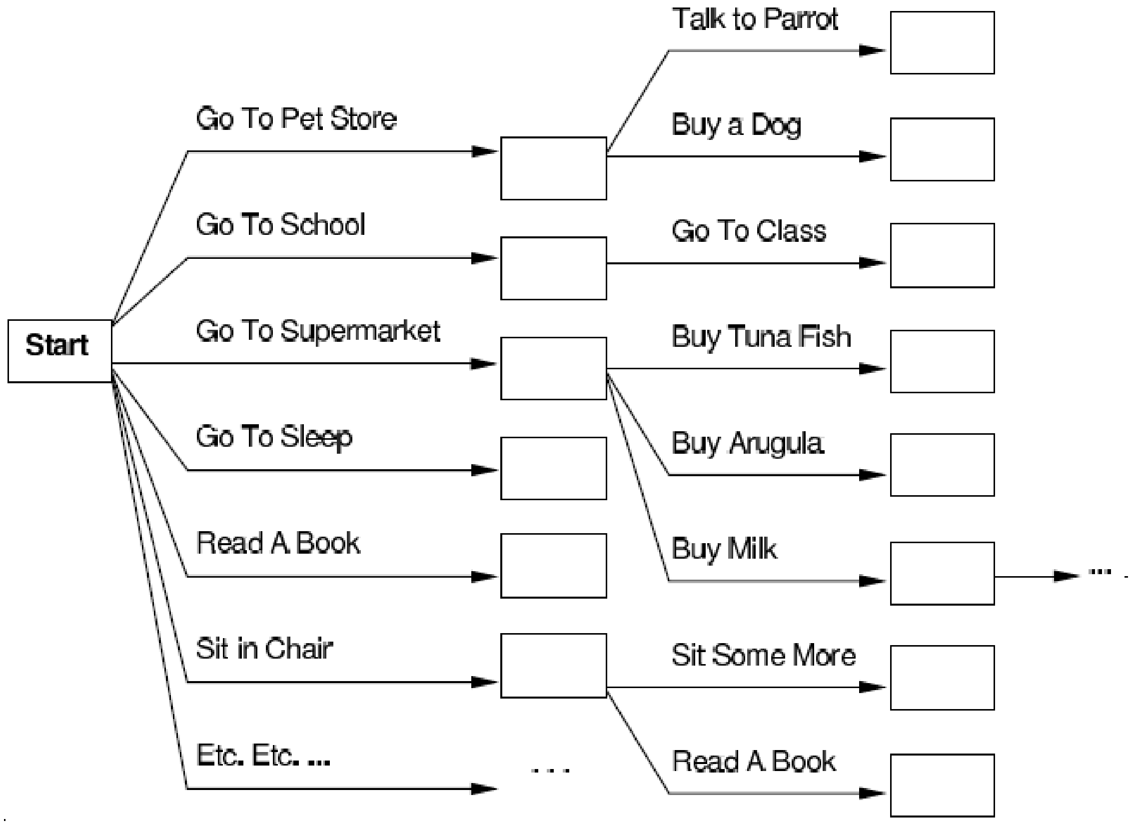
Planning

Outline

- Search vs. Planning
- STRIPS (Stanford Research Institute Problem Solver)
- Partial Order Planning
- The Real World
- Conditional Planning
- Monitoring and Replanning

Search vs. Planning

- Consider the following task:
  - Get milk, bananas, and a cordless drill
- Standard search algorithms seem to fail miserably



Search vs. Planning

- **Actions have requirements & consequences that should constrain applicability in a given state**
  - **Stronger interaction between actions and states needed**

Search vs. Planning

- **Actions have requirements & consequences that should constrain applicability in a given state**
  - **Stronger interaction between actions and states needed**
- **Most parts of the world are independent of most other parts**
  - **Solve subgoals independently**

Search vs. Planning

- **Actions have requirements & consequences that should constrain applicability in a given state**
  - **Stronger interaction between actions and states needed**
- **Most parts of the world are independent of most other parts**
  - **Solve subgoals independently**
- **Human beings plan goal-directed; they construct important intermediate solutions first**
  - **Flexible sequence for construction of solution**

Search vs. Planning

- Planning systems do the following
  - Unify action and goal representation to allow selection (use logical language for both)
  - Divide-and-conquer by subgoaling
  - Relax requirement for sequential construction of solutions

STRIPS

- **STRIPS**
- **STanford Research Institute Problem Solver**
  - **Tidily arranged actions descriptions**
  - **Restricted language (function-free literals)**
  - **Efficient algorithms**

STRIPS: States

- **States represented by:**
  - **Conjunction of ground (function-free) atoms**
- **Example**

At(*Home*), *Have*(*Bread*)

STRIPS: States

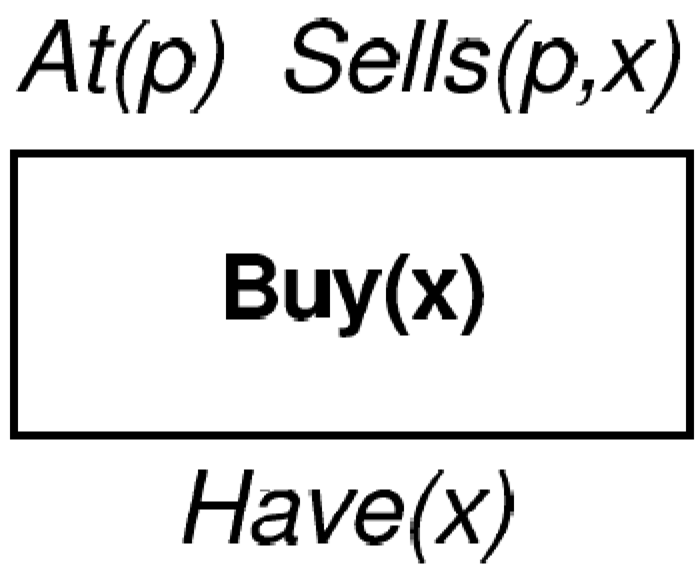
- **States represented by:**
  - **Conjunction of ground (function-free) atoms**
- **Example**
  - *At*(*Home*), *Have*(*Bread*)
- **Closed world assumption**
  - **Atoms that are not present are assumed to be false**
- **Example**
  - **State:** *At*(*Home*), *Have*(*Bread*)
  - **Implicitly:** ¬*Have*(*Milk*), ¬*Have*(*Bananas*), ¬*Have*(*Drill*)

STRIPS: Operators

- **Operator description consists of:**
  - **Action name**
    - **Positive literal**
    - *Buy*(*Milk*)
  - **Precondition**
    - **Conjunction of positive literals**
    - *At*(*Shop*)∧*Sells*(*Shop,Milk*)
  - **Effect**
    - **Conjunction of literals**
    - *Have*(*Milk*)

STRIPS: Operators

- **Operator description consists of:**
  - **Action name**
    - **Positive literal**
    - *Buy*(*Milk*)
  - **Precondition**
    - **Conjunction of positive literals**
    - *At*(*Shop*)∧*Sells*(*Shop,Milk*)
  - **Effect**
    - **Conjunction of literals**
    - *Have*(*Milk*)
- **Operator schema**
  - **Operator containing variables**

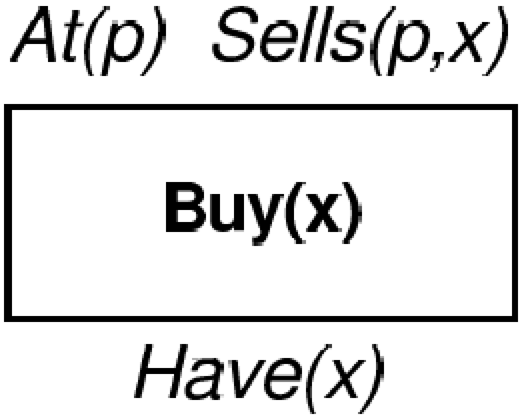


STRIPS: Operator Application

- **Operator applicability**
  - **Operator *o* applicable in state *s* if:**
  - **There is substitution *Subst* of the free variables such that**
    - $Subst(precond(o)) \subseteq s$

STRIPS: Operator Application

- **Operator applicability**
  - **Operator *o* applicable in state *s* if:**
  - **There is substitution *Subst* of the free variables such that**
    - *Subst*(*precond*(*o*)) ⊆ *s*
- **Example**
  - *Buy*(*x*) **is applicable in state**
    - *At*(*Shop*)∧*Sells*(*Shop,Milk*)∧*Have*(*Bread*)
  - **with substitution**
    - *Subst* = {*p/Shop, x/Milk*}



STRIPS: Operator Application

- **Resulting state**
- **Computed from old state and literals in** *Subst*(*effect*)
  - **Positive literals are added to the state**
  - **Negative literals are removed from the state**
  - **All other literals remain unchanged (avoids the frame problem)**

STRIPS: Operator Application

- **Resulting state**
- **Computed from old state and literals in** *Subst*(*effect*)
  - **Positive literals are added to the state**
  - **Negative literals are removed from the state**
  - **All other literals remain unchanged (avoids the frame problem)**
- **Formally:**

$$s' = (s \cup \{P \mid P \text{ a positive atom}, P \in Subst(effect(o))\}) \setminus \{P \mid P \text{ a positive atom}, \neg P \in Subst(effect(o))\}$$

STRIPS: Operator Application

- **Example**
- **Application of**
  - *Drive*(*a,b*)
    - *precond:* *At*(*a*);*Road(a,b)*
    - *effect:* *At*(*b*), ¬*At(a)*

STRIPS: Operator Application

- **Example**
- **Application of**
  - *Drive*(*a,b*)
    - *precond:* *At*(*a*);*Road(a,b)*
    - *effect:* *At*(*b*), ¬*At(a)*
- **to state**
  - *At*(*Koblenz*), *Road*(*Koblenz*;*Landau*)

STRIPS: Operator Application

- **Example**
- **Application of**
  - *Drive*(*a,b*)
    - *precond:* *At*(*a*);*Road(a,b)*
    - *effect:* *At*(*b*), ¬*At*(*a*)
- **to state**
  - *At*(*Koblenz*), *Road*(*Koblenz*;*Landau*)
- **results in**
  - *At*(*Landau*), *Road*(*Koblenz,Landau*)

State Space vs. Plan Space

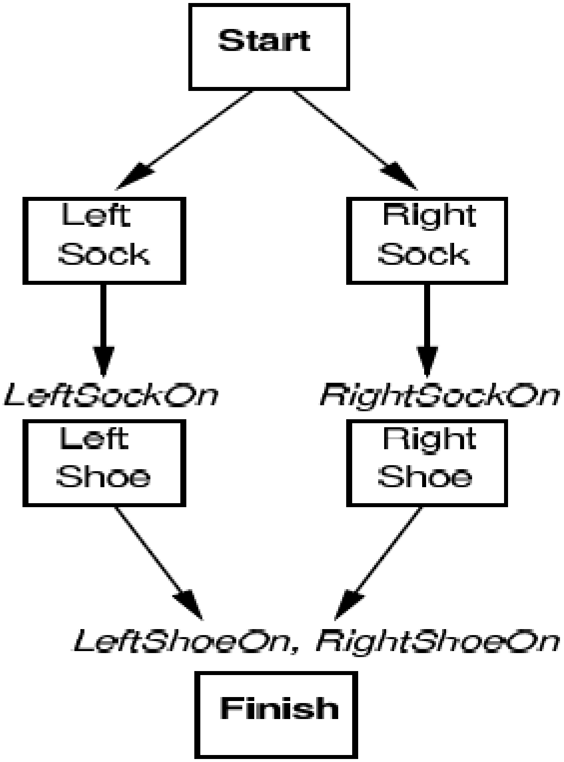
- **Planning problem**
  - **Find a sequence of actions that make instance of the goal true**
- **Nodes in search space**
  - **Standard search:**
    - **node = concrete world state**
  - **Planning search:**
    - **node = partial plan**
- **(Partial) Plan consists of**
  - **Set of operator applications** S_i
  - **Partial (temporal) order constraints** $S_i \prec S_j$
  - **Causal links** $S_i \longrightarrow S_j$
- **Meaning:**
  - **"**S_i **achieves** $c \in precond(S_j)$**"**
  - **(record purpose of steps)**

State Space vs. Plan Space

- **Operators on partial plans**
  - **Add an action and a causal link to achieve an open condition**
  - **Add a causal link from an existing action to an open condition**
  - **Add an order constraint to order one step w.r.t. another**
- **Open condition**
  - **A precondition of an action not yet causally linked**
- **Note**
  - **We move from incomplete/vague plans to complete, correct plans**

Partially Ordered Plans

- **Special steps with empty action**
- *Start*
  - **no precond, initial assumptions as effect)**
- *Finish*
  - **goal as precond, no effect**
- **Note**
  - **Different paths in partial plan are *not* alternative plans, but alternative sequences of actions**

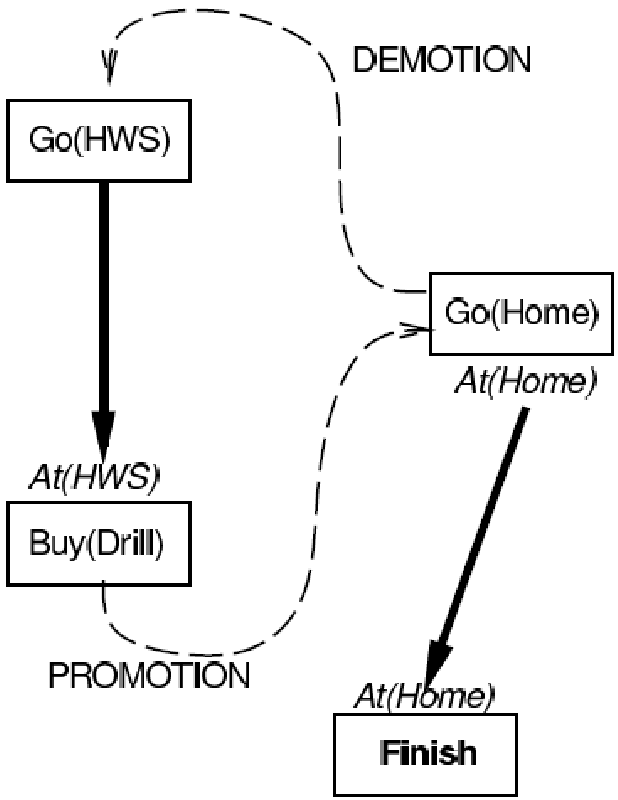


Partially Ordered Plans

- **Complete plan**
  - **A plan is complete iff every precondition is achieved**
- **A precondition c of a step S_j is achieved (by S_i) if**
  - $S_i \prec S_j$
  - $c \in effect(S_i)$
  - **there is no S_k with $S_i \prec S_k \prec S_j$ and $\neg c \in effect(S_k)$**
  - **(otherwise S_k is called a clobberer or threat)**
- **Clobberer / threat**
  - **A potentially intervening step that destroys the condition achieved by a causal link**

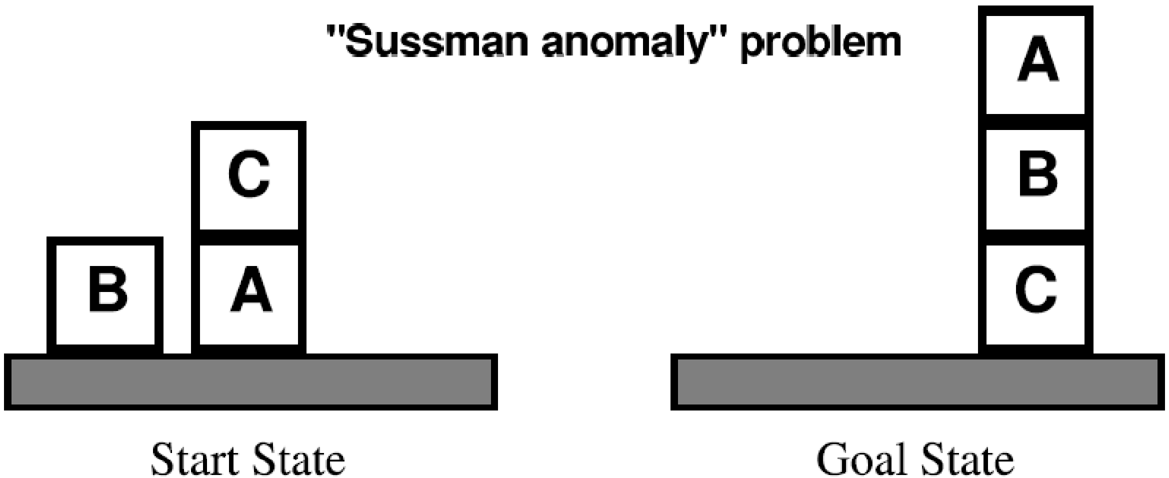
Clobbering and Promotion / Demotion

- **Example**
- *Go*(*Home*) **clobbers** *At*(*HWS*)
- **Demotion**
  - **Put before** *Go*(*HWS*)
- **Promotion**
  - **Put after** *Buy*(*Drill*)



Example: Blocks world

"Sussman anomaly" problem



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)

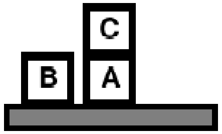
~On(x,z) Clear(z) On(x,Table)

\+ several inequality constraints

Example: Blocks World

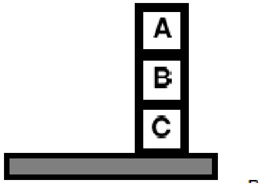
START

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

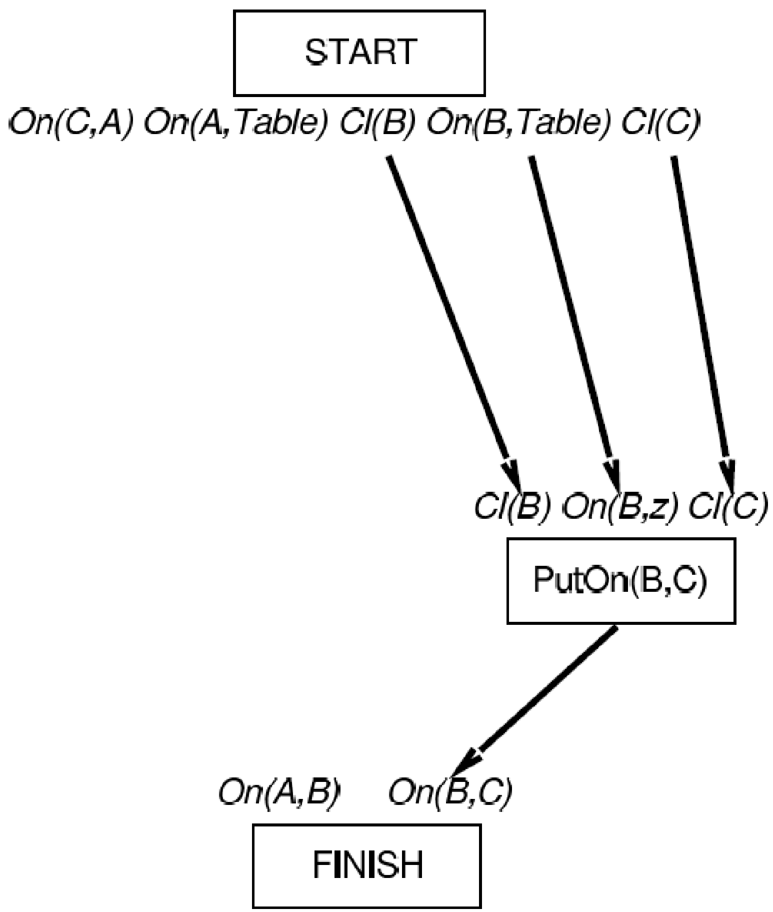


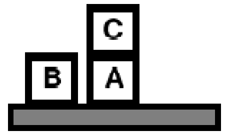
On(A,B) *On(B,C)*

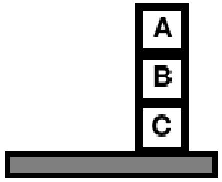
FINISH



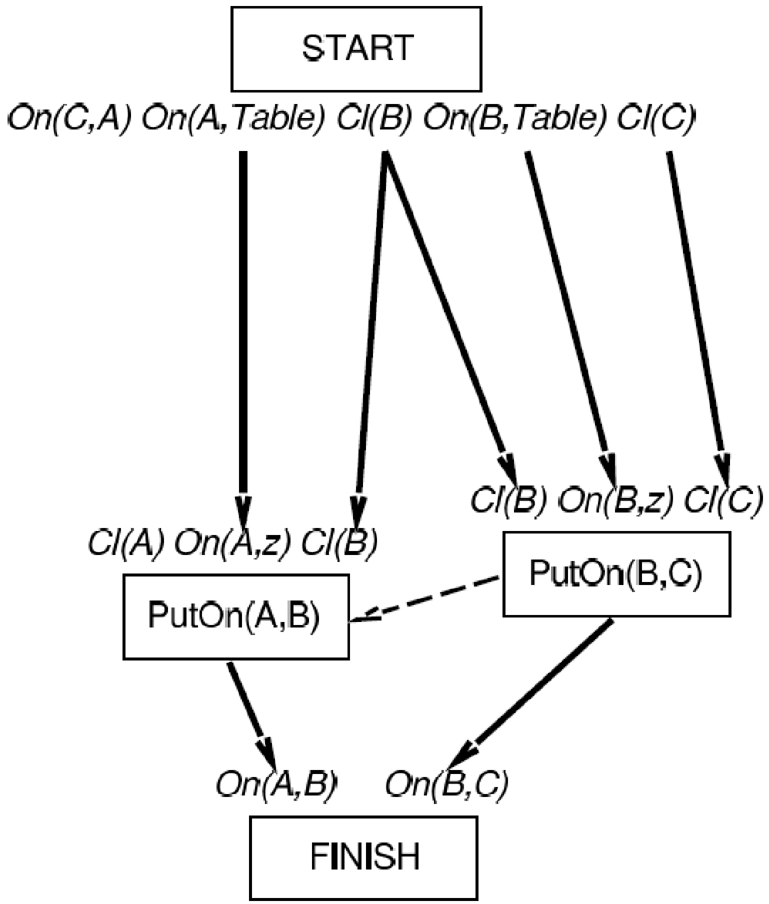
Example: Blocks World

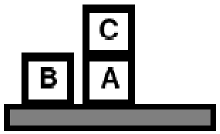




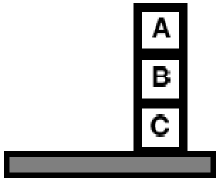


Example: Blocks World

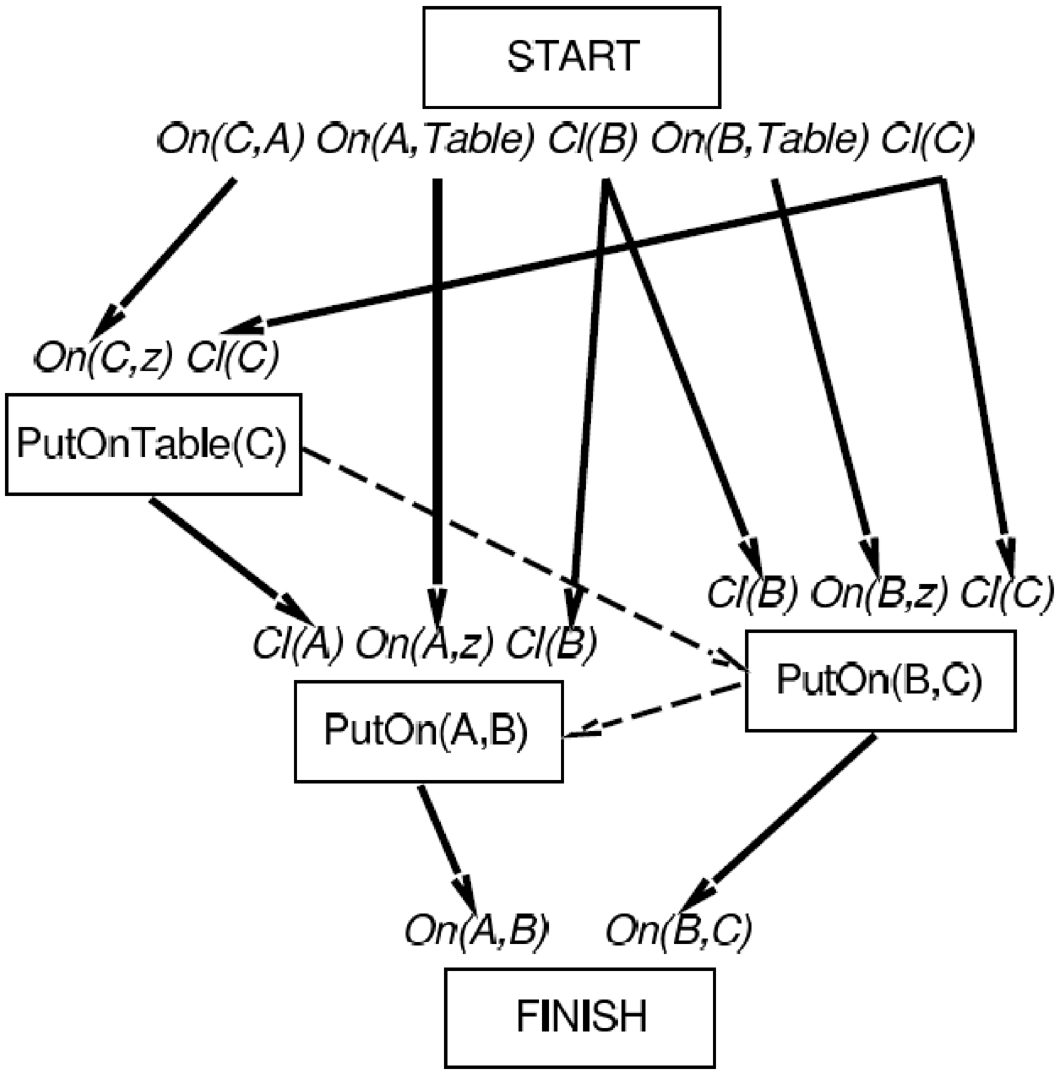


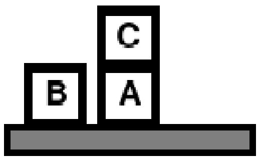


PutOn(A,B)
clobbers Cl(B)
=> order after
PutOn(B,C)



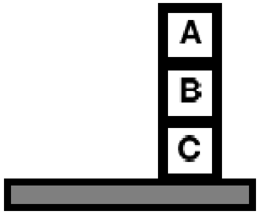
Example: Blocks World





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

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



POP (Partial Order Planner) Algorithm Sketch

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

  plan ← MAKE-MINIMAL-PLAN(*initial, goal*)
  loop do
    if SOLUTION?(*plan*) **then return** *plan*   % complete and consistent
    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'd)

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*)

POP Algorithm (Cont'd)

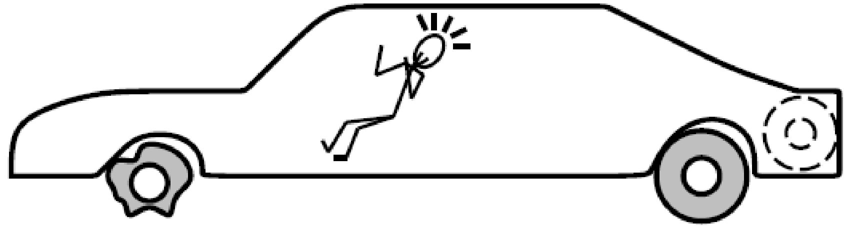
procedure RESOLVE-THREATS(*plan*)

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

Properties of POP

- **Non-deterministic search for plan, backtracks over choicepoints on failure:**
  - **Choice of S_{add} to achieve S_{need}**
  - **Choice of promotion or demotion for clobberer**
- **Sound and complete**
- **There are extensions for:**
  - **disjunction, universal quantification, negation, conditionals**
- **Efficient with good heuristics from problem description**
  - **But: very sensitive to subgoal ordering**
- **Good for problems with loosely related subgoals**

The Real World



On(x) ~Flat(x)

START

~Flat(Spare) Intact(Spare) Off(Spare)
On(Tire1) Flat(Tire1)

FINISH

On(x)

Remove(x)

Off(x) ClearHub

Off(x) ClearHub

Puton(x)

On(x) ~ClearHub

Intact(x) Flat(x)

Inflate(x)

~Flat(x)

Things Go Wrong

- **Incomplete information**
  - **Unknown preconditions**
  - **Example:** *Intact*(*Spare*)**?**

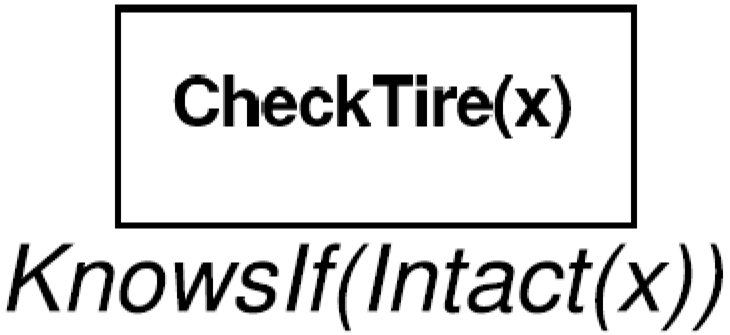
  - **Disjunctive effects**
  - **Example:** *Inflate*(*x*) **causes**
  - *Inflated*(*x*) ∨ *SlowHiss*(*x*) ∨ *Burst*(*x*) ∨ *BrokenPump* ∨ ...
- **Incorrect information**
  - **Current state incorrect**
  - **Example: spare NOT intact Missing/incorrect postconditions in operators**
- **Qualification problem**
  - **Can never finish listing all the required preconditions and possible conditional outcomes of actions**

Solutions

- **Conditional planning**
  - **Plan to obtain information (observation actions)**
  - **Subplan for each contingency**
  - **Example:**
    - [*Check*(*Tire1)*, **If**(*Intact*(*Tire1)*, [*Inflate*(*Tire1*)], [*CallHelp*])]
  - **Disadvantage: Expensive because it plans for many unlikely cases**
- **Monitoring/Replanning**
  - **Assume normal states / outcomes**
  - **Check progress during execution, replan if necessary**
  - **Disadvantage: Unanticipated outcomes may lead to failure**

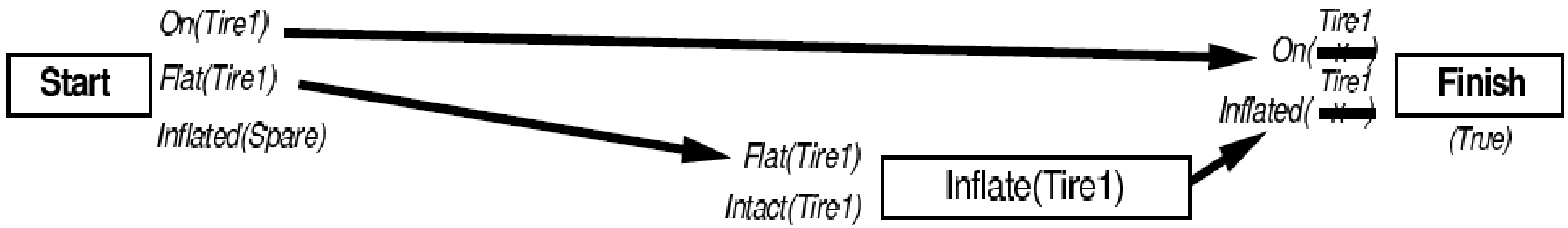
Conditional Planning

- **Execution of conditional plan**
  - [… ; **If**(*p,* [*thenPlan*], [*elsePlan*]), …]
  - **Check** *p* **against current knowledge base, execute** *thenPlan* **or** *elsePlan*
- **Conditional planning**
  - **Just like** POP **except:**
  - **If an open condition can be established by observation action**
    - **Add the action to the plan**
    - **Complete plan for each possible observation outcome**
    - **Insert conditional step with these subplans**

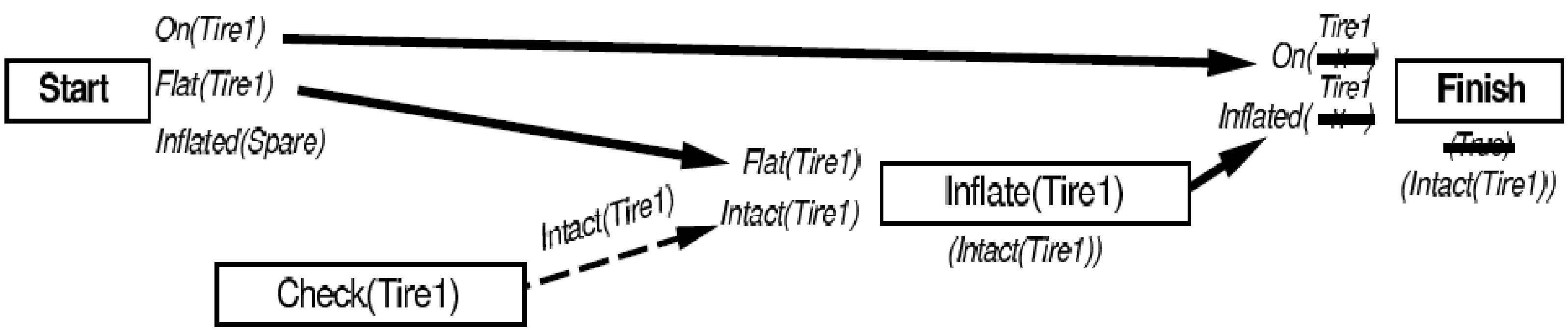


Conditional Planning Example

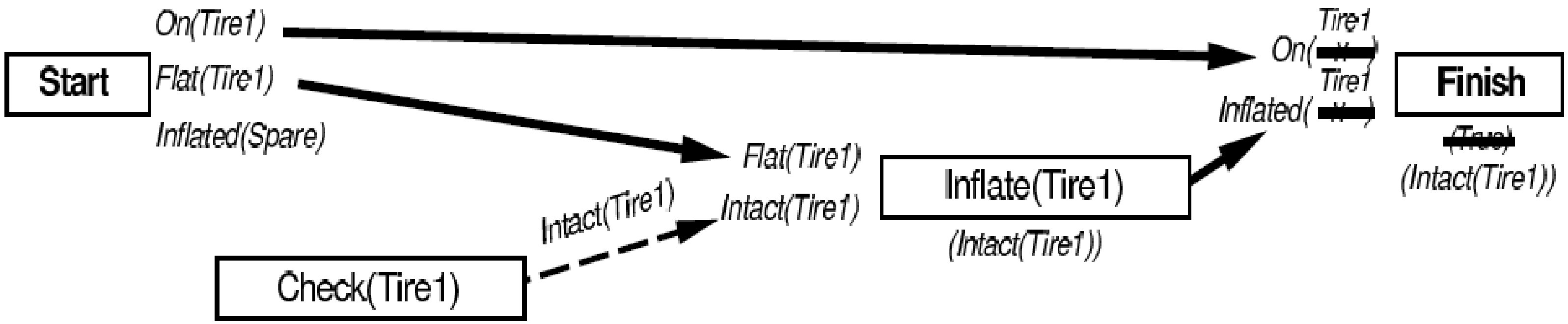
Conditional Planning Example

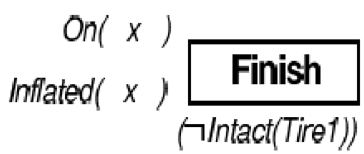


Conditional Planning Example

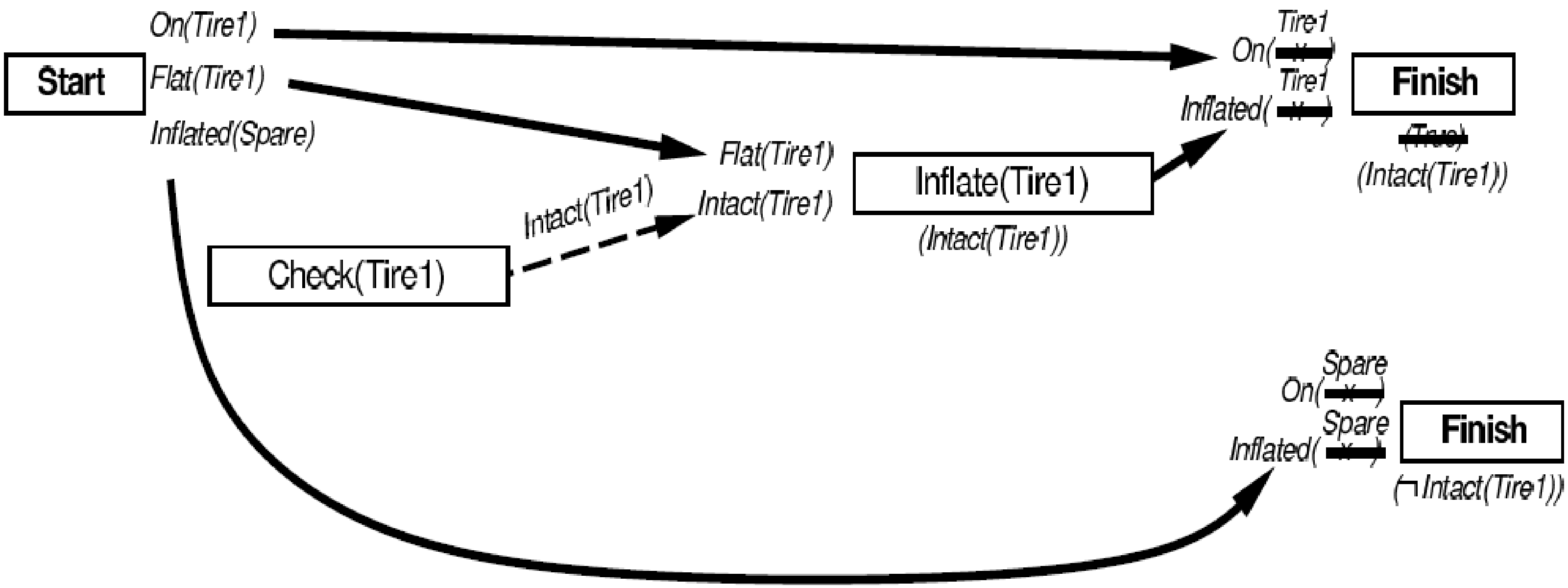


Conditional Planning Example

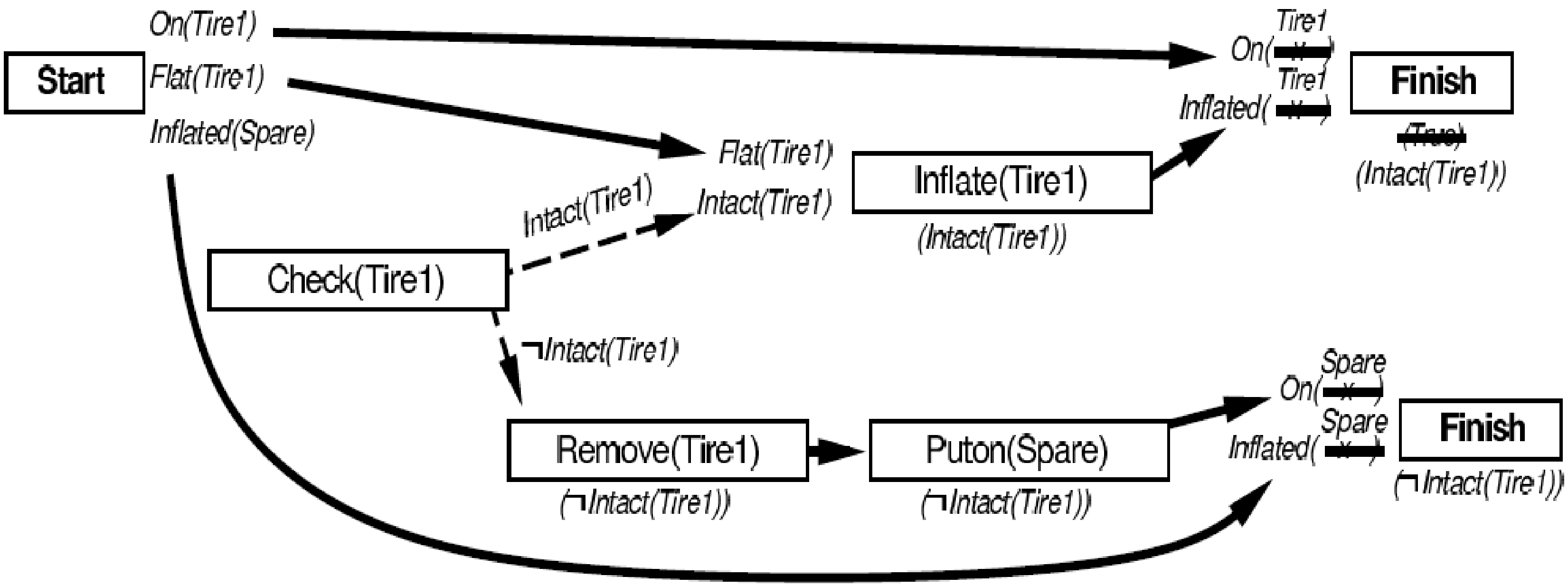




Conditional Planning Example



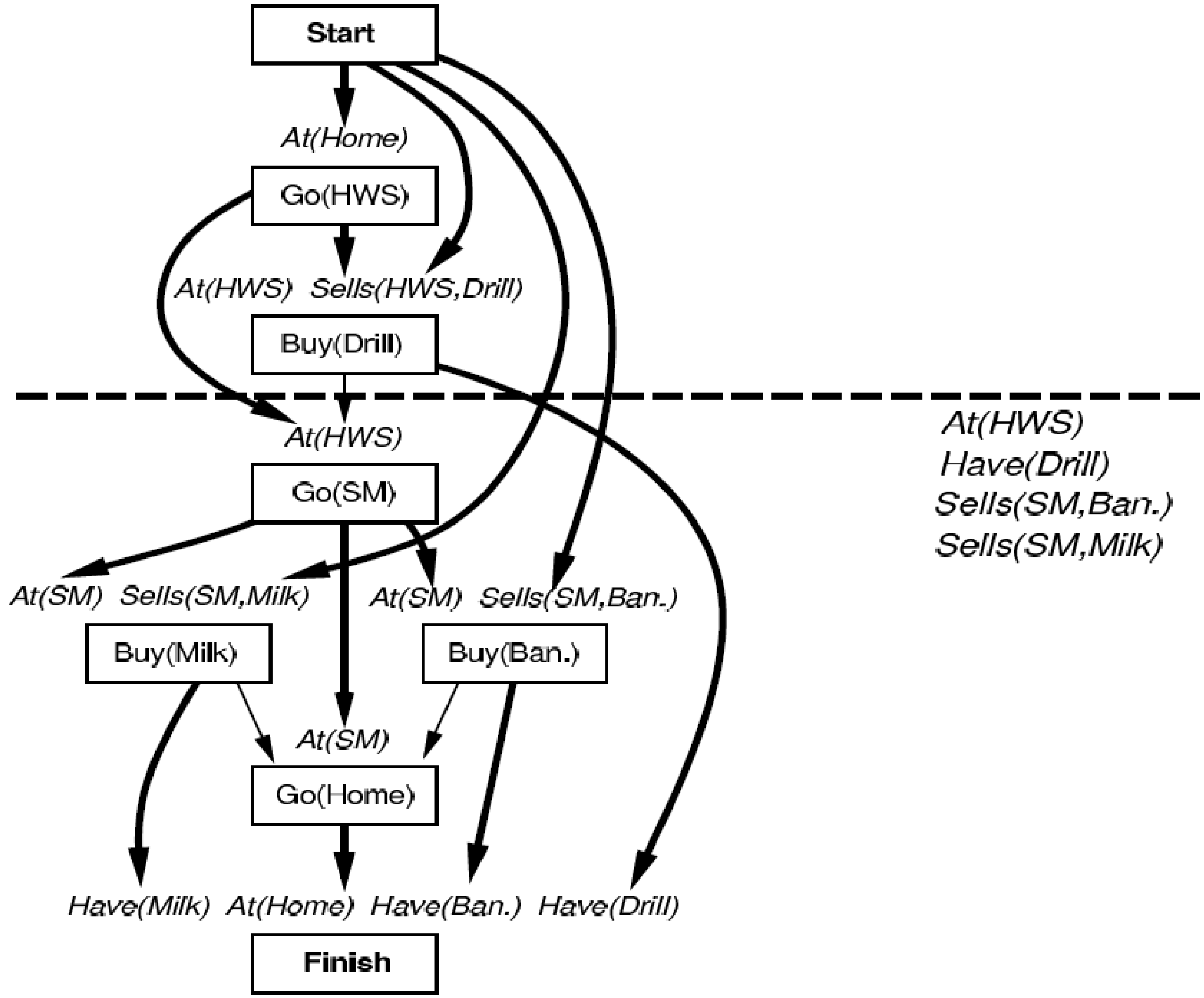
Conditional Planning Example



Monitoring

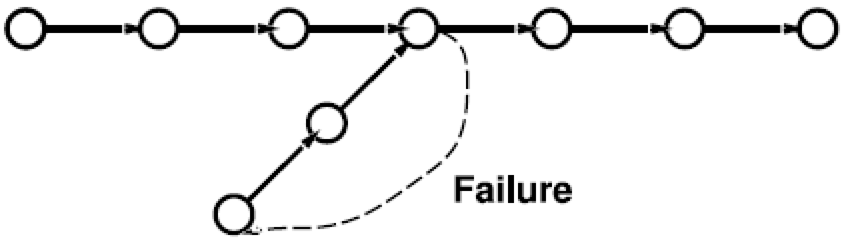
- **Execution monitoring**
  - **Failure:**
    - **Preconditions of remaining plan not met**
- **Action monitoring**
  - **Failure:**
    - **Preconditions of next action not met (or action itself fails, e.g., robot bump sensor)**
- **Consequence of failure**
  - **Need to replan**

Preconditions for Remaining Plan

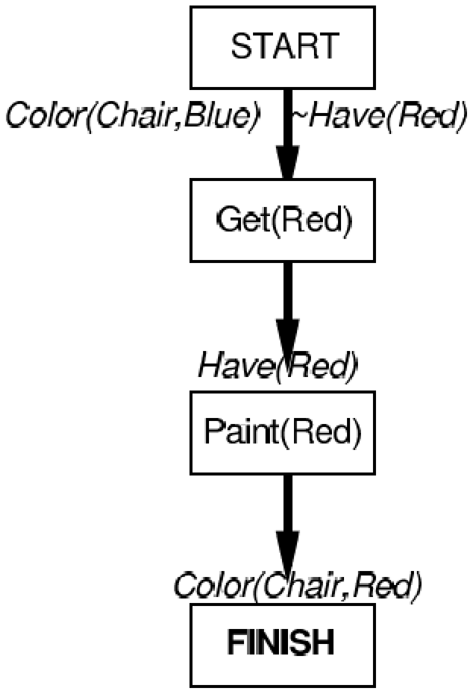


Replanning

- **Simplest**
  - **On failure, replan from scratch**
- **Better**
  - **Plan to get back on track by reconnecting to best continuation**



Replanning: Example



PRECONDITIONS	FAILURE RESPONSE
none	N/A
Have(Red)	Fetch more red
Color(Chair,Red)	Repaint

Summary Planning

- Differs from general problem search; subgoals solved independently
- STRIPS: restricted format for actions, logic-based
- Nodes in search space are partial plans
- POP algorithm
- Standard planning cannot cope with incomplete/incorrect information
- Conditional planning with sensing actions to complete information; expensive at planning stage
- Replanning based on monitoring of plan execution; expensive at execution stage