Planning

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Outline

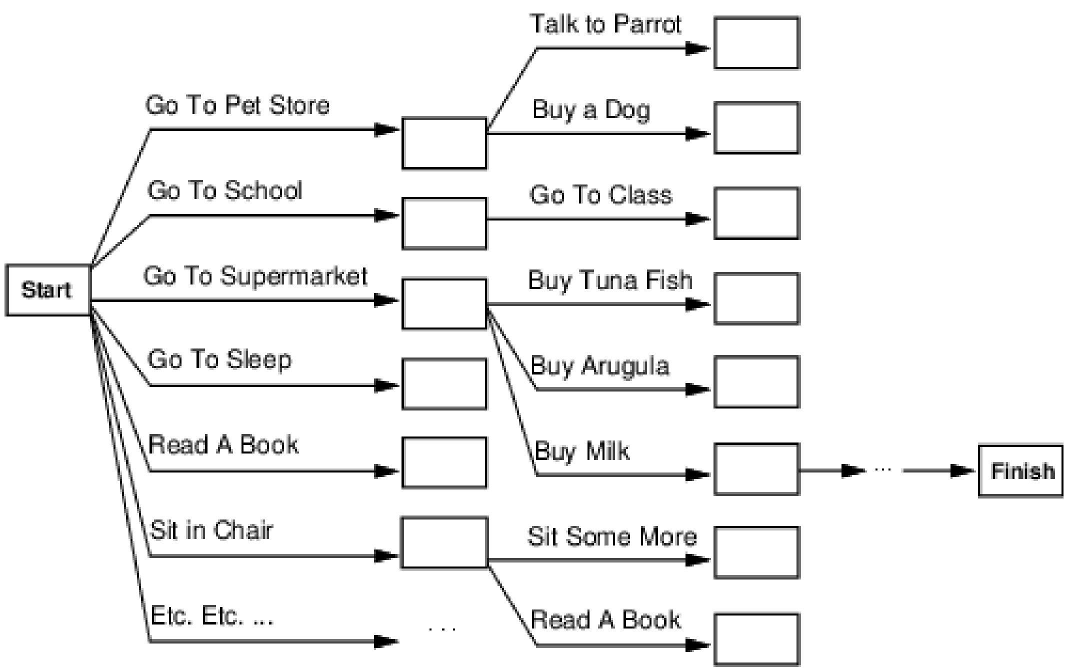
- Search vs. planning
- STRIPS operators
- Partial-order planning
- The real world
- Conditional planning
- Monitoring and replanning

search vs. planning

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. improve action and goal representation to allow selection
  2. divide-and-conquer by **subgoaling**
  3. relax requirement for sequential construction of solutions

- Differences

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

strips operators

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 $\implies$ efficient algorithm
  Precondition: conjunction of positive literals
  Effect: conjunction of literals

partial-order planning

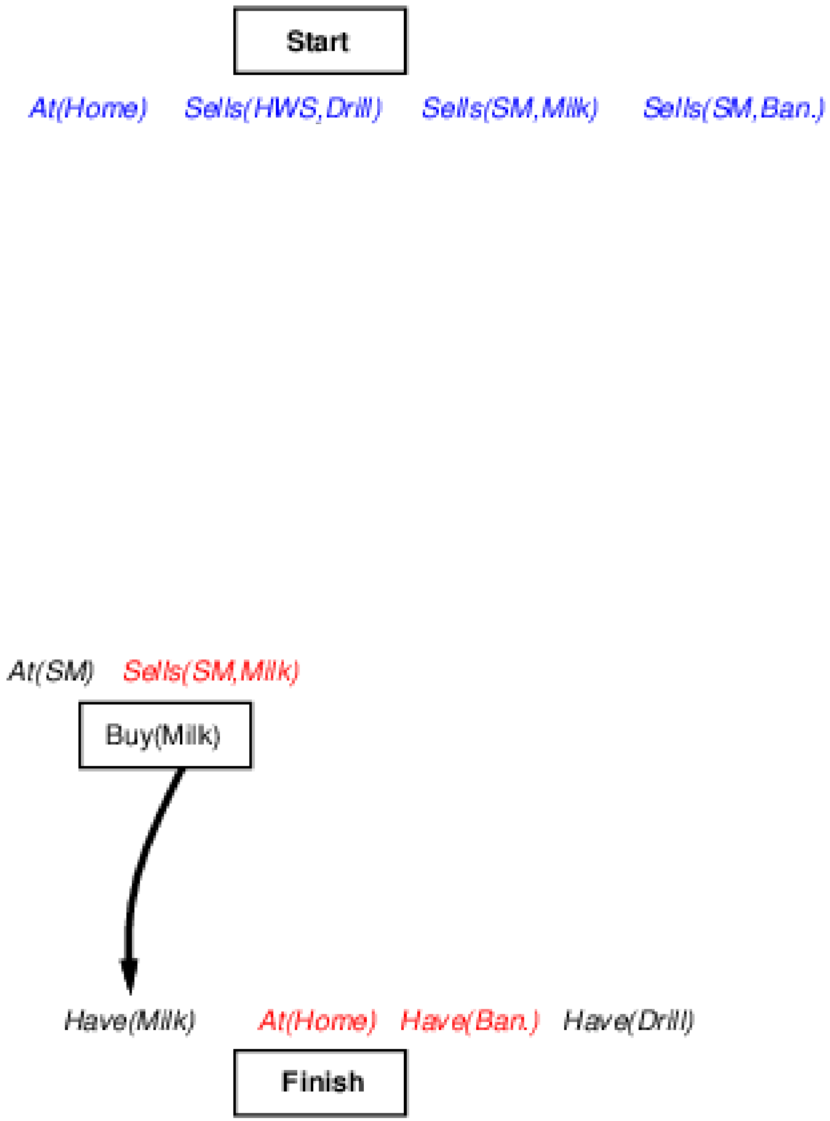
Partially Ordered Plans

- *Partially ordered* collection of steps with
  - $Start$ step has the initial state description as its effect
  - $Finish$ step has the goal description as its precondition
  - causal links from outcome of one step to precondition of another
  - temporal ordering between pairs of steps
- Open condition = precondition of a step not yet causally linked
- A plan is complete iff every precondition is achieved
- A precondition is achieved iff it is the effect of an earlier step and no possibly intervening step undoes it

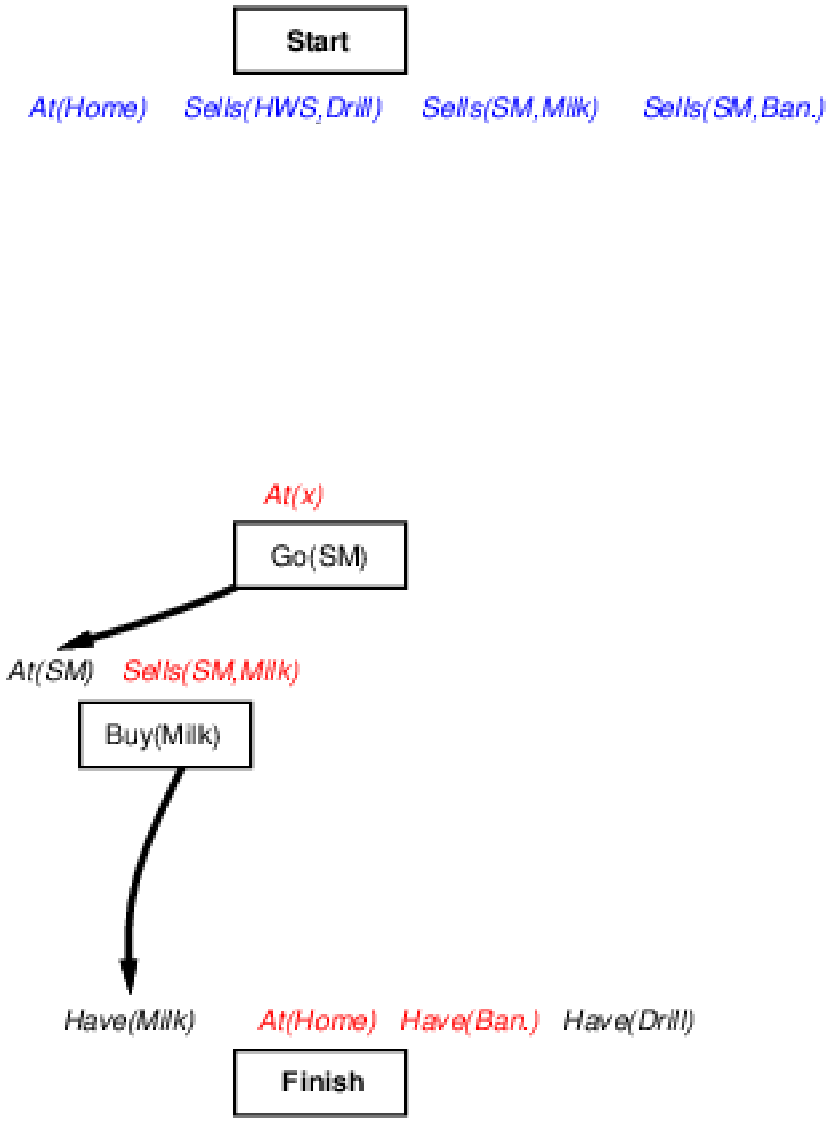
Example


Start
At(Home)
Sells(HWS,Drill)
Sells(SM,Milk)
Sells(SM,Ban.)
Have(Milk)
At(Home)
Have(Ban.)
Have(Drill)
Finish

Example

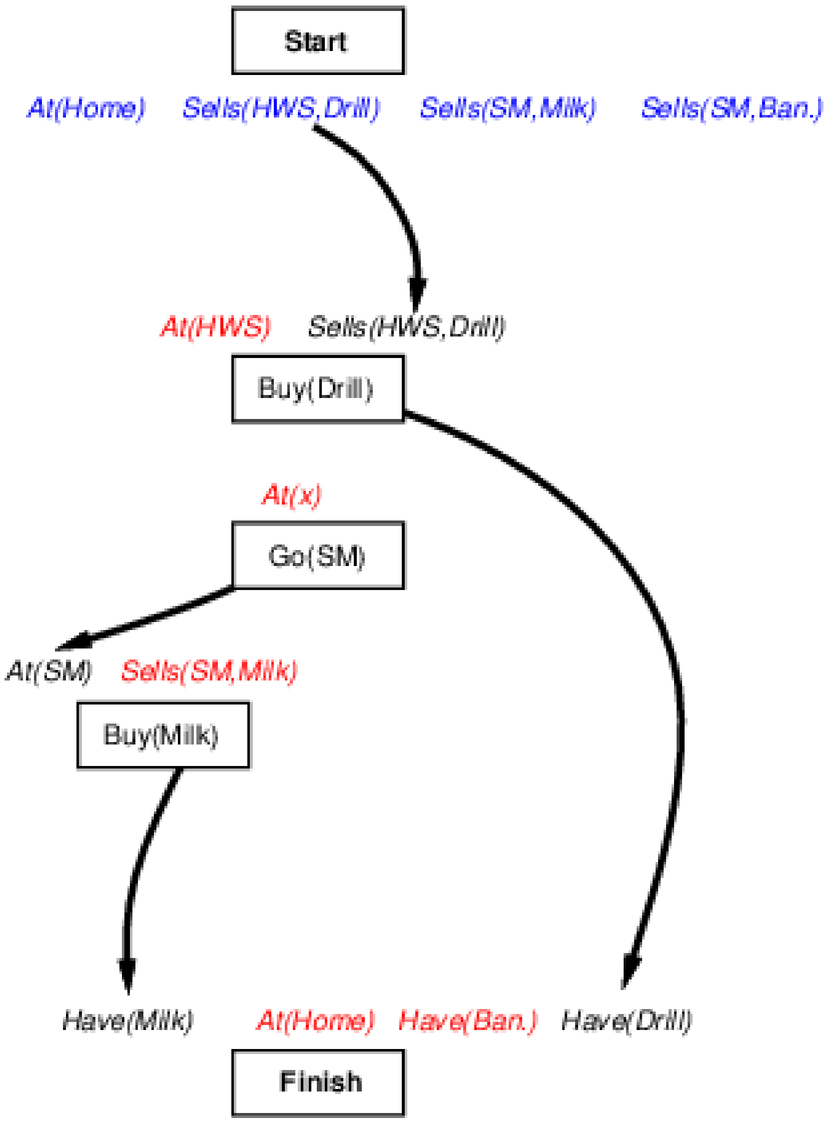

Start
At(Home)
Sells(HWS,Drill)
Sells(SM,Milk)
Sells(SM,Ban.)
At(SM)
Sells(SM,Milk)
Buy(Milk)
Have(Milk)
At(Home)
Have(Ban.)
Have(Drill)
Finish

Example



Start
At(Home)
Sells(HWS,Drill)
Sells(SM,Milk)
Sells(SM,Ban.)
At(x)
Go(SM)
At(SM)
Sells(SM,Milk)
Buy(Milk)
Have(Milk)
At(Home)
Have(Ban.)
Have(Drill)
Finish

Example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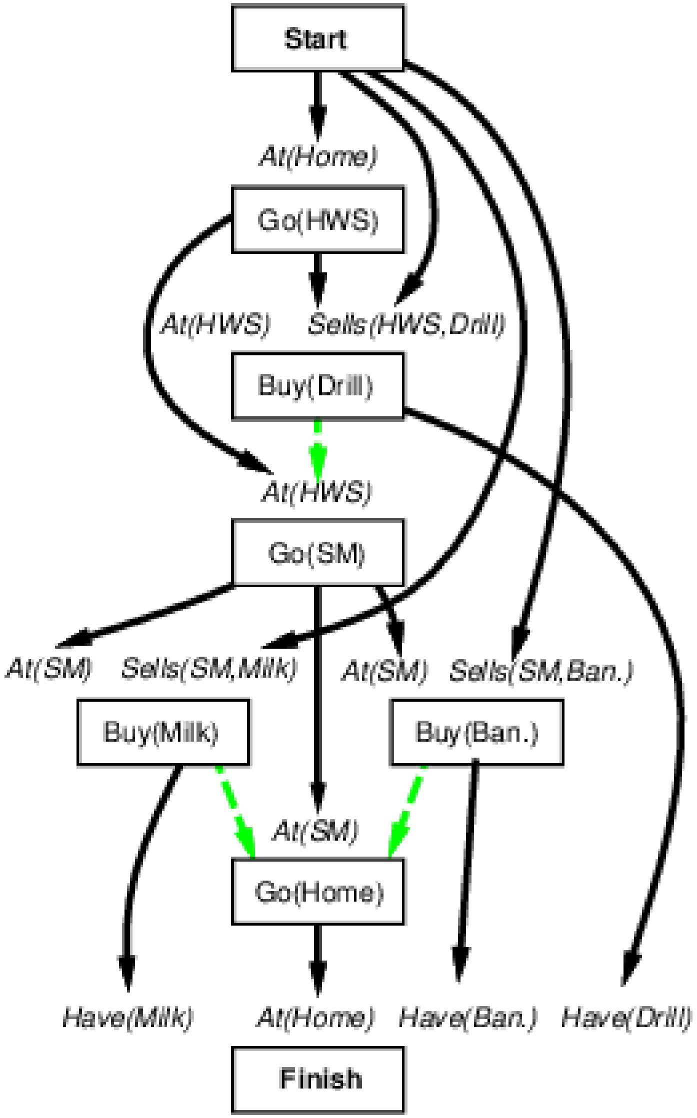
Have(Drill)
Finish

Example



Start
At(Home)
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Buy(Drill)
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At(SM)
Sells(SM,Milk)
At(SM)
Sells(SM,Ban.)
Buy(Milk)
Buy(Ban.)
At(SM)
Go(Home)
Have(Milk)
At(Home)
Have(Ban.)
Have(Drill)
Finish

Planning Process

- 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 to remove possible conflicts
- Gradually move from incomplete/vague plans to complete, correct plans
- Backtrack if an open condition is unachievable or
  if a conflict is unresolvable

Partially Ordered Plans Algorithm

```
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
```

Partially Ordered Plans Algorithm

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*)

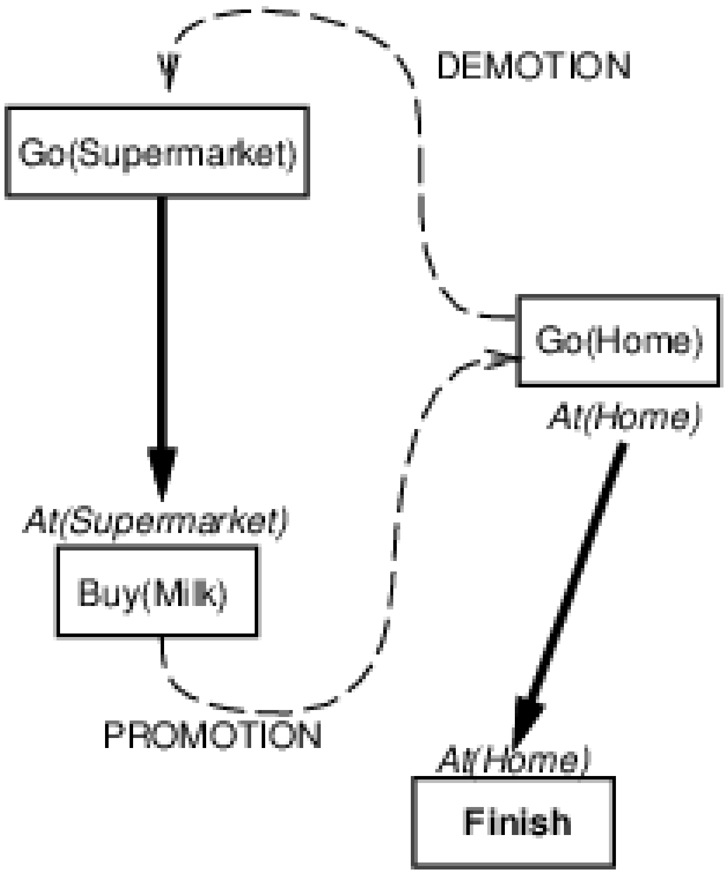
---

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

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 $At(Supermarket)$:



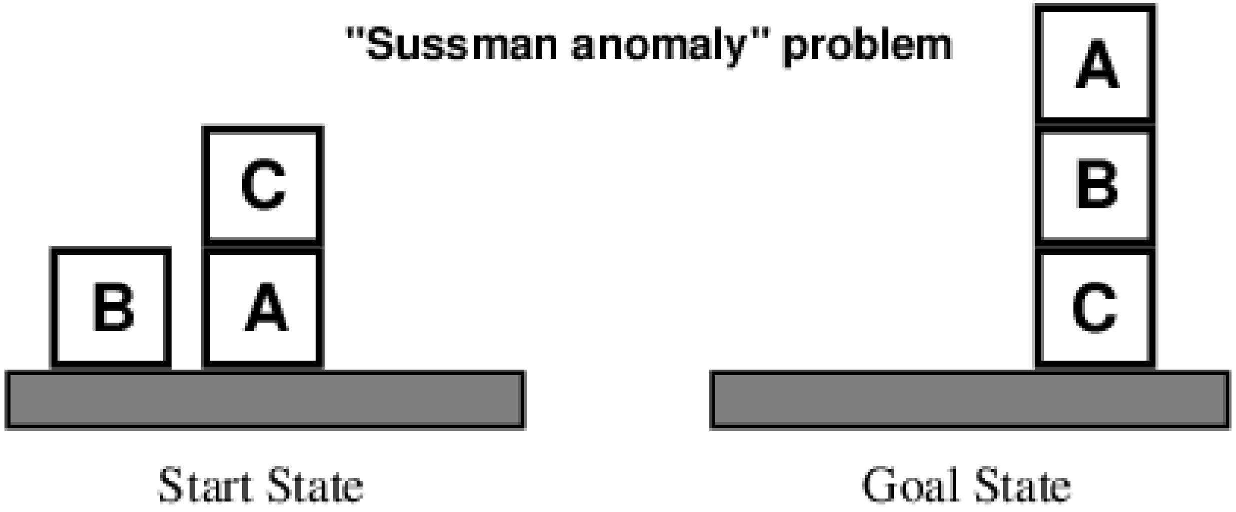
Demotion: put before $Go(Supermarket)$

Promotion: put after $Buy(Milk)$

Properties of Partially Ordered Plans

- Nondeterministic algorithm: backtracks at choice points on failure
  - choice of S_{add} to achieve S_{need}
  - choice of demotion or promotion for clobberer
  - selection of S_{need} is irrevocable
- Partially Ordered Plans is sound, complete, and systematic (no repetition)
- Extensions for disjunction, universals, negation, conditionals
- Can be made efficient with good heuristics derived from problem description
- Particularly good for problems with many loosely related subgoals

Example: Blocks World



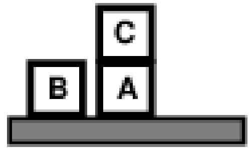
PutOn(x,y)	PutOnTable(x)
Preconditions: *Clear(x) On(x,z) Clear(y)*	Preconditions: *Clear(x) On(x,z)*
Effects: *~On(x,z) ~Clear(y) Clear(z) On(x,y)*	Effects: *~On(x,z) Clear(z) On(x,Table)*

+ several inequality constraints

Example

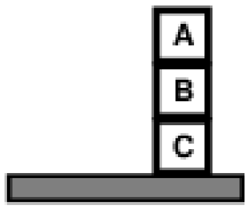
START

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

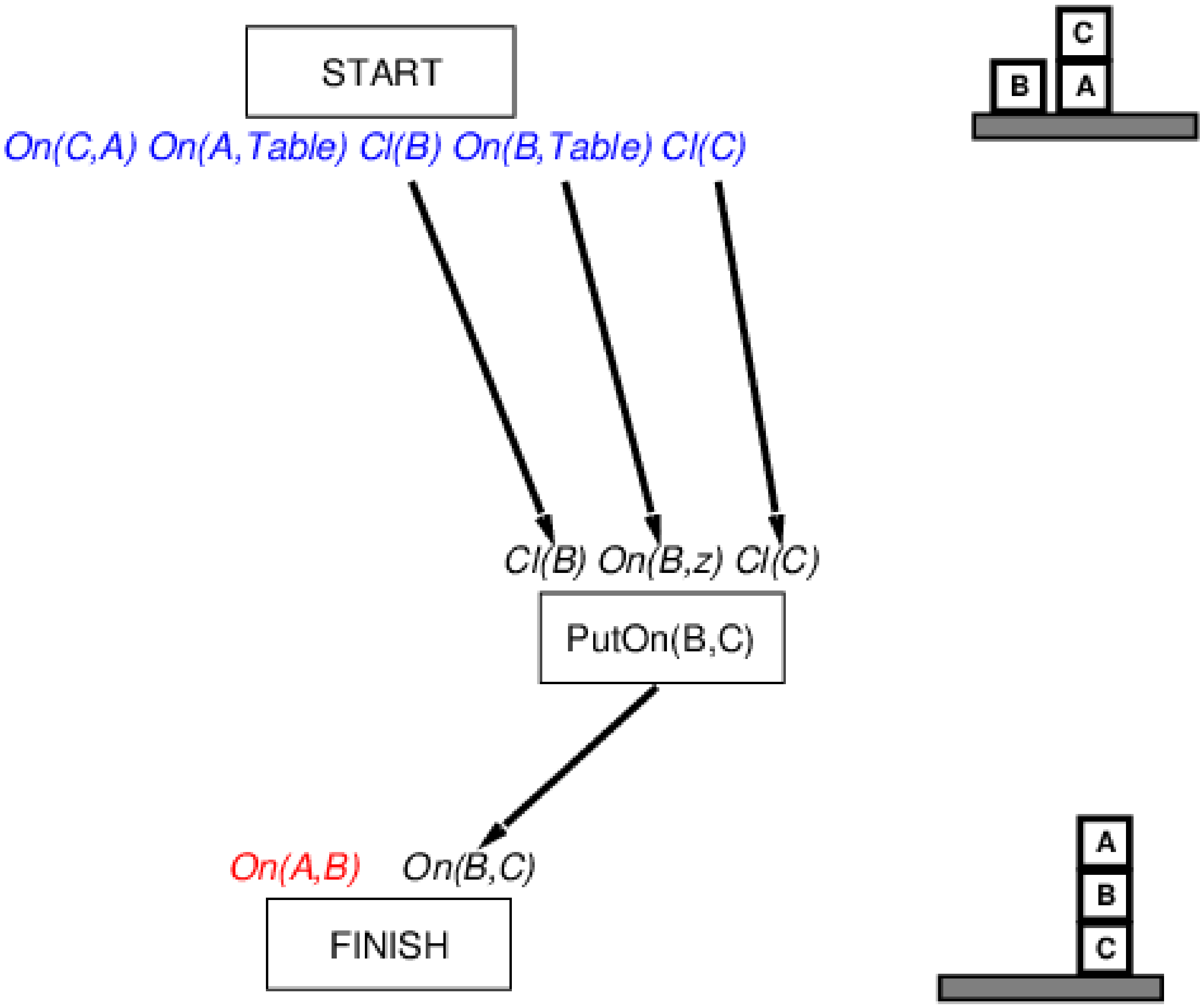


On(A,B) *On(B,C)*

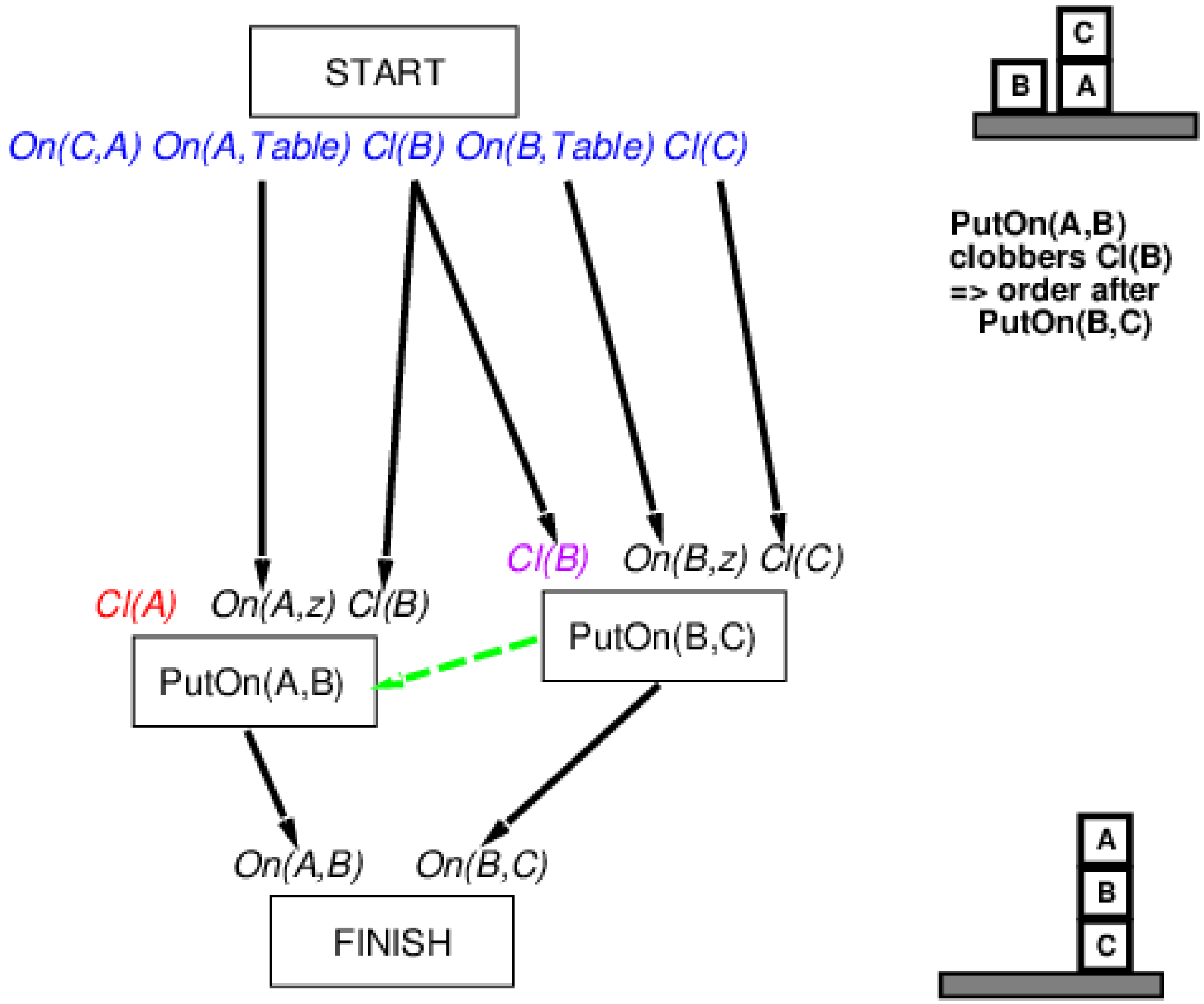
FINISH



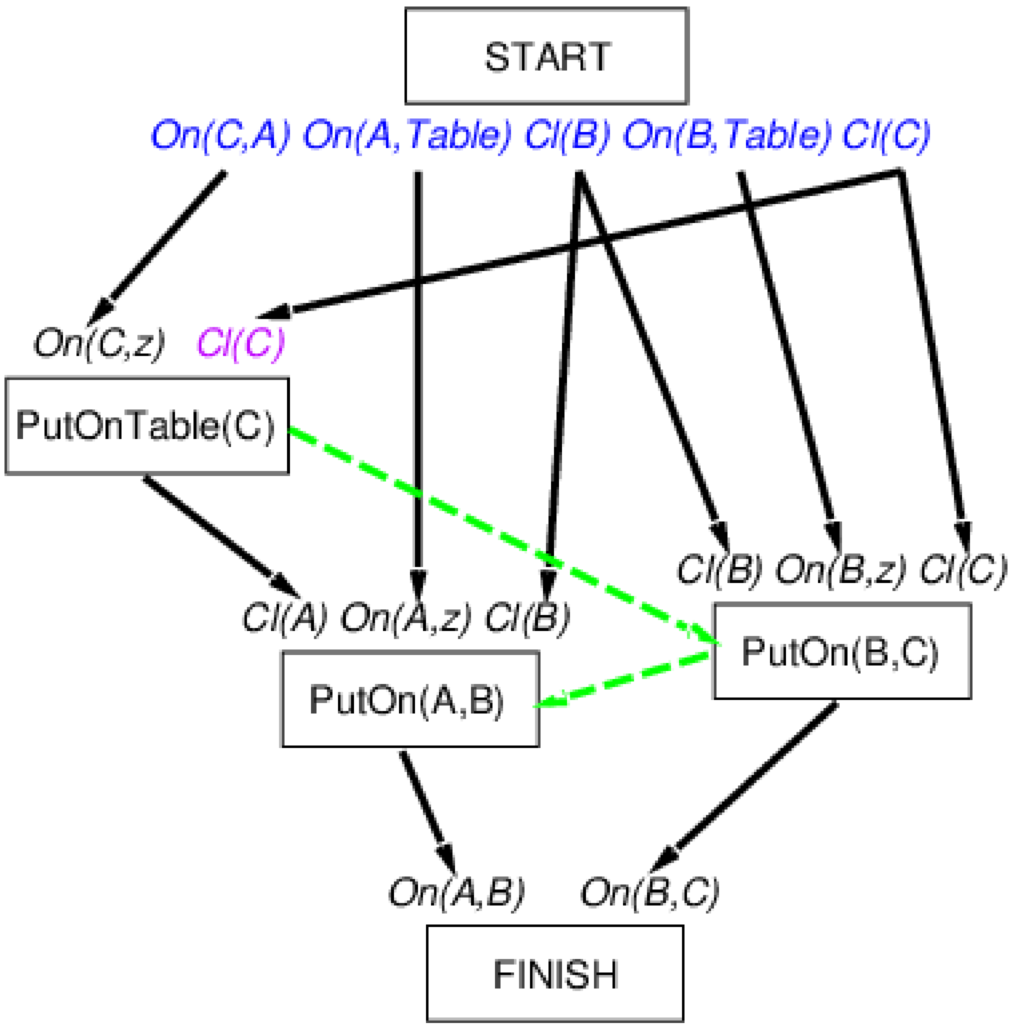
Example

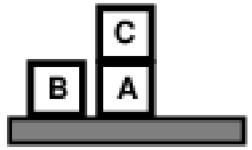

START
On(C,A) On(A,Table) Cl(B) On(B,Table) Cl(C)
C
B
A
Cl(B) On(B,z) Cl(C)
PutOn(B,C)
On(A,B) On(B,C)
FINISH
A
B
C

Example


START
On(C,A) On(A,Table) Cl(B) On(B,Table) Cl(C)
Cl(B) On(B,z) Cl(C)
Cl(A) On(A,z) Cl(B)
PutOn(B,C)
PutOn(A,B)
On(A,B) On(B,C)
FINISH
C
B
A
PutOn(A,B)
clobbers Cl(B)
=> order after
PutOn(B,C)
A
B
C

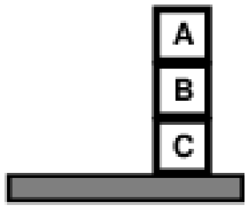
Example





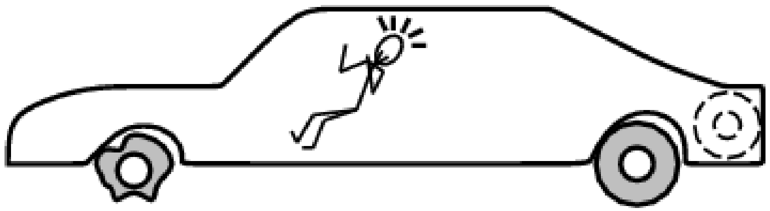
PutOn(A,B) clobbers Cl(B) => order after PutOn(B,C)

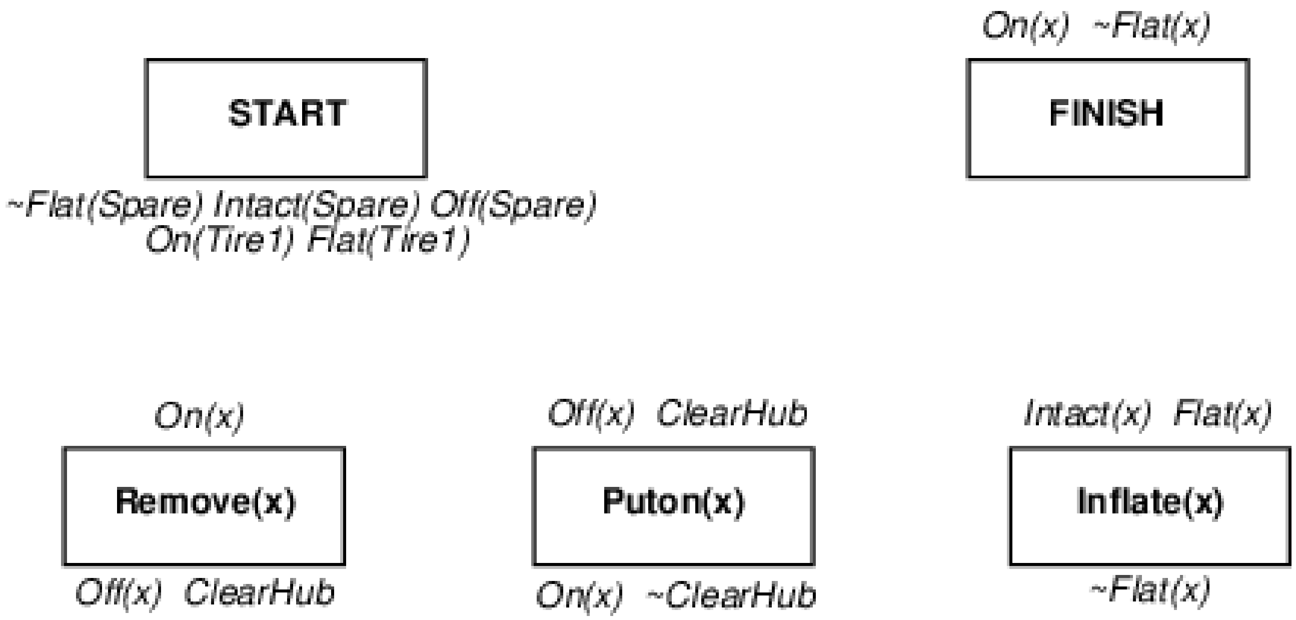
PutOn(B,C) clobbers Cl(C) => order after PutOnTable(C)



the real world

The Real World





Things Go Wrong

- *Incomplete information*
  - Unknown preconditions, e.g., $Intact(Spare)$?
  - Disjunctive effects, e.g., $Inflate(x)$ causes $Inflated(x) \lor SlowHiss(x) \lor Burst(x) \lor BrokenPump \lor \ldots$
- *Incorrect information*
  - Current state incorrect, e.g., 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

- Conformant or sensorless planning

  Devise a plan that works regardless of state or outcome

  Such plans may not exist

- Conditional planning

  Plan to obtain information (**observation actions**)

  Subplan for each contingency, e.g.,

  $[Check(Tire1),$ **if** $Intact(Tire1)$ **then** $Inflate(Tire1)$ **else** $CallAAA]$

  Expensive because it plans for many unlikely cases

- Monitoring/Replanning

  Assume normal states, outcomes

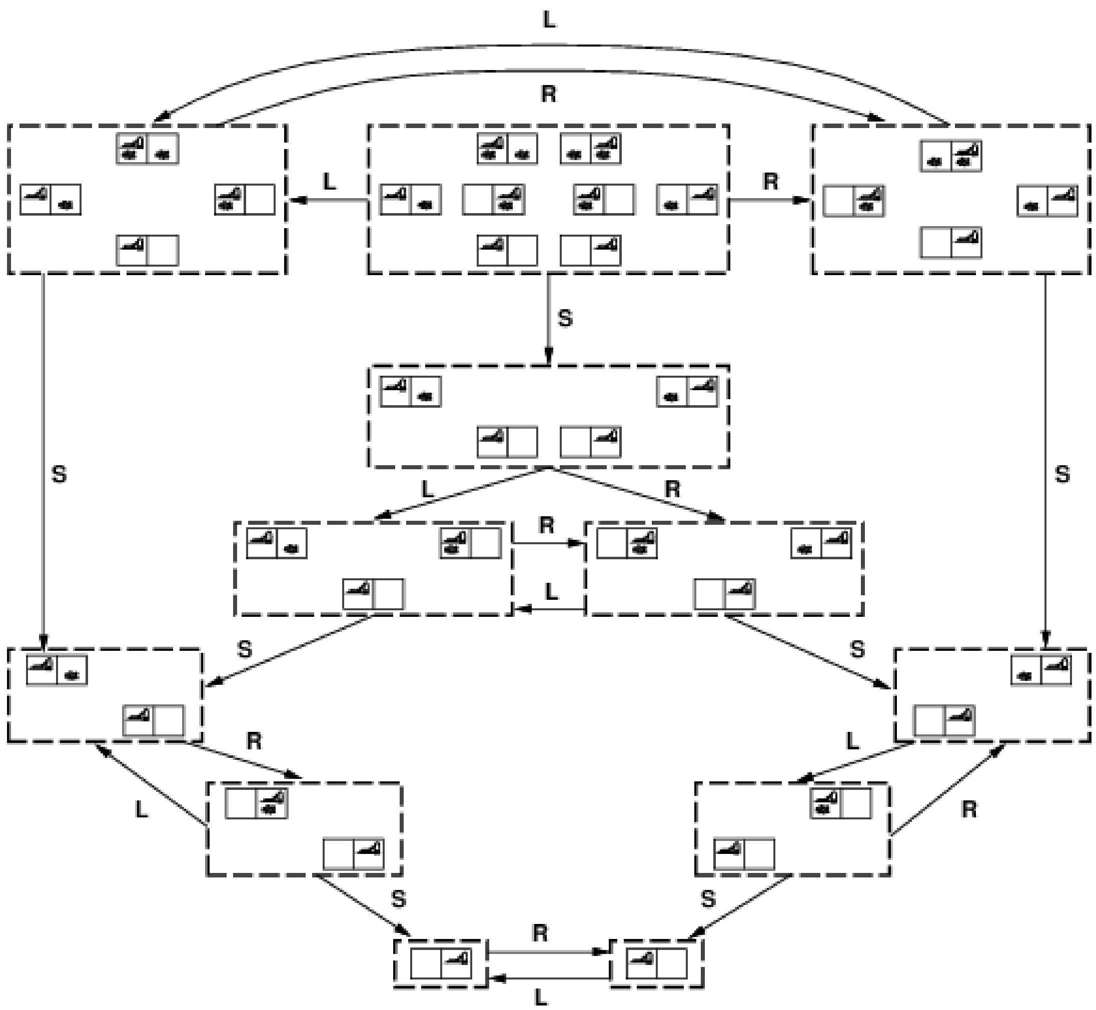
  Check progress *during execution*, replan if necessary

  Unanticipated outcomes may lead to failure (e.g., no AAA card)

$\Rightarrow$ Really need a combination; plan for likely/serious eventualities, deal with others when they arise, as they must eventually.

Conformant Planning

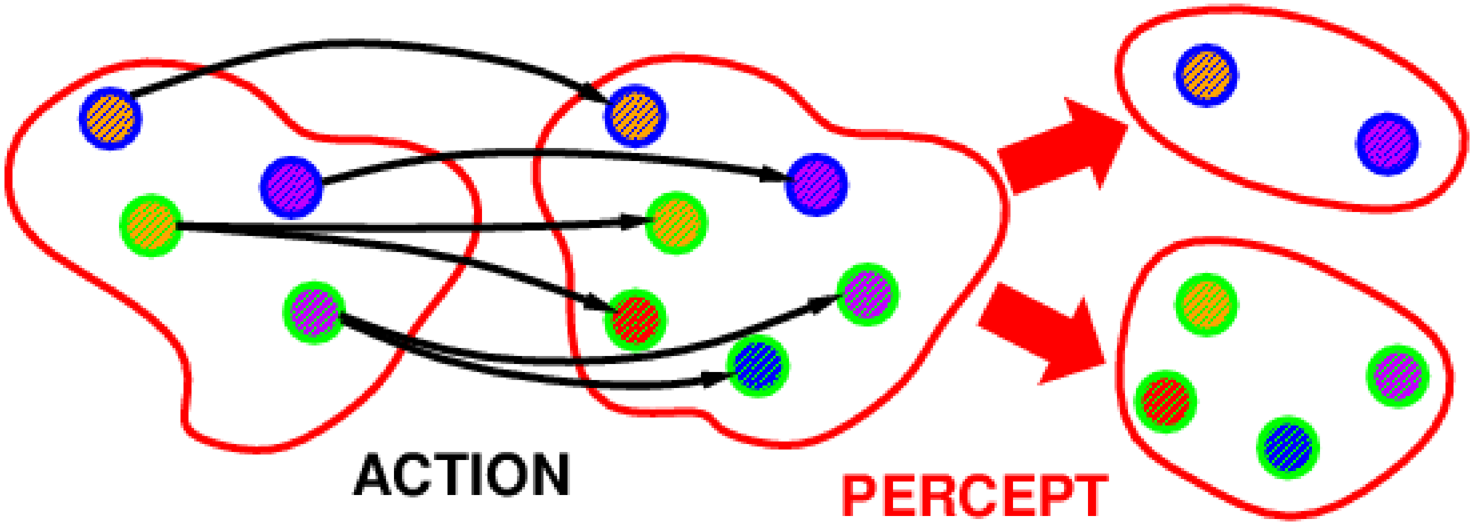
- Search in space of belief states (sets of possible actual states)



conditional planning

Conditional Planning

- If the world is nondeterministic or partially observable
  then percepts usually *provide information*,
  i.e., *split up* the belief state

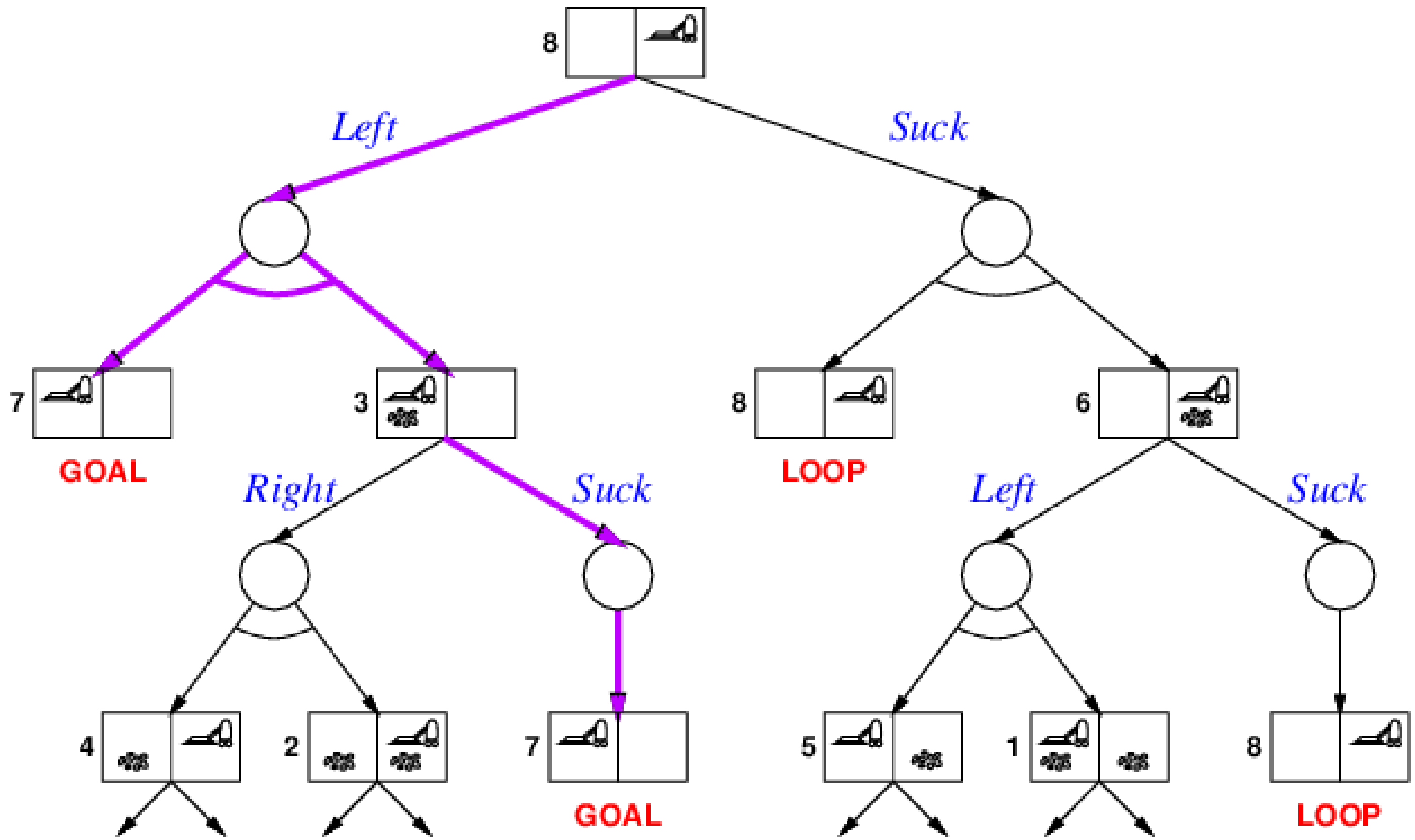


Conditional Planning

- Conditional plans check (any consequence of KB +) percept
- $[\ldots,$ **if** C **then** $Plan_A$ **else** $Plan_B, \ldots]$
- Execution: check C against current KB, execute "then" or "else"
- Need *some* plan for *every* possible percept
  - game playing: *some* response for *every* opponent move
  - backward chaining: *some* rule such that *every* premise satisfied
- AND–OR tree search (very similar to backward chaining algorithm)

Example

- Double Murphy: sucking or arriving may dirty a clean square



monitoring and replanning

Execution Monitoring

- Plan with Partially Ordered Plans algorithms

- Process plan, one step at a time

- Validate planned conditions against perceived reality

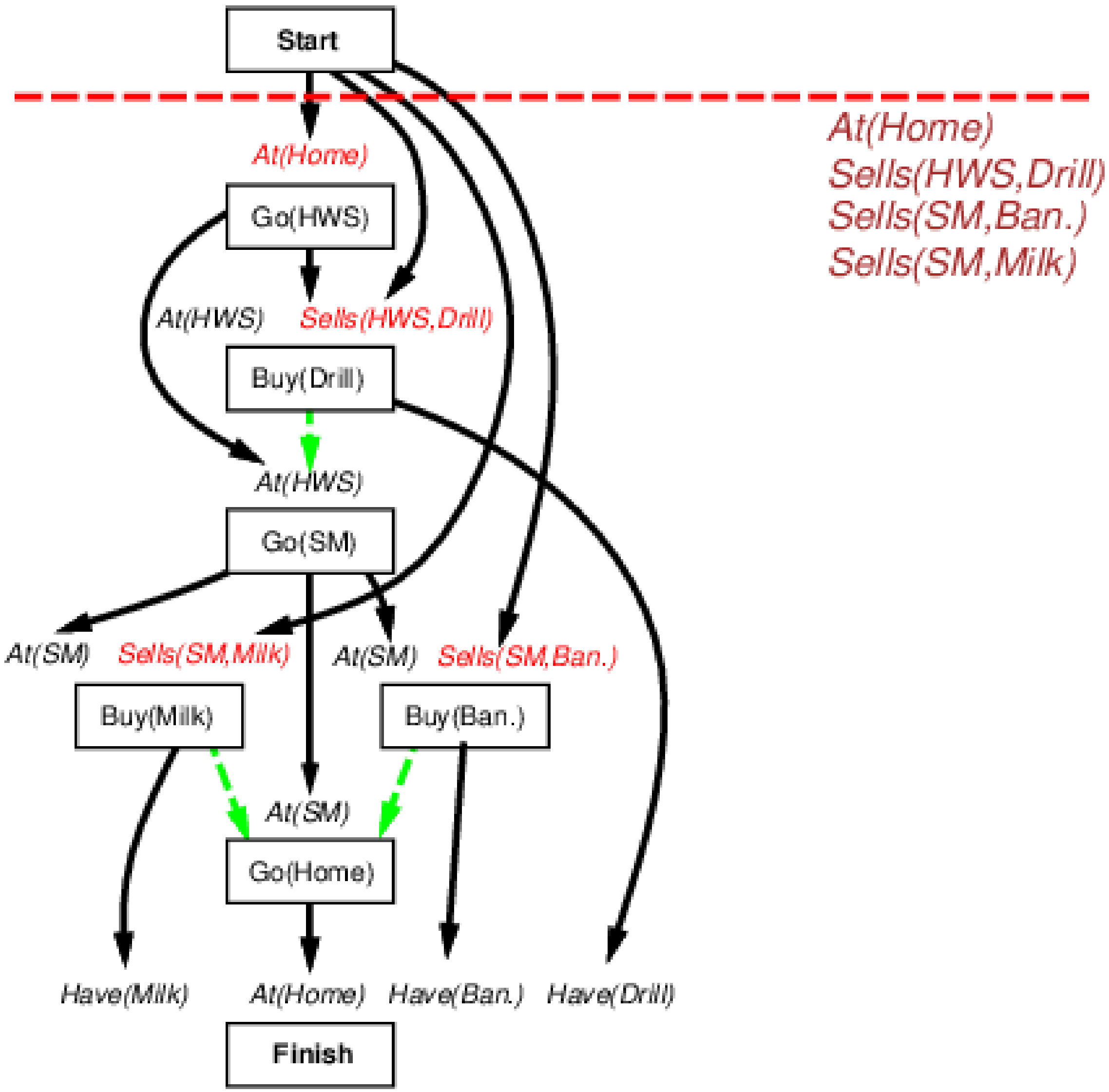
- "Failure" = preconditions of *remaining plan* not met

- Preconditions of remaining plan
  = all preconditions of remaining steps not achieved by remaining steps
  = all causal links *crossing* current time point

Responding to Failure

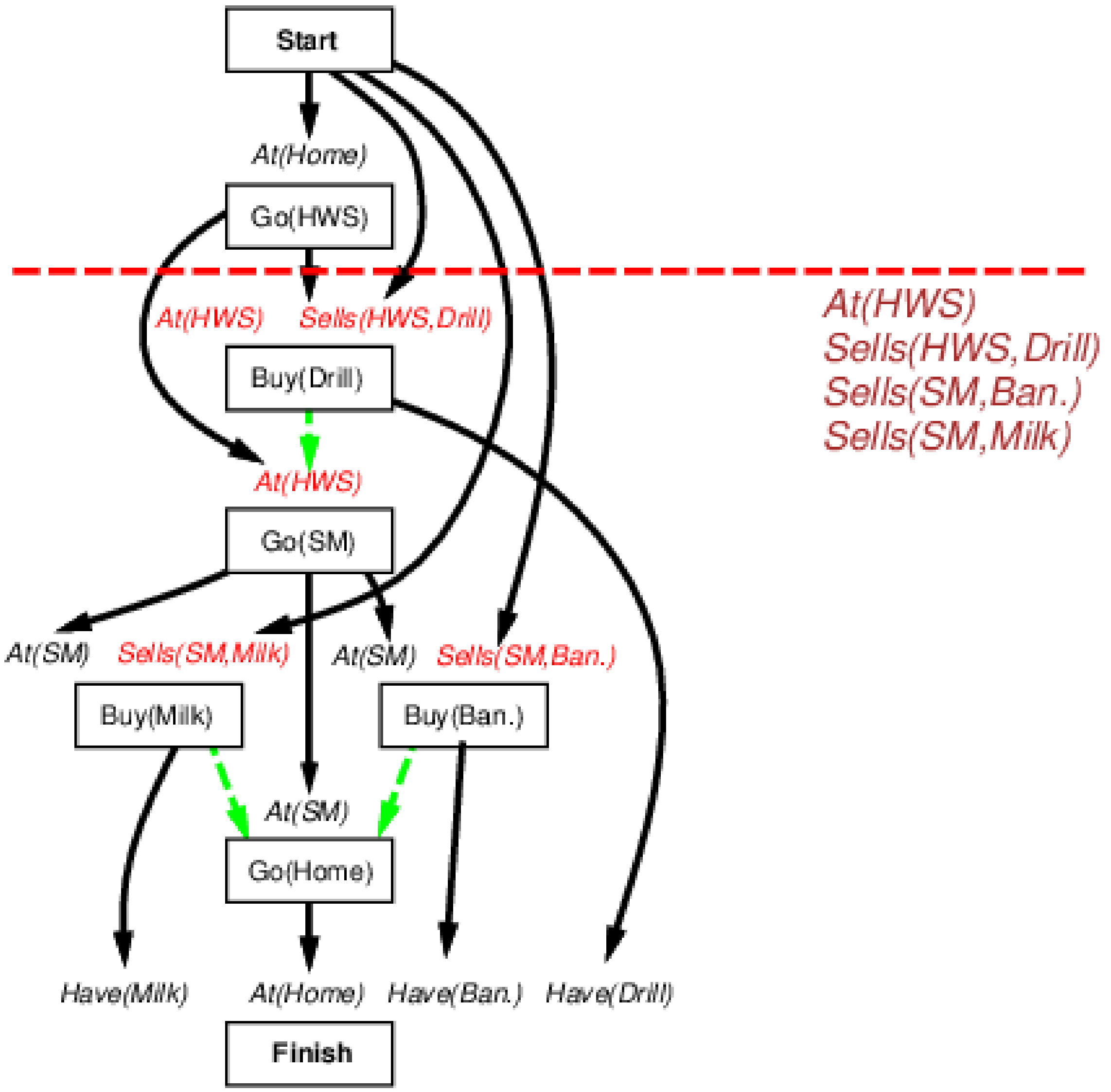
- Run Partially Ordered Plans algorithms again
- Resume Partially Ordered Plans to achieve open conditions from current state
- IPEM (Integrated Planning, Execution, and Monitoring)
  - keep updating $Start$ to match current state
  - links from actions replaced by links from $Start$ when done

Example



At(Home)
Sells(HWS,Drill)
Sells(SM,Ban.)
Sells(SM,Milk)

Example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Go(Home)
Have(Milk)
At(Home)
Have(Ban.)
Have(Drill)
Finish
At(HWS)
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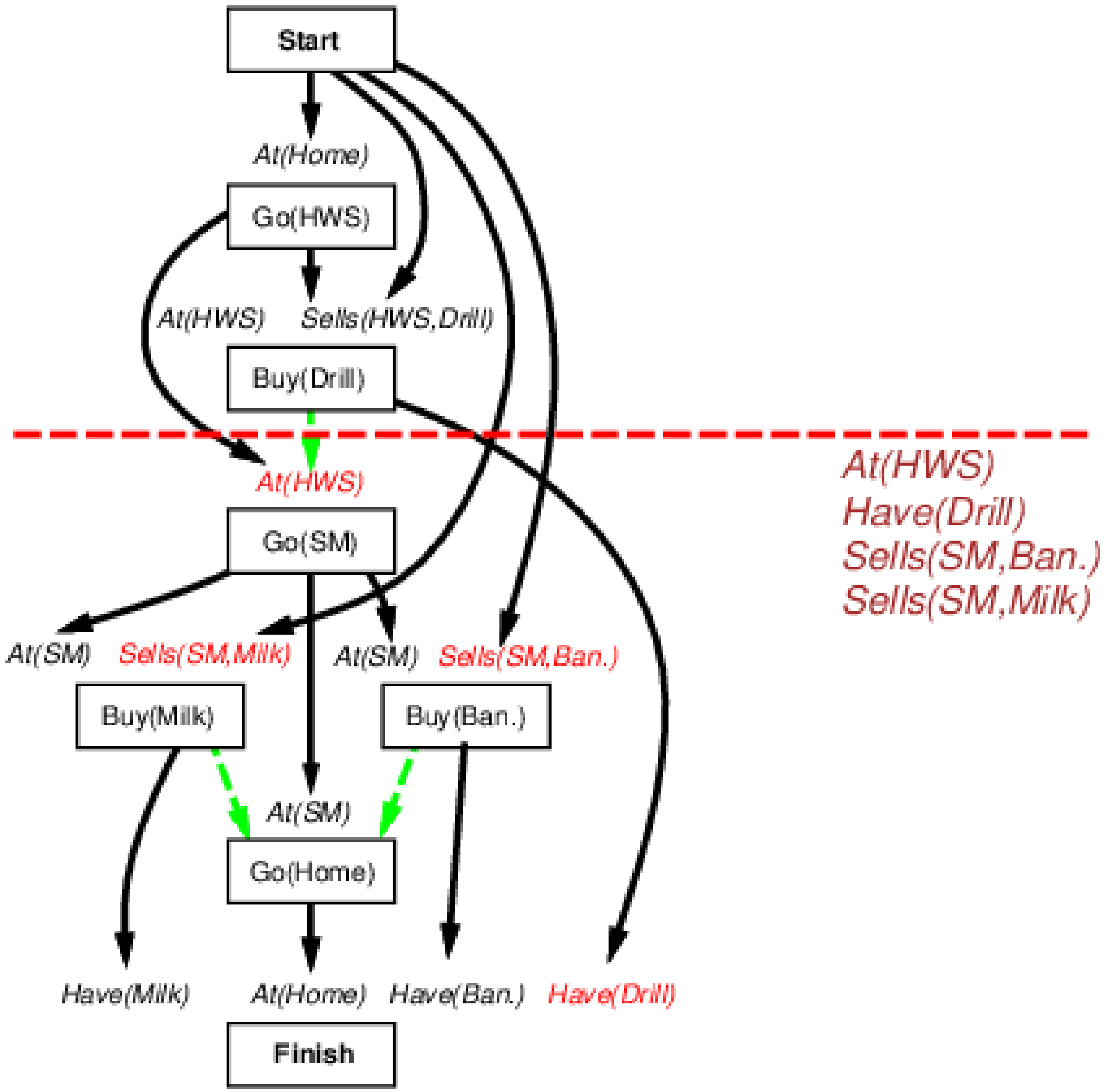
Example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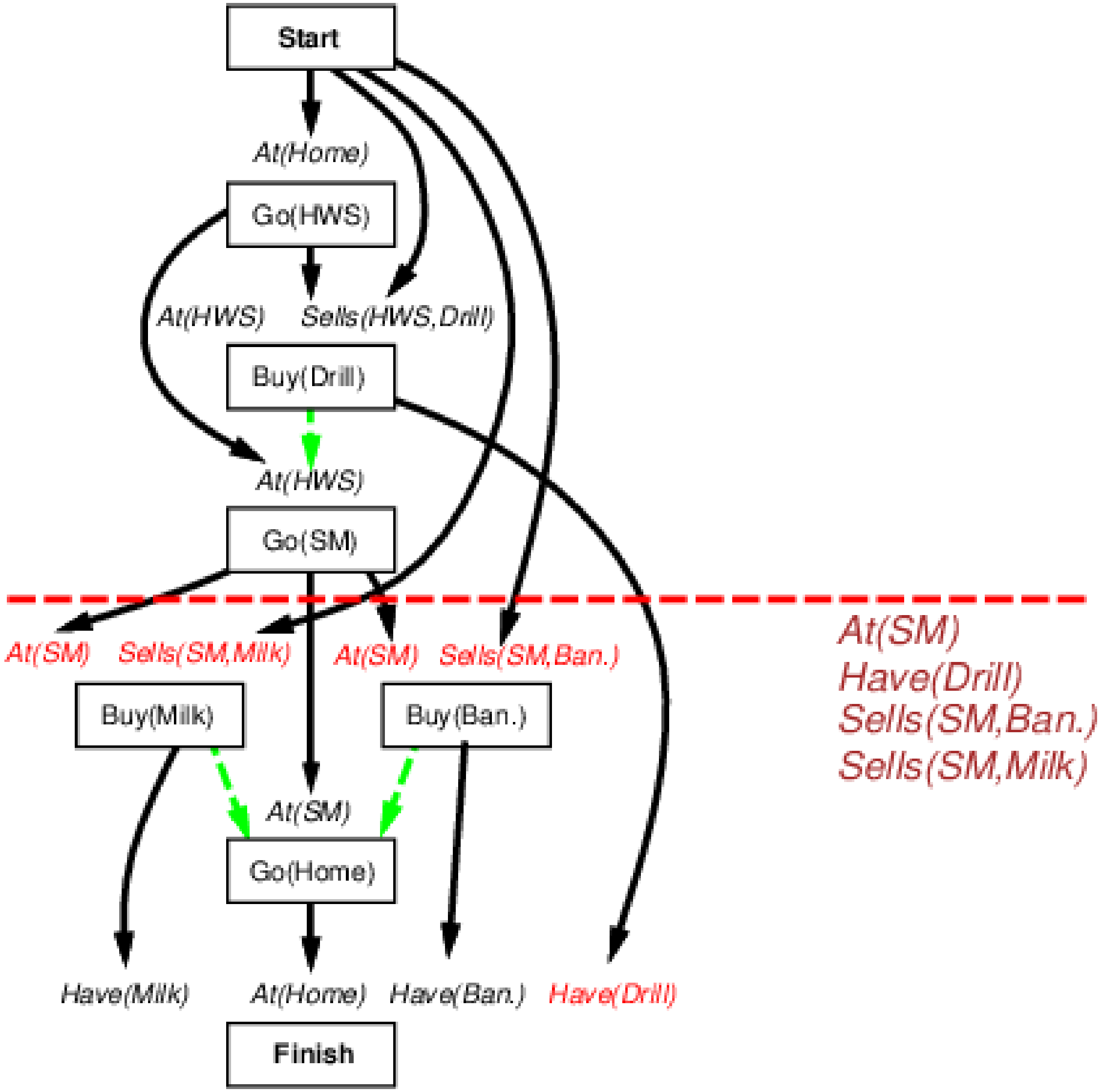
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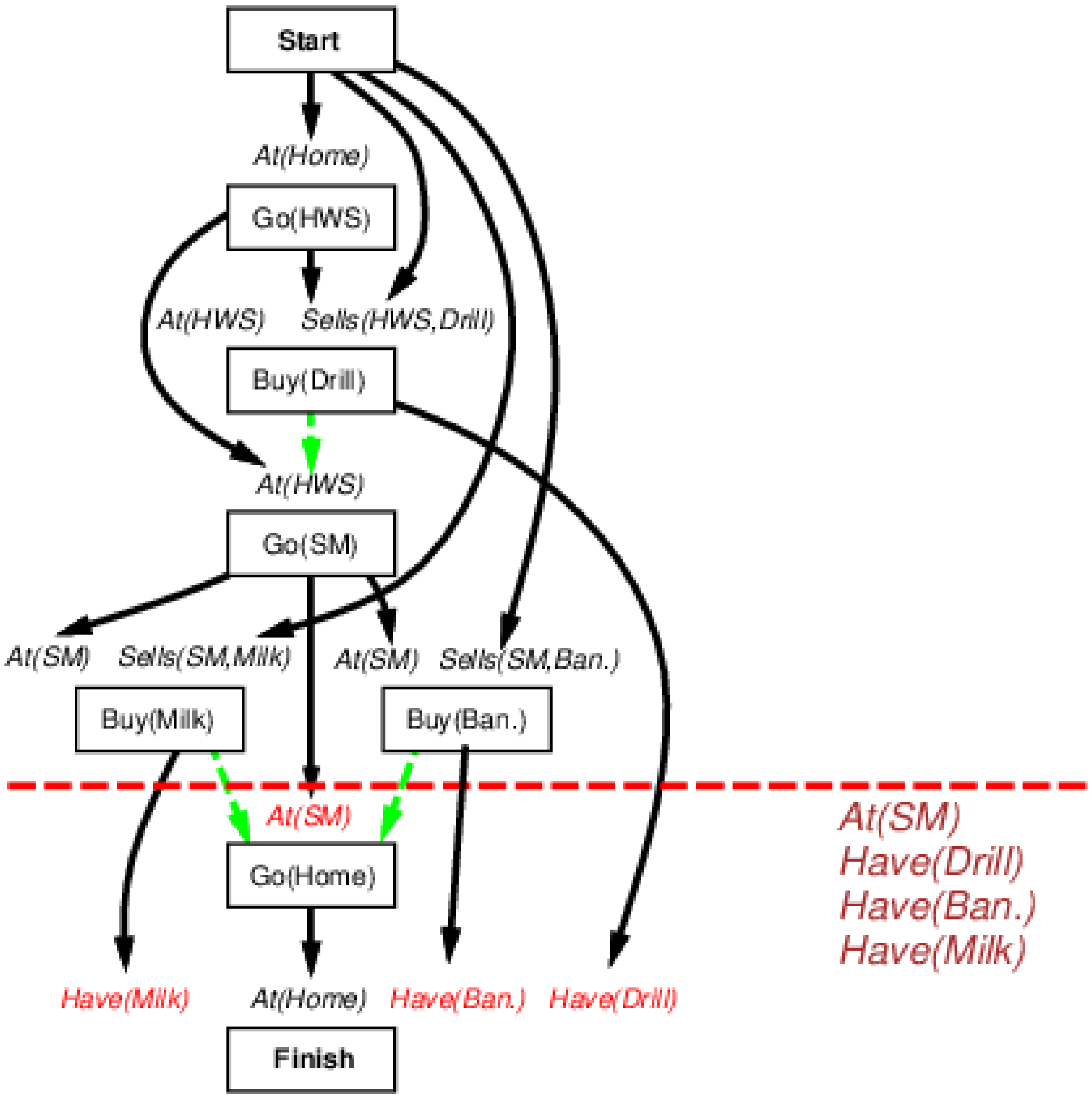
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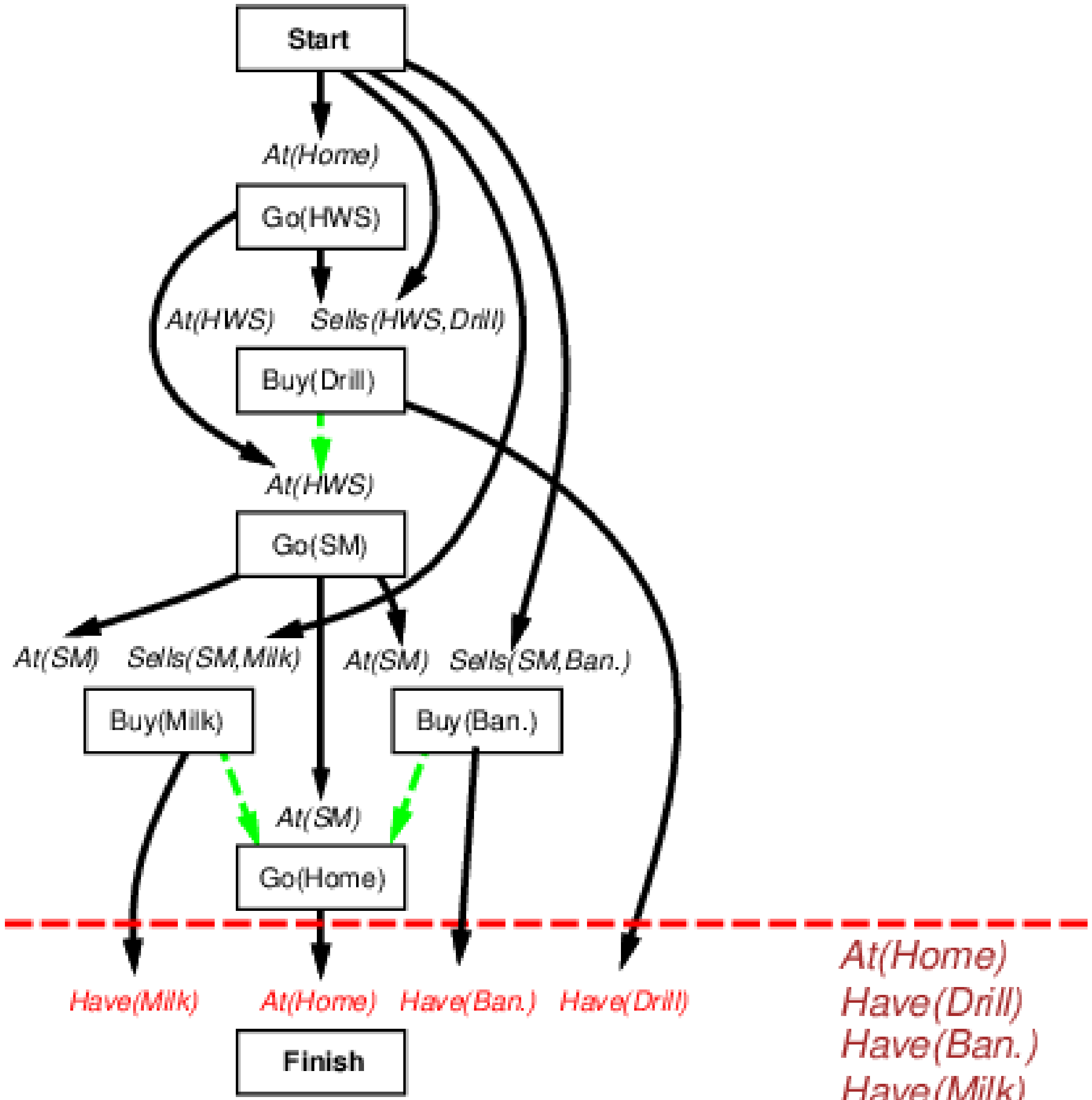

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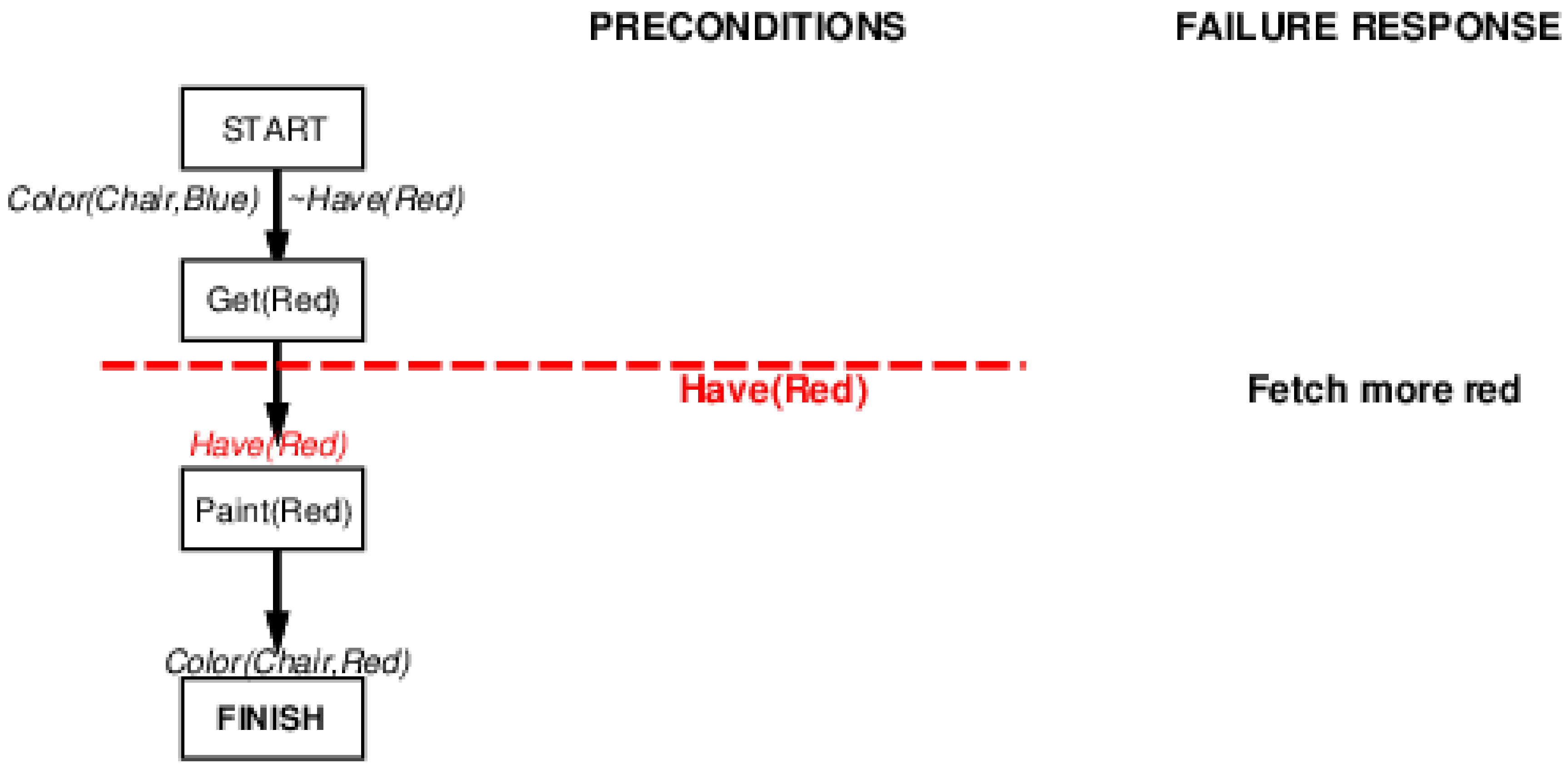
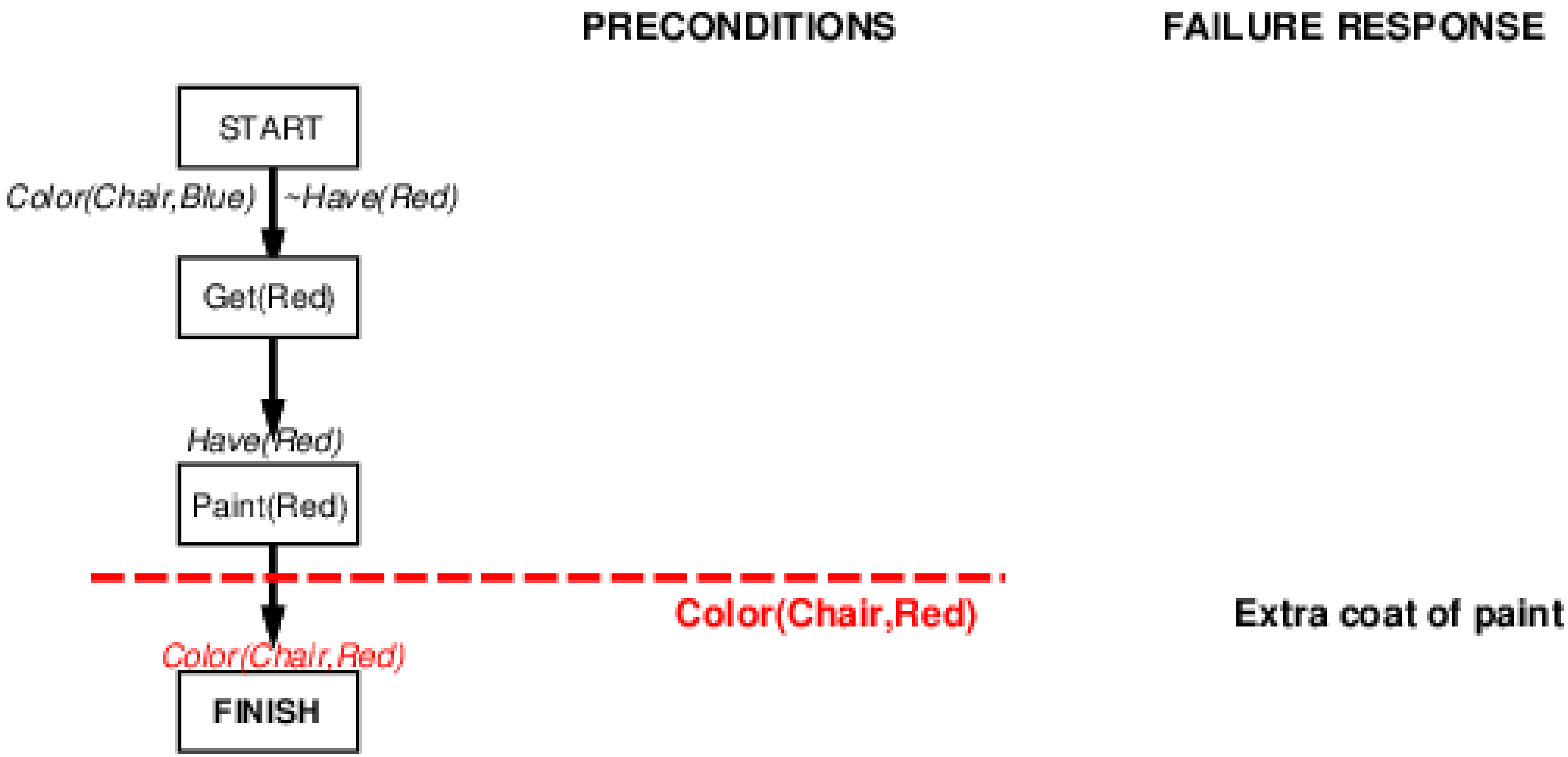
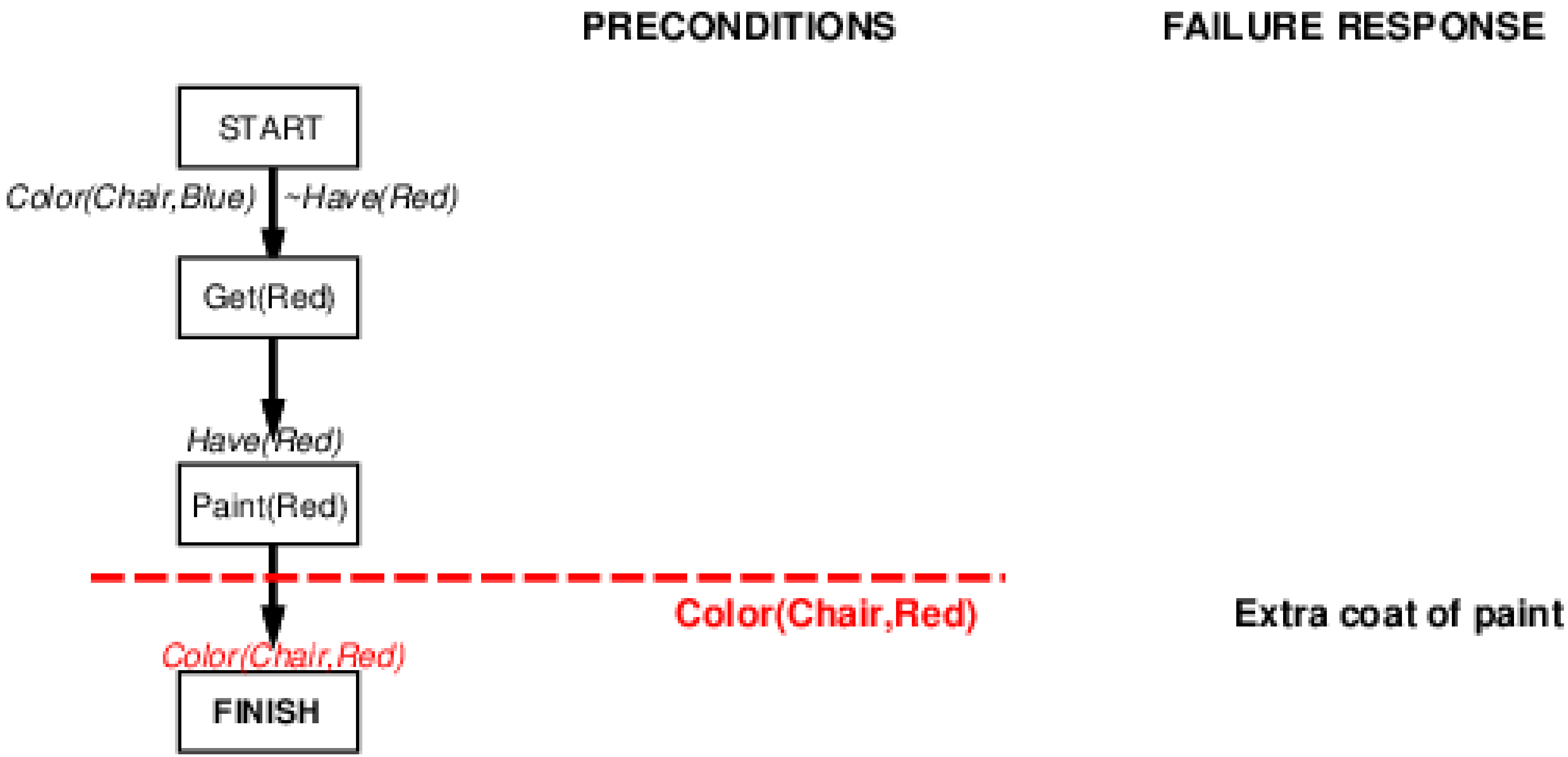
Emergent Behavior



Emergent Behavior



Emergent Behavior



- "Loop until success" behavior *emerges* from interaction between monitor/replan agent design and uncooperative environment

Summary

- Planning
  - break down problem into subgoals
  - search for plans for subgoals
  - merge sub-plans
- Defined actions in terms of preconditions and effects
- Partially Ordered Plans algorithm
- Clobbering: need to deal with steps that destroy clausal link in plan
- Real world: incomplete and incorrect information

⇒ conformant or conditional planning, monitoring and replanning