Causal-link Planning II

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## Planning as Search

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POP algorithm

POP(((A, O, L), agenda, actions)

If agenda = () then return (A, O, L)

Pick (Q, a_{\text{need}}) from agenda

a_{\text{add}} = \text{choose}(\text{actions}) \text{ s.t. } Q \in \text{effects}(a_{\text{add}})

If no such action a_{\text{add}} exists, fail.

L' := L \cup (a_{\text{add}}, Q, a_{\text{need}}) ;
O' := O \cup (a_{\text{add}} < a_{\text{need}})

agenda' := agenda - (Q, a_{\text{need}})

If a_{\text{add}} is new, then A := A \cup a_{\text{add}} and

\forall P \in \text{preconditions}(a_{\text{add}}), \text{add } (P, a_{\text{add}}) \text{ to agenda'}

For every action a_t that threatens any causal link (a_p, Q, a_c) in L'

choose to add a_t < a_p or a_c < a_t to O.

If neither choice is consistent, fail.

POP(((A', O', L'), agenda, actions)

Termination
Goal Selection
Action Selection

Step Addition
Step Reuse

Update goals

Protect causal links

Demotion
Promotion

a_t < a_p
a_c < a_t
More expressive action representation

- Actions with variables
- Conditional effects
- Disjunctive preconditions
- Universal quantification

$\Rightarrow$ UCPOP [Penberthy & Weld 92]
Propositional STRIPS

Move-C-from-A-to-Table:
precondition: (and (on C A) (clear C))
effects: (and (on C Table)
            (not (on C A))
            (clear A))

- With n blocks => $O(n^3)$ actions!
- Many actions not relevant for goal
Action schemata

Move ?b from ?x to ?y

parameters: ?b, ?x, ?y

preconds: (and (on ?b ?x) (clear ?b) (clear ?y)
         (≠ ?y Table))

effects: (and (on ?b ?y)
             (not (on ?b ?x))
             (clear ?x)
             (not (clear ?y)))
Modifications to POP to handle actions with variables (1)

- Plan = (A, O, L, B), where
  - A: set of actions in the plan
  - O: temporal orderings between actions (a < b)
  - L: causal links linking actions via a literal
  - B: binding constraints (co-designation and non co-designation)

- Unification (instead of matching)
  - To satisfy (Q, a_{need}) we can use an action a_{add} such that P ∈ effects(a_{add}) and MGU(P, Q, B) ≠ ⊥
  - For example, use a new action move(?b ?x ?y) to satisfy on(A C), since MGU(on(?b ?y), on(A C), B) = ((?b = A) (?y = C)) ≠ ⊥
Modifications to POP to handle actions with variables (2)

- Distinct variables for new action instances
  - Move(?b1 ?x1 ?y1), Move(?b2 ?x2 ?y2), ...

- Add codesignation constrains in the preconditions of a new action to the bindings B
  - After adding move(?b ?x ?y) to satisfy on(A C),
    \[ B := B \cup ((?b \neq ?x) \land (?x \neq ?y) \land (?b = A) \land (?y = C)) \]
    \[ (?b \neq ?y) \land (?y \neq \text{Table}) \text{ are already satisfied} \]
    \[ \text{since } ?b \text{ and } ?y \text{ are bound to constants} \]
Modifications to POP to handle actions with variables (3)

- **Threat resolution:**
  - Delay threat checks until ground values are known for variables, or
  - “Separation”: add (inequality) binding that ensures condition does not unify.

- **Ensure all actions eventually grounded**
  - Require ground initial state (no variables)
  - “Safe” operators: \( \text{vars(effects)} \subseteq \text{vars (precs)} \)
POP with variables

A0

(\text{on C A}) \quad (\text{on-table A}) \quad (\text{on-table B}) \quad (\text{clear C}) \quad (\text{clear B})

\begin{align*}
\text{(clear ?b2)} & \quad (\text{clear ?y2}) \quad (\text{on ?b2 ?x2}) \\
\text{A2: move ?b2 from ?x2 to ?y2} & \\
(\text{on ?b2 Table}) & \quad (\text{clear ?y2}) \quad (\text{on ?b2 ?y2}) \\
((?b2 A) & \quad (?y2 B) \quad ... )
\end{align*}

\text{Step addition}

\begin{align*}
\text{Step addition} & \\
(\text{on A B}) & \quad (\text{on B C})
\end{align*}

Ainf

\begin{align*}
(\text{clear ?b1}) & \quad (\text{clear ?y1}) \quad (\text{on ?b1 ?x1}) \\
\text{A1: move ?b1 from ?x1 to ?y1} & \\
(\text{on ?b1 Table}) & \quad (\text{clear ?y1}) \quad (\text{on ?b1 ?y1}) \\
((?b1= B) & \quad (?y1 = C) \quad (?b1 \neq ?x1) \quad (?x1 \neq ?y1) \quad (?y1 \neq \text{Table}))
\end{align*}

\text{Step reuse}
Conditional effects

Move ?b from ?x to ?y
parameters: ?b, ?x, ?y
preconds: (and (on ?b ?x) (clear ?b) (clear ?y)
effects: (and
        (on ?b ?y)
        (not (on ?b ?x))
        (clear ?x)
        (when (≠ ?y Table)
            (not (clear ?y)))))
Conditional Effects

(when P Q)

- means if P holds in the state before the action is applied, then Q will hold in the state resulting from the application of the action

- In the situation calculus:
  \[ P(x, s) \rightarrow Q(y, \text{do}(a,s)) \]
Modifications to POP to handle conditional effects

- Allow conditional effects to be used for causal links
  - Add the antecedent of conditional effect to the agenda.

- Threat resolution by “confrontation”:
  - Add the negation of the antecedent of the conditional effect to the agenda.

- Handle negated goals
  - Same as positive goals
  - Closed world assumption for initial state
Disjunctive preconditions

- Ex: (and (on ?x ?y)
  (or (clear ?x) (big-and-flat ?x)))

- Modifications to POP:
  - Put (or Q1 Q2) on the agenda when the action is selected.
  - When (or Q1 Q2) is picked from the agenda, choose either Q1 or Q2 to work on.

- Note: No disjunctive effects
Universal quantification in preconditions and effects

Move-briefcase(?b ?loc1 ?loc2)
  preconds: (and (briefcase ?b) (at ?b ?loc1)
              (forall ((padlock ?p)) (not (locked ?b ?p)))
              (≠ ?loc1 ?loc2))
  effects: (and (at ?b ?loc2)
                (not (at ?b ?loc1))
                (forall ((object ?x))
                  (when (in ?x ?b) (and (at ?x ?loc2)
                                          (not (at ?x ?loc1)))))

Universal quantification restricted to finite, static types

- Assume a finite, static set of typed objects
  - No object creation
  - No object destruction

- Example:
  - \( \text{Extension}[(\text{briefcase } ?b)] = \{B1\} \)
  - \( \text{Extension}[(\text{padlock } ?p)] = \{P1, P2\} \)
  - \( \text{Extension}[(\text{object } ?x)] = \{B1, P1, P2, O1, O2, O3, ...\} \)
Approach: Replace quantified expressions with ground literals

- Since quantification is over a finite set (type), replace “forall” goals with the conjunction of all the ground formulas obtained from the instances of the type.

- Universal base:
  \[
  Y(\forall_{t_1}x \Delta(x)) = Y(\Delta(c_1)) \land \ldots \land Y(\Delta(c_n))
  \]
  where the instances of \(t_1\) are \((c_1, \ldots, c_n)\)

- Example: if Extension[\((\text{padlock } ?x)) = \{p1, p2\}] = \{p1, p2\}, then
  \[
  (\forall ((\text{padlock } ?x)) \neg (\text{locked } ?x ?b))) \\
  \rightarrow (\text{and} \neg (\text{locked } p1 ?b)) (\neg (\text{locked } p2 ?b)))
  \]
Modifications to POP to handle quantification

- Replace a universally quantified goal with its universal base.
- Use ground literals from the universal base of a quantified effect as needed for causal links.
- Consider threats when their bindings refer to universally quantified variables.
Briefcase example

A0

(briefcase B) (at B home) (in P B) (at P home)

(at B office) (at P home)

A_{inf}
Briefcase example: No threats yet

A0

(briefcase B)  (at B home)  (in P B)  (at P home)

move B ?l office

(briefcase B)  (at B ?l)  (in ?o1 B)

(at B office)  (not (at B ?l))  (at ?o1 office)  (not (at ?o1 ?l))

Ainf

(at B office)  (at P home)
Briefcase example:
(?l = home) => threat to (at P home)
Briefcase example:
Solve threat by confrontation

\[
\begin{align*}
A_0 & \quad \text{(briefcase B)} \quad \text{(at B home)} \quad \text{(in P B)} \quad \text{(at P home)} \\
\text{move B home office} & \quad \text{(at B office)} \quad \text{(not (at B home))} \quad \text{(at \ensuremath{\text{o1}} office)} \quad \text{(not (in P B))} \\
\text{move B off} & \quad \text{(at B off)} \quad \text{(at P home)} \\
A_{\text{inf}} & \quad \text{(not (at \ensuremath{\text{o1}} home))} 
\end{align*}
\]
Briefcase example: Final Plan

A0

(briefcase B) (at B home) (in P B) (at P home)

(in P B) take-out P B (not (in P B))

(briefcase B) (at B home) (in ?o1 B) (not (in P B))

move B home office

(at B office) (not (at B home)) (at ?o1 office) (not (at ?o1 home))

(at B off) (at P home)

Ainf
Quantified goal example

\[\text{start}\]
(object D) (object B) (briefcase B) (at B home) \sim (in D B) (at D office)

(forall ((object ?x)) (at ?x home))

\[\text{end}\]
Quantified goal example

*start*

(object D) (object B) (briefcase B) (at B home) ~ (in D B) (at D office)

(briefcase B) (at B ?l) (in ?o1 B)

move B ?l home

(at B home) ~ (at B ?l) (at ?o1 home) ~ (at ?o1 ?l)

(at B home) (at D home)

*end*
Quantified goal example

*start*

(object D) (object B) (briefcase B) (at B home) \sim (in D B) (at D office)

(briefcase B) (at B ?!) (in D B) (in ?o1 B)

move B ?! home

(at B home) \sim (at B ?!) (at D home) \sim (at D ?!) (at ?o1 home) ...

(at B home) (at D home)

*end*
*start*

(object D) (object B) (briefcase B) (at B home) ~(in D B) (at D office)

(briefcase B) (at B home) ~(in D B) (in ?o3 B)

**move B home office**

(at B office) ~(at B home) (at ?o3 office) ~(at ?o3 home)

(briefcase B) (at B office) (at D office)

**put-in D B**

(in D B)

(object D) (briefcase B) (at B office) (in D B) (in ?o1 B)

**move B office home**

(at B home) ~(at B office) (at D home) ~(at D office) (at ?o1 home) ...

(at B home) (at D home)

*end*