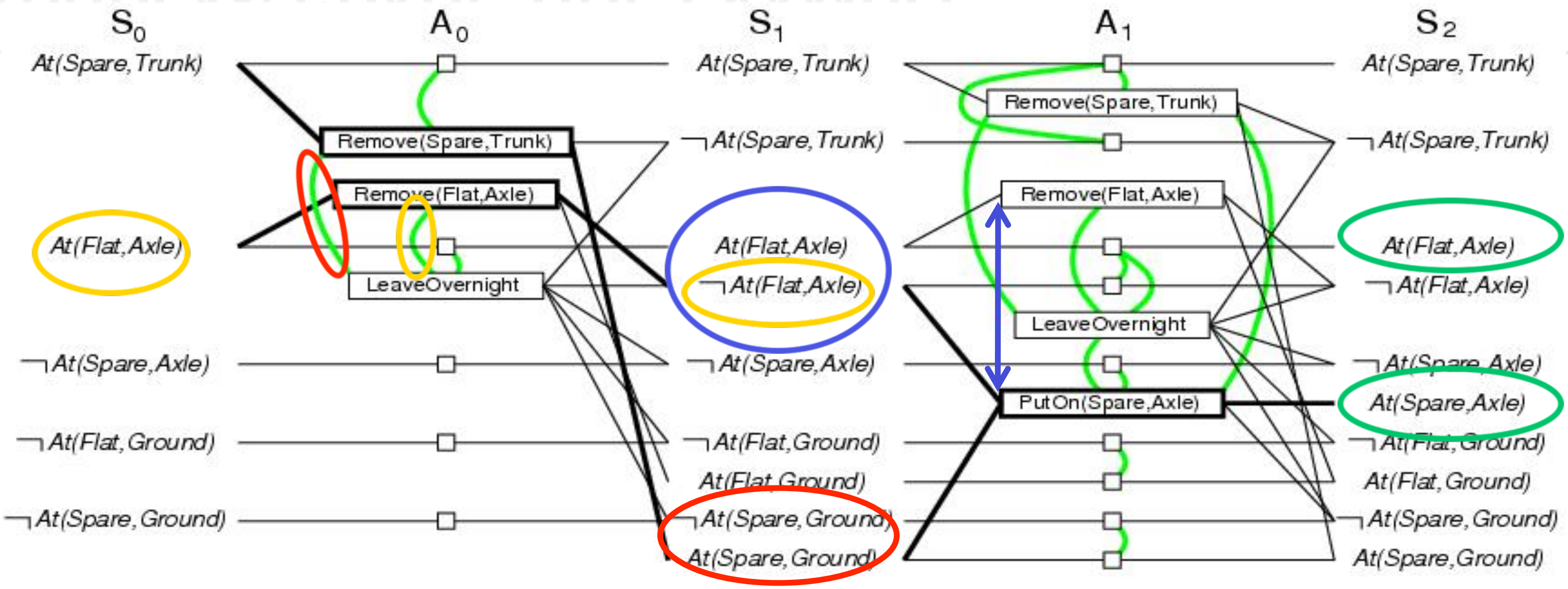
- S_0 is initialized to 5 literals
  - from the problem initial state and the relevant negative literals
- no goal literal in S_0 so **EXPAND-GRAPH add actions**
  - those with preconditions satisfied in S_0
  - also adds *persistence actions* for literals in S_0
  - adds the effects at level S_1, analyzes & adds m utex relations
- repeat until the goal is in level S_i or failure

Init(At(Flat, Axle) ∧ At(Spare, Trunk))

Goal(At(Spare, Axle))

Action(Remove(Spare, Trunk)
PRECOND: At(Spare, Trunk)
EFFECT: ¬At(Spare, Trunk) ∧ At(Spare, Ground))
Action(Remove(Flat, Axle)
PRECOND: At(Flat, Axle)
EFFECT: ¬At(Flat, Axle) ∧ At(Flat, Ground))
Action(PutOn(Spare, Axle)
PRECOND: At(Spare, Ground) ∧¬At(Flat, Axle)
EFFECT: At(Spare, Axle) ∧ ¬At(Spare, Ground))
Action(LeaveOvernight
PRECOND:
EFFECT: ¬ At(Spare, Ground) ∧ ¬ At(Spare, Axle)
∧ ¬ At(Spare, Trunk) ∧ ¬ At(Flat, Ground)
∧ ¬ At(Flat, Axle))

GRAPHPLAN SPARE TIRE EXAMPLE



EXPAND-GRAPH adds constraints: mutex relations

- inconsistent effects (action x vs action y)
  - Remove(Spare, Trunk) & LeaveOvernight:
  - At(Spare, Ground) & ¬At(Spare, Ground)
- interference (effect negates a precondition)
  - Remove(Flat, Axle) & LeaveOvernight:
  - At(Flat, Axle) as PRECOND & ¬At(Flat, Axle) as EFFECT
- competing needs (mutex preconditions)
  - PutOn(Spare, Axle) & Remove(Flat, Axle):
  - At(Flat, Axle) & ¬At(Flat, Axle)
- inconsistent support (actions to produce literals are mutex)
  - in S2, At(Spare, Axle) & At(Flat, Axle): only way to achieve At(Spar e, Axle) is by PutOn(Spare,Axle) and that is mutex with the only a ction for obtaining At(Flat,Axle) .

Init(At(Flat, Axle) ∧ At(Spare, Trunk))

Goal(At(Spare, Axle))

Action(Remove(Spare, Trunk)
PRECOND: At(Spare, Trunk)
EFFECT: ¬At(Spare, Trunk) ∧ At(Spare, Ground))
Action(Remove(Flat, Axle)
PRECOND: At(Flat, Axle)
EFFECT: ¬At(Flat, Axle) ∧ At(Flat, Ground))
Action(PutOn(Spare, Axle)
PRECOND: At(Spare, Ground) ∧¬At(Flat, Axle)
EFFECT: At(Spare, Axle) ∧ ¬At(Spare, Ground))
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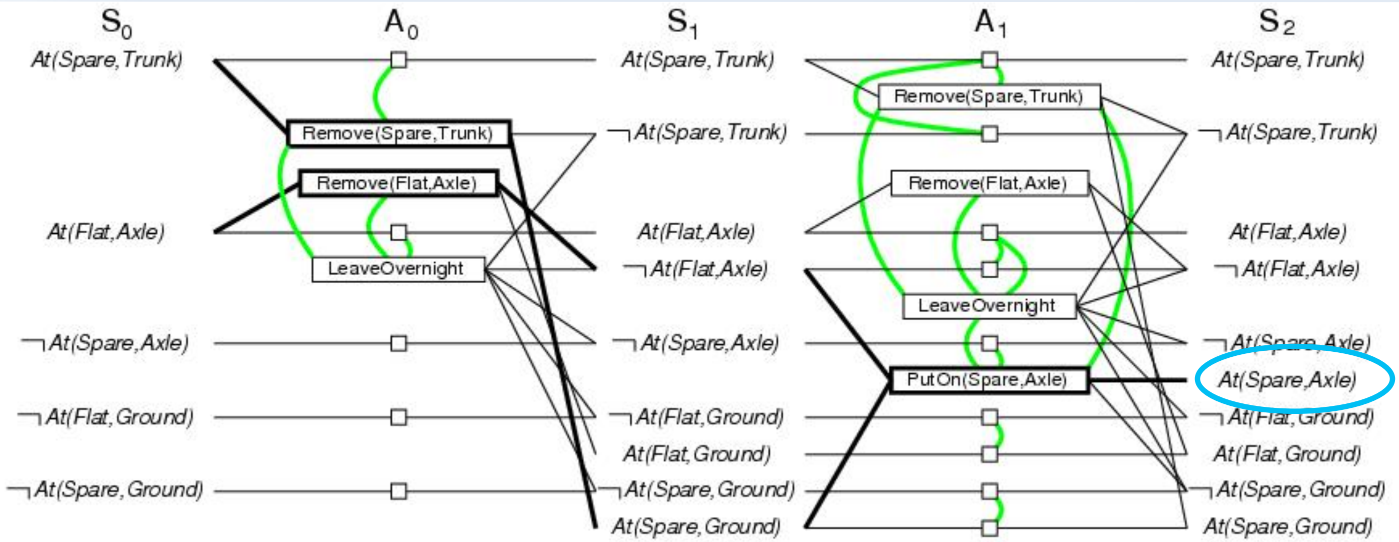
∧ ¬ At(Flat, Axle))

GRAPHPLAN SPARE TIRE EXAMPLE



- In S2, the goal literals exist, and they are not mutex with any other
  - Just 1 goal literal so obviously not mutex with any other goal
  - Since a solution may exist, EXTRACT-SOLUTION tries to find it
- EXTRACT-SOLUTION as backward search problem (other methods possible)
  - Initial state: last level of the PG, S_n, along with the goals from the planning problem
  - Actions from S_i
    - Select any conflict-free actions in A_{i-1} with effects covering the goals
    - Conflict free = no 2 actions are mutex & no pair of their preconditions are mutex
  - Goal: Reach a state at level S_0 such that all goals are satisfied
  - Cost: 1 for each action

GRAPHPLAN SOLUTIONS

- If EXTRACT-SOLUTION fails
  - At that point it records (level, goals) as a "*no-good*"
  - Subsequent calls can fail immediately if they require the same goals at that level
- Complexity
  - We already know planning problems are computationally hard (PSPACE-complete)
    - Require good heuristics
  - Heuristic for choosing an action at each level in backward search

    - Greedy search with level cost of literals
    - 1. Pick literal with highest level cost
    - 2. To achieve it, pick actions with easier preconditions
      - Choose action with smallest sum (or max) of level costs for its preconds

GRAPHPLAN SOLUTIONS

- Alternative to backward search for a solution
  - EXTRACT-SOLUTION could formulate a Boolean CSP
    - variables are actions at each level
    - values are Boolean: an action is either *in* or *out* of the plan
    - constraints are mutex relations & the need to satisfy each goal & pre condition

GRAPHPLAN TERMINATION

GRAPHPLAN will in fact terminate and return failure when there is no solution.

- Recall that level off means consecutive PG levels are identical
- Now note that a graph may level off before a solution can be found, on a problem for which there is a solution
  - Ex. Air Cargo: 1 plane and n pieces of cargo at airport A, all of which have airport B as their destination. Where only one piece of cargo can fit in the plane at a time.
    - Graph levels off at level 4, from which full solution can't be extracted (that would require 4n – 1 steps)
- We need to take account of the no-goods (goals that were not achievable) as well
  - If it is possible that there might be fewer no-goods in the next level, then we should continue
- Graph itself and the no-goods have both leveled off, with no solution found, we can terminate with failure

GRAPHPLAN TERMINATION

- Does GRAPHPLAN terminate?
- Evidences that both graph and no-goods will level off
  - Literals increase monotonically (and there are finite # of them)
    - Once a literal appears, its persistence action causes it to stay
  - Actions increase monotonically (and there are finite # of them)
    - Once preconditions (literals) of an action appear at one level, they will a ppear at subsequent levels, and thus so will the action.
  - Mutexes decrease monotonically
    - Of 2 actions are mutex at A_i, they are also mutex at all previous levels wh ere they appear
      - The graph simplifying conventions may not show it
    - Same holds for 2 literals
  - No-goods decrease monotonically
    - If a set of goals is not achievable at level i, they are not achievable at an y previous level