Planning

- Search vs. planning
- STRIPS operators
- Partial-order planning

What we have so far

- Can TELL KB about new percepts about the world
- KB maintains model of the current world state
- Can ASK KB about any fact that can be inferred from KB

How can we use these components to build a planning agent,

i.e., an agent that constructs plans that can achieve its goals, and that then executes these plans?

Example: Robot Manipulators

- Example: (courtesy of Martin Rohrmeier)
  - [Puma 560]
  - [Kr6]

Remember: Problem-Solving Agent

```
function SIMPLE-PROBLEM-SOLVING-AGENT( p) returns an action
    inputs: p, a percept
    static: s, an action sequence, initially empty
            state, some description of the current world state
            g, a goal, initially null
            problem, a problem formulation

    state ← UPDATE-STATE(state, p)
    if s is empty then
        g ← FORMULATE-GOAL(state)
        problem ← FORMULATE-PROBLEM(state, g)
        s ← SEARCH( problem)
    action ← RECOMMENDATION(s, state)
    s ← REMAINDER(s, state)
    return action
```

Note: This is *offline* problem-solving. *Online* problem-solving involves acting w/o complete knowledge of the problem and environment

Simple planning agent

- Use percepts to build model of current world state
- IDEAL-PLANNER: Given a goal, algorithm generates plan of action
- STATE-DESCRIPTION: given percept, return initial state description in format required by planner
- MAKE-GOAL-QUERY: used to ask KB what next goal should be

A Simple Planning Agent

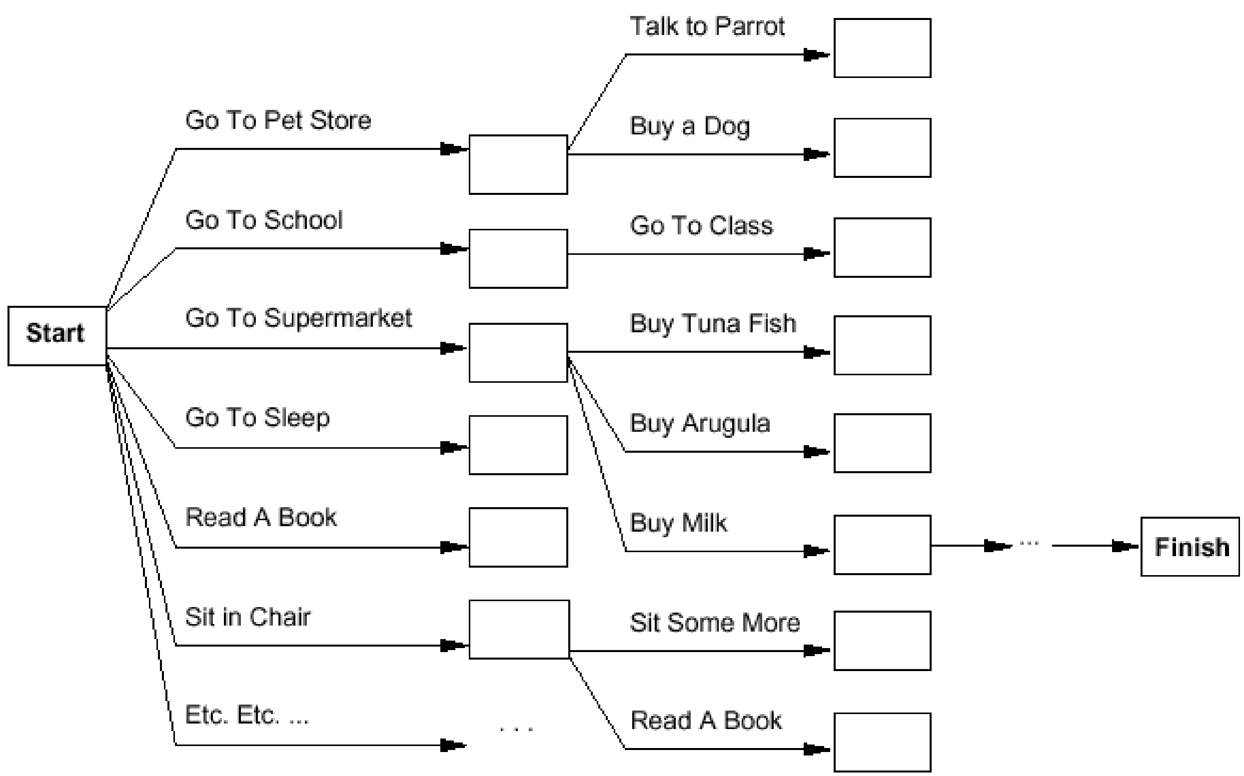
```
function SIMPLE-PLANNING-AGENT(percept) returns an action
    static:          KB, a knowledge base (includes action descriptions)
                     p, a plan (initially, NoPlan)
                     t, a time counter (initially 0)
    local variables: G, a goal
                     current, a current state description
    TELL(KB, MAKE-PERCEPT-SENTENCE(percept, t))
    current ← STATE-DESCRIPTION(KB, t)
    if p = NoPlan then
        G ← ASK(KB, MAKE-GOAL-QUERY(t))
        p ← IDEAL-PLANNER(current, G, KB)
    if p = NoPlan or p is empty then
        action ← NoOp
    else
        action ← FIRST(p)
        p ← REST(p)
    TELL(KB, MAKE-ACTION-SENTENCE(action, t))
    t ← t+1
    return action
```

Like popping from a stack

Search vs. planning

Consider the task *get milk, bananas, and a cordless drill*

Standard search algorithms seem to fail miserably:



After-the-fact heuristic/goal test inadequate

Search vs. planning

Planning systems do the following:

1) open up action and goal representation to allow selection
2) divide-and-conquer by subgoaling
3) relax requirement for sequential construction of solutions

	Search	**Planning**
States	Lisp data structures	Logical sentences
Actions	Lisp code	Preconditions/outcomes
Goal	Lisp code	Logical sentence (conjunction)
Plan	Sequence from S_0	Constraints on actions

Planning in situation calculus

$PlanResult(p, s)$ is the situation resulting from executing p in s

$$PlanResult([], s) = s$$
$$PlanResult([a|p], s) = PlanResult(p, Result(a, s))$$

Initial state $At(Home, S_0) \wedge \neg Have(Milk, S_0) \wedge \ldots$

Actions as Successor State axioms

$Have(Milk, Result(a, s)) \;\; \Leftrightarrow$

$[(a = Buy(Milk) \wedge At(Supermarket, s)) \vee (Have(Milk, s) \wedge a \neq \ldots)]$

Query

$$s = PlanResult(p, S_0) \wedge At(Home, s) \wedge Have(Milk, s) \wedge \ldots$$

Solution

$$p = [Go(Supermarket), Buy(Milk), Buy(Bananas), Go(HWS), \ldots]$$

Principal difficulty: unconstrained branching, hard to apply heuristics

Basic representation for planning

- Most widely used approach: uses STRIPS language

- states: conjunctions of function-free ground literals (I.e., predicates applied to constant symbols, possibly negated); e.g.,

  $At(Home) \wedge \neg Have(Milk) \wedge \neg Have(Bananas) \wedge \neg Have(Drill) \ldots$

- goals: also conjunctions of literals; e.g.,

  $At(Home) \wedge Have(Milk) \wedge Have(Bananas) \wedge Have(Drill)$

  but can also contain variables (implicitly universally quant.); e.g.,

  $At(x) \wedge Sells(x, Milk)$

Planner vs. theorem prover

- Planner: ask for sequence of actions that makes goal true if executed

- Theorem prover: ask whether query sentence is true given KB

STRIPS operators

Tidily arranged actions descriptions, restricted language

ACTION: $Buy(x)$
PRECONDITION: $At(p), Sells(p, x)$
EFFECT: $Have(x)$

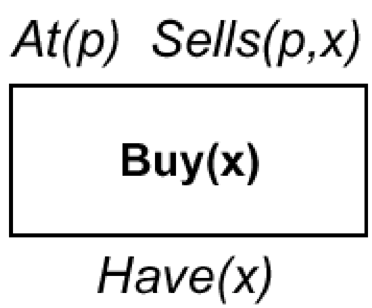
[Note: this abstracts away many important details!]

Restricted language $\Rightarrow$ efficient algorithm

Precondition: conjunction of positive literals

Effect: conjunction of literals

Graphical notation:



Types of planners

- Situation space planner: search through possible situations

- Progression planner: start with initial state, apply operators until goal is reached

  Problem: high branching factor!

- Regression planner: start from goal state and apply operators until start state reached

  Why desirable? usually many more operators are applicable to initial state than to goal state.

  Difficulty: when want to achieve a conjunction of goals

Initial STRIPS algorithm: situation-space regression planner

State space vs. plan space

Standard search: node = concrete world state

Planning search: node = partial plan

Search space of plans rather than of states.

Defn: open condition is a precondition of a step not yet fulfilled

Operators on partial plans:

add a link from an existing action to an open condition

add a step to fulfill an open condition

order one step wrt another

Gradually move from incomplete/vague plans to complete, correct plans

Operations on plans

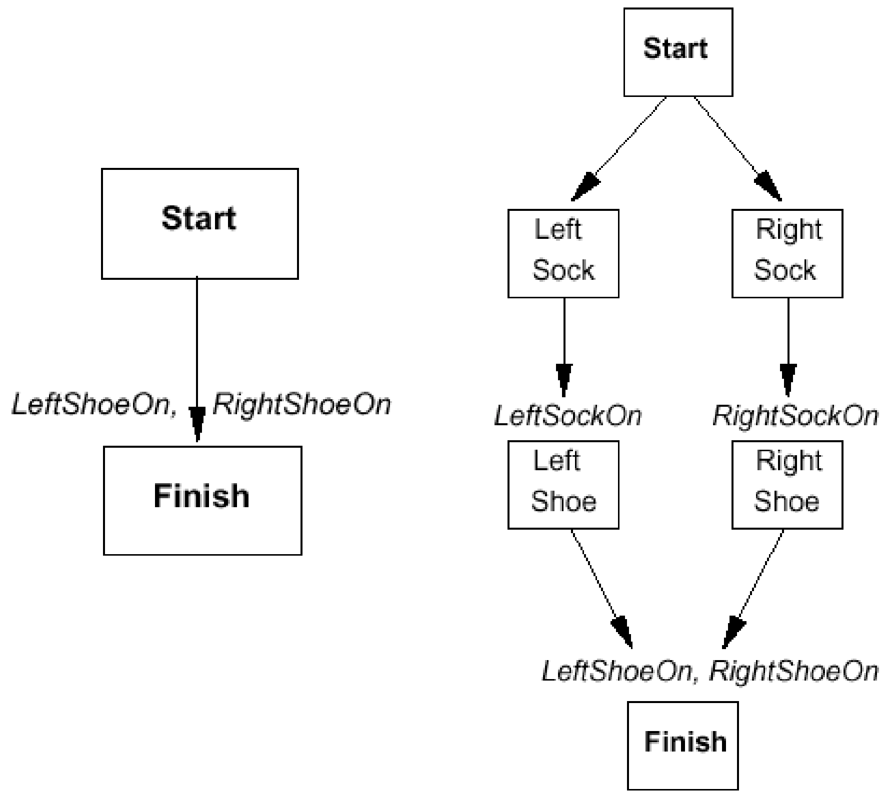
- Refinement operators: add constraints to partial plan

- Modification operator: every other operators

Types of planners

- Partial order planner: some steps are ordered, some are not
- Total order planner: all steps ordered (thus, plan is a simple list of steps)
- Linearization: process of deriving a totally ordered plan from a partially ordered plan.

Partially ordered plans



A plan is <u>complete</u> iff every precondition is achieved

A precondition is <u>achieved</u> iff it is the effect of an earlier step and no <u>possibly intervening</u> step undoes it

Plan

We formally define a plan as a data structure consisting of:

- Set of plan steps (each is an operator for the problem)
- Set of step ordering constraints

  e.g., $A \prec B$ means "A before B"

- Set of variable binding constraints

  e.g., $v = x$ where v variable and x constant or other variable

- Set of causal links

  e.g., $A \xrightarrow{c} B$ means "A achieves c for B"

POP algorithm sketch

function POP(*initial*, *goal*, *operators*) **returns** *plan*

    plan ← MAKE-MINIMAL-PLAN(*initial*, *goal*)
    loop do
        if SOLUTION?(*plan*) **then return** *plan*
        S_{need}, c ← SELECT-SUBGOAL(*plan*)
        CHOOSE-OPERATOR(*plan*, *operators*, S_{need}, c)
        RESOLVE-THREATS(*plan*)
    end

---

function SELECT-SUBGOAL(*plan*) **returns** S_{need}, c

    pick a plan step S_{need} from STEPS(*plan*)
        with a precondition c that has not been achieved
    return S_{need}, c

POP algorithm (cont.)

procedure CHOOSE-OPERATOR(*plan*, *operators*, S_{need}, *c*)

  choose a step S_{add} from *operators* or STEPS(*plan*) that has c as an effect
  if there is no such step **then fail**
  add the causal link $S_{add} \xrightarrow{c} S_{need}$ to LINKS(*plan*)
  add the ordering constraint $S_{add} \prec S_{need}$ to ORDERINGS(*plan*)
  if S_{add} is a newly added step from *operators* **then**
    add S_{add} to STEPS(*plan*)
    add $Start \prec S_{add} \prec Finish$ to ORDERINGS(*plan*)

---

procedure RESOLVE-THREATS(*plan*)

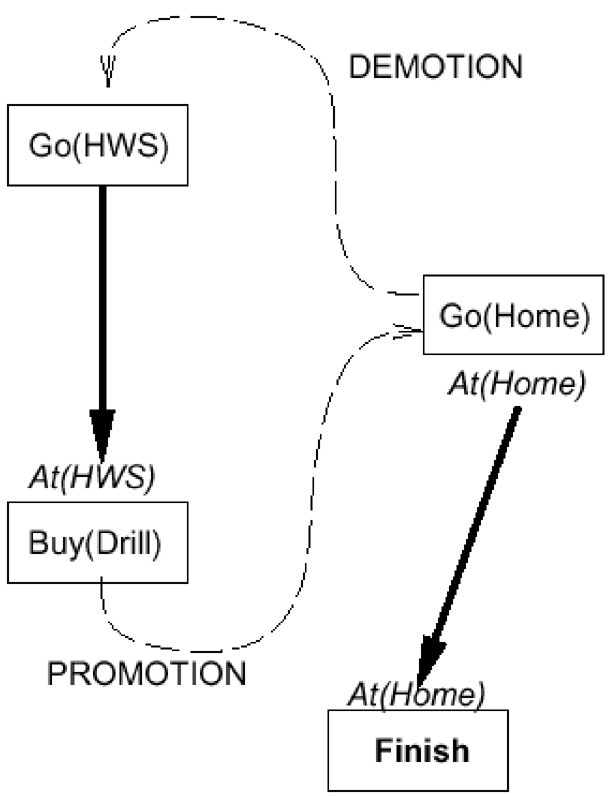
  for each S_{threat} that threatens a link $S_i \xrightarrow{c} S_j$ in LINKS(*plan*) **do**
    choose either
      Demotion: Add $S_{threat} \prec S_i$ to ORDERINGS(*plan*)
      Promotion: Add $S_j \prec S_{threat}$ to ORDERINGS(*plan*)
    if not CONSISTENT(*plan*) **then fail**
  end

POP is sound, complete, and systematic (no repetition)

Extensions for disjunction, universals, negation, conditionals

Clobbering and promotion/demotion

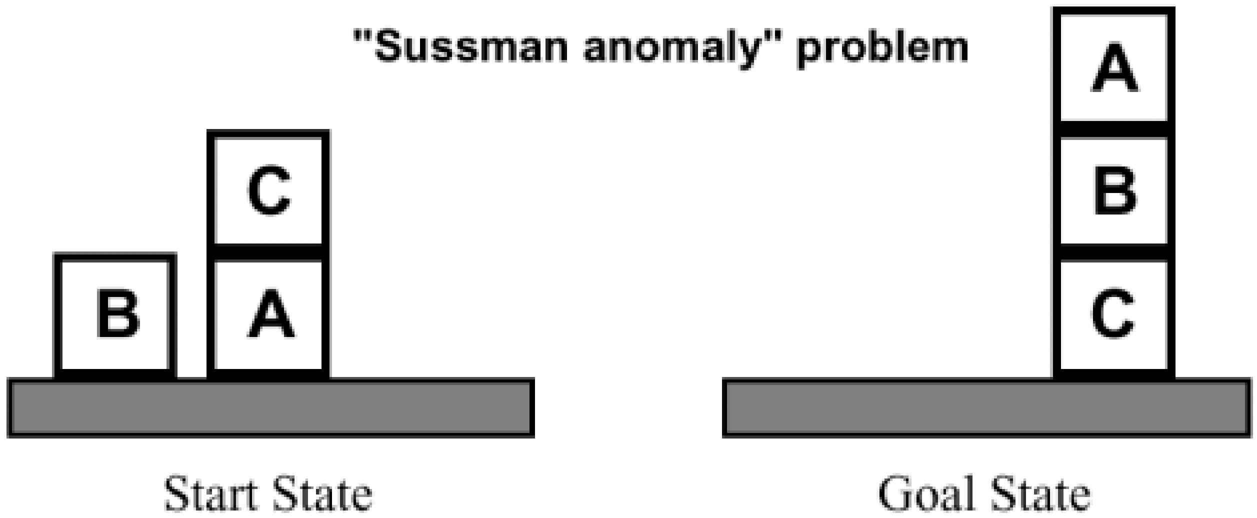
A clobberer is a potentially intervening step that destroys the condition achieved by a causal link. E.g., $Go(Home)$ clobbers $At(HWS)$:



Demotion: put before $Go(HWS)$

Promotion: put after $Buy(Drill)$

Example: block world



Clear(x) On(x,z) Clear(y)

PutOn(x,y)

~On(x,z) ~Clear(y)
Clear(z) On(x,y)

Clear(x) On(x,z)

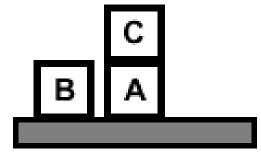
PutOnTable(x)

~On(x,z) Clear(z) On(x,Table)

+ several inequality constraints

Example (cont.)

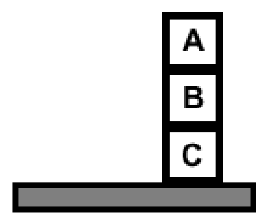
START



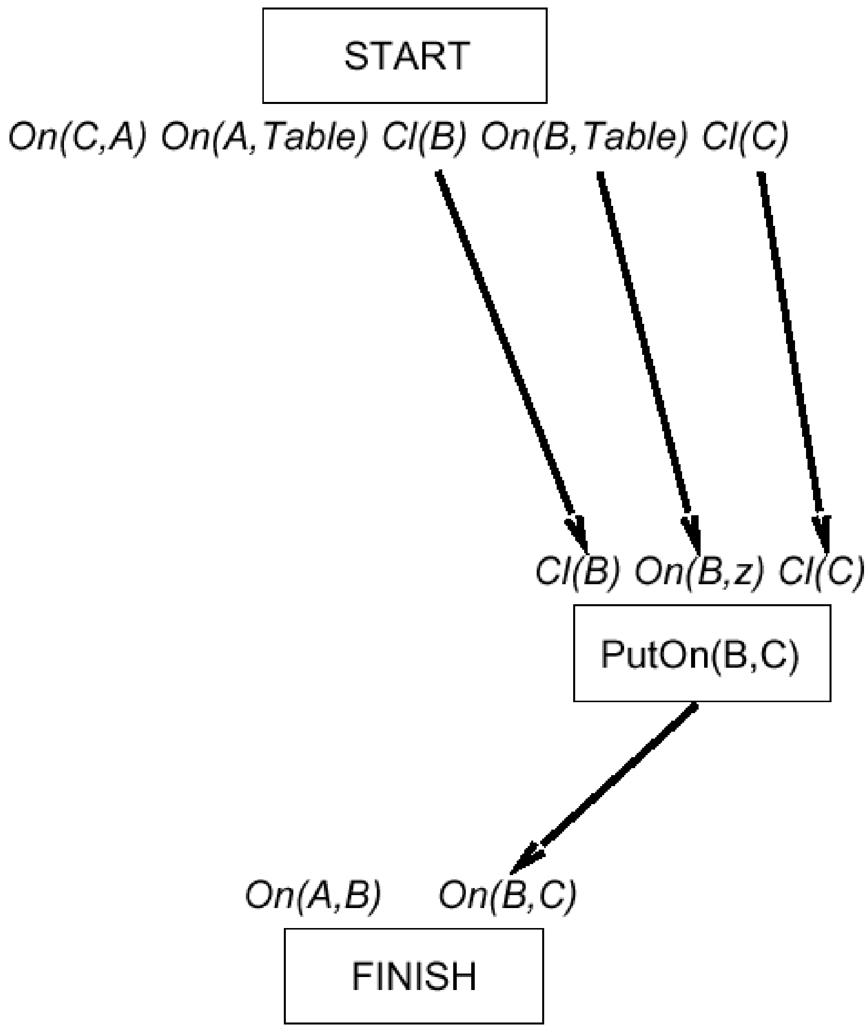
On(C,A) On(A,Table) Cl(B) On(B,Table) Cl(C)

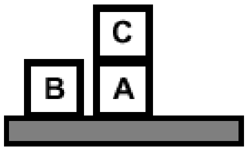
On(A,B)   *On(B,C)*

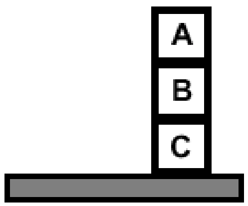
FINISH



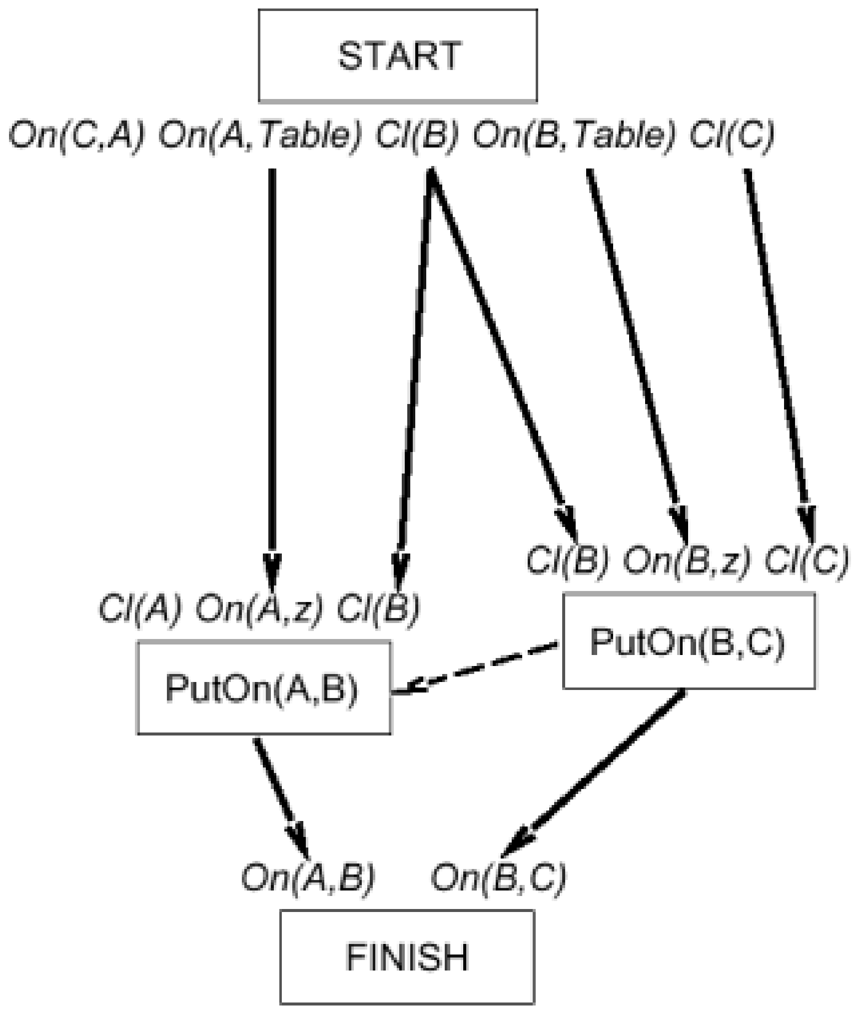
Example (cont.)

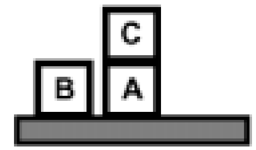




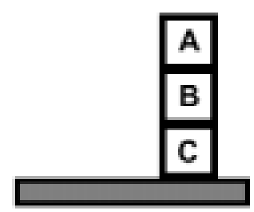


Example (cont.)

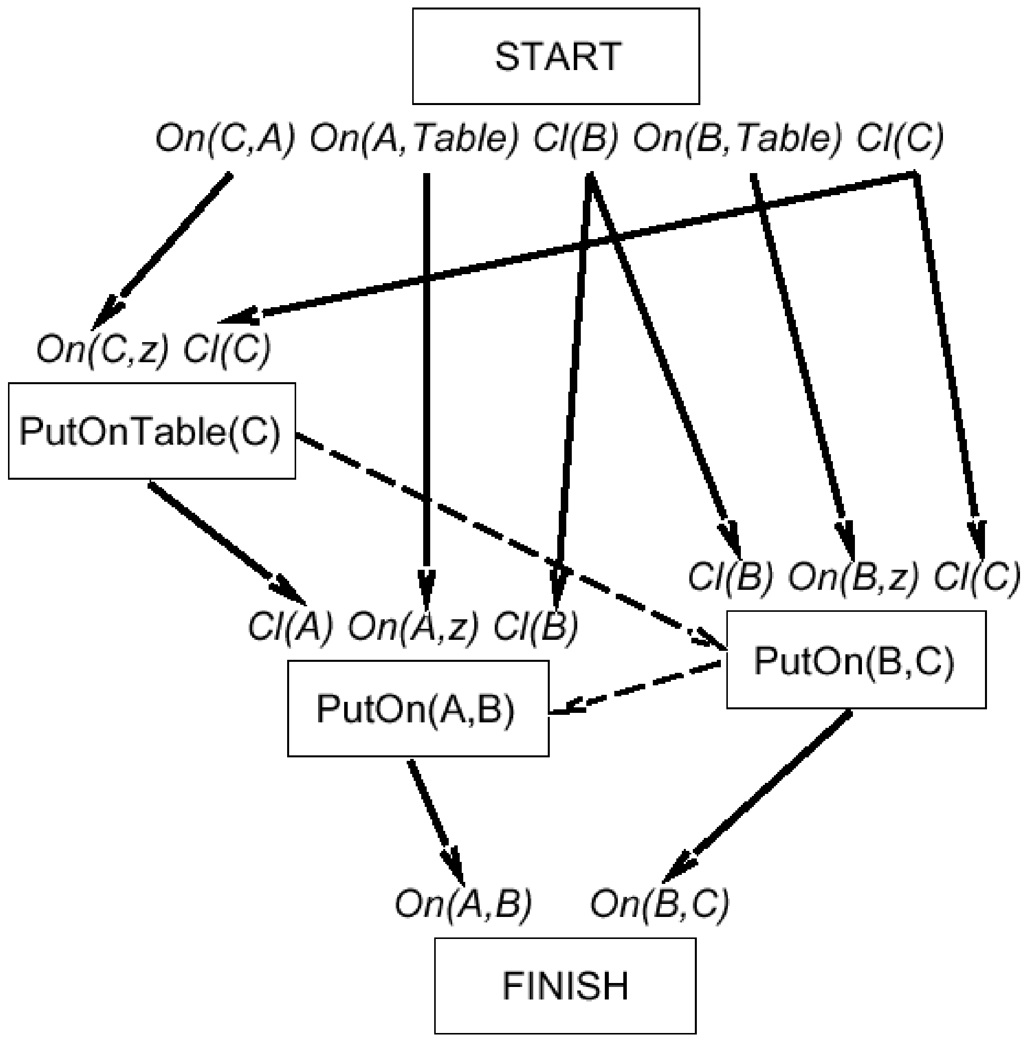


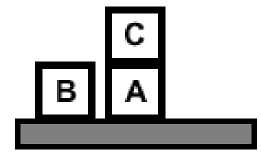


PutOn(A,B) clobbers Cl(B) => order after PutOn(B,C)



Example (cont.)





PutOn(A,B) clobbers Cl(B) => order after PutOn(B,C)

PutOn(B,C) clobbers Cl(C) => order after PutOnTable(C)