GraphPlan

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* Based in part on slides by Daniel Weld and José Luis Ambite

GraphPlan

http://www.cs.cmu.edu/~avrim/graphplan.html

- Many planning systems use ideas from Graphplan:
  - IPP, STAN, SGP, Blackbox, Medic
- History
  - Before GraphPlan appeared in 1995, most planning researchers were working under the framework of "plan-space search" (we will not cover this topic)
  - GraphPlan outperformed those prior planners by orders of magnitude
  - GraphPlan started researchers thinking about fundamentally different frameworks
- Recent planning algorithms run much faster than GraphPlan
  - However, many have been influenced by GraphPlan

Big Picture

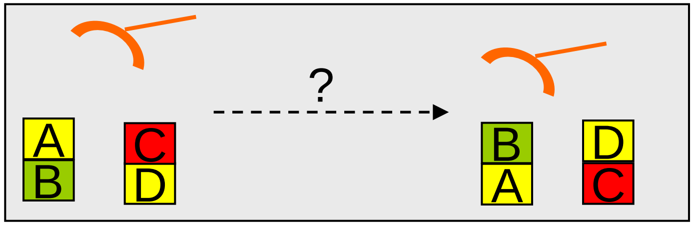
- A big source of inefficiency in search algorithms is the large branching factor
- GraphPlan reduces the branching factor by searching in a special data structure

- Phase 1 – Create a Planning Graph
  - built from initial state
  - contains actions and propositions that are possibly reachable from initial state
  - does not include unreachable actions or propositions
- Phase 2 - Solution Extraction
  - Backward search for the solution in the planning graph
    - backward from goal

Layered Plans

- Graphplan searches for **layered plans** (often called parallel plans)

- A layered plan is a sequence of **sets** of actions
  - actions in the same set must be **compatible**
    - a1 and a2 are compatible iff a1 does not delete preconditions or positive effects of a2 (and vice versa)
  - all sequential orderings of compatible actions gives same result

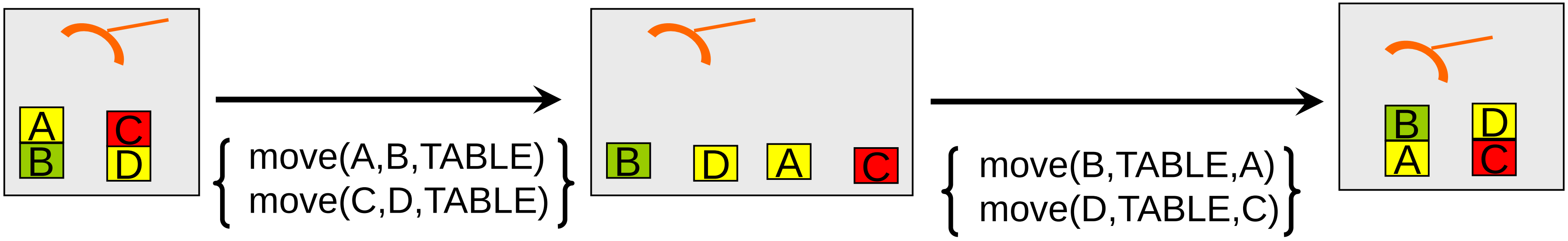


Layered Plan: (a two layer plan)

$$\left\{ \begin{array}{l} \text{move(A,B,TABLE)} \\ \text{move(C,D,TABLE)} \end{array} \right\} ; \left\{ \begin{array}{l} \text{move(B,TABLE,A)} \\ \text{move(D,TABLE,C)} \end{array} \right\}$$

Executing a Layered Plans

- A set of actions is applicable in a state if all the actions are applicable.
- Executing an applicable set of actions yields a new state that results from executing each individual action (order does not matter)



Planning Graph

*A **literal** is just a positive or negative propositon*

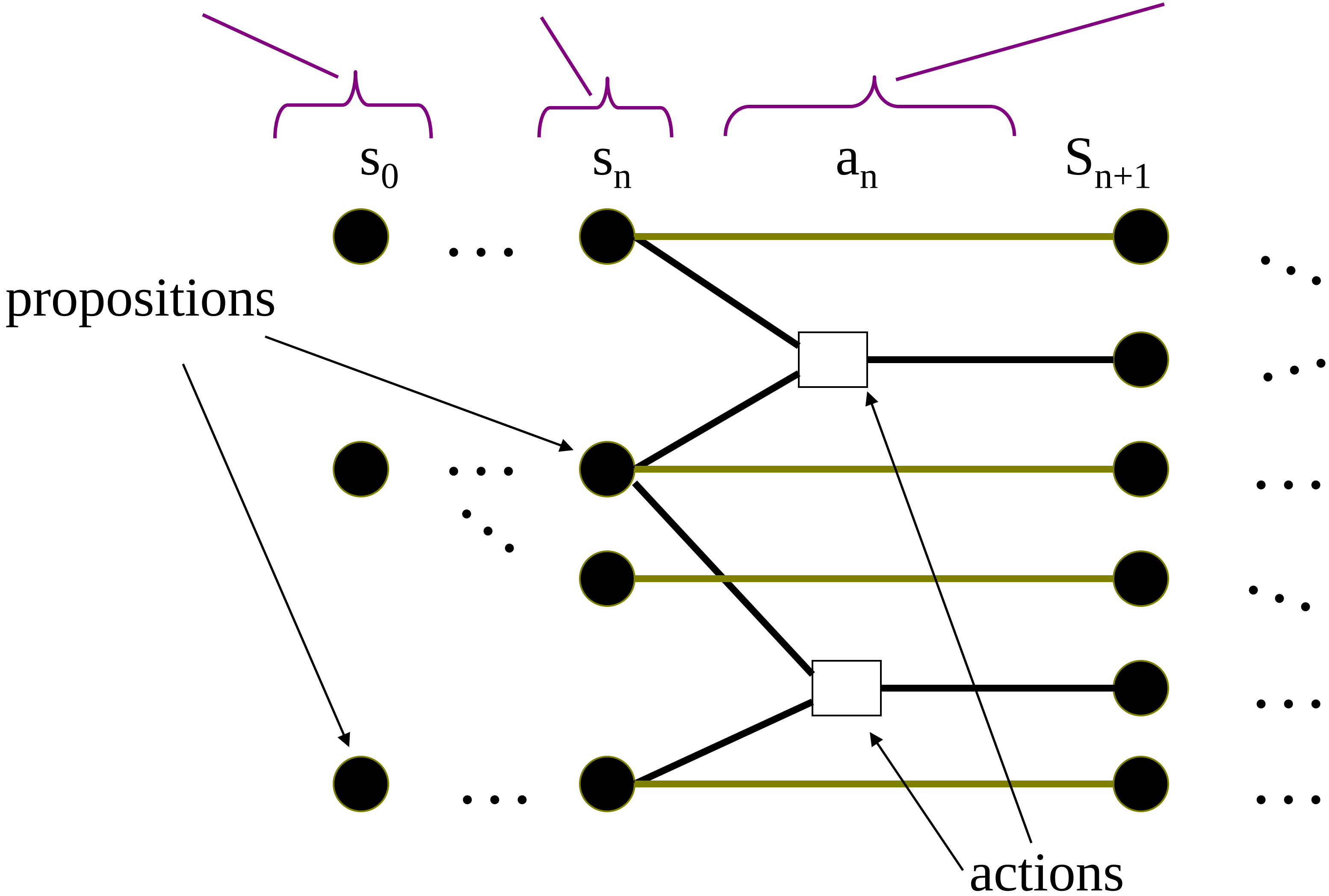
- A planning graph has a sequence of levels that correspond to time-steps in the plan:
  - Each level contains a set of literals and a set of actions
  - Literals are those that could possibly be true at the time step
  - Actions are those that their preconditions could be satisfied at the time step.
- Idea: construct superset of literals that could be possibly achieved after an *n*-level layered plan
  - Gives a compact (but approximate) representation of states that are reachable by *n* level plans

Planning Graph

state-level 0: propositions true in s_0

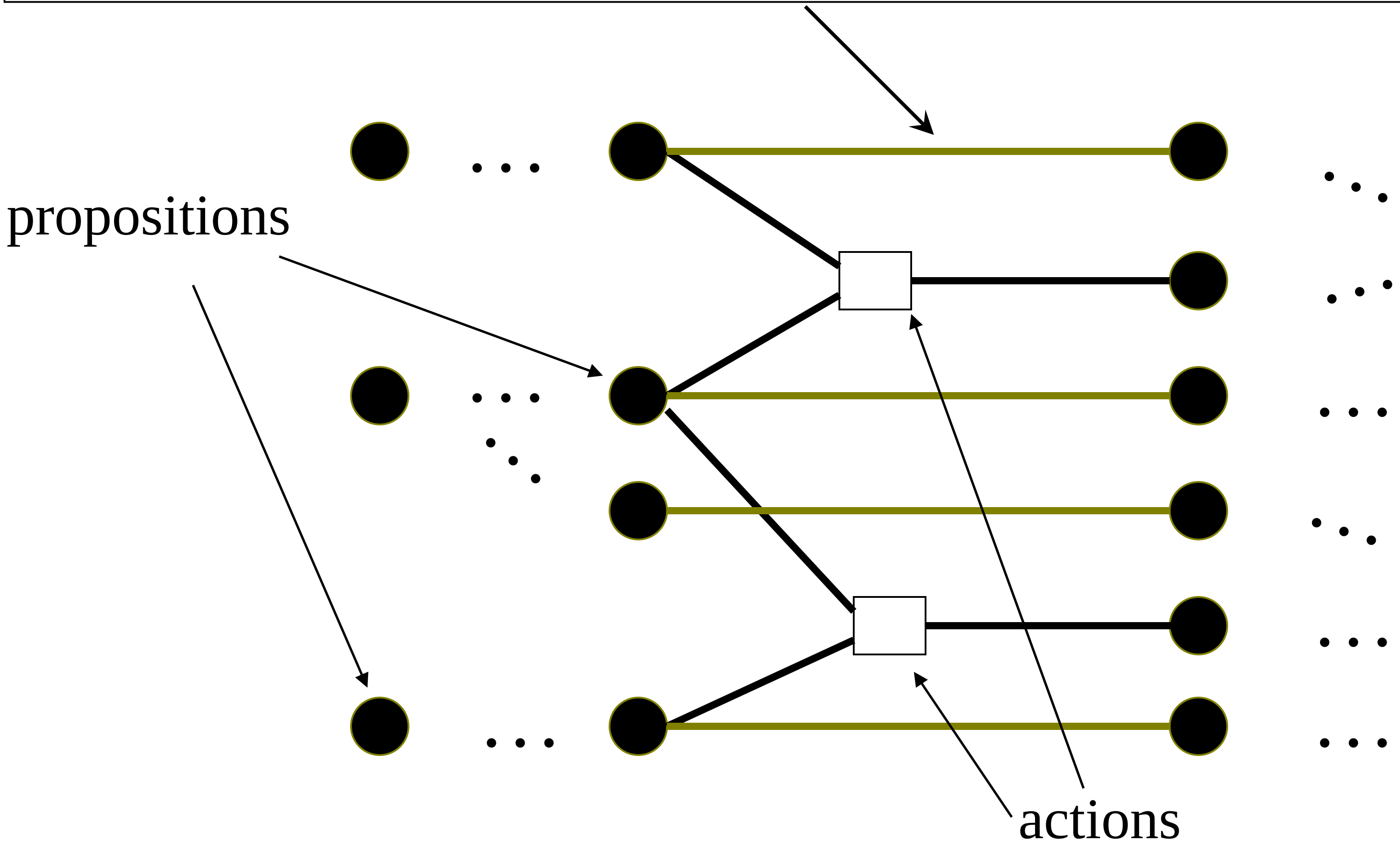
state-level *n*: literals that may possibly be true after some *n* level plan

action-level *n*: actions that may possibly be applicable after some *n* level plan



Planning Graph

- maintenance action (persistence actions)
  - represents what happens if no action affects the literal
  - include action with precondition c and effect c, for each literal c



Graph expansion

- Initial proposition layer
  - Just the propositions in the initial state
- Action layer n
  - If all of an action's preconditions are in proposition layer n, then add action to layer *n*
- Proposition layer *n*+1
  - For each action at layer *n* (including persistence actions)
  - Add all its effects (both positive and negative) at layer **n**+1

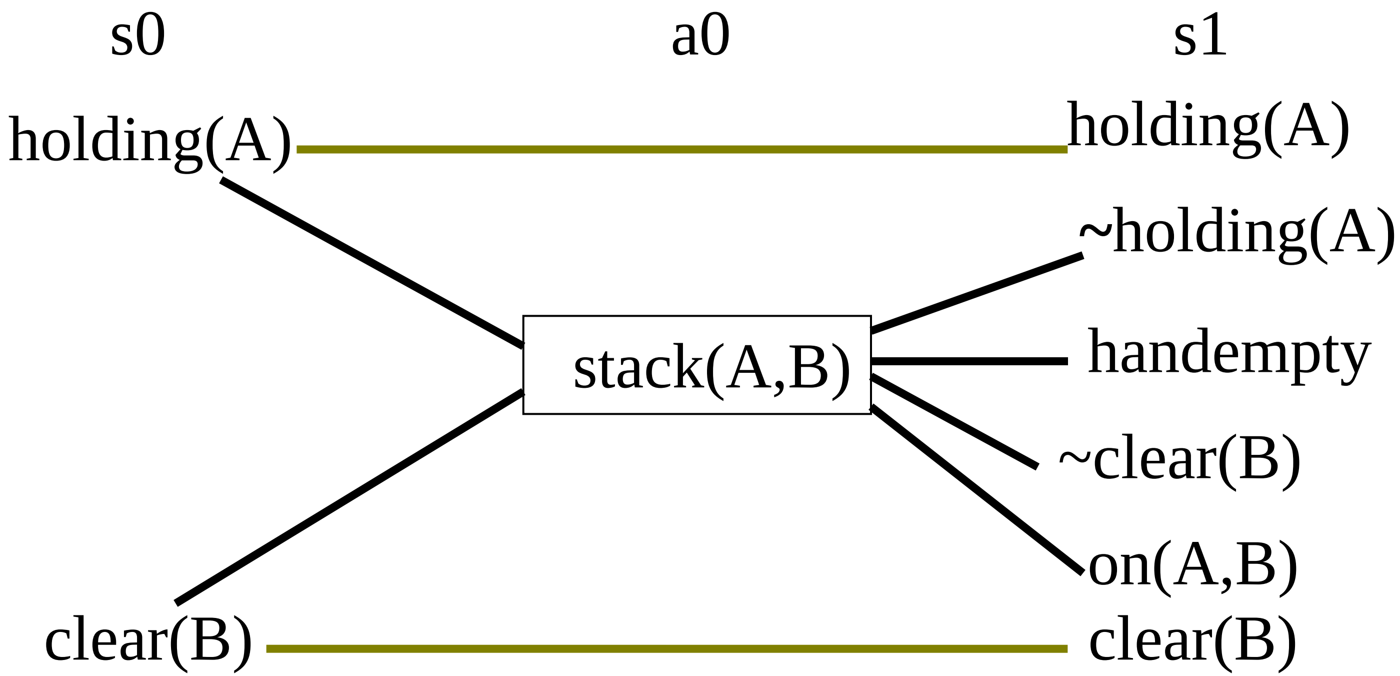
    (Also allow propositions at layer *n* to persist to *n*+1)
- Propagate mutex information
  (we'll talk about this in a moment)

Example

stack(A,B)

precondition: holding(A), clear(B)

effect: ~holding(A), ~clear(B), on(A,B), clear(B), handempty



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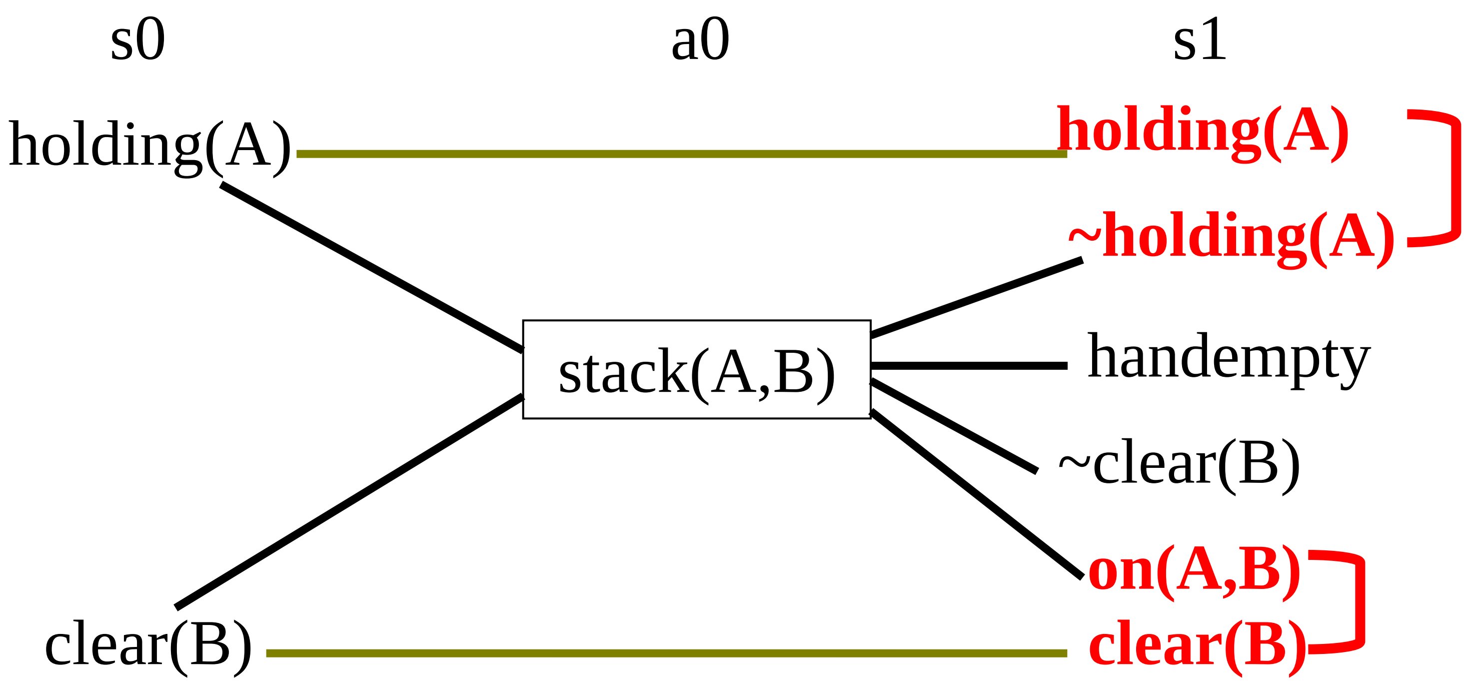


Notice that not all literals in s1 can be made true simultaneously after 1 level:
e.g. holding(A), ~holding(A) and on(A,B), clear(B)

Mutual Exclusion (Mutex)

- Mutex between pairs of actions at layer *n* means
  - no valid plan could contain both actions at layer *n*
  - E.g., stack(a,b), unstack(a,b)
- Mutex between pairs of literals at layer *n* means
  - no valid plan could produce both at layer *n*
  - E.g., clear(a), ~clear(a)
    on(a,b), clear(b)
- GraphPlan checks pairs only
  - mutex relationships can help rule out possibilities during search in phase 2 of Graphplan

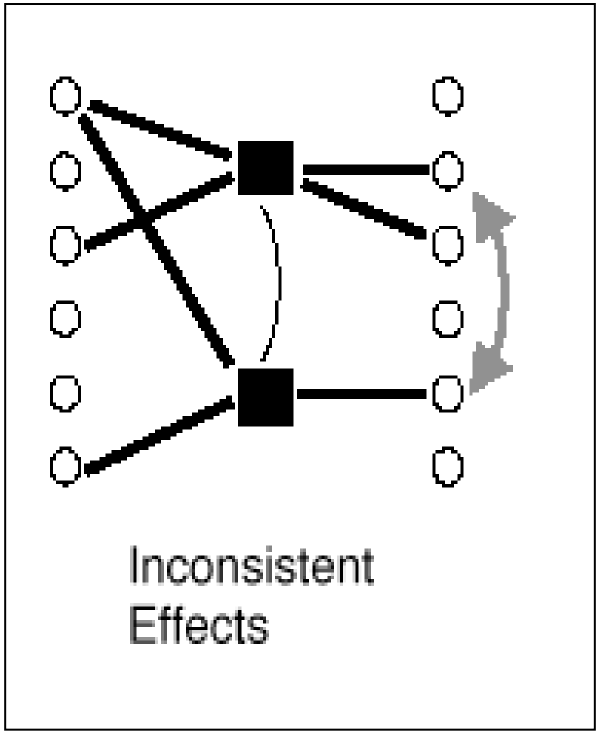
Action Mutex: condition 1

- Inconsistent effects
  - an effect of one negates an effect of the other

- E.g., stack(a,b) & unstack(a,b)

add handempty

delete handempty
(add ~handempty)

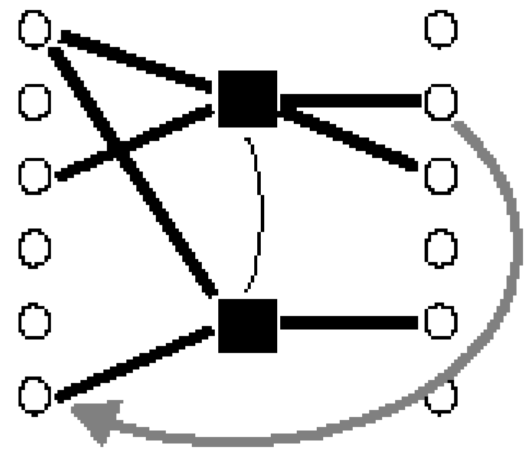


Action Mutex: condition 2

- *Interference :*
  - one deletes a precondition of the other

- E.g., stack(a,b) & putdown(a)

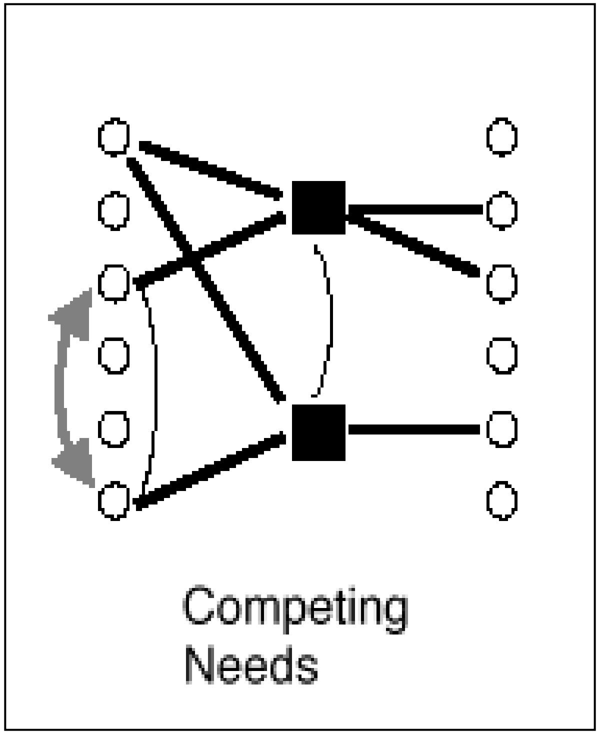
deletes holdindg(a) needs holding(a)



Interference

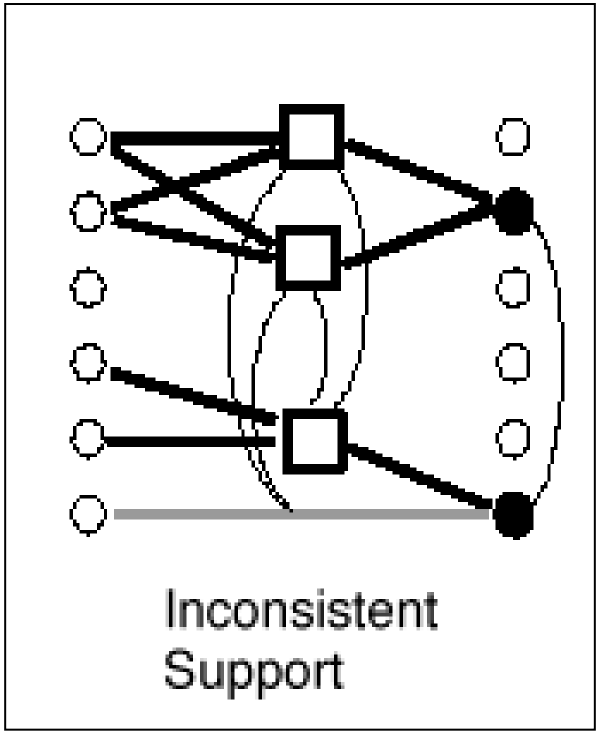
Action Mutex: condition 3

- *Competing needs:*
  - they have mutually exclusive preconditions
  - Their preconditions can't be true at the same time



Literal Mutex: two conditions

- *Inconsistent support :*
  - one is the negation of the other
    E.g., handempty and ~handempty
  - or all ways of achieving them via actions are are pairwise mutex



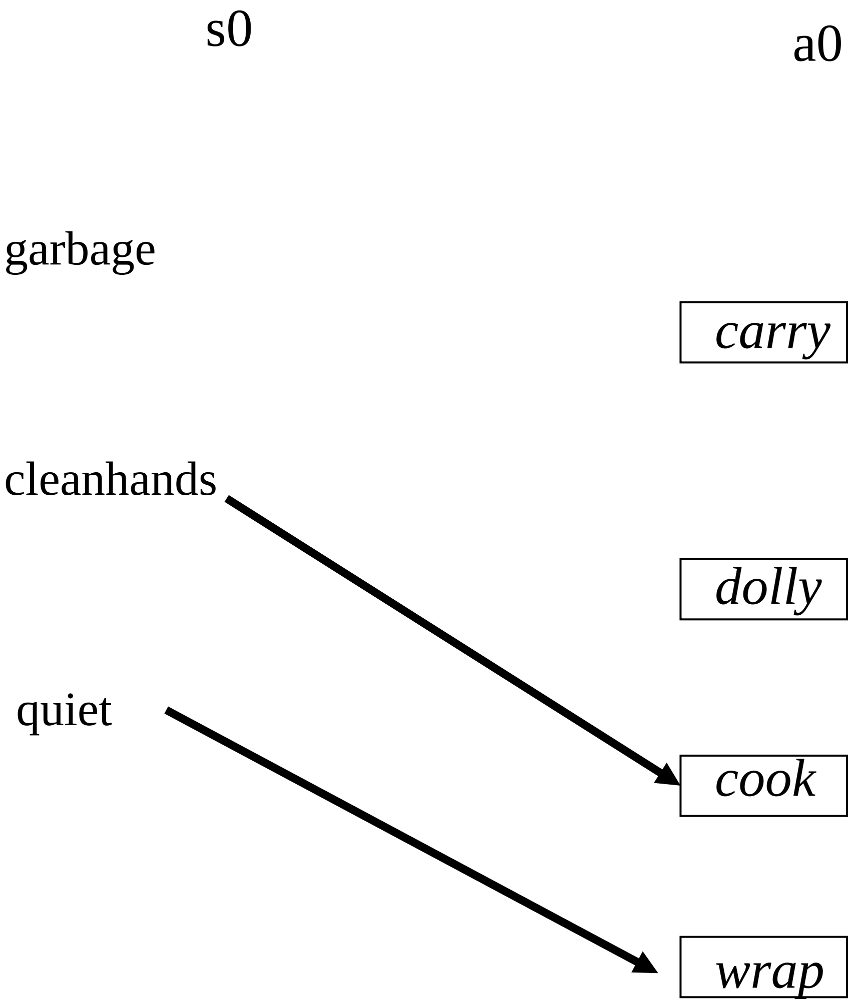
Example – Dinner Date

- Suppose you want to prepare dinner as a surprise for your sweetheart (who is asleep)
  - Initial State: {cleanHands, quiet, garbage}
  - Goal: {dinner, present, ~garbage}
  - **Action Preconditions Effects**

Action	Preconditions	Effects
cook	cleanHands	dinner
wrap	quiet	present
carry	*none*	~garbage, ~cleanHands
dolly	*none*	~garbage, ~quiet

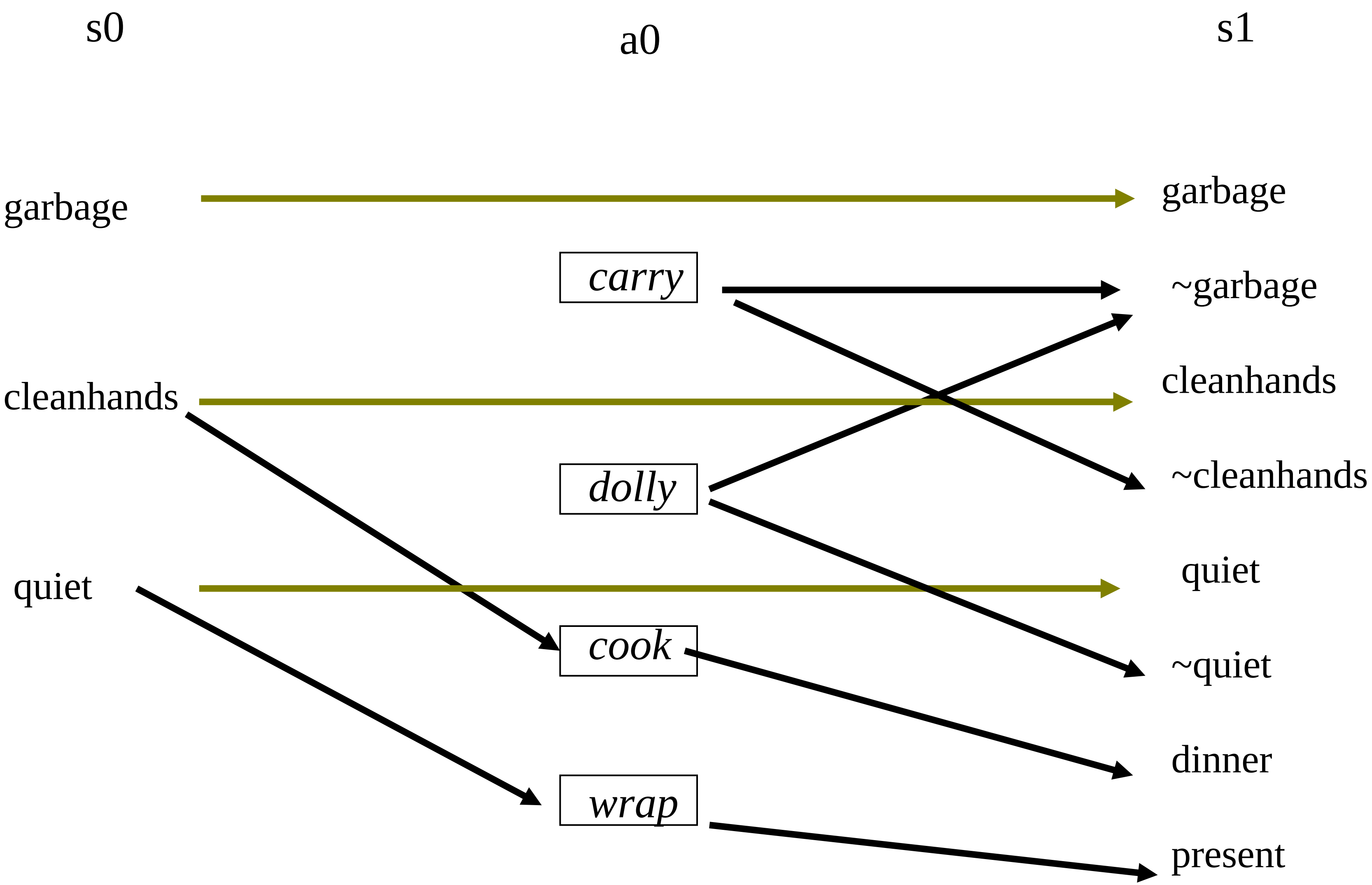
Also have the “maintenance actions”

Example – Plan Graph Construction



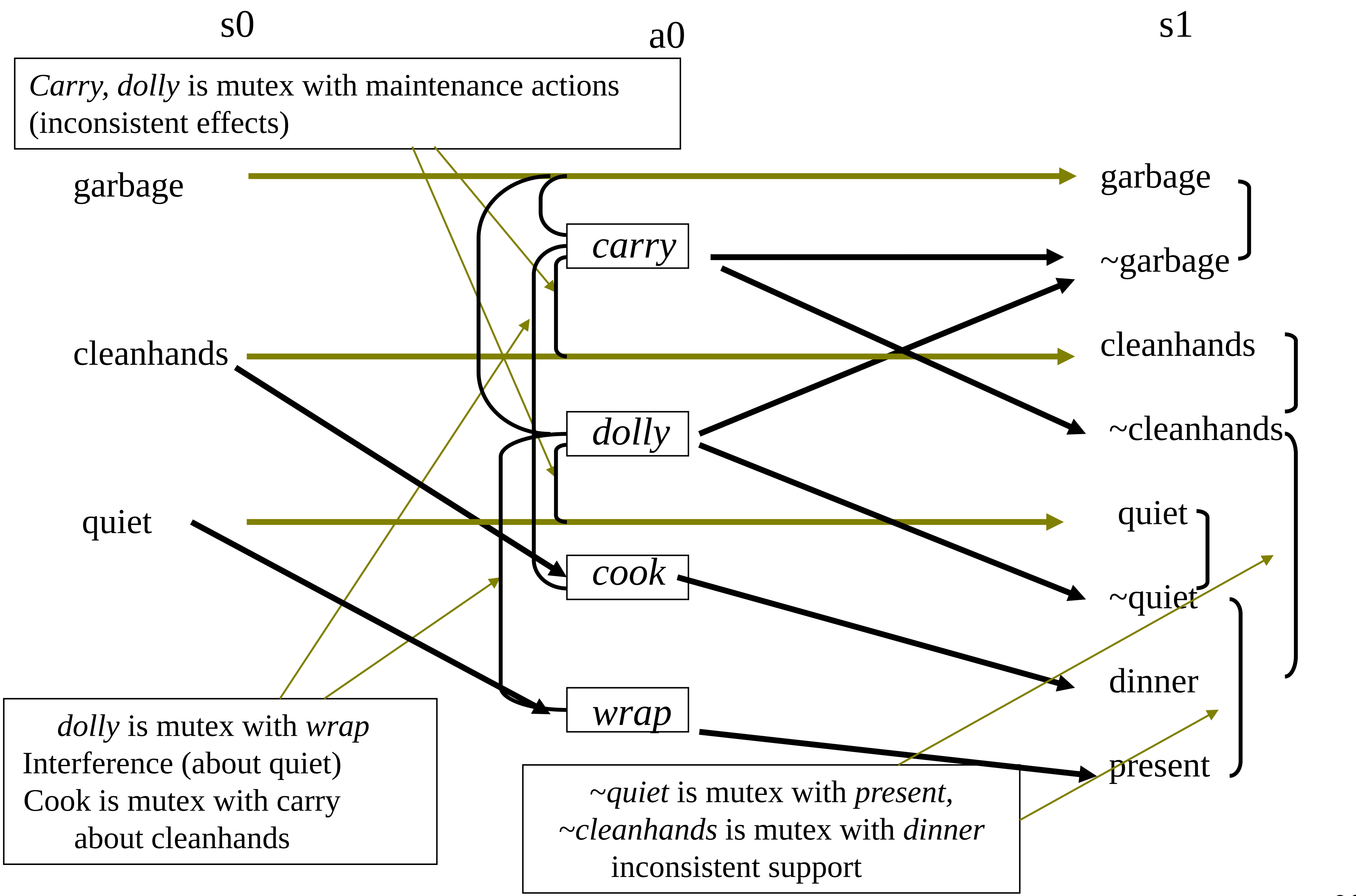
Add the actions that can be executed in initial state

Example - continued



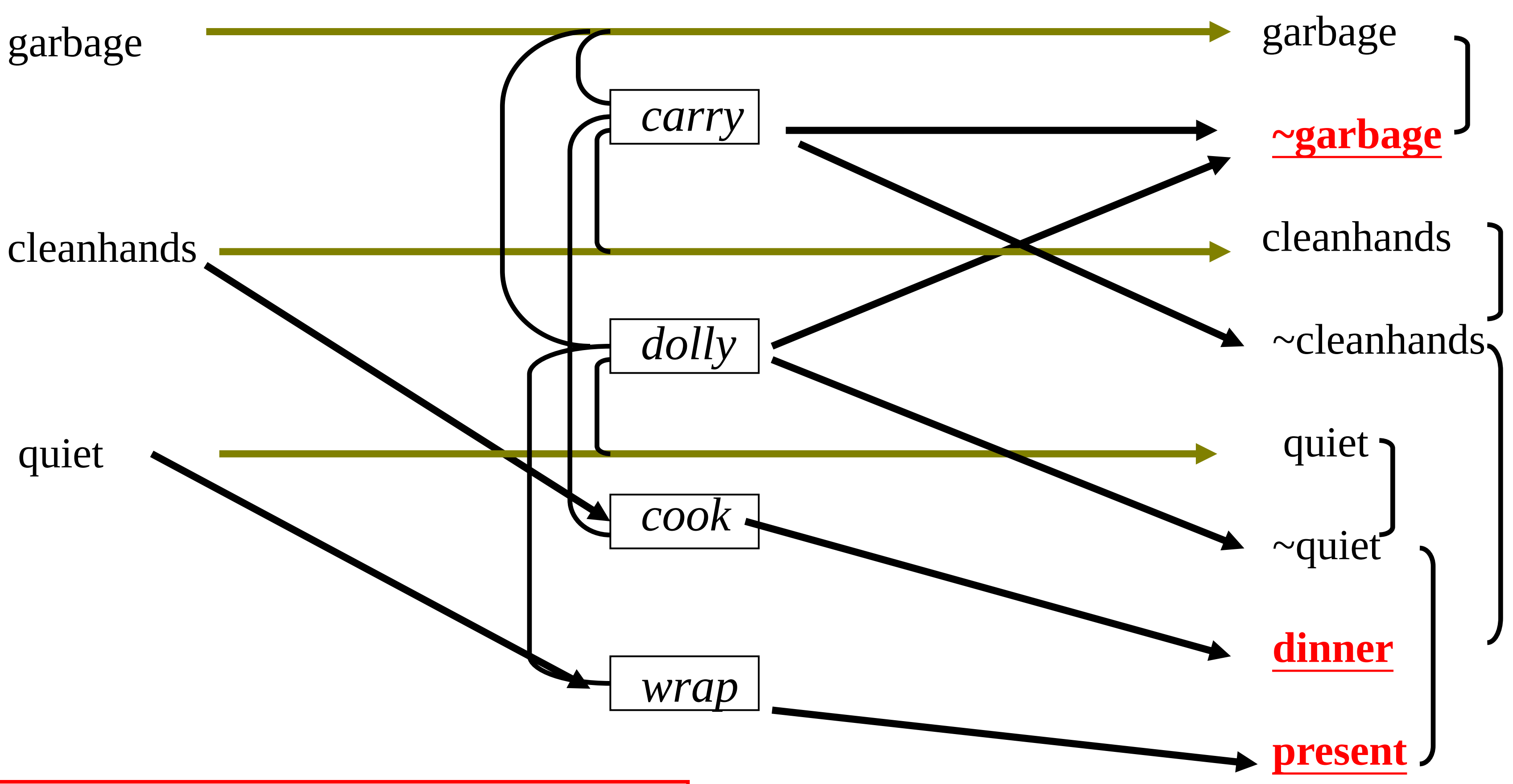
Add the literals that can be achieved in first step

Example - continued



Do we have a solution?

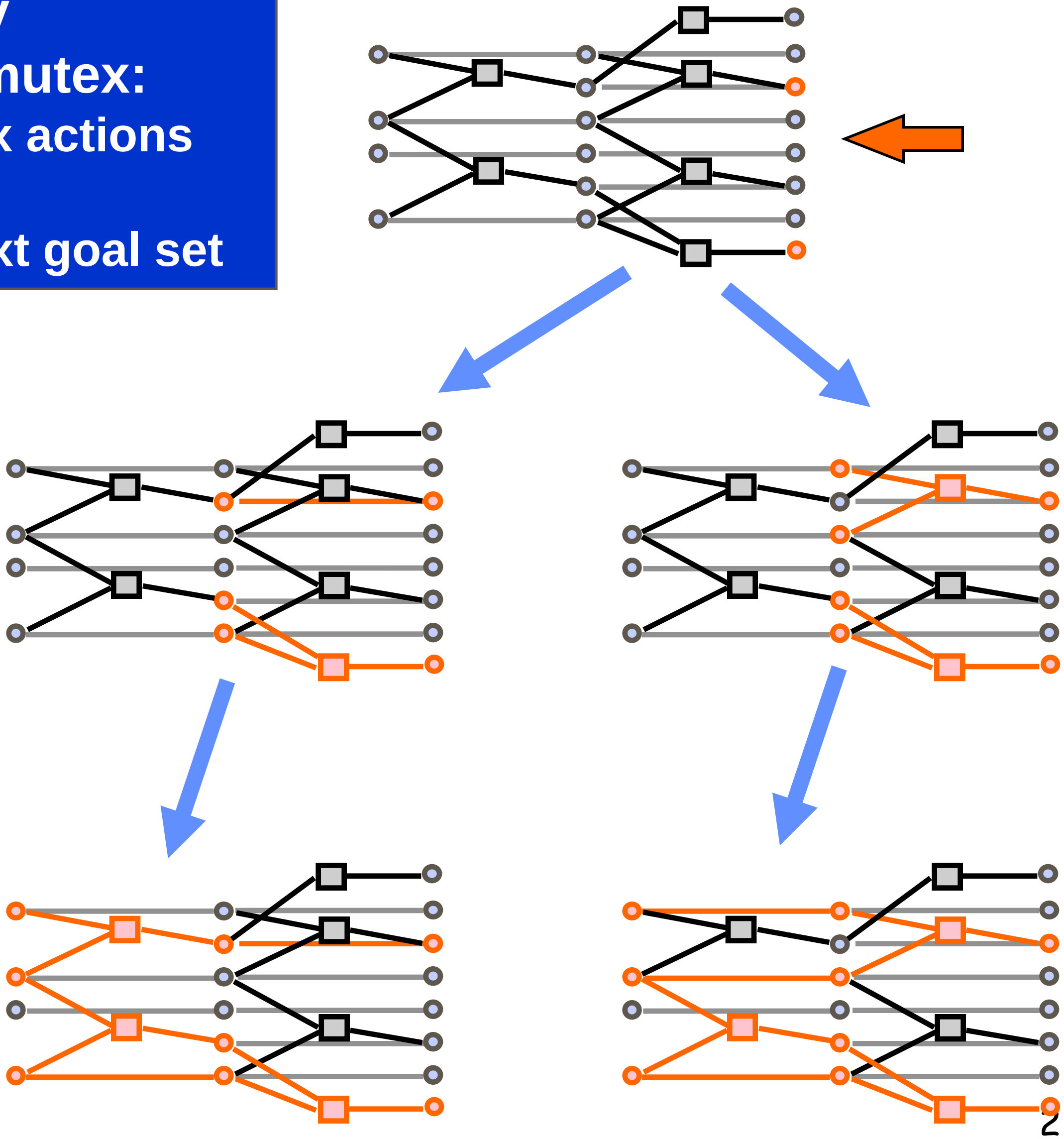
The goal is: **{dinner, present,~garbage}**
All are possible in layer s1
None are mutex with each other



There is a chance that a plan exists
Now try to find it – solution extraction

Solution Extraction: Backward Search

Repeat until goal set is empty
If goals are present & non-mutex:
1) Choose set of non-mutex actions to achieve each goal
2) Add preconditions to next goal set

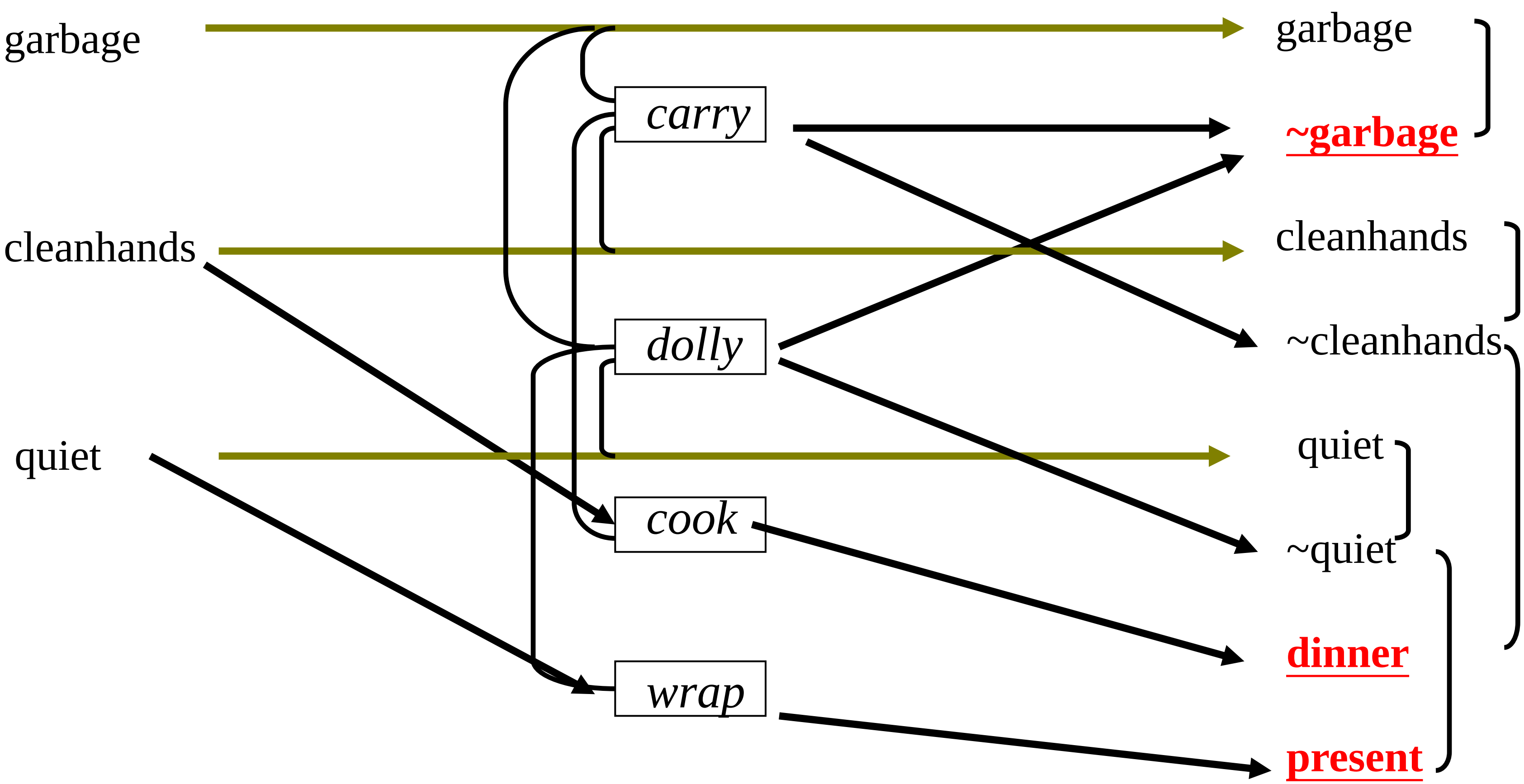


Searching for a solution plan

- Backward chain on the planning graph
- Achieve goals level by level
- At level k, pick a subset of non-mutex actions to achieve current goals. Their preconditions become the goals for k-1 level.
- Build goal subset by picking each goal and choosing an action to add. Use one already selected if possible (backtrack if can’t pick non-mutex action)
- If we reach the initial proposition level and the current goals are in that level (i.e. they are true in the initial state) then we have found a successful layered plan

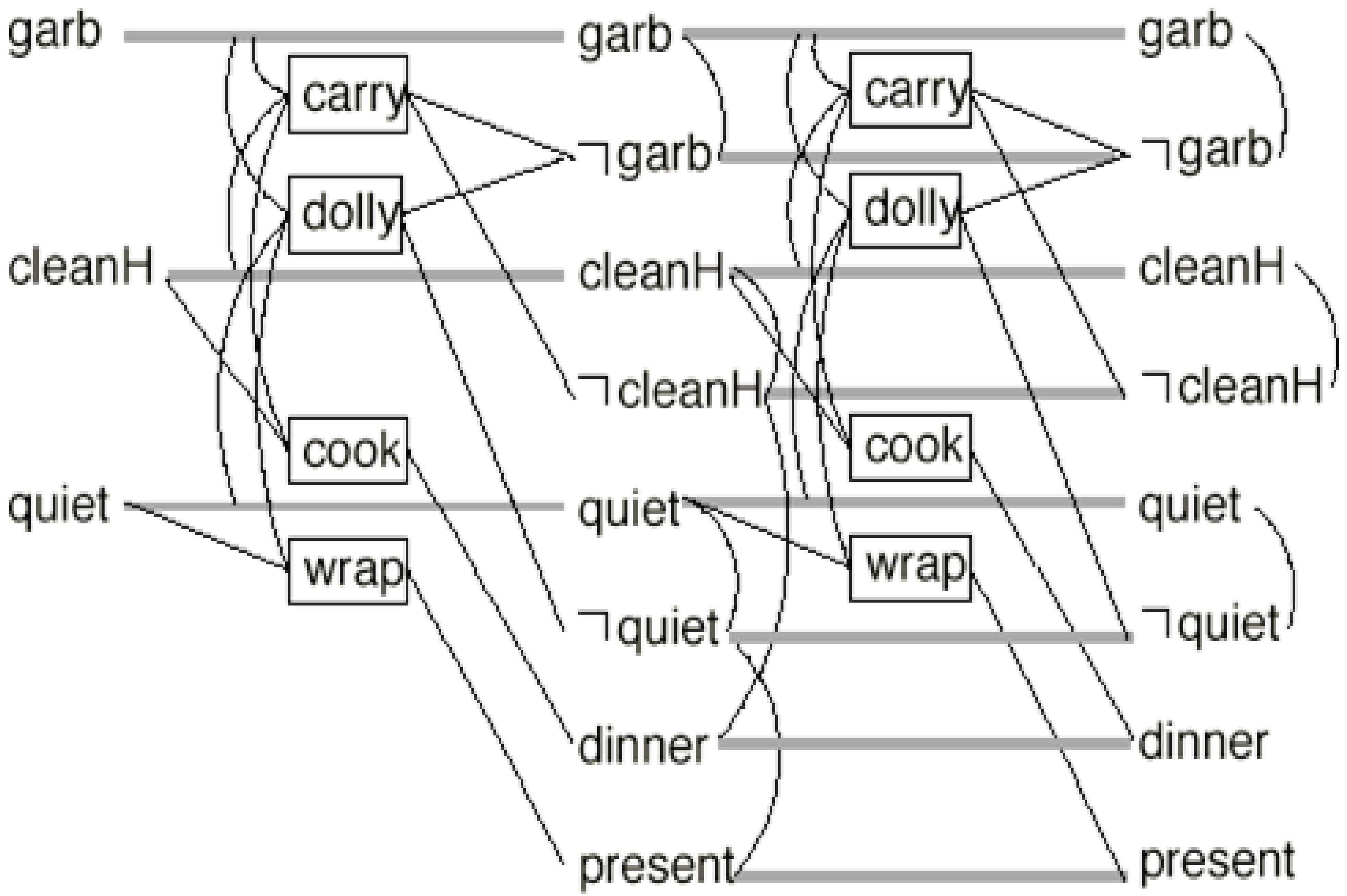
Possible Solutions

- Two possible sets of actions for the goals at layer s1:
  {wrap, cook, dolly}   and   {wrap, cook, carry}
- Neither set works -- both sets contain actions that are mutex



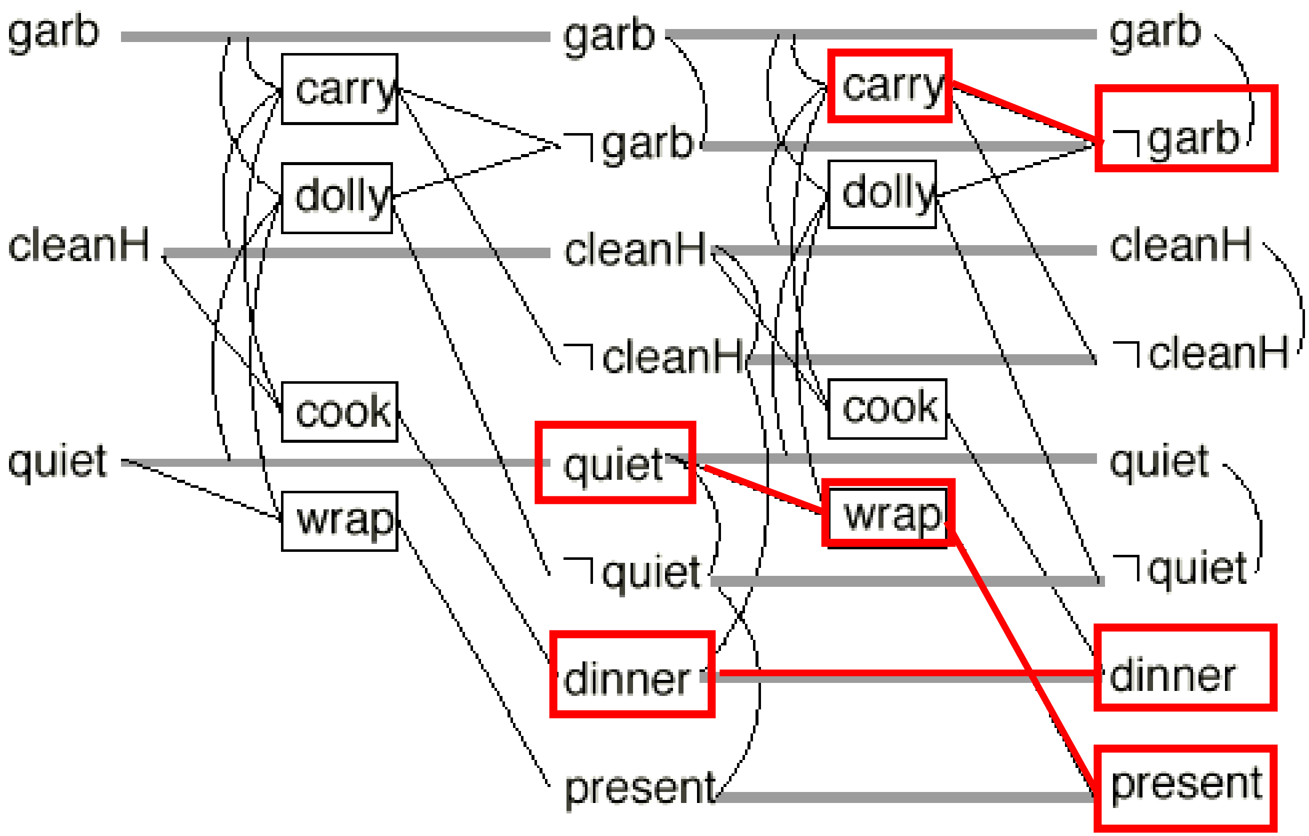
Add new layer…

Adding a layer provided new ways to achieve propositions
This may allow goals to be achieved with non-mutex actions



Do we have a solution?

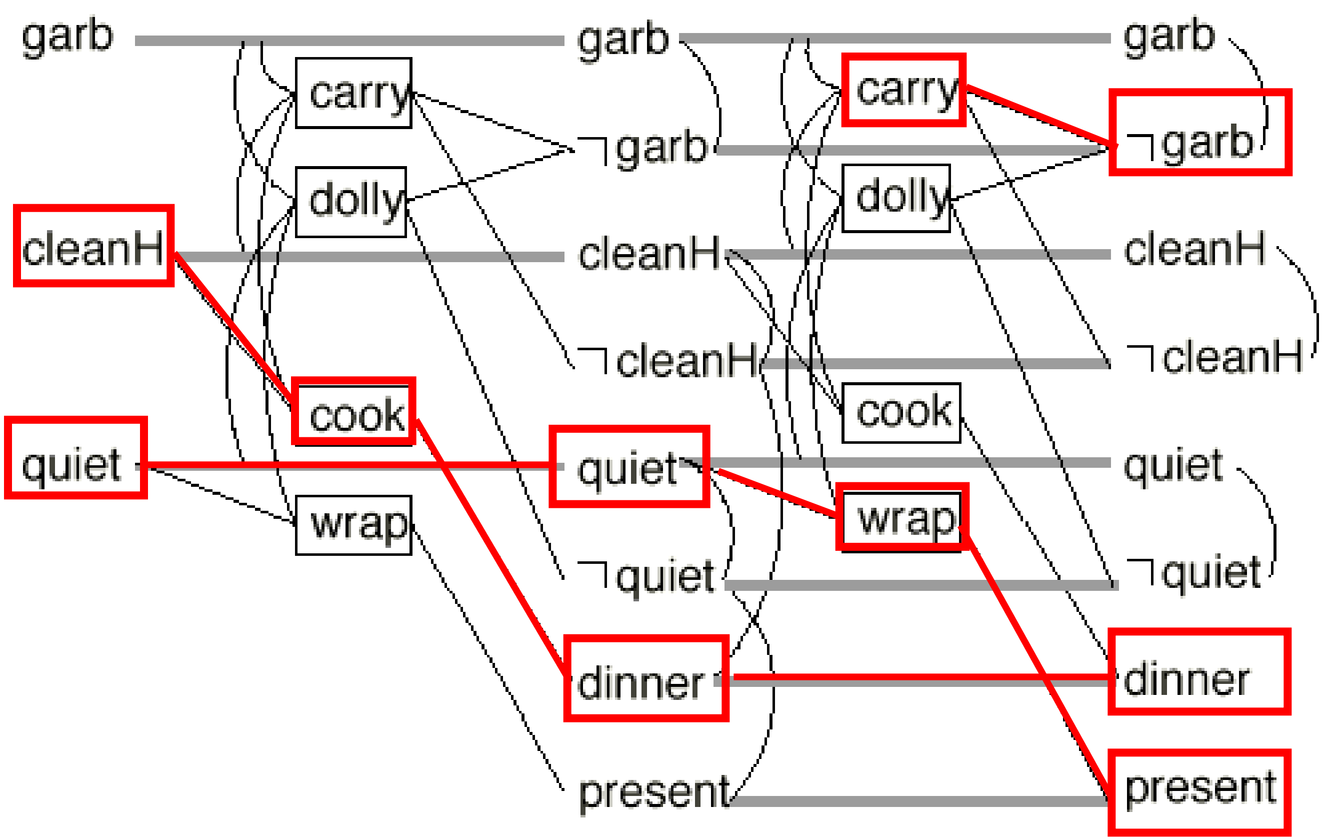
Several action sets look OK at layer 2
Here's one of them
We now need to satisfy their preconditions



Do we have a solution?

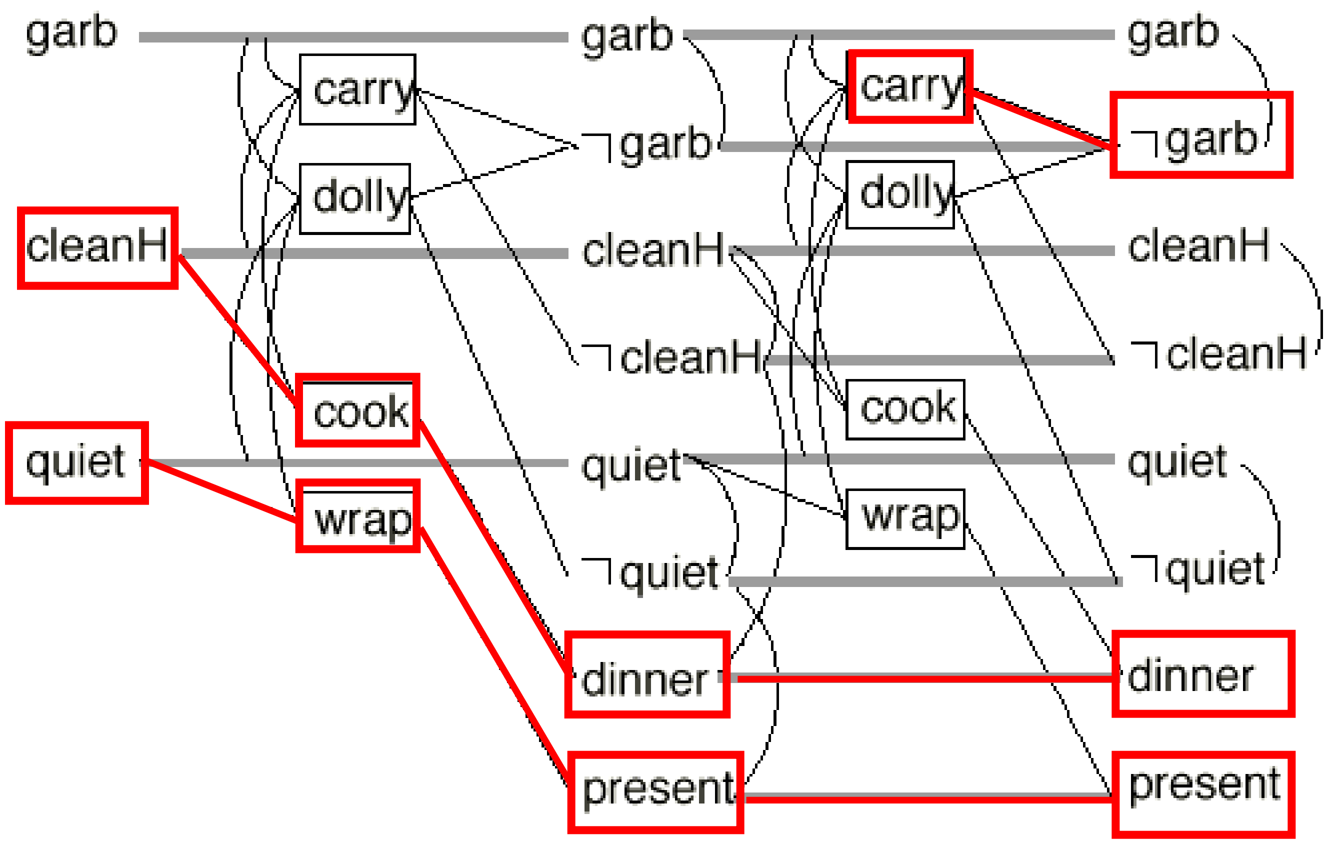
The action set {cook, quite} at layer 1 supports preconditions
Their preconditions are satisfied in initial state
So we have found a solution:

{cook} ; {carry, wrap}



Another solution:

{cook,wrap} ; {carry}



GraphPlan algorithm

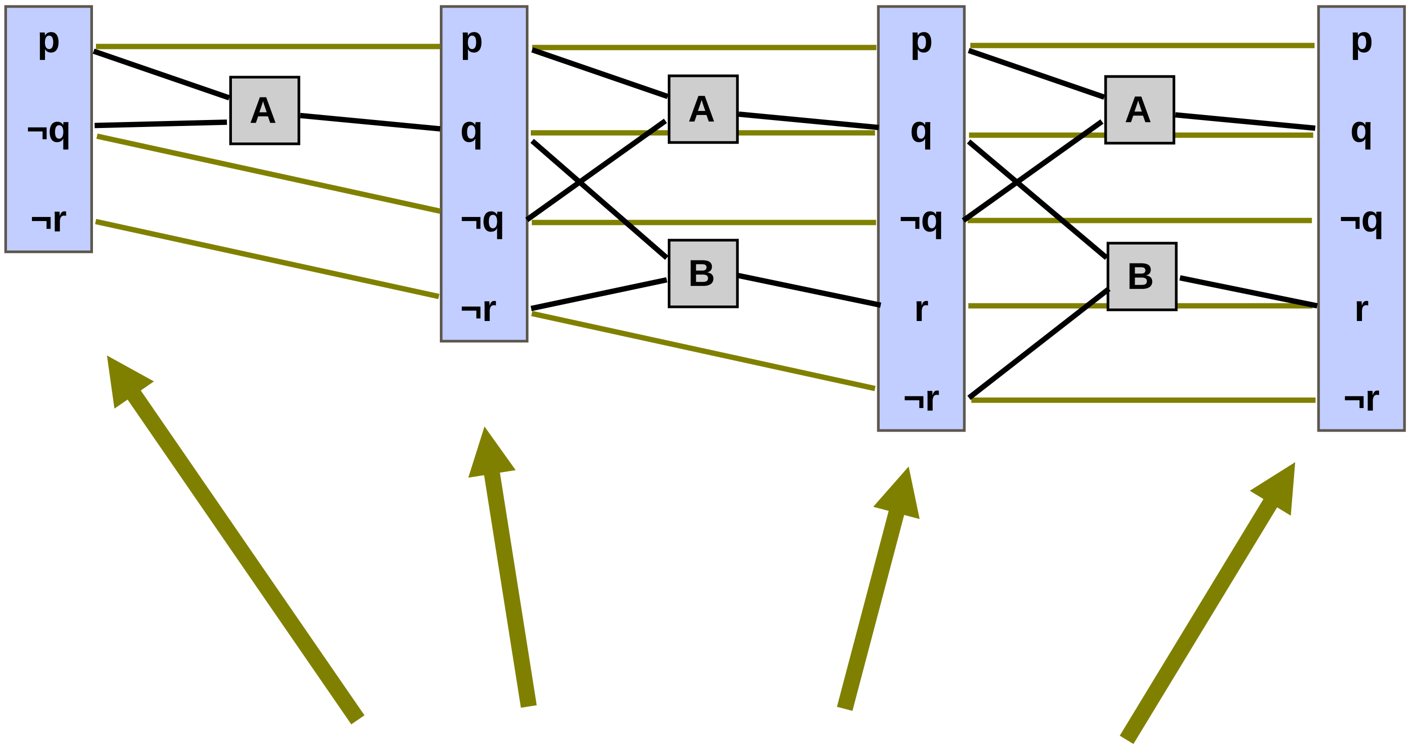
- Grow the planning graph (PG) to a level *n* such that all goals are reachable and not mutex
  - necessary but ***insufficient*** condition for the existence of an *n* level plan that achieves the goals
  - if PG levels off before non-mutex goals are achieved then fail
- Search the PG for a valid plan
- If none found, add a level to the PG and try again
- If the PG levels off and still no valid plan found, then return failure

Termination is guaranteed by PG properties

This termination condition does not guarantee completeness. Why?

A more complex termination condition exists that does, but we won't cover in class (see book material on termination)

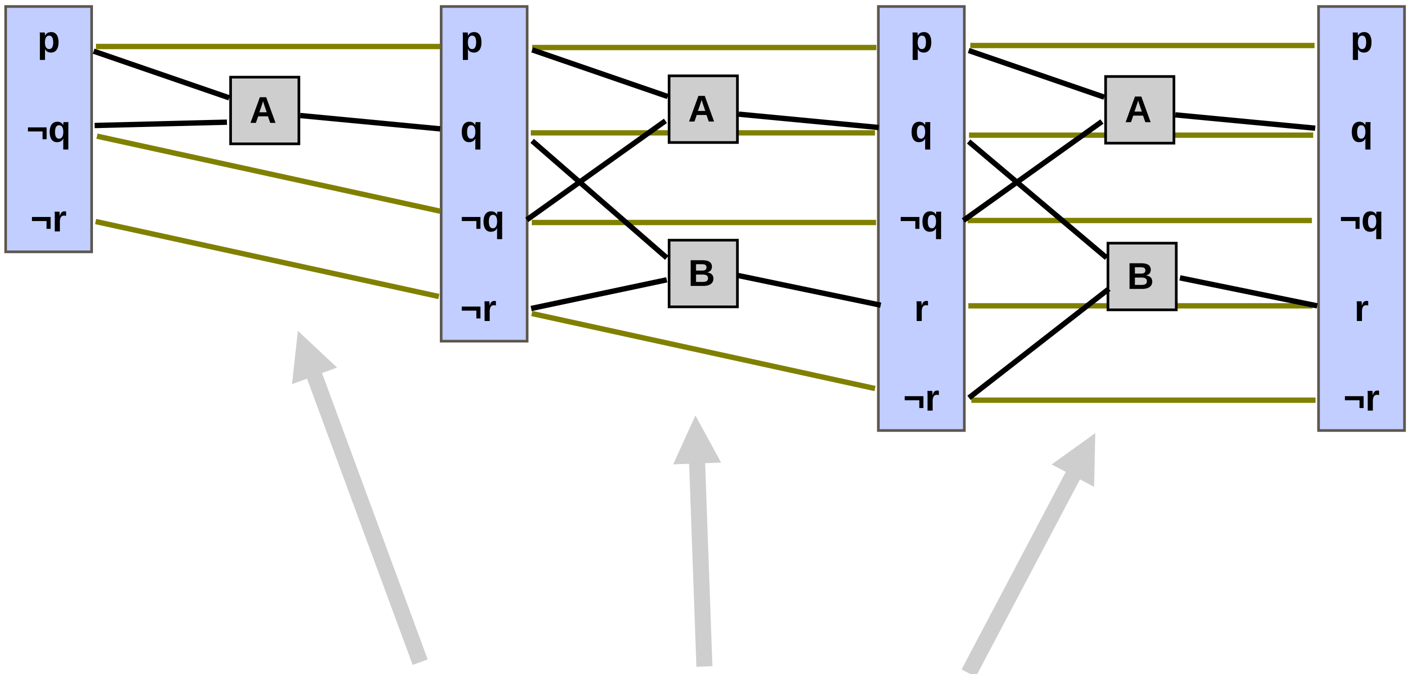
Propery 1



Propositions monotonically increase

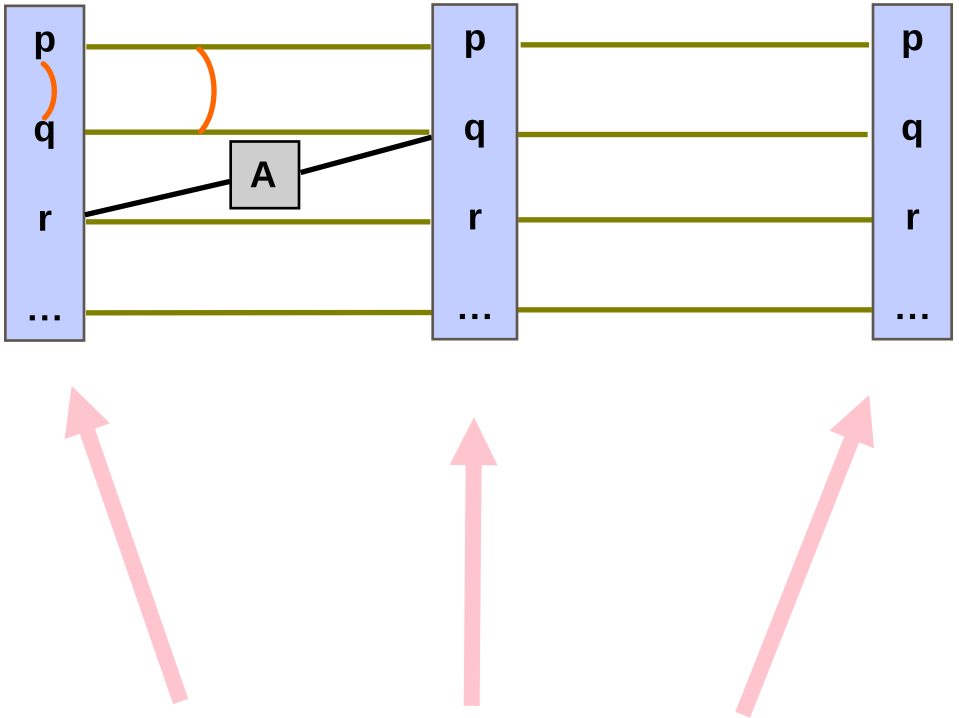
(always carried forward by no-ops)

Property 2



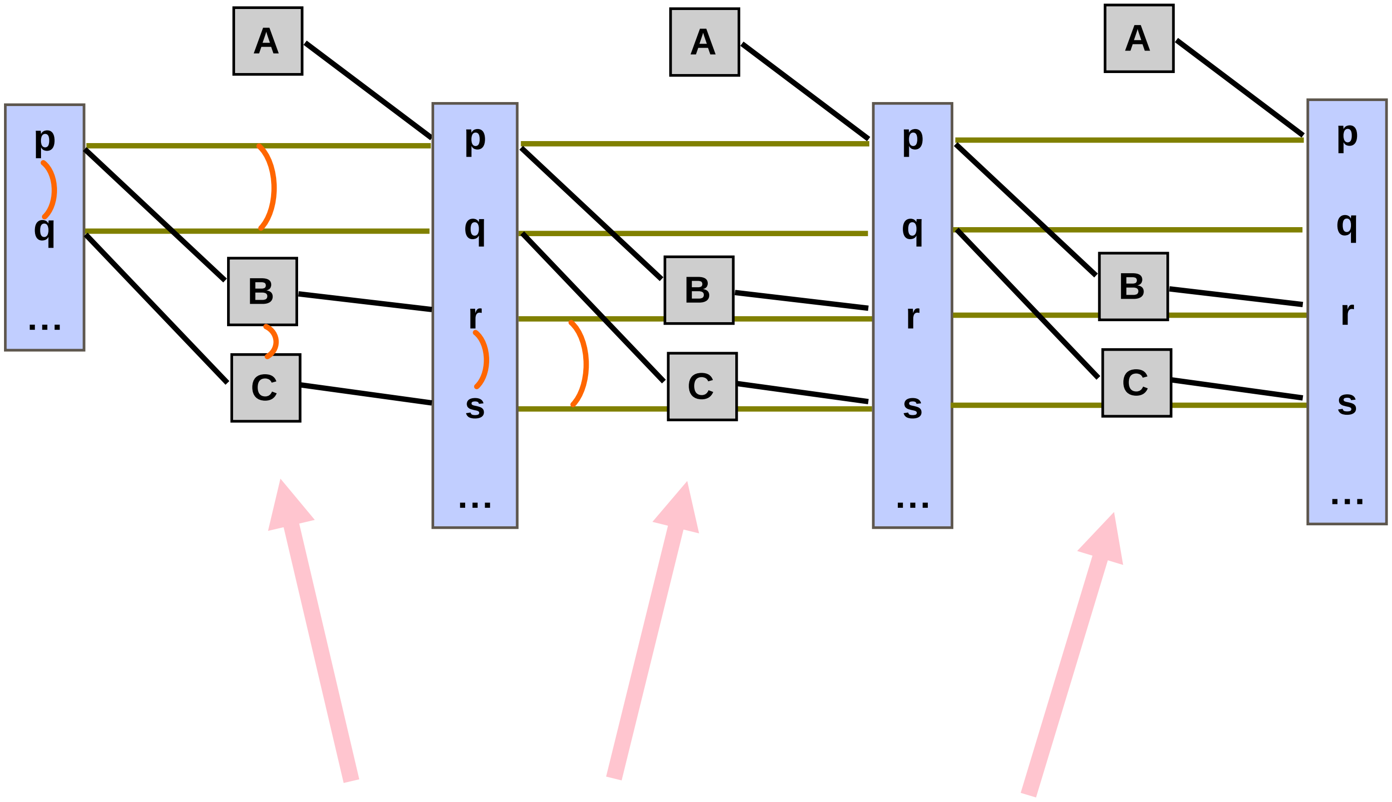
Actions monotonically increase

Properties 3



- Proposition mutex relationships monotonically decrease
- Specifically, if p and q are in layer n and are not mutex then they will not be mutex in future layers.

Properties 4



Action mutex relationships monotonically decrease

Properties 5

Planning Graph ‘levels off’.

- After some time k all levels are identical
  - In terms of propositions, actions
- This is because there are a finite number of propositions and actions, the set of literals never decreases and mutexes don’t reappear.

Important Ideas

- Plan graph construction is polynomial time
  - Though construction can be expensive when there are many "objects" and hence many propositions
- The plan graph captures important properties of the planning problem
  - Necessarily unreachable literals and actions
  - Possibly reachable literals and actions
  - Mutually exclusive literals and actions
- Significantly prunes search space compared to previously considered planners
- Plan graphs can also be used for deriving admissible (and good non-admissible) heuristics

Planning Graphs for Heuristic Search

- After GraphPlan was introduced, researchers found other uses for planning graphs.

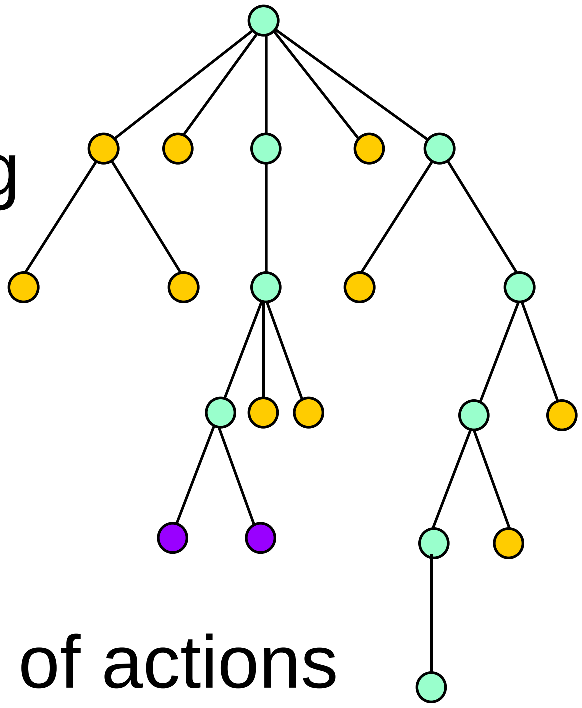
- One use was to compute heuristic functions for guiding a search from the initial state to goal
  - Sect. 10.3.1 of book discusses some approaches

- First lets review the basic idea behind heuristic search

Planning as heuristic search

- Use standard search techniques, e.g. A*, best-first, hill-climbing etc.
  - Find a path from the initial state to a goal
  - Performance depends very much on the quality of the "heuristic" state evaluator
- Attempt to extract heuristic state evaluator automatically from the Strips encoding of the domain
- The planning graph has inspired a number of such heuristics

Review: Heuristic Search



- A* search is a best-first search using node evaluation

  $$f(s) = g(s) + h(s)$$

  where

  g(s) = accumulated cost/number of actions

  h(s) = estimate of future cost/distance to goal

- h(s) is ***admissible*** if it does not overestimate the cost to goal
- For admissible h(s), A* returns optimal solutions

Simple Planning Graph Heuristics

- Given a state s, we want to compute a heuristic h(s).
- **Approach 1:** Build planning graph from s until all goal facts are present w/o mutexes between them
  - Return the # of graph levels as h(s)
    - Admissible. Why?
    - Can sometimes grossly underestimate distance to goal
- **Approach 2:** Repeat above but for a “sequential planning graph” where only one action is allowed to be taken at any time
  - Implement by including mutexes between all actions
  - Still admissible, but more accurate.

Relaxed Plan Heuristics

- Computing those heuristics requires “only” polynomial time, but must be done many times during search (think millions)
  - Mutex computation is quite expensive and adds up
  - Limits how many states can be searched
- *A very popular approach is to ignore mutexes*
  - Compute heuristics based on ***relaxed problem*** by assuming no delete effects
  - Much more efficient computaiton
- This is the idea behind the very well-known planner FF (for FastForward)
  - Many state-of-the-art planners derive from FF

Heuristic from Relaxed Problem

- Relaxed problem ignores delete lists on actions

PutDown(A,B):

PRE: { holding(A), clear(B) }
ADD: { on(A,B), handEmpty, clear(A)}
DEL: { holding(A), clear(B) }

PutDown(B,A):

PRE: { holding(B), clear(A) }
ADD: { on(B,A), handEmpty, clear(B) }
DEL: { holding(B), clear(A) }

⇩ Problem Relaxation

PutDown(A,B):

PRE: { holding(A), clear(B) }
ADD: { on(A,B), handEmpty, clear(A)}
DEL: { }

PutDown(B,A):

PRE: { holding(B), clear(A) }
ADD: { on(B,A), handEmpty, clear(B) }
DEL: { }

- The length of optimal solution for the relaxed problem is admissible heuristic for original problem. Why?

Heuristic from Relaxed Problem

- BUT – still finding optimal solution to relaxed problem is NP-hard
  - So we will approximate it
  - …. and do so very quickly

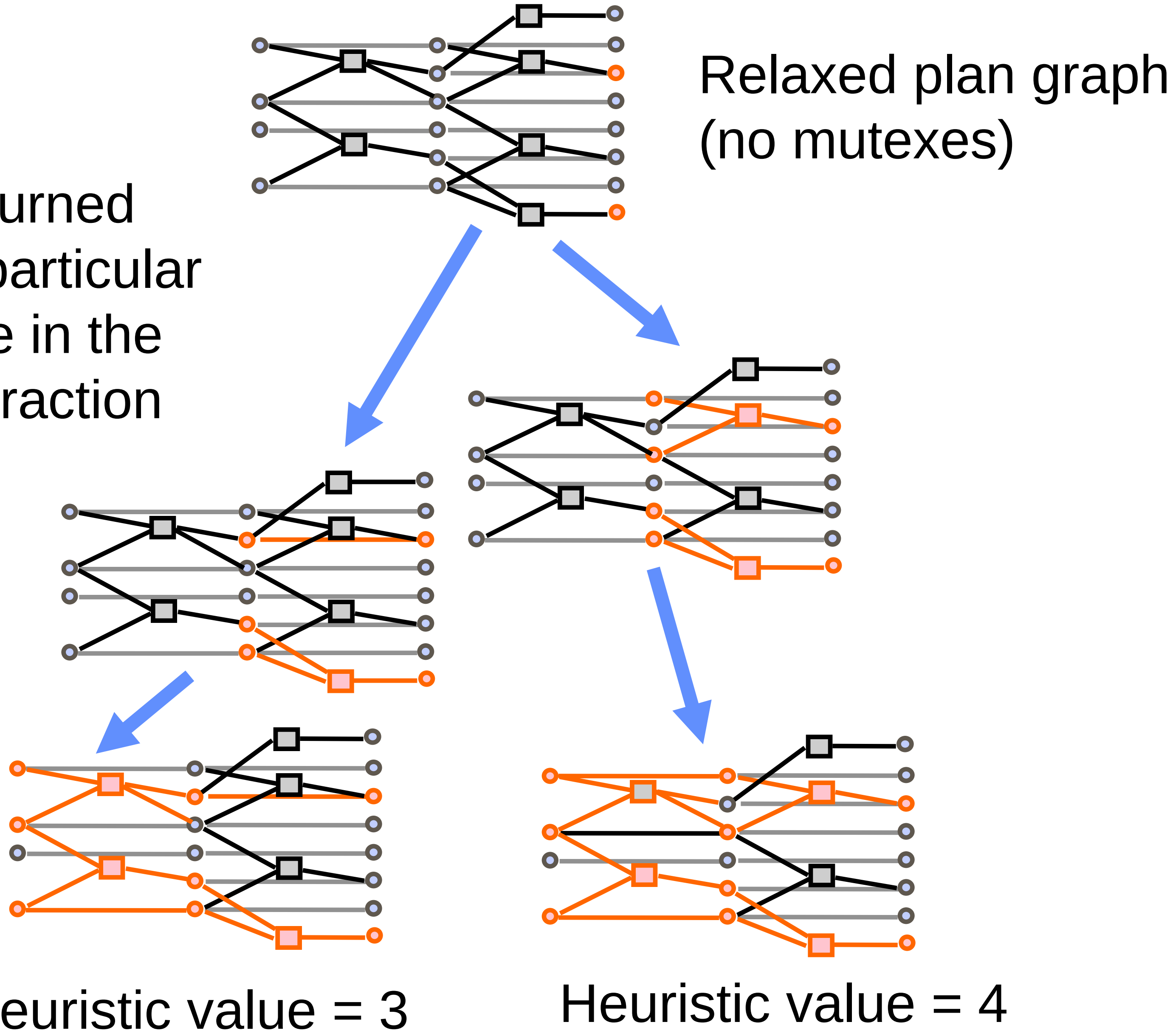
- One way is to explicitly search for a relaxed plan
  - Finding a relaxed plan can be done in polynomial time using a planning graph
  - Take relaxed-plan length to be the heuristic value
  - FF (for FastForward) uses this approach

FF Planner: finding relaxed plans

- Consider running Graphplan while ignoring the delete lists
  - No mutexes (avoid computing these altogether)
  - Implies no backtracking during solution extraction search!
  - So we can find a relaxed solutions efficiently
- After running the "no-delete-list Graphplan" then the # of actions in layered plan is the heuristic value
  - Different choices in solution extraction can lead to different heuristic values
- The planner FastForward (FF) uses this heuristic in forward state-space best-first search
  - Also includes several improvements over this

Example: Finding Relaxed Plans

The value returned depends on particular choices made in the backward extraction



Summary

- Many of the state-of-the-art planners today are based on heuristic search
  - Popularized by FF, which computed relaxed plans with blazing speed
- Lots of work on make heuristics more accurate without increasing the computation time too much
  - Trade-off between heuristic computation time vs. heuristic accuracy
- Most of these planners are not optimal
  - The most effective optimal planners tend to use different techniques (e.g. SatPlan, our next framework)