Planning and Acting in the Real World

Chapter 11

Outline

- ♢ Time, schedules, and resources
- ♢ Planning in nondeterministic domains
- ♢ Monitoring and replanning
- ♢ Multiagent planing

Planning/acting in Real world

♢ So far only looked at classical planning, i.e. environments are fully observable, static, determinist. Also assumed that action descriptions are correct and complete.

♢ Unrealistic in many real-world applications: Don't know everything - may even hold incorrect information. Actions can go wrong.

♢ Distinction: bounded vs. unbounded indeterminacy: can possible pre-conditions and effects be listed at all? Unbounded indeterminacy related to qualification problem

♢ Real world include **temporal** and **resource** constraints:

- classical planning talks about what to do, and in what order, but cannot talk about time: how long an action takes
- an airline has a limited number of staff - and staff who are on one flight cannot be on another at the same time.

A job-shop scheduling problem

Assembling two cars with resource constraints.

Jobs	(AddEngine1 $\prec$ AddWheels1 $\prec$Inspect1 , AddEngine2 $\prec$AddWheels2 $\prec$Inspect2)
Resources	(EngineHoists(1),WheelStations (1), Inspectors (2), LugNuts(500))
Action	(AddEngine1 , DURATION:30, USE:EngineHoists(1))
Action	(AddEngine2 , DURATION:60, USE:EngineHoists(1))
Action	(AddWheels1 , DURATION:30, CONSUME:LugNuts(20), USE:WheelStations(1))
Action	(AddWheels2 , DURATION:15, CONSUME:LugNuts(20), USE:WheelStations(1))
Action	(Inspect i, DURATION:10, USE:Inspectors (1))

Solving scheduling problems

Begin by considering just the temporal constraints, ignoring resource constraints.

Critical path method: to determine the possible start and end times of each action.

Critical path is that path whose total duration is longest

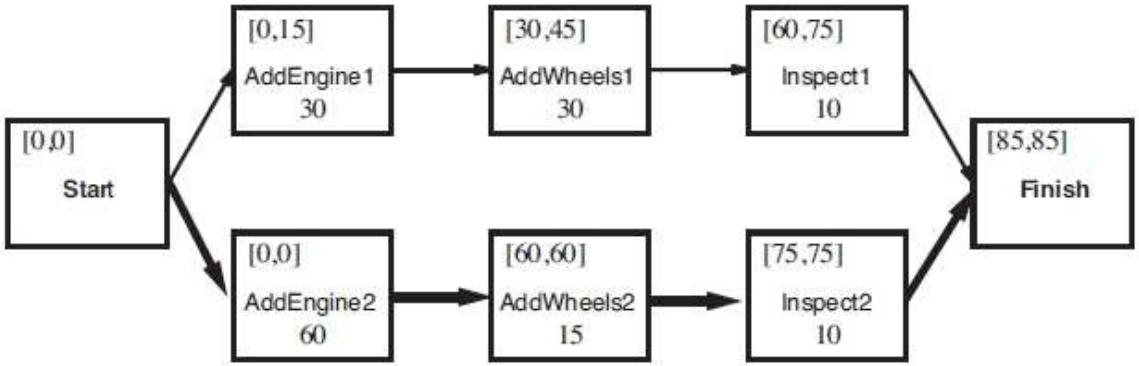
Actions have a window of time [ES,LS]

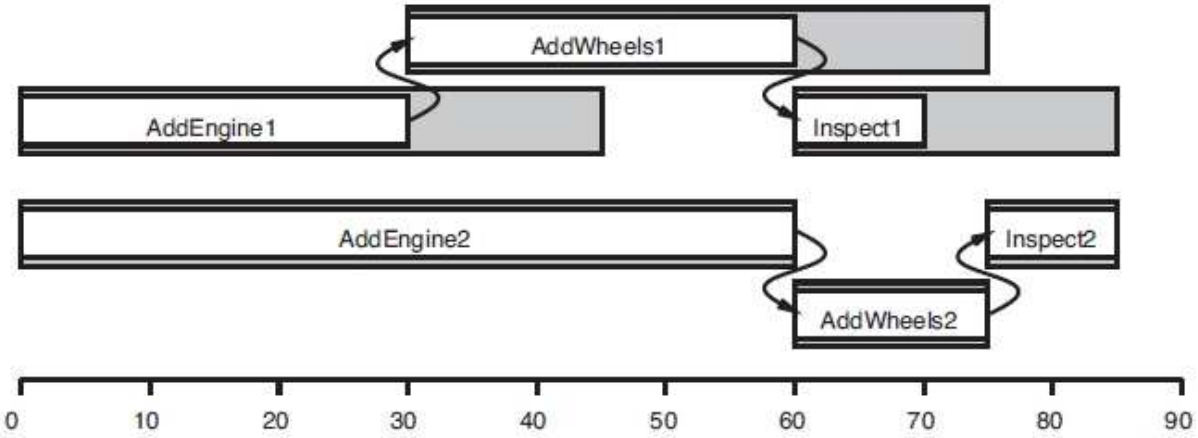
ES - earliest possible start time, LS - latest possible start time

Given A, B actions and $A \prec B$:

$ES(Start) = 0$
$ES(B) = max_{A \prec B} ES(A) + Duration(A)$
$LS(Finish) = ES(Finish)$
$LS(A) = min_{B \succ A} LS(B) - Duration(A)$

Critical path algorithm





Considering resource constraints

Cannot overlap constraint: disjunction of two linear inequalities, one for each possible ordering

Minimum slack algorithm:

♢ on each iteration, schedule for the earliest possible start whichever unscheduled action has all its predecessors scheduled and has the least slack;

♢ then update the ES and LS times for each affected action and repeat.

How long is the solution with the minimum slack algorithm for the assembly problem?

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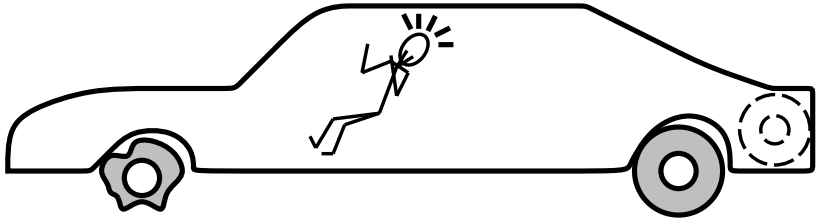
The real world



On(x) ~Flat(x)

START

FINISH

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

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, 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

Methods for handling indeterminacy

Conformant or sensorless planning (env. with no observations)

Devise a plan that works regardless of state or outcome

Such plans may not exist

Conditional planning (partially observable and nondeterministic)

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

Subplan for each contingency, e.g.,

$[Check(Tire1), \textbf{if}\ Intact(Tire1)\ \textbf{then}\ Inflate(Tire1)\ \textbf{else}\ CallAAA]$

Expensive because it plans for many unlikely cases

Monitoring/Replanning (unknown environments)

Check progress *during execution*, replan if necessary

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

(Really need a combination; plan for likely/serious eventualities,
deal with others when they arise, as they must eventually)

Running scenario

Given a chair and a table, the goal is to have them match.

In the initial state we have two cans of paint, but the colors of the paint and the furniture are unknown. Only the table is initially in the agents field of view

There are two actions: removing the lid from a paint can and painting an object using the paint from an open can.

How would each of the following handle this problem?

Classical planning?
Conformant (sensorless) plan?
Contingent (conditional) plan?
Online (replanning)?

Running scenario

Now, we allow preconditions and effects to contain variables that are not part of the action's variable (e.g. Paint(x, can)).

Init (Object(Table) $\wedge$ Object(Chair) $\wedge$ Can(C1) $\wedge$ Can(C2) $\wedge$ InView(Table))

Goal (Color (Chair, c) $\wedge$ Color (Table, c))

Action(RemoveLid(can),
PRECOND:Can(can)
EFFECT:Open(can))
Action(Paint(x , can),
PRECOND:Object(x) $\wedge$ Can(can) $\wedge$ Color (can, c) $\wedge$ Open(can)
EFFECT:Color (x , c))
Action(LookAt (x),
PRECOND:InView(y) $\wedge$ (x $\neq$ y)
EFFECT:InView(x) $\wedge$ $\neg$ InView(y))

Model of sensors

To solve a partially observable problem, the agent will have to reason about the percepts it will obtain when it is executing the plan.

Percept schema: models the agents sensors. It tells the agent what it knows, given certain conditions about the state it's in

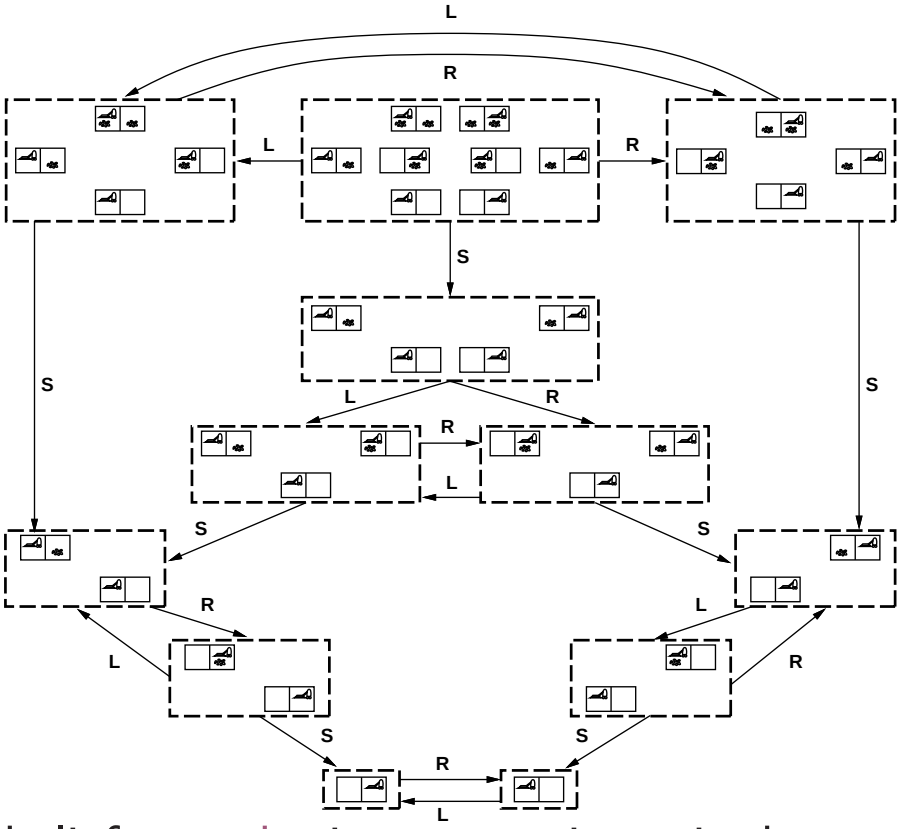
Percept (Color (x, c),
    PRECOND:Object(x) $\wedge$ InView(x))
Percept (Color (can, c),
    PRECOND:Can(can) $\wedge$ InView(can) $\wedge$ Open(can))

A fully observable environment has a percept axiom for each fluent with no preconditions!

A sensorless planner has no percept schemata at all!

Conformant planning

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



The update of a belief state b given an action a is the set of all states that result from doing a in each possible state s that satisfies belief state b.

$$b' = Result(b, a) = \{s' : s' = Result_P(s, a) \wedge s \in b\}$$

Conformant planning

Initial belief state: $b_0 = Color(x, C(x))$ from $\forall x \; \exists c \; Color(x, c)$

Open-world assumption: in which states contain both positive and negative fluents, and if a fluent does not appear, its value is unknown

[RemoveLid(Can1), Paint(Chair, Can1), Paint (Table, Can1)]

1. If action adds l, then l is true in b' regardless of its initial value.
2. If action deletes l, then l is false in b' regardless initial value.
3. If action says nothing about l, then l will retain its b-value.

$$b' = RESULT(b, a) = (b - DEL(a)) \cup ADD(a)$$

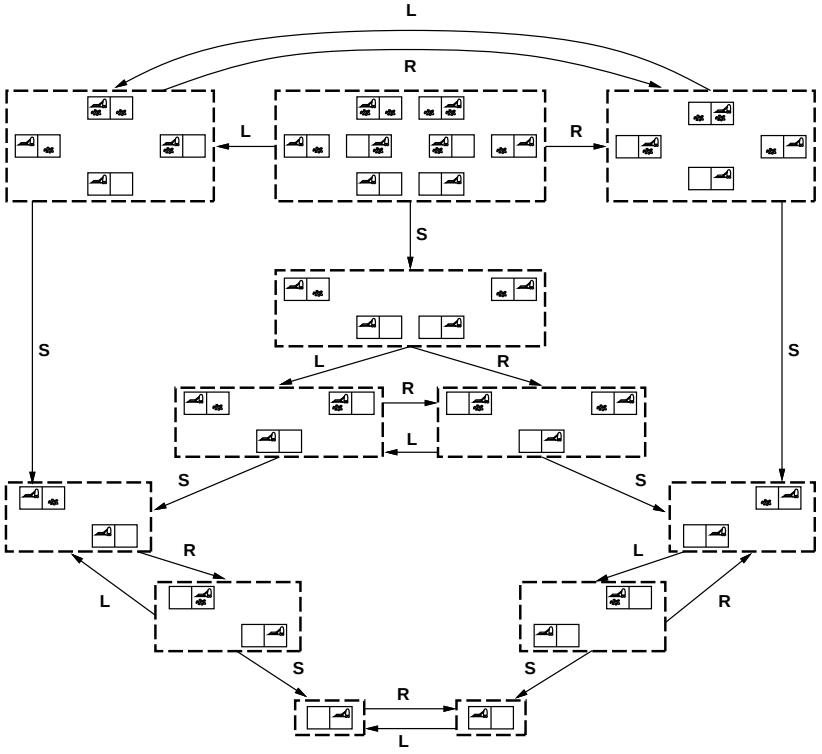
$$b_1 = RESULT(b_0, RemoveLid(C1)) = Color(x, C(x)) \wedge Open(Can1)$$

$$b_2 = Color(x, C(x)) \wedge Open(Can1) \wedge Color(Chair, C(Can1))$$

$$b_3 = Color(x, C(x)) \wedge Open(Can1) \wedge Color(Chair, C(Can1)) \wedge Color(Table, C(Can1))$$

Conditional effects

So far, we have only considered actions that have the same effects on all states where the preconditions are satisfied



Action(Suck, EFFECT: **when** *AtL: CleanL* $\wedge$ **when** *AtR: CleanR*)

$b_0 = true$ $\qquad$ $b_1 = (AtL \wedge CleanL) \vee (AtR \wedge CleanR)$

$Action(SuckL$, PRECOND:AtL; EFFECT:$CleanL$)
$Action(SuckR$, PRECOND:AtR; EFFECT:$CleanR$)

We cannot determine the applicability of SuckL and SuckR in b_0

For sensorless planning, it is better to have conditional effects than an inapplicable action.

[Right, Suck, Left, Suck]: b_0, b_1, b_2, b_3, b_4

Augment STRIPS to allow for nondeterminism:

♢ Add Disjunctive effects (e.g., to model when action sometimes fails):
Action(Left,Precond:AtR,Effect:AtL $\vee$ AtR)

♢ Add Conditional effects (i.e., depends on state in which its executed):
Form: when<condition>:<effect>
Action(Suck,Precond:,Effect:(when AtL: CleanL)$\wedge$(when AtR: CleanR)

Contingent planning

A contingent planner can do better than a sensorless planning:

1. Look at the table and chair to sense their colours.
2. If theyre the same colour, youre done.
3. If not, look at the paint cans.
4. If one of the cans is the same colour as one of the pieces of furniture, then apply that paint to the other piece of furniture.
5. Otherwise, paint both pieces with one of the cans.

Conditional planning

[LookAt (Table), LookAt (Chair),
if Color (Table, c) $\wedge$ Color (Chair, c) **then** NoOp
else [RemoveLid(Can_1), LookAt (Can_1),RemoveLid (Can_2), LookAt (Can_2),
if Color (Table, c) $\wedge$ Color (can, c) **then** Paint(Chair, can)
else if Color (Chair, c) $\wedge$ Color (can, c) **then** Paint(Table, can)
else [Paint(Chair, Can_1), Paint (Table, Can_1)]]]

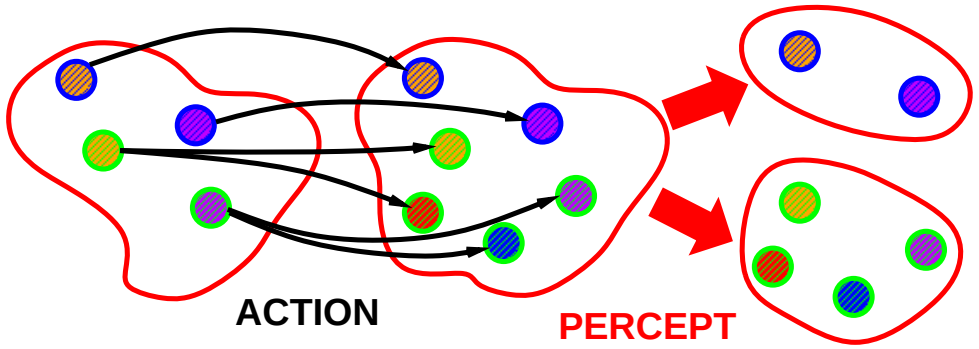
Percept (Color (x, c), PRECOND:Object(x) $\wedge$ InView(x)
Percept (Color (can, c),PRECOND:Can(can) $\wedge$ InView(can) $\wedge$ Open(can)
Action(LookAt (x),
PRECOND:InView(y) $\wedge$ (x $\neq$ y)
EFFECT:InView(x) $\wedge$ $\neg$ InView(y))

Computing b' an action and subsequent percept is done in two stages:

1. calculates the belief state after the action, just as for the sensorless agent:
   $b' = (b - DEL(a)) \cup ADD(a)$
2. add information for the percept axioms with the conditions satisfied

Games against nature

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



Conditional plans should succeed regardless of circumstances

Need *some* plan for *every* possible percept

Nesting conditional steps results in trees

Similar to adversarial search, games against nature

(Cf. game playing: *some* response for *every* opponent move)

(Cf. backward chaining: *some* rule such that *every* premise satisfied

AND–OR tree search (very similar to backward chaining algorithm)

Robot takes action in state nodes.

Nature decides outcome at chance nodes.

Plan needs to take some action at every state it reaches (i.e., Or nodes)

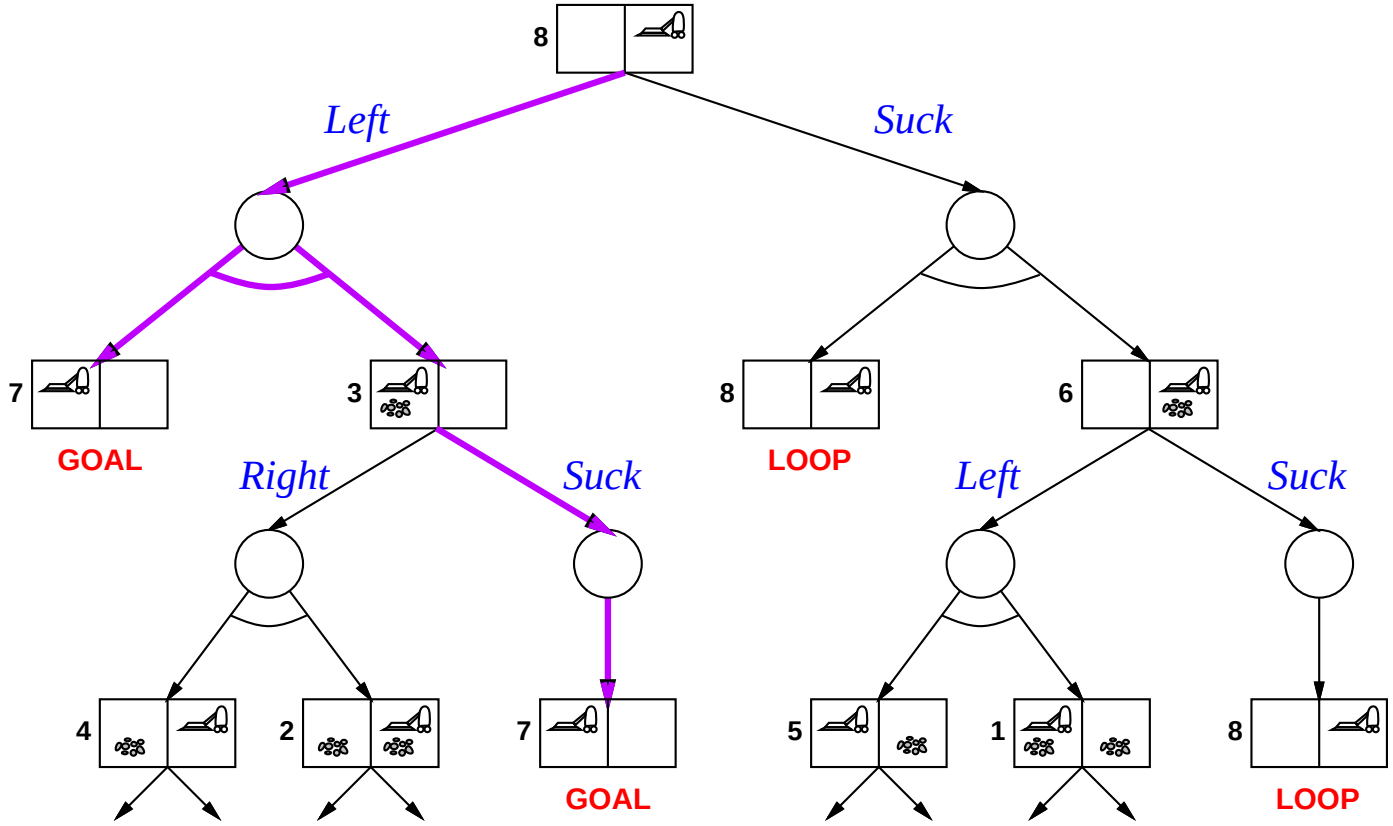
Plan must handle every outcome for the action it takes (i.e., And nodes)

Solution is a subtree with (1) goal node at every leaf, (2) one action specified at each state node, and (3) includes every outcome at chance nodes.

Exemple: Double Murphy

sucking or arriving may dirty a clean square

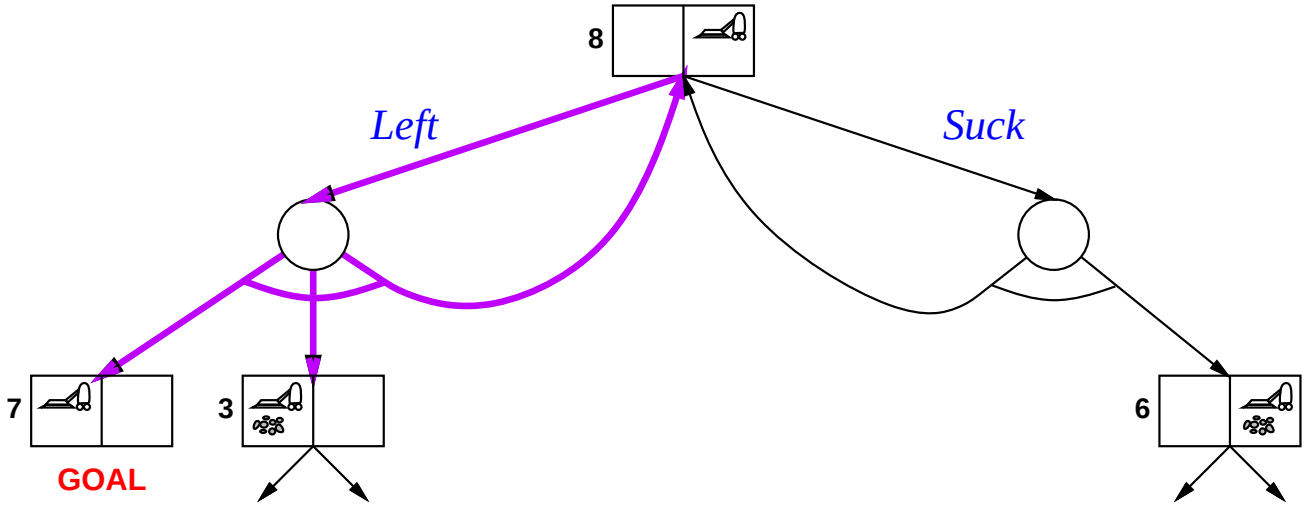
Solution is a subtree with (1) goal node at every leaf, (2) one action specified at each state node, and (3) includes every outcome at chance nodes.



Plan: [Left, **if** CleanL **then** [] **else** Suck]

Example

Triple Murphy: also sometimes stays put instead of moving



$[L_1 : \ Left, \textbf{if } AtR \textbf{ then } L_1 \textbf{ else } [\textbf{if } CleanL \textbf{ then } [\,] \textbf{ else } Suck]]$

or $[\textbf{while } AtR \textbf{ do } [Left], \textbf{if } CleanL \textbf{ then } [\,] \textbf{ else } Suck]$

"Infinite loop" but will eventually work unless action always fails

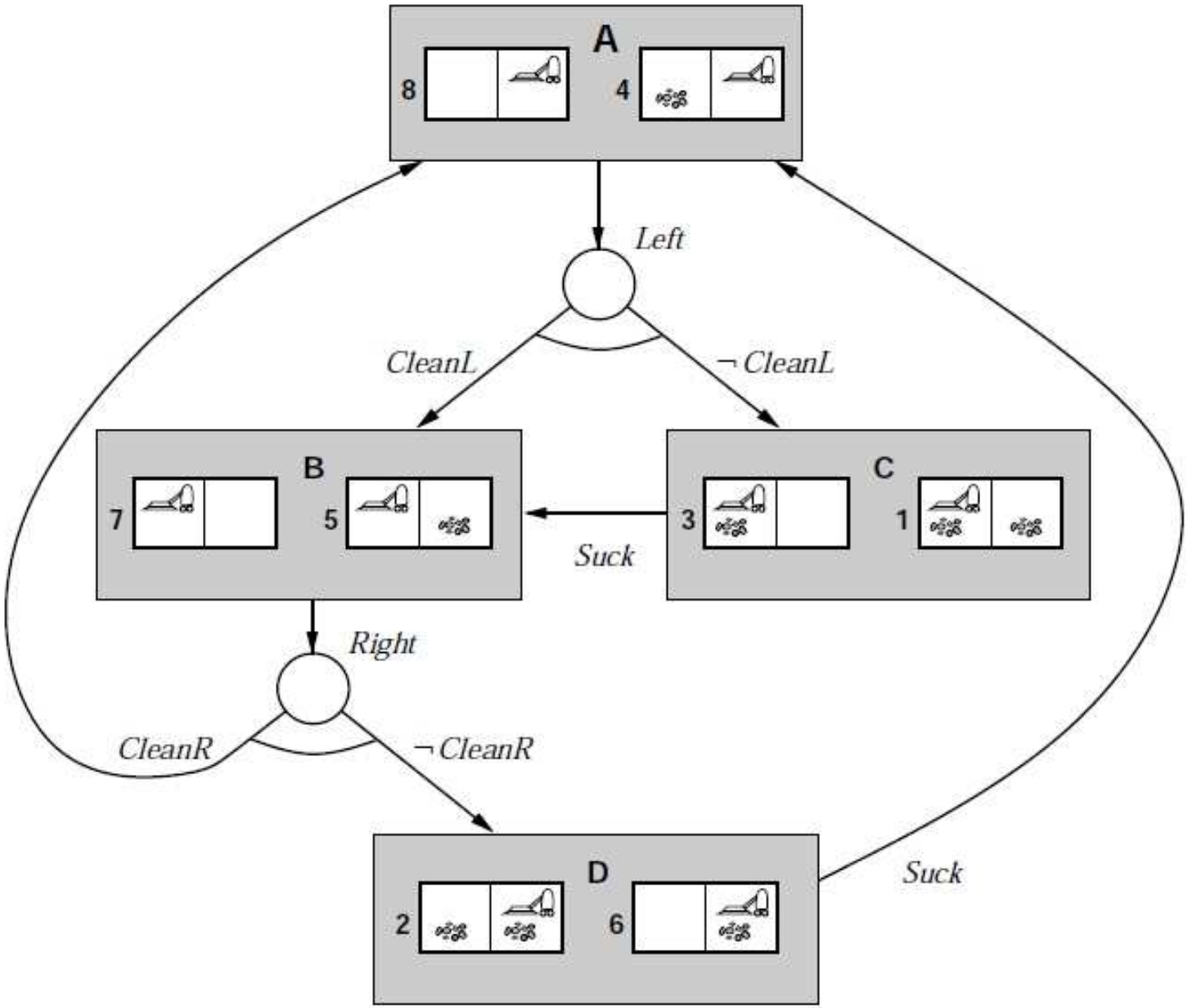
Nondeterminism and partially observable env.

Alternate double Murphy:

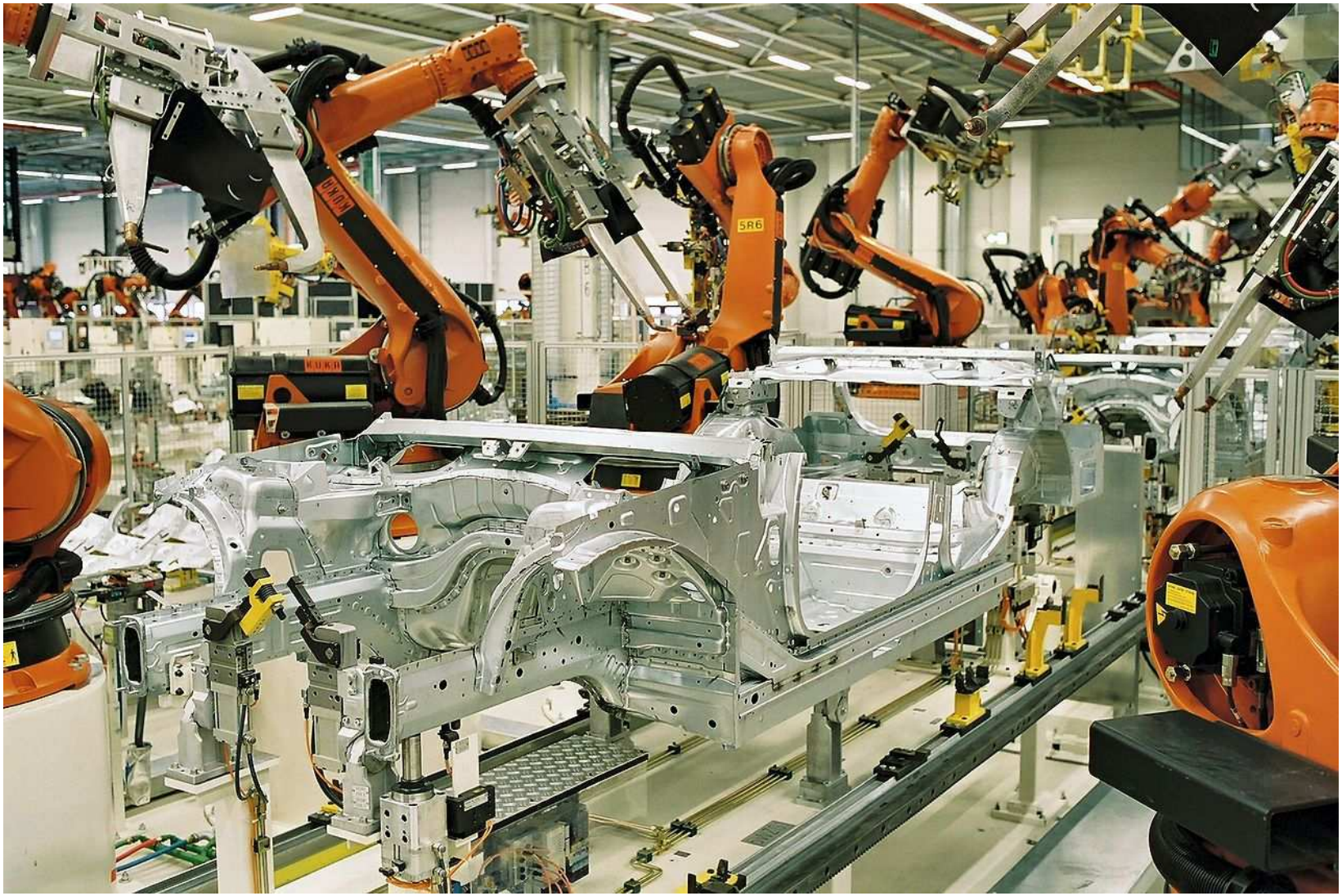
Vacuum cleaner can sense cleanliness of square its in, but not the other square, and

dirt can sometimes be left behind when leaving a clean square.

Plan in fully observable world: Keep moving left and right, sucking up dirt whenever it appears, until both squares are clean and in the left square. But now goal test cannot be performed!


A
8
4
Left
CleanL
¬ CleanL
B
7
5
C
3
1
Suck
Right
CleanR
¬ CleanR
D
2
6
Suck

Execution monitoring and replanning



Execution monitoring and replanning

Execution monitoring: checking whether things are going according to plan (necessitated by unbounded indeterminacy in realistic environments or agent gets tired of planning for every little contingency)

Some branches of a partially constructed contingent plan can simply say Replan

Action monitoring: checking whether next action is feasible

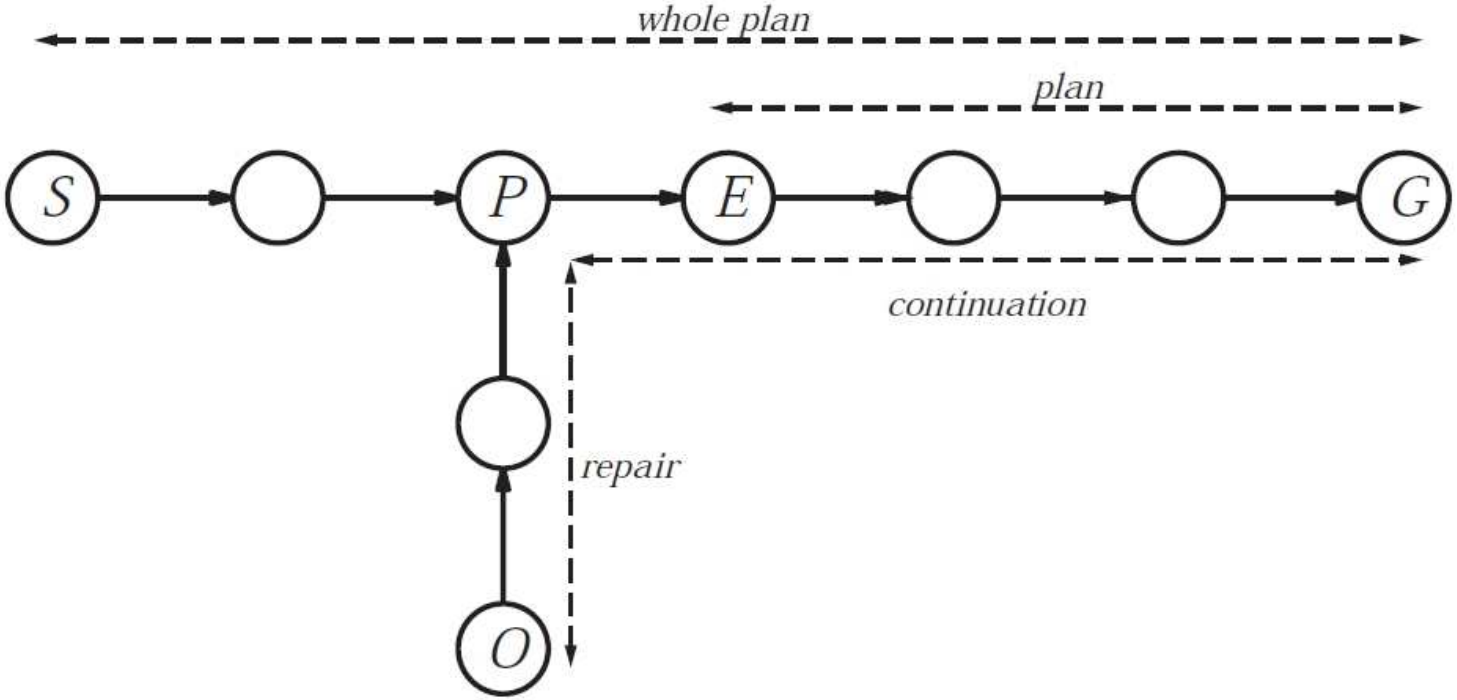
Plan monitoring: checking whether remainder of plan is feasible

Replanning: ability to find new plan when things go wrong (usually repairing the old plan). Replanning may also be needed if the agents model of the world is incorrect

- missing precondition: removing the lid of a paint requires a screwdriver
- missing efect: painting an object may get paint on the floor
- missing state variable: no notion of the amount of paint in a can

- exogenous events: someone knocking over the paint can

While attempting to get from S to G, a problem is encountered in E, agent discovers actual state is O and plans to get to P and execute the rest of the original plan



Replanning Example

[LookAt (Table), LookAt (Chair),
  if Color(Table, c) $\wedge$ Color(Chair, c) **then** NoOp
    else [RemoveLid(Can1), LookAt (Can1),
      if Color (Table, c) $\wedge$ Color(Can1, c) **then** Paint(Chair, Can1)
      else REPLAN]]

Suppose the agent observes that the table and can of paint are white and the chair is black.

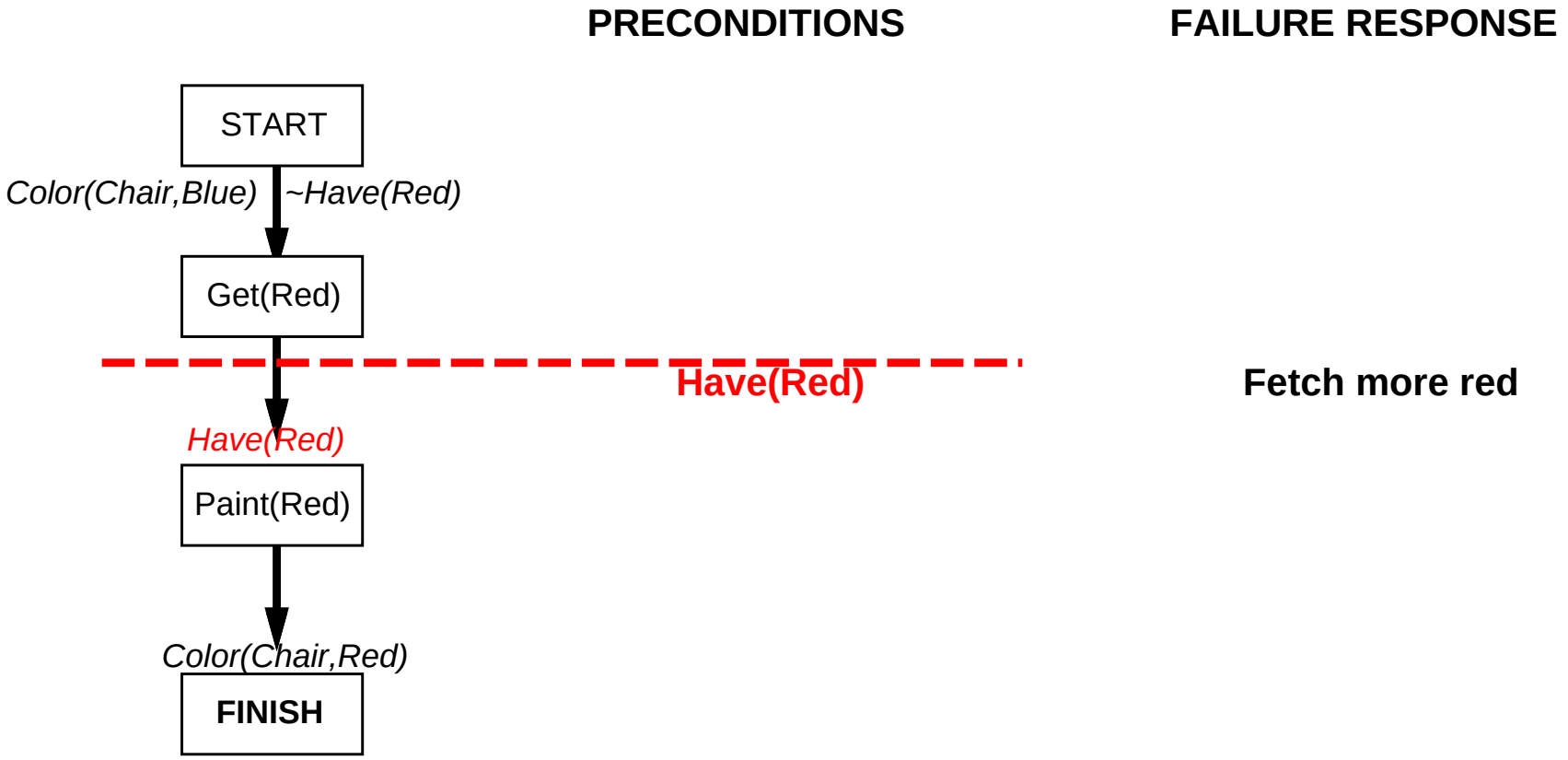
The current state is identical to the precondition before the $Paint(Chair, Can1)$

Repair: []; Plan: $[Paint]$

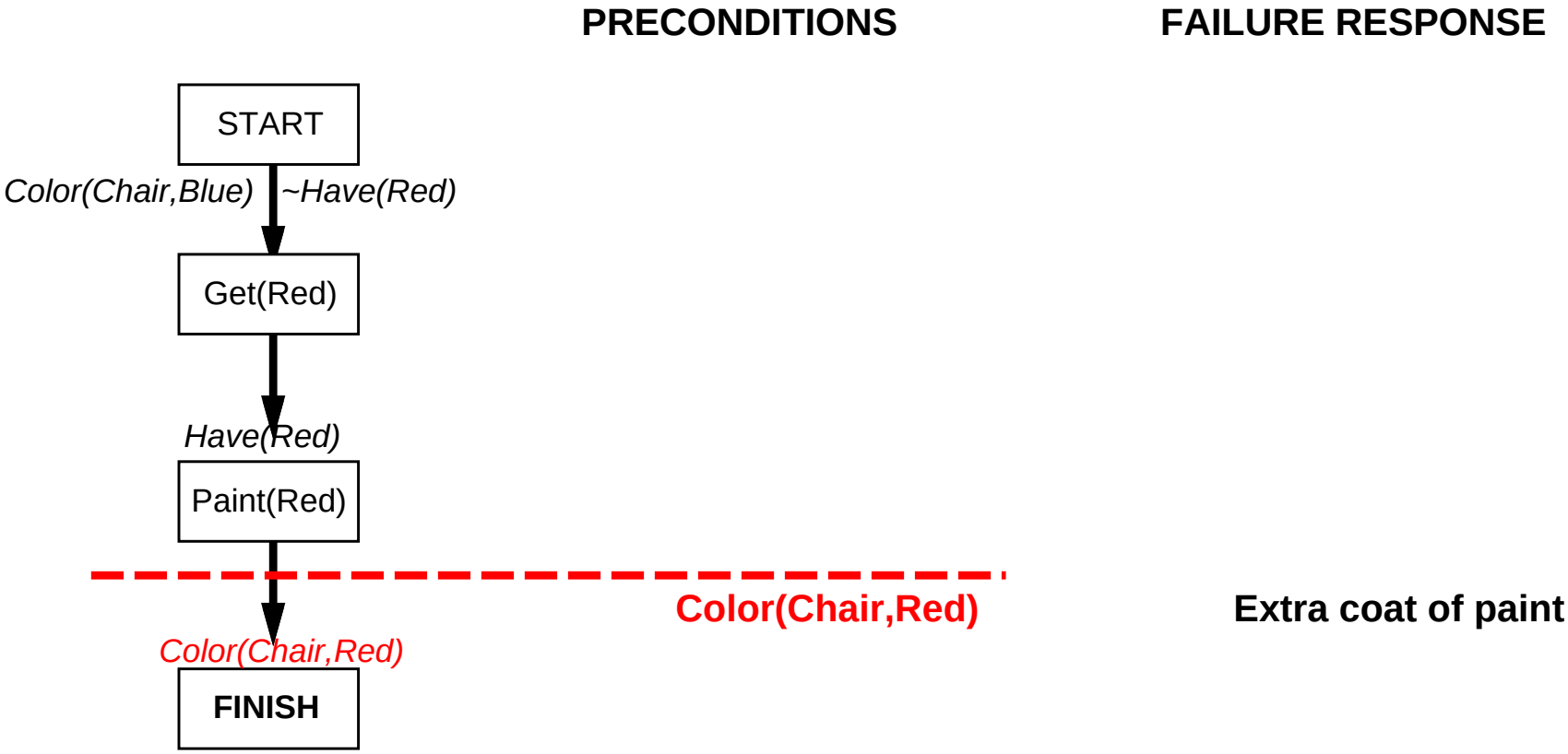
Loop created by a process of plan-execute-replan, not by an explicit loop in a plan

Action monitoring leads to less intelligent behavior than plan monitoring:
- red paint enough only for the chair

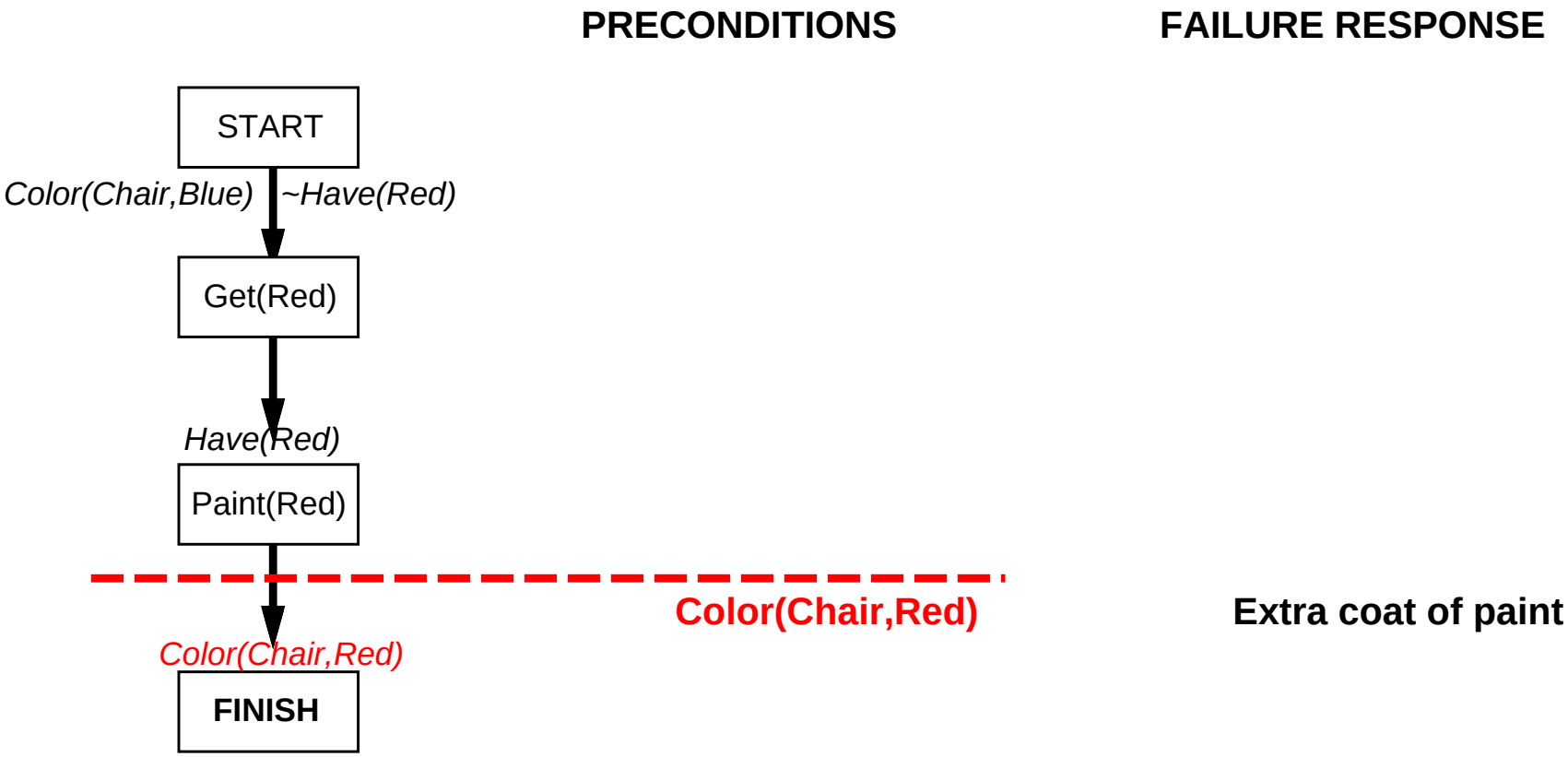
Emergent behavior



Emergent behavior



Emergent behavior



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

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Multiagent planning

Between the purely single-agent and truly multiagent cases is a wide spectrum of problems that exhibit various degrees of decomposition of the monolithic agent

Multieffector planning: to manage each effector while handling positive and negative interactions among the effectors

Multibody planning: effectors are physically decoupled into detached units - as in a fleet of delivery robots in a factory

Decentralized planning: multiple reconnaissance robots covering a wide area may often be out of radio contact with each other and should share their findings during times when communication is feasible.

Coordination: multagents with the same goal (e.g. tenis)

Planning with multiple simultaneous actions

The double tennis problem

Actors(A,B)
Init (At(A,LeftBaseline) $\wedge$ At(B,RightNet) $\wedge$
    Approaching(Ball, RightBaseline)) $\wedge$ Partner (A,B) $\wedge$ Partner (B,A)
Goal (Returned(Ball) $\wedge$ (At(a, RightNet) $\vee$ At(a, LeftNet))
Action(Hit (actor, Ball),
    PRECOND: Approaching(Ball, loc) $\wedge$ At(actor, loc)
    EFFECT: Returned(Ball))
Action(Go(actor, to),
    PRECOND: At(actor, loc) $\wedge$ to $\neq$ loc,
    EFFECT: At(actor, to) $\wedge$ $\neg$ At(actor, loc))

Assume perfect synchronization: each action takes the same amount of time and actions at each point in the joint plan are simultaneous

Joint action $\langle a_1, ..., a_n \rangle$, where a_i is the action taken by the ith actor.

Loosely coupled: focus on $decoupling$ the actors to the extent possible, so that the complexity of the problem grows linearly with n rather than exponentially.

Joint plan:

PLAN 1:

$$A : [Go(A, RightBaseline), Hit(A, Ball)]$$
$$B : [NoOp(B), NoOp(B)]$$

Problems arise, however, when a plan has both agents hitting the ball at the same time.

The difficulty is that preconditions constrain the state in which an action can be executed successfully, but do not constrain other actions that might mess it up.

Concurent action list

$Action(Hit(a, Ball)$,
CONCURRENT:$b \neq a \Rightarrow \neg Hit(b, Ball)$
PRECOND: $Approaching(Ball, loc) \wedge At(a, loc)$
EFFECT: $Returned(Ball))$

For some actions, the desired effect is achieved only when another action occurs concurrently:

$Action(Carry(a, cooler, here, there)$,
CONCURRENT: $b \neq a \wedge Carry(b, cooler, here, there)$
PRECOND: $At(a, here) \wedge At(cooler, here) \wedge Cooler(cooler)$
EFFECT: $At(a, there) \wedge At(cooler, there) \wedge \neg At(a, here) \wedge \neg At(cooler, here))$

Cooperation and coordination

PLAN 1: $A : [Go(A, RightBaseline), Hit(A, Ball)]$
$B : [NoOp(B), NoOp(B)]$

PLAN 2: $A : [Go(A, LeftNet), NoOp(A)]$
$B : [Go(B, RightBaseline), Hit(B, Ball)]$

Convention: any constraint on the selection of joint plans (e.g., "stick to your side of the court").

Social laws: widespread conventions

Communication: "Mine!"

Plan recognition: If agent A heads for the net, then agent B is obliged to go back to the baseline to hit the ball, because PLAN 2 is the only joint plan that begins with As heading for the net

Summary

♢ Many actions consume resources. It is convenient to treat these resources as numeric measures in a pool rather than try to reason about each individual resource it is usually cheap and effective to check partial plans for satisfaction of resource constraints before attempting further refinements

♢ Time is one of the most important resources. It can be handled by specialized scheduling algorithms

♢ An online planning agent uses execution monitoring and splices in repairs as needed to recover from unexpected situations, which can be due to nondeterministic actions, exogenous events, or incorrect models of the environment.

♢ Incomplete info: use conditional plans, conformant planning (can use belief states)

♢ Incorrect info: use execution monitoring and replanning