Classical Planning
Chapter 10

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(Based on slides of Dan Weld, Marie desJardins)
Planning

• Given
  – a logical description of the world states,
  – a logical description of a set of possible actions,
  – a logical description of the initial situation, and
  – a logical description of the goal conditions,

• 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

- (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)

Typed constants:
- block a, b, c

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

No. of state variables = 16
No. of states = $2^{16}$
No. of reachable states = ?
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
• :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 \(\rightarrow\) 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 world states

• 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
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 (e.g., Rich ∧ Famous)
Planning vs. General Search

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.

- **Operators/Actions:** Axioms or transformation on formulae in a logical form
  → agent can gain information about the effects of actions by inspecting the operators.

- **Goal conditions** as logical formulae vs. goal test (black box)
  → agent can reflect on its goals.
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

Initial State

Goal State
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
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

- 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

\[ G' \xrightarrow{\text{pred}} A \xrightarrow{\text{eff}} G \]

- :action pickup-table ?b
  :precondition
  (on-table ?b)
  (clear ?b)
  (arm-empty)

- :effect
  (holding ?b)
  (not (on-table ?b))
  (not (arm-empty))

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
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
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
  - $h(s) = \text{level at which goal appears non-mutex}$
    - Admissible? YES

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

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• 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) \rightarrow \text{prec}(a,i-1); \text{Action}(a,i) \rightarrow \text{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) \rightarrow \text{Action}(a1,i) \lor \text{Action}(a2,i)\ldots \text{[for all } a_i \text{ 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
Application: Mars Rover
Application: Network Security Analysis
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)