Classical Planning
Chapter 10

Mausam

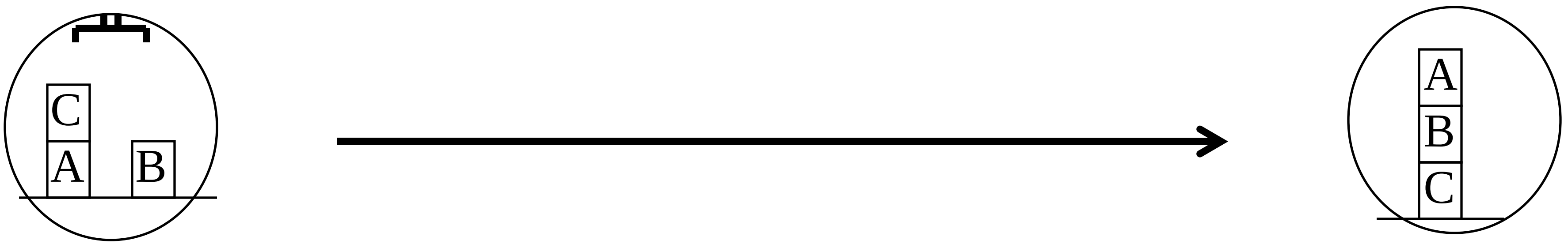
(Based on slides of Dan Weld, Marie desJardins)

Planning

- Given
  - a logical description of the **initial situation**,
  - a logical description of the **goal conditions**, and
  - a logical description of a set of **possible actions**,

- find
  - a **sequence of actions** (a **plan of actions**) that brings us from the initial situation to a situation in which the goal conditions hold.

Example: BlocksWorld



Planning Input: State Variables/Propositions

- Types: block --- a, b, c
- (on-table a) (on-table b) (on-table c)
- (clear a) (clear b) (clear c)
- (arm-empty)
- (holding a) (holding b) (holding c)
- (on a b) (on a c) (on b a) (on b c) (on c a) (on c b)

No. of state variables =16

No. of states = 2^{16}

No. of reachable states = ?

- (on-table ?b); clear (?b)
- (arm-empty); holding (?b)
- (on ?b1 ?b2)

Planning Input: Actions

- pickup a b, pickup a c, …
- place a b, place a c, …
- pickup-table a, pickup-table b, …
- place-table a, place-table b, …

- pickup ?b1 ?b2
- place ?b1 ?b2
- pickup-table ?b
- place-table ?b

Total: 6 + 6 + 3 + 3 = 18 "ground" actions

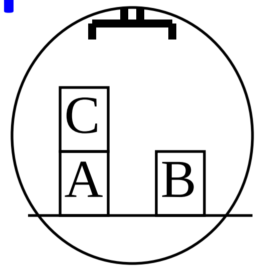
Total: 4 action schemata

Planning Input: Actions (contd)

- :action pickup ?b1 ?b2
  :precondition
    (on ?b1 ?b2)
    (clear ?b1)
    (arm-empty)
  :effect
    (holding ?b1)
    (not (on ?b1 ?b2))
    (clear ?b2)
    (not (arm-empty))

- :action pickup-table ?b
  :precondition
    (on-table ?b)
    (clear ?b)
    (arm-empty)
  :effect
    (holding ?b)
    (not (on-table ?b))
    (not (arm-empty))

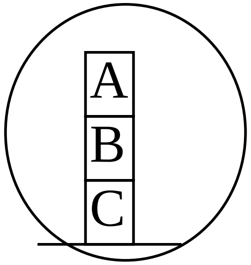
Planning Input: Initial State



- (on−table a) (on−table b)
- (arm−empty)
- (clear c) (clear b)
- (on c a)

- All other propositions false
  - not mentioned → false

Planning Input: Goal



- (on−table c) AND (on b c) AND (on a b)

- Is this a state?

- In planning a goal is a set of states

Planning Input Representation

- Description of initial state of world
  - Set of propositions
- Description of goal: i.e. set of worlds
  - E.g., Logical conjunction
  - Any world satisfying conjunction is a goal
- Description of available actions

Planning vs. Problem-Solving

Basic difference: **Explicit, logic-based representation**

- States/Situations: descriptions of the world by logical formulae
→ agent can explicitly reason about and communicate with the world.
- Goal conditions as logical formulae vs. goal test (black box)
→ agent can reflect on its goals.
- Operators/Actions: Axioms or transformation on formulae in a logical form
→ agent can gain information about the effects of actions by inspecting the operators.

Classical Planning

- Simplifying assumptions
  - Atomic time
  - Agent is omniscient (no sensing necessary).
  - Agent is sole cause of change
  - Actions have deterministic effects

- STRIPS representation
  - World = set of true propositions (conjunction)
  - Actions:
    - Precondition: (conjunction of *positive* literals, no functions)
    - Effects (conjunction of literals, no functions)
  - Goal = conjunction of *positive* literals

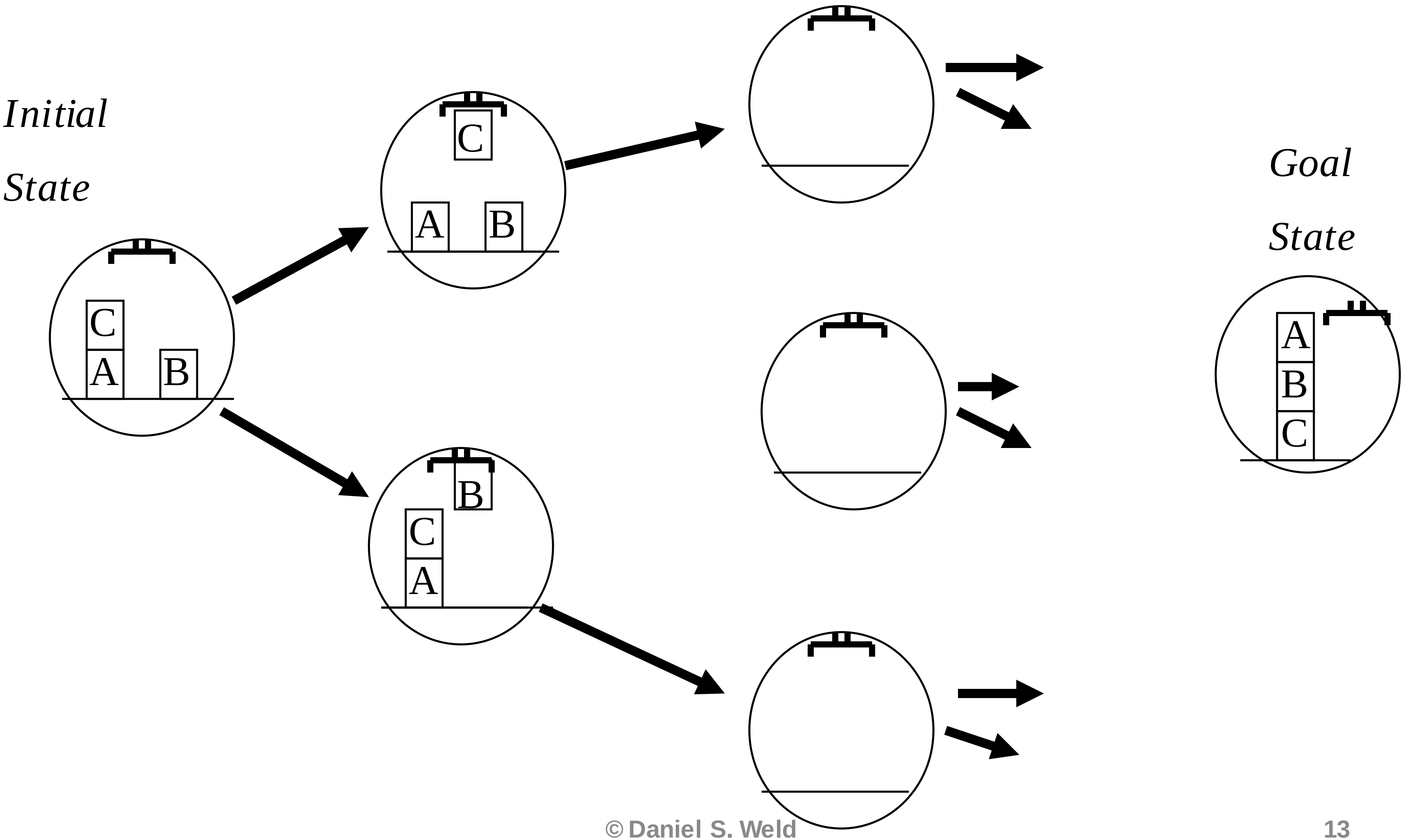
  - Is Blocks World in STRIPS?

  - Goals = conjunctions (Rich ^ Famous)

Planning as Search

- Forward Search in ? Space
  - World State Space
  - start from start state; look for a state with goal property
    - dfs/bfs
    - A*
- Backward Search in ? Space
  - Subgoal Space
  - start from goal conjunction; look for subgoal that holds in initial state
    - dfs/bfs/A*
- Local Search in ? Space
  - Plan Space

Forward World-Space Search



Forward State-Space Search

- Initial state: set of positive ground literals (CWA: literals not appearing are false)
- Actions:
  - applicable if preconditions satisfied
  - add positive effect literals
  - remove negative effect literals
- Goal test: checks whether state satisfies goal
- Step cost: typically 1

Heuristics for State-Space Search

- Count number of false goal propositions in current state

  Admissible?

  NO

- Subgoal independence assumption:
  - Cost of solving conjunction is sum of cost of solving each subgoal independently
  - Optimistic: ignores negative interactions
  - Pessimistic: ignores redundancy
  - Admissible? No
  - Can you make this admissible?

Heuristics for State Space Search (contd)

- Delete all preconditions from actions, solve easy relaxed problem, use length

  Admissible?

  YES

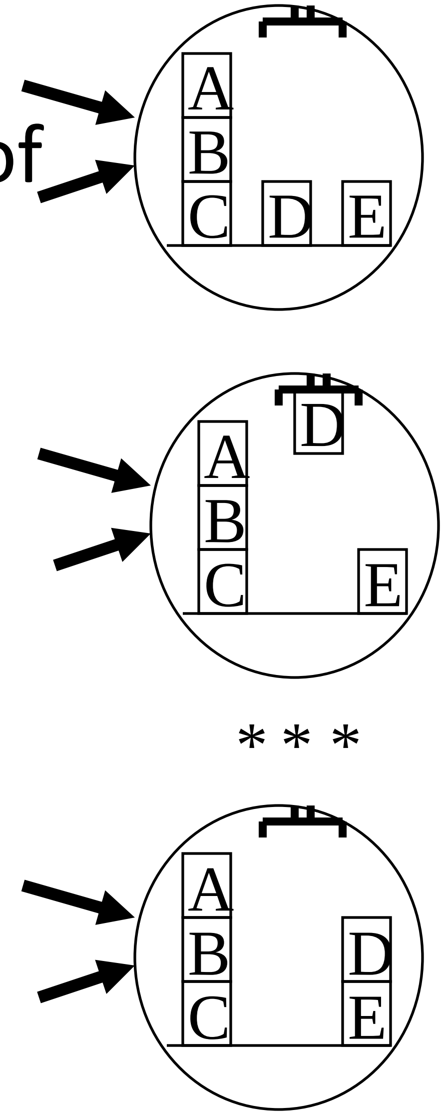
- Delete negative effects from actions, solve easier relaxed problem, use length

  Admissible?

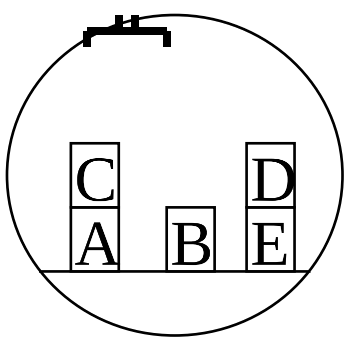
  YES (if Goal has only positive literals, true in STRIPS)

Backward Subgoal-Space Search

- Regression planning
- Problem: Need to find predecessors of state
- Problem: Many possible goal states are equally acceptable.
- From which one does one search?

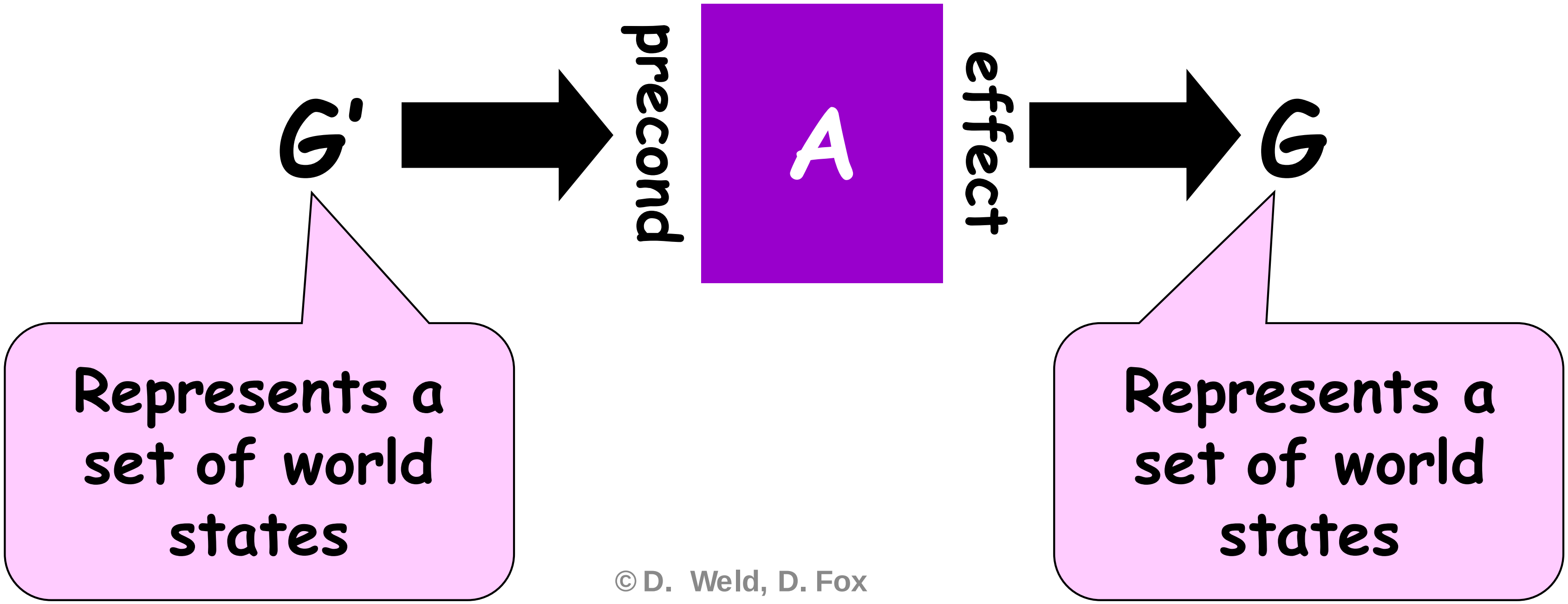


Initial State is completely defined

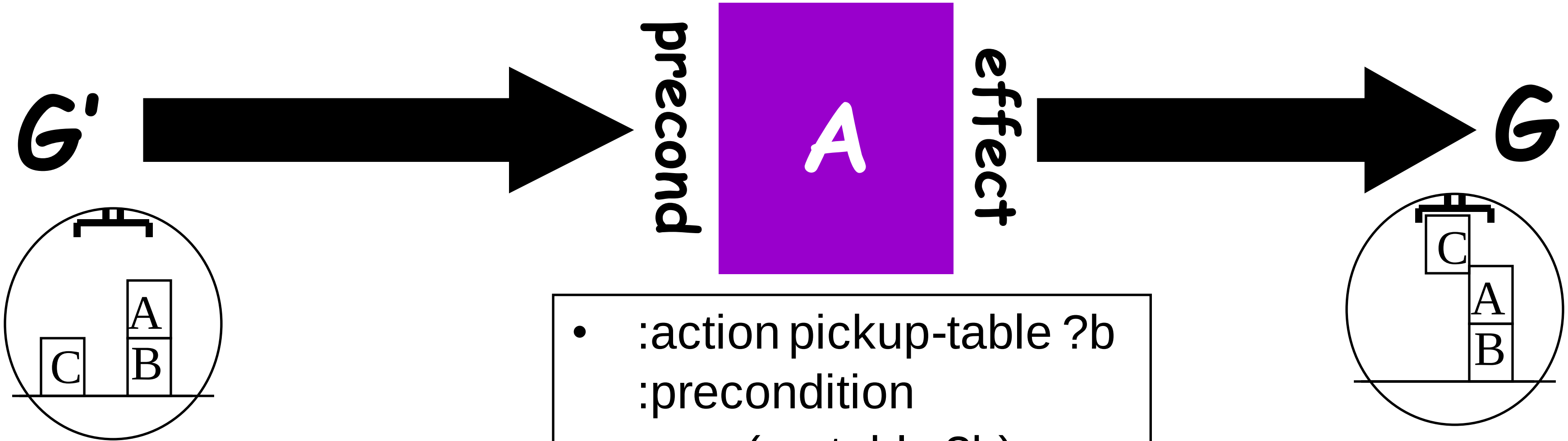


Regression

- Let G be a KR sentence (e.g. in logic)
- Relevance: needs to achieve one subgoal
- Consistency: does not undo any other subgoal
- Regressing a goal, G, thru an action, A yields the weakest precondition G'
  - Such that: if G' is true before A is executed
  - G is guaranteed to be true afterwards



Regression Example



(and (clear C)
(on-table C)
(arm-empty)
(on A B))

- :action pickup-table ?b
  :precondition
  (on-table ?b)
  (clear ?b)
  (arm-empty)
  :effect
  (holding ?b)
  (not (on-table ?b))
  (not (arm-empty))

(and (holding C)
(on A B))

Remove positive effects
Add preconditions for A

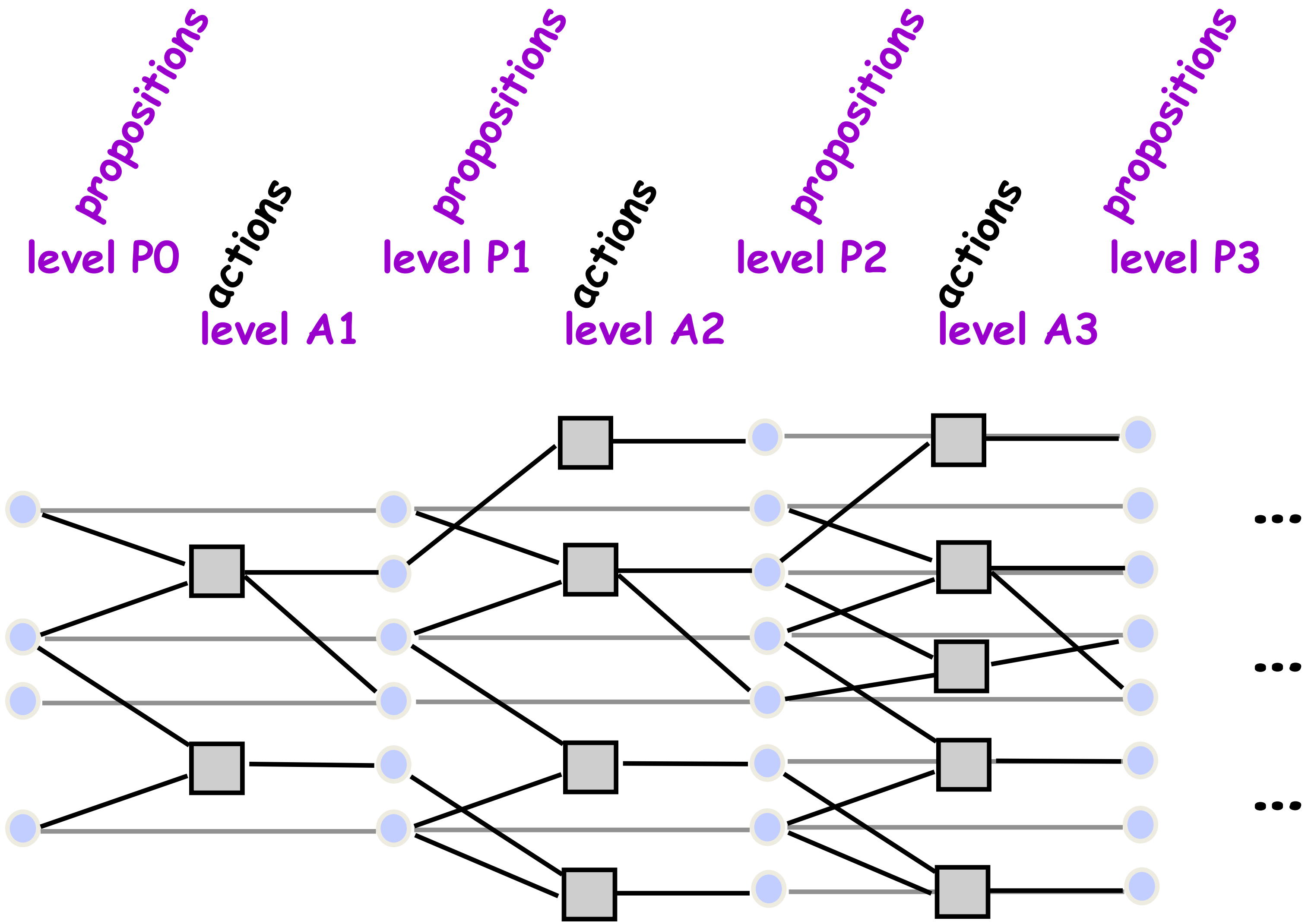
Complexity of Planning

- Size of Search Space
  - Forward: size of world state space
  - Backward: size of subsets of partial state space!
- Size of World state space
  - exponential in problem representation
- What to do?
  - Informative heuristic that can be computed in polynomial time!

Planning Graph: Basic idea

- Construct a planning graph: encodes constraints on possible plans
- Use this planning graph to compute an informative heuristic (Forward A*)
- Planning graph can be built for each problem in polynomial time

The Planning Graph



Note: a few noops missing for clarity

Graph Expansion

Proposition level 0

initial conditions

Action level i

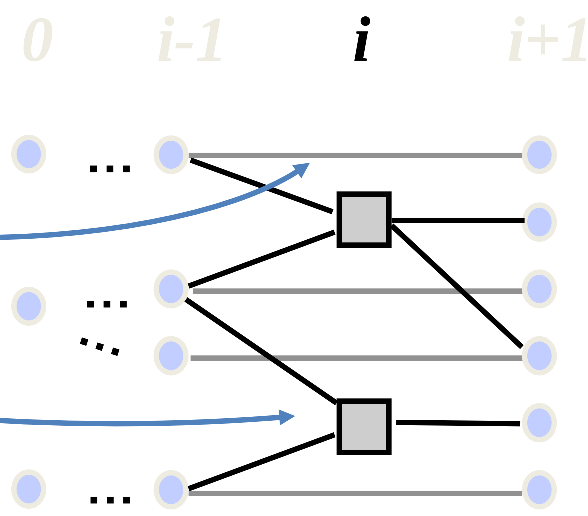
no-op for each proposition at level i-1

action for each operator instance whose

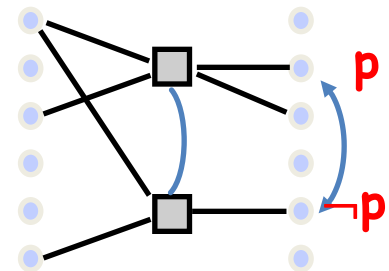
preconditions exist at level i-1

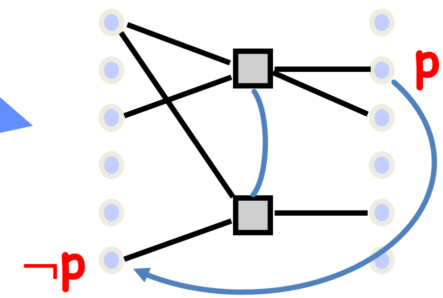
Proposition level i

effects of each no-op and action at level i



Mutual Exclusion



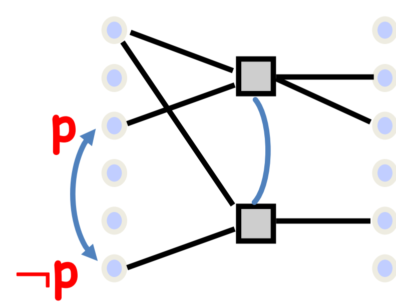


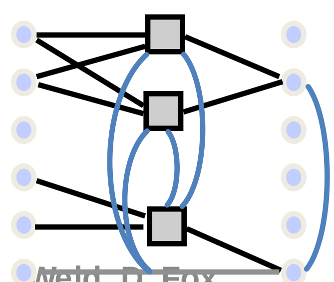
Two actions are mutex if

- one clobbers the other's effects or preconditions
- they have mutex preconditions

Two proposition are mutex if

- one is the negation of the other
- all ways of achieving them are mutex





Dinner Date

Initial Conditions: (:and (cleanHands) (quiet))

Goal: (:and (noGarbage) (dinner) (present))

Actions:

(:operator **carry** *:precondition*
:effect (:and (noGarbage) (:not (cleanHands)))
(:operator **dolly** *:precondition*
:effect (:and (noGarbage) (:not (quiet)))
(:operator **cook** *:precondition* (cleanHands)
:effect (dinner))
(:operator **wrap** *:precondition* (quiet)
:effect (present))

Planning Graph

noGarb

carry

cleanH cleanH

dolly

quiet quiet

cook

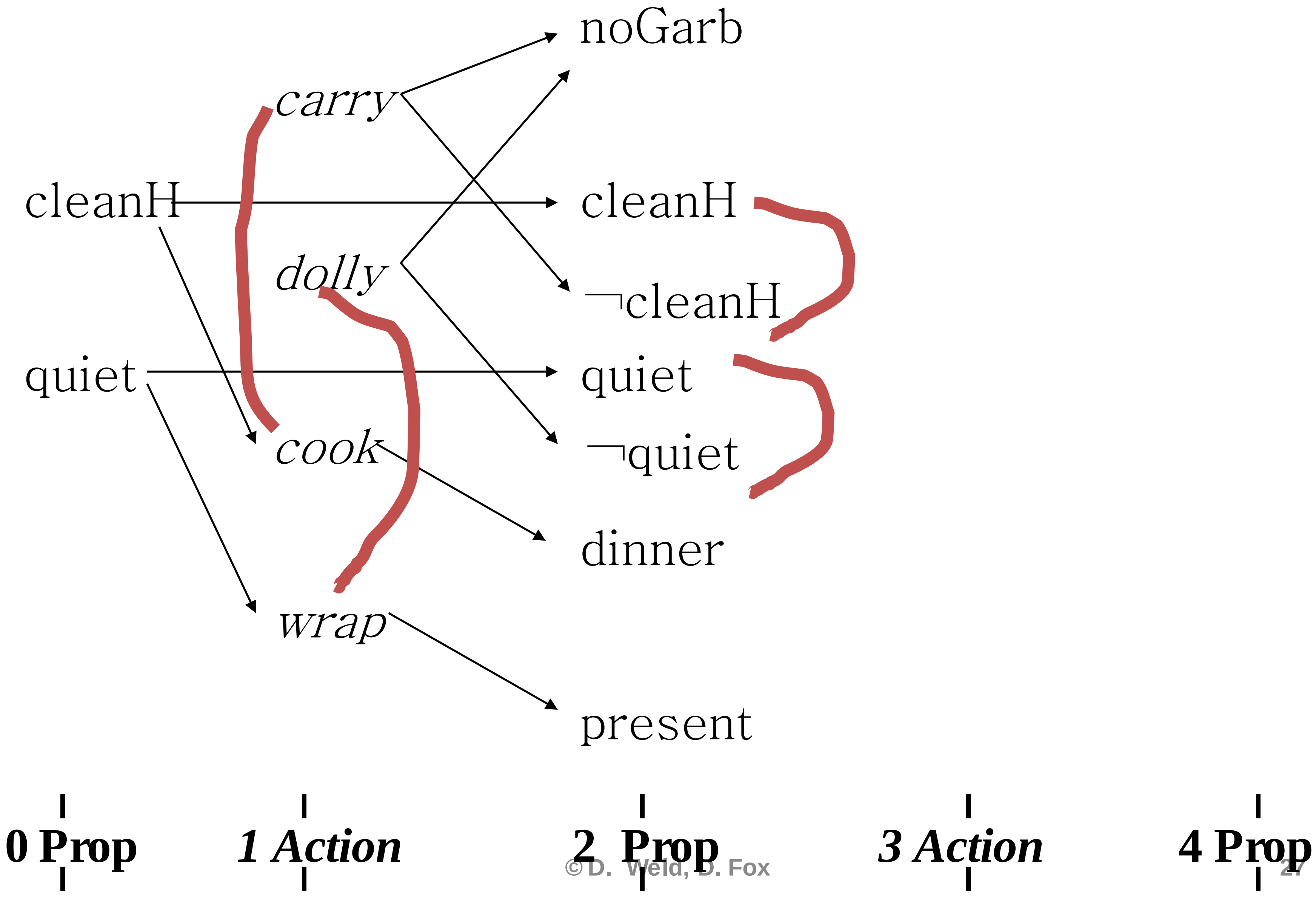
dinner

wrap

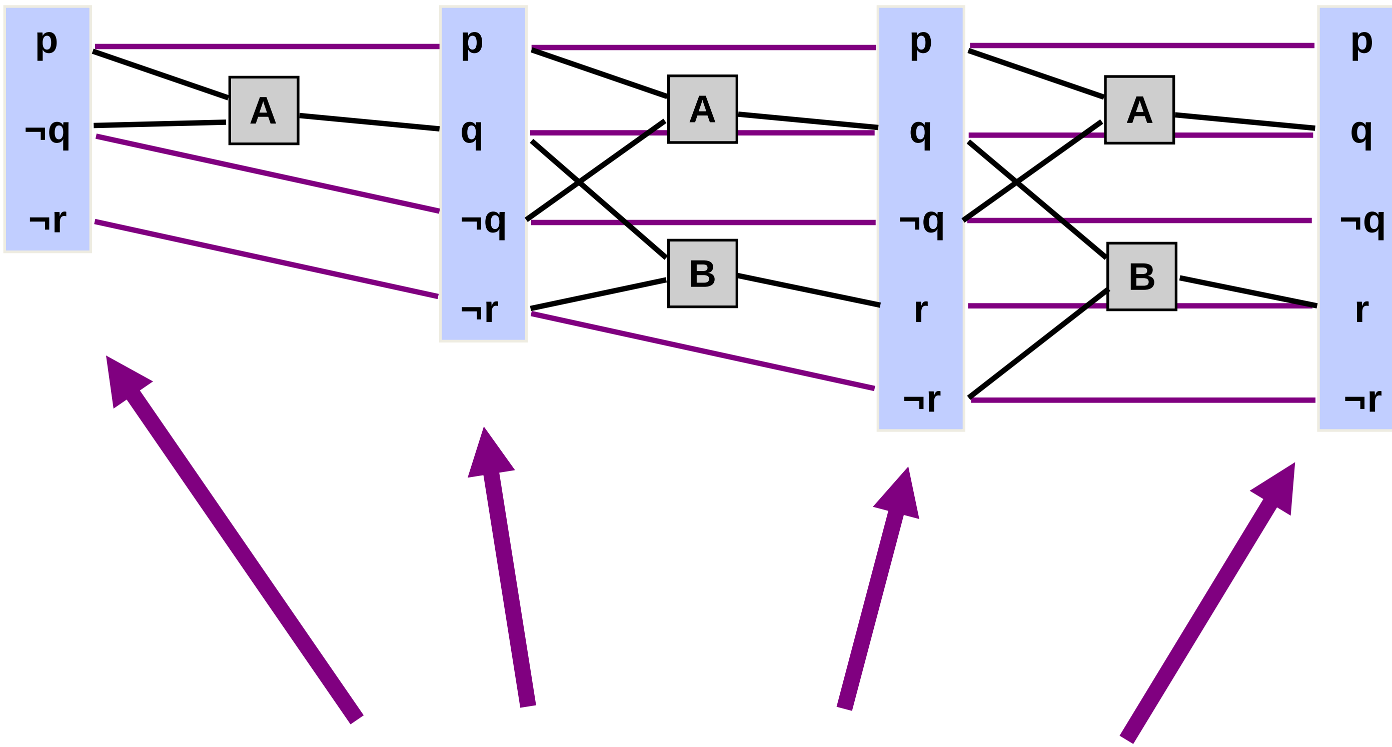
present

0 Prop ***1 Action*** **2 Prop** ***3 Action*** **4 Prop**

Are there any exclusions?

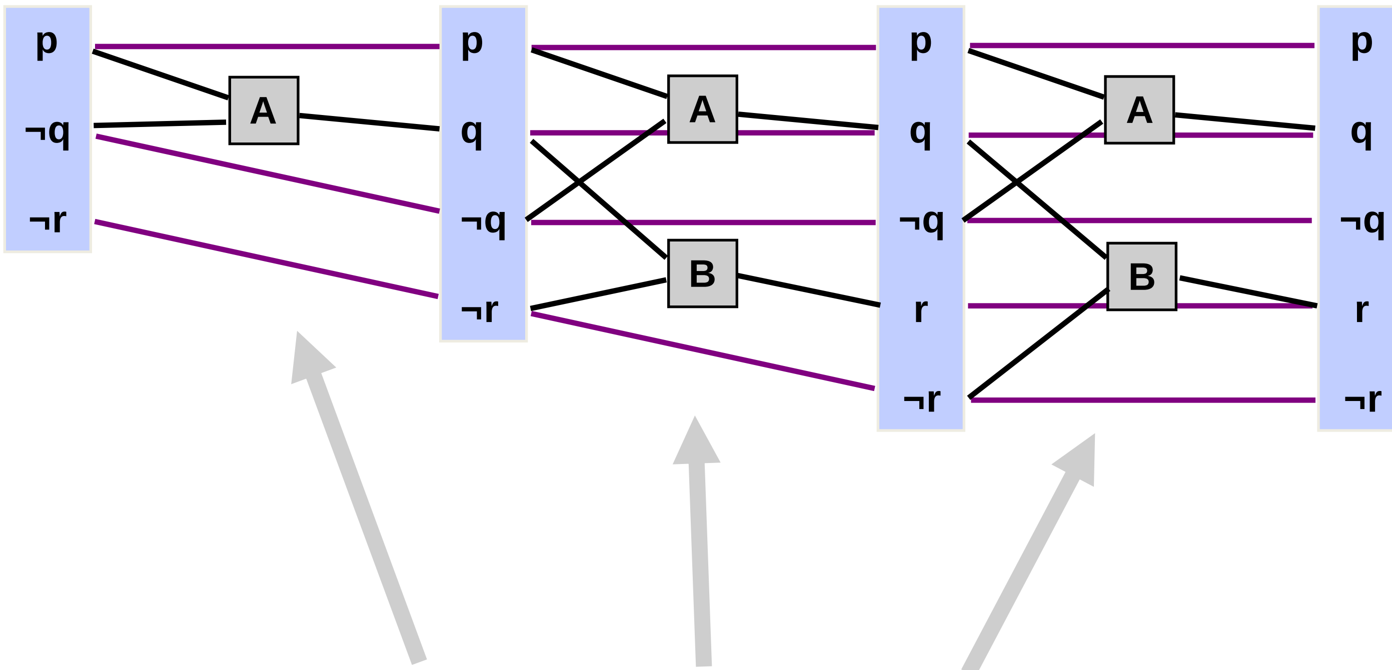


Observation 1



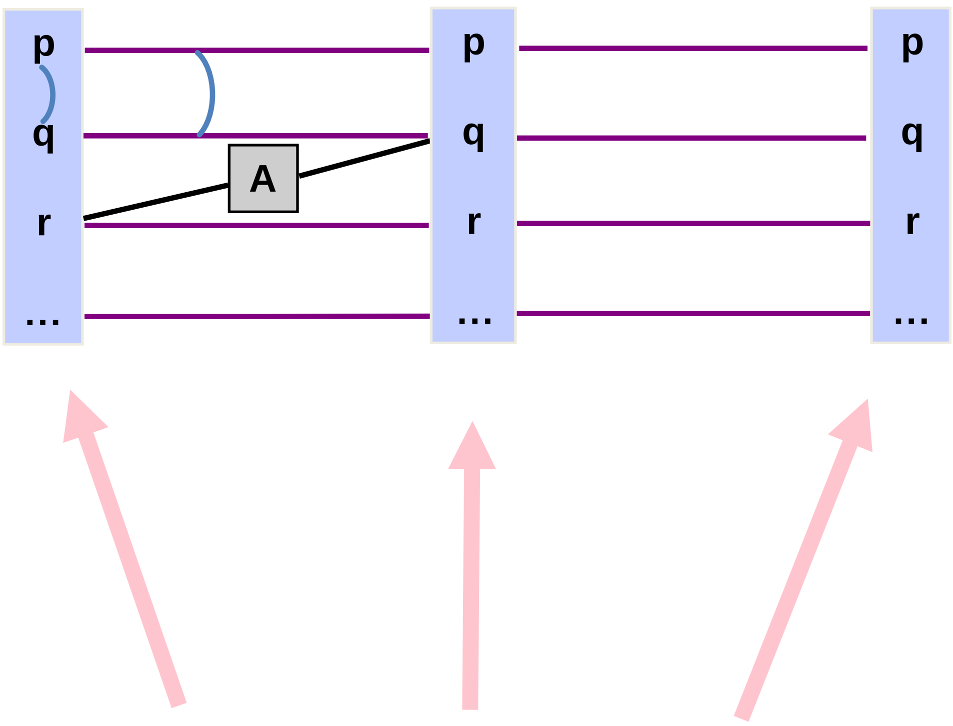
Propositions monotonically increase
(always carried forward by no-ops)

Observation 2



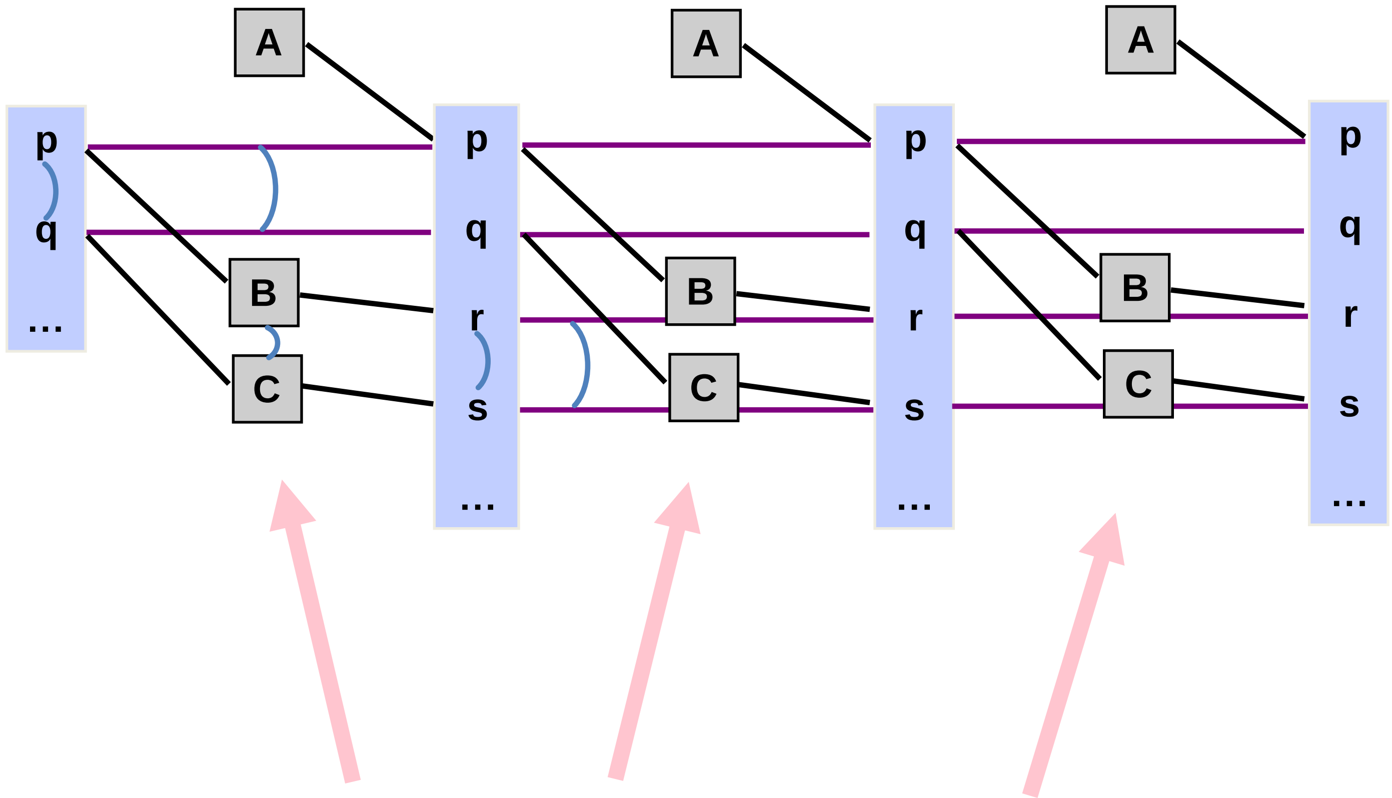
Actions monotonically increase

Observation 3



Proposition mutex relationships monotonically decrease

Observation 4



Action mutex relationships monotonically decrease

Observation 5

Planning Graph ‘levels off’.

- After some time k all levels are identical
- Because it’s a finite space, the set of literals never decreases and mutexes don’t reappear.

Properties of Planning Graph

- If goal is absent from last level
  - Goal cannot be achieved!
- If there exists a path to goal

    goal is present in the last level

- If goal is present in last level

  there may not exist any path still

Heuristics based on Planning Graph

- Construct planning graph starting from s
- h(s) = level at which goal appears non-mutex
  - Admissible?
  - YES

- Relaxed Planning Graph Heuristic
  - Remove negative preconditions build plan. graph
  - Use heuristic as above
  - Admissible? YES
  - More informative? NO
  - Speed: FASTER

FF

- Topmost classical planner until 2009
- State space local search
  - Guided by relaxed planning graph
  - Full bfs to escape plateaus – enforced hill climbing
  - A few other bells and whistles…

SATPlan: Planning as SAT

- Formulate the planning problem as a CSP
- Assume that the plan has k actions
- Create a binary variable for each possible action a:
  - Action(a,i) (TRUE if action a is used at step i)
- Create variables for each proposition that can hold at different points in time:
  - Proposition(p,i) (TRUE if proposition p holds at step i)

Constraints

- XOR: Only one action can be executed at each time step
- At least one action must be executed at each time step
- Constraints describing effects of actions
  - Action(a,i) → prec(a,i-1); Action(a,i) → eff(a,i)
- Maintain action: if an action does not change a prop p, then maintain action for proposition p is true
  - Action(maint_p,i) → Action(a1,i) v Action(a2,i)… [for all a_i that don't effect p]
- A proposition is true at step i only if some action (possibly a maintain action) made it true
- Constraints for initial state and goal state

Popular Application

Planning Summary

- Problem solving algorithms that operate on explicit propositional representations of states and actions.
- Make use of specific heuristics.
- STRIPS: restrictive propositional language
- State-space search: forward (progression) / backward (regression) search
- Local search FF; using compilation into SAT

- Partial order planners search space of plans from goal to start, adding actions to achieve goals (did not cover)