Introduction to Artificial Intelligence

Planning

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Wintersemester 2003/2004

Outline

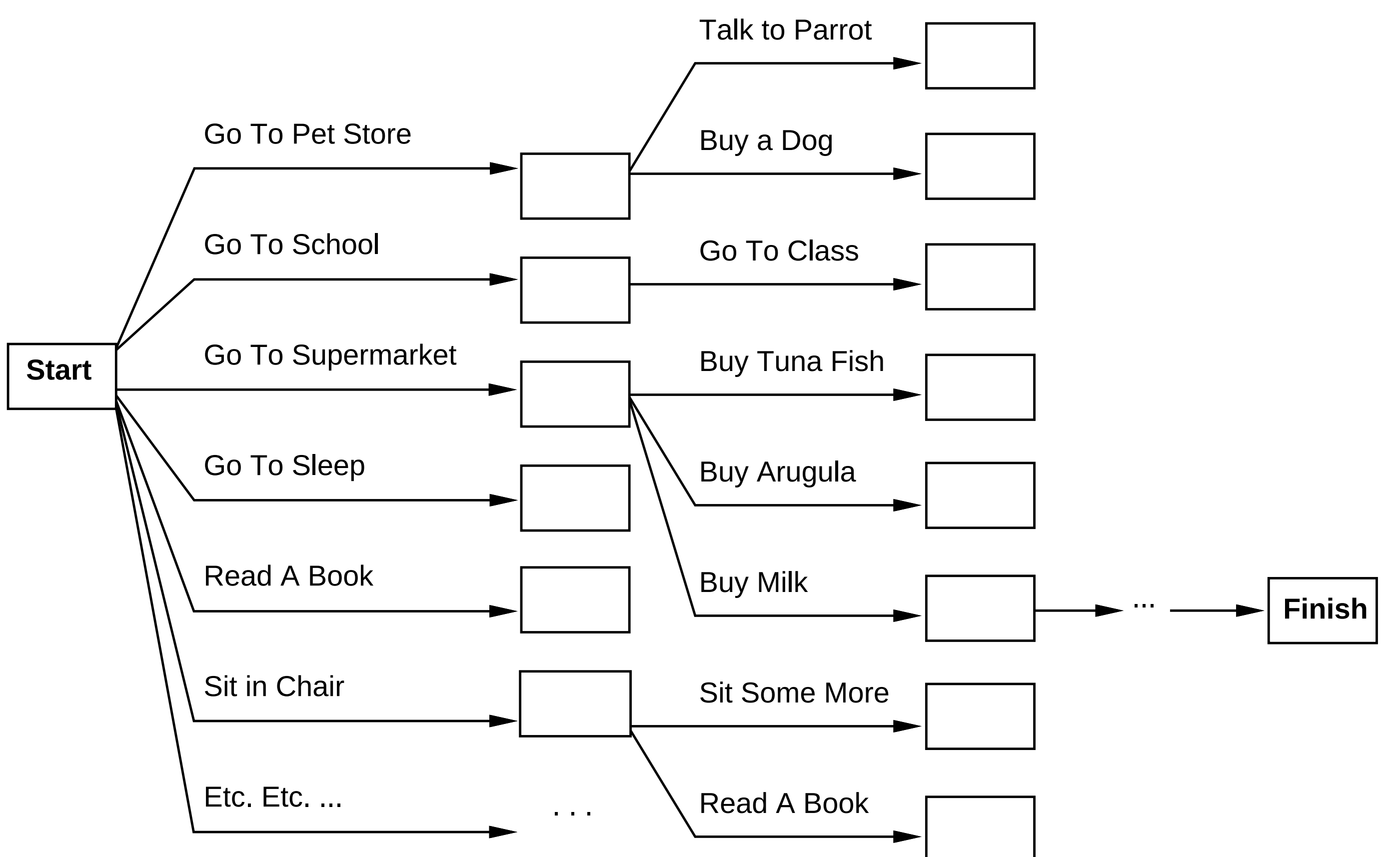
- Search vs. planning
- STRIPS operators
- Partial-order planning
- The real world
- Conditional planning
- Monitoring and replanning

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**

  $\Rightarrow$ **stronger interaction between actions and states needed**

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- Most parts of the world are independent of most other parts

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- Human beings plan goal-directed;
  they construct important intermediate solutions first

  $\Rightarrow$ **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

STandford 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

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Closed world assumption

Atoms that are not present are assumed to be false

Example

State: $At(Home),\ Have(Bread)$

Implicitly: $\neg Have(Milk), \neg Have(Bananas), \neg Have(Drill)$

STRIPS: Operators

Operator description consists of:

Action name	**Positive literal**	$Buy(Milk)$
Precondition	**Conjunction of positive literals**	$At(Shop) \wedge Sells(Shop, Milk)$
Effect	**Conjunction of literals**	$Have(Milk)$

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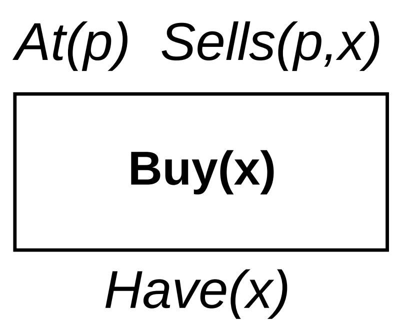
Operator schema

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

$$Subst(precond(o)) \subseteq s$$

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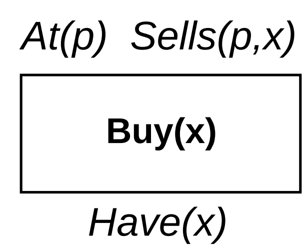
Example

$Buy(x)$ **is applicable in state**

$$At(Shop) \wedge Sells(Shop, Milk) \wedge Have(Bread)$$

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

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Formally

$$\begin{aligned} s' = {} & (s \cup \{P \mid P \textbf{ a positive atom}, P \in \mathit{Subst}(\mathit{effect}(o))\}) \\ & \setminus \{P \mid P \textbf{ a positive atom}, \neg P \in \mathit{Subst}(\mathit{effect}(o))\} \end{aligned}$$

STRIPS: Operator Application

Example

Application of

$Drive(a,b)$

precond: $At(a), Road(a,b)$

effect: $At(b), \neg At(a)$

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to state

$At(Koblenz),\ Road(Koblenz, Landau)$

STRIPS: Operator Application

Example

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$Drive(a, b)$

precond: $At(a), Road(a, b)$

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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

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Nodes in search space

Standard search: **node = concrete world state**

Planning search: **node = partial plan**

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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** $S_i \xrightarrow{c} S_j$

  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

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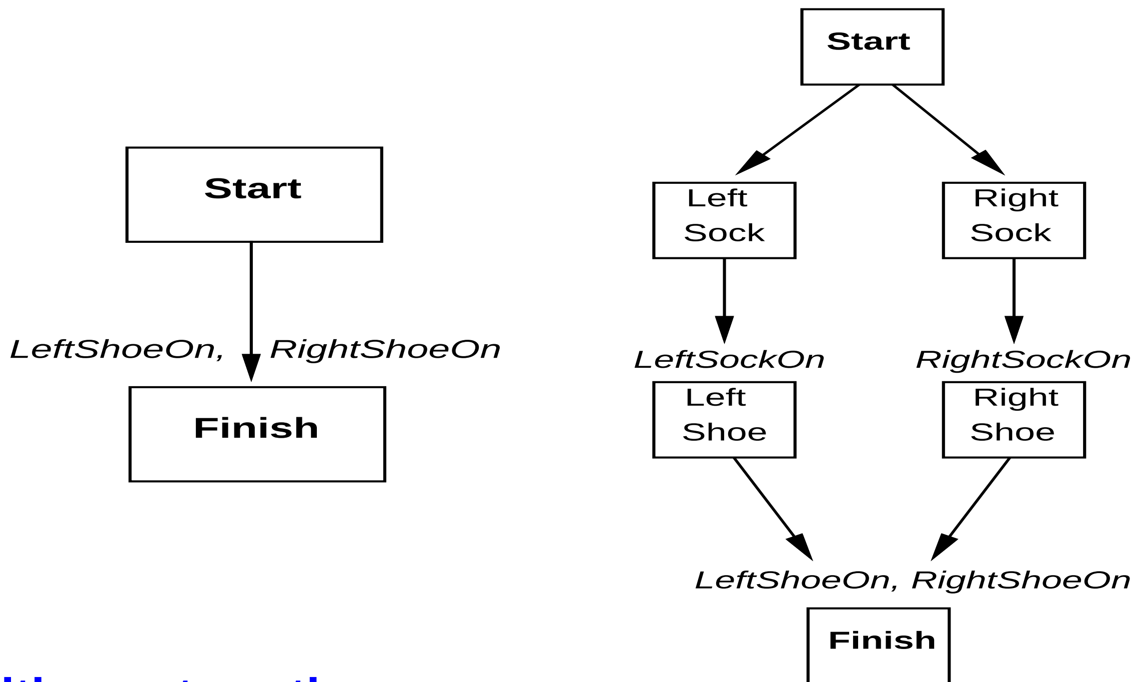
Note

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

Partially Ordered Plans

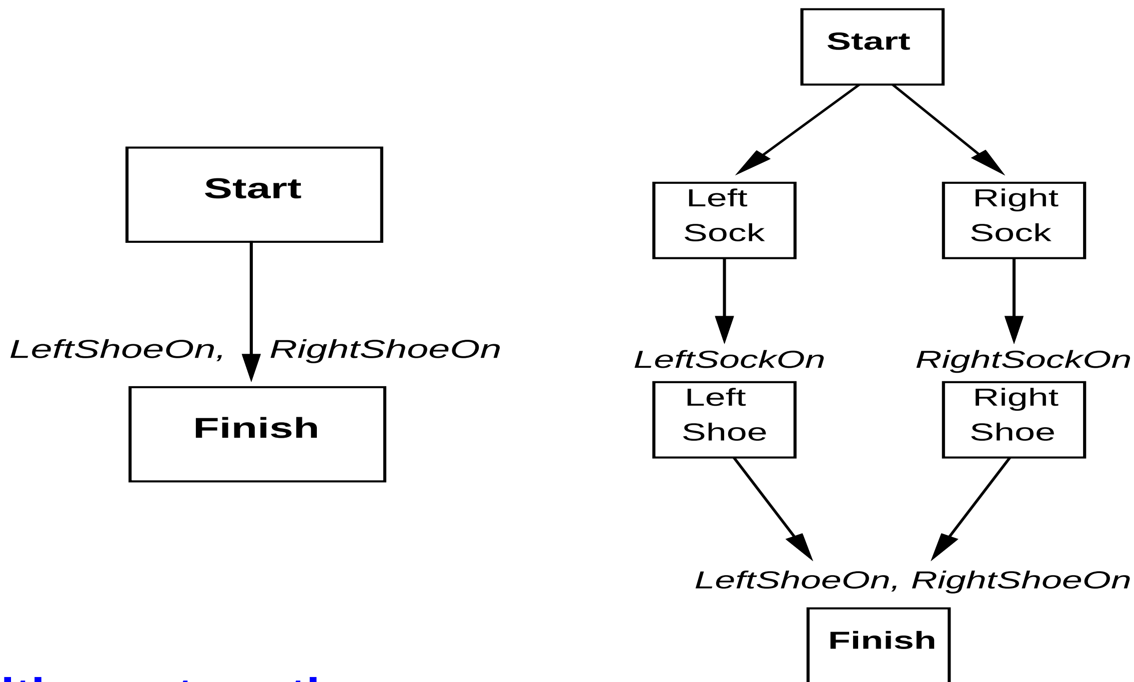


Special steps with empty action

Start **no precond, initial assumptions as effect)**

Finish **goal as precond, no effect**

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

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A precondition c **of a step** S_j **is achieved (by** S_i**) if**

- $S_i \prec S_j$
- $c \in \mathit{effect}(S_i)$
- **there is no** S_k **with** $S_i \prec S_k \prec S_j$ **and** $\neg c \in \mathit{effect}(S_k)$
  (otherwise S_k **is called a clobberer or threat)**

Partially Ordered Plans

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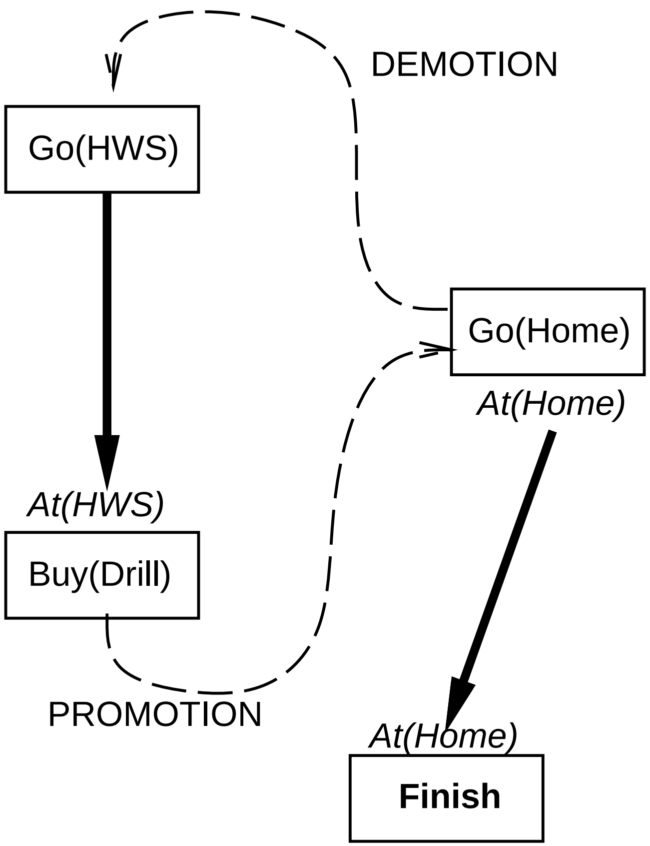
Clobberer / threat

A potentially intervening step that destroys the condition achieved by a causal link

Clobbering and Promotion/Demotion

Example

$Go(Home)$ **clobbers** $At(HWS)$



Demotion

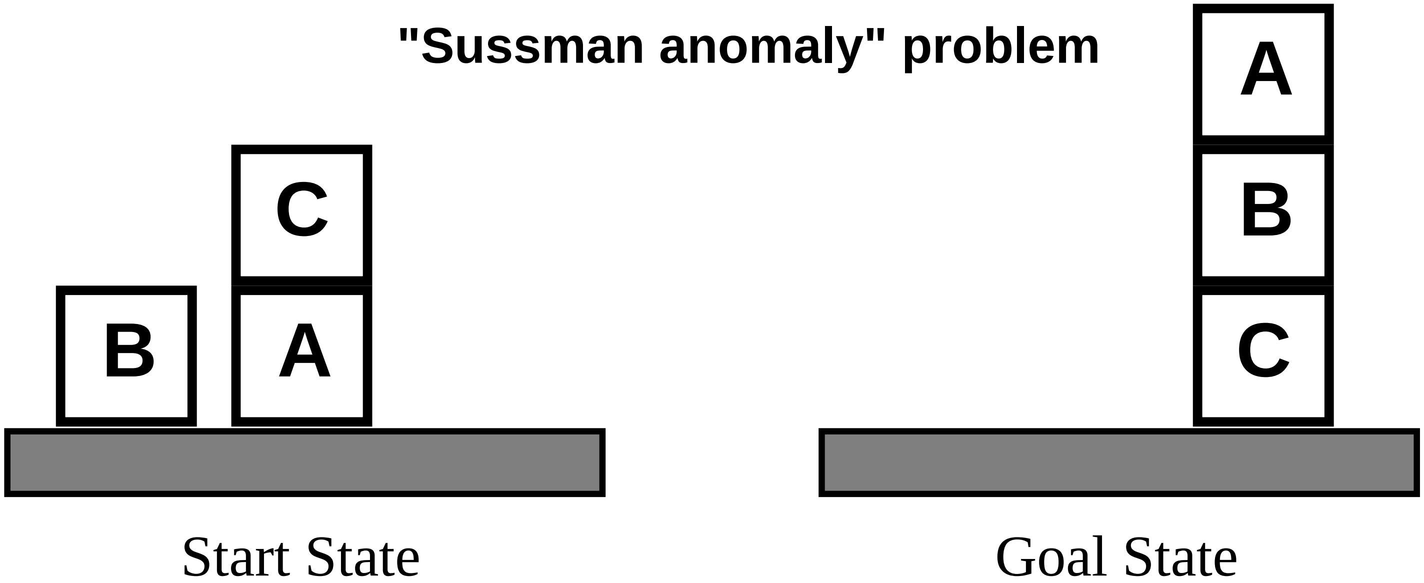
Put before $Go(HWS)$

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)

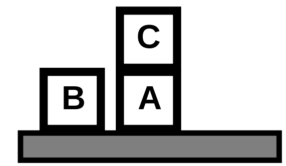
~On(x,z) Clear(z) On(x,Table)

+ several inequality constraints

Example: Blocks World

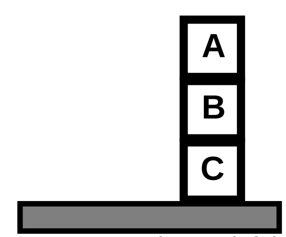
START

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



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

FINISH



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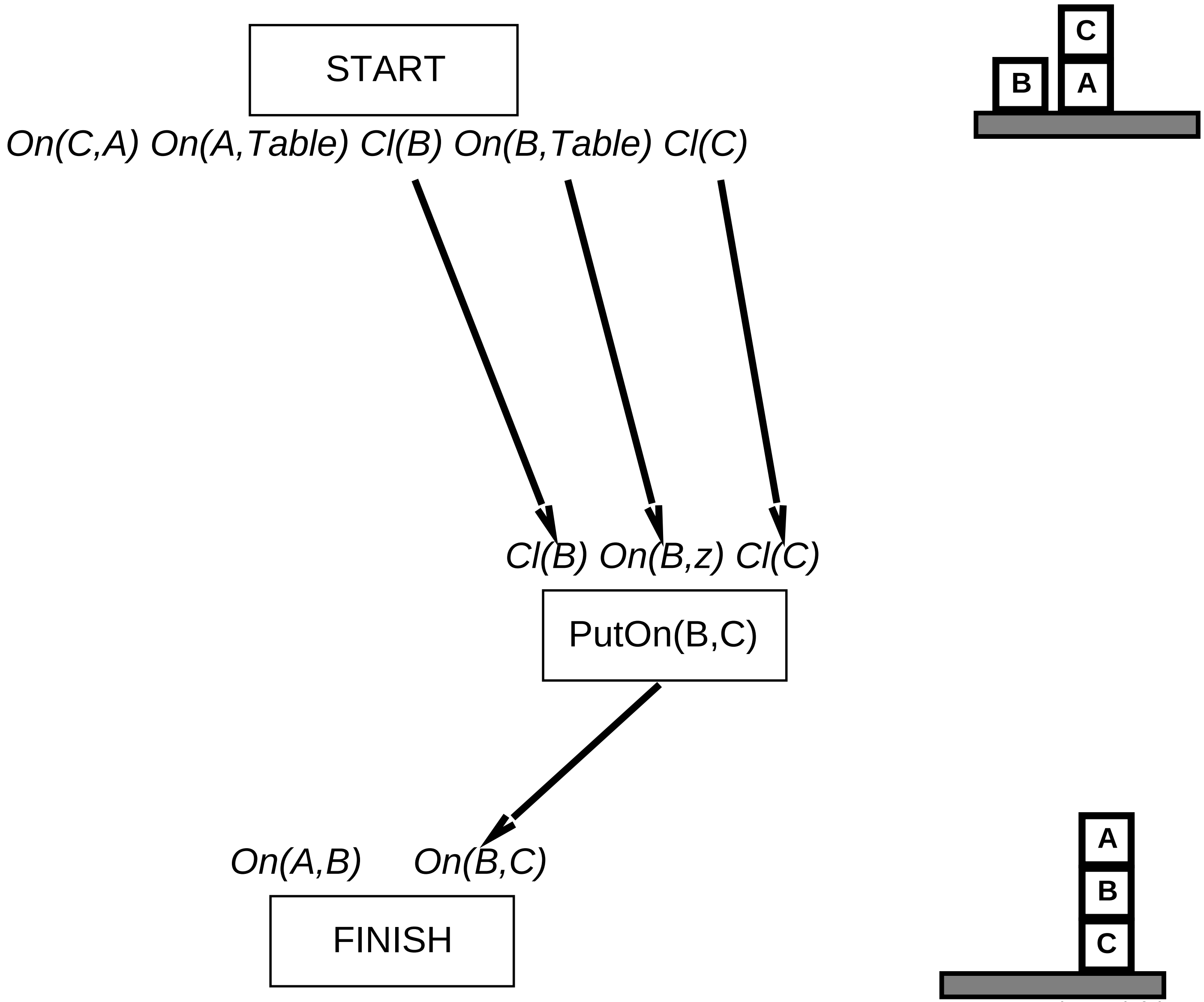

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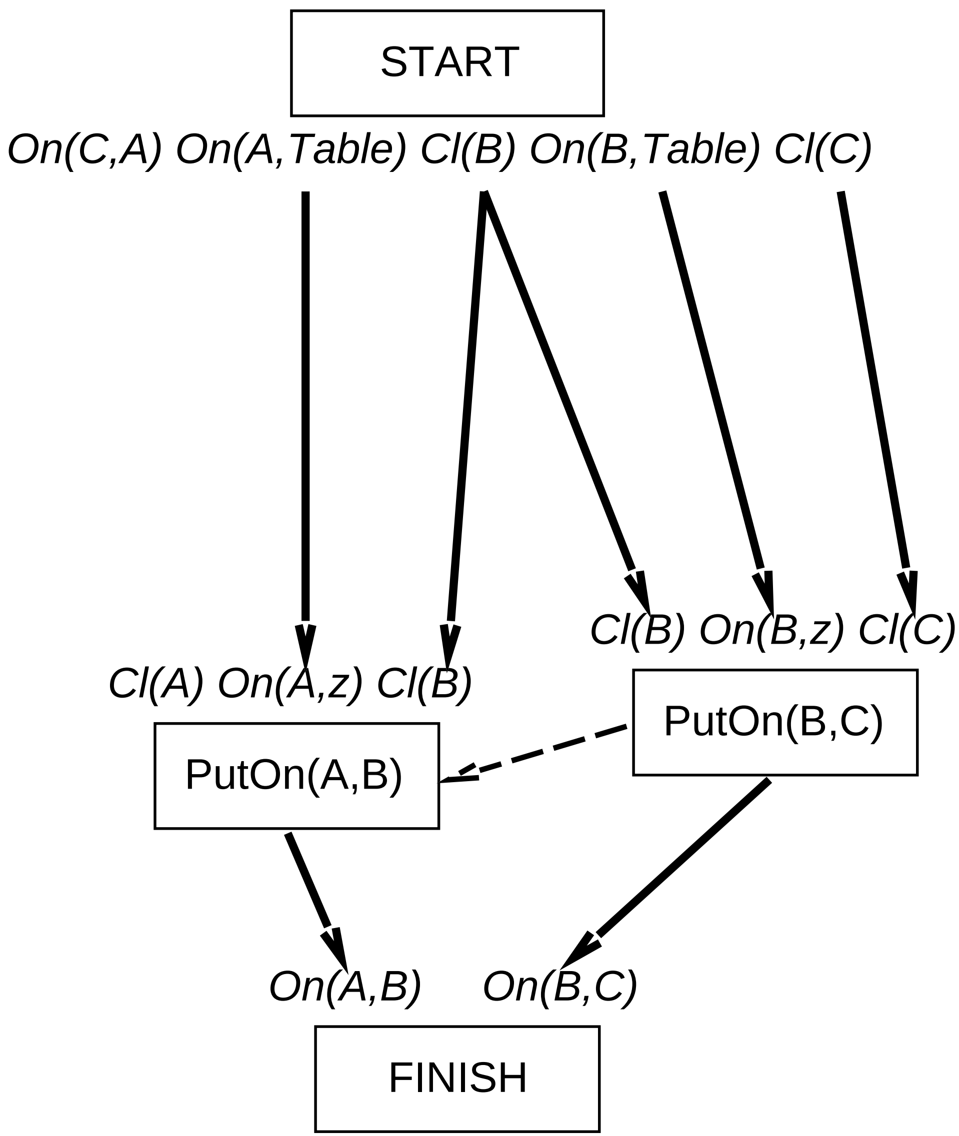
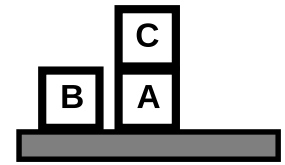
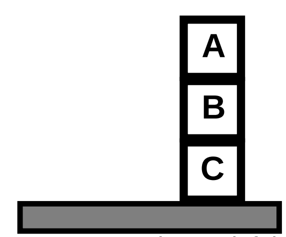




PutOn(A,B) clobbers Cl(B) => order after PutOn(B,C)



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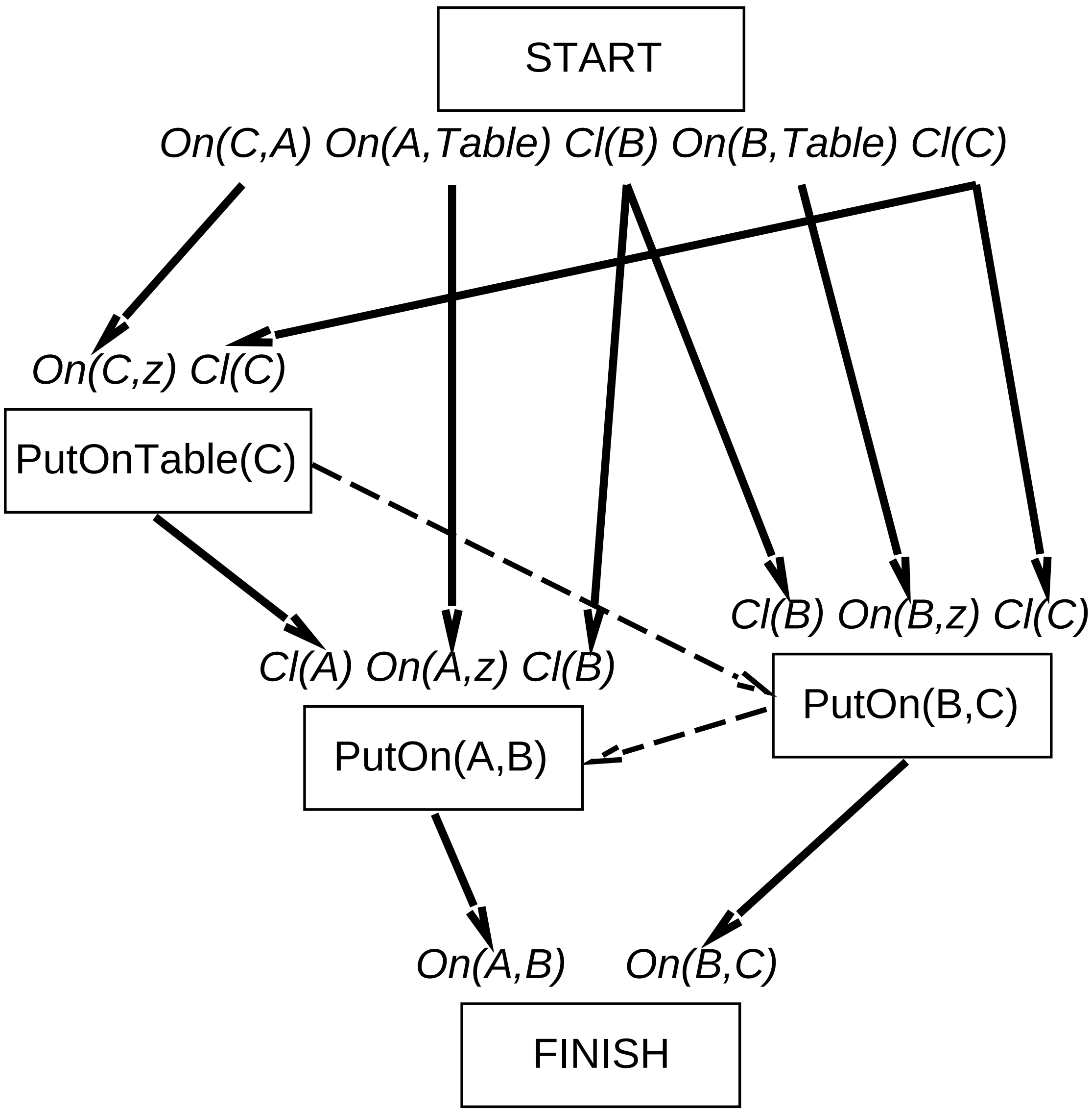
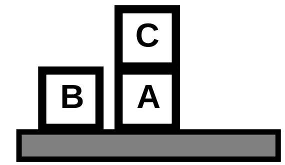
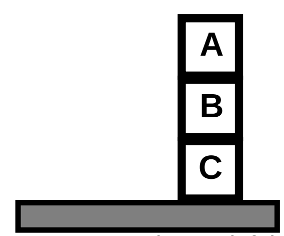




PutOn(A,B) clobbers Cl(B) => order after PutOn(B,C)

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**

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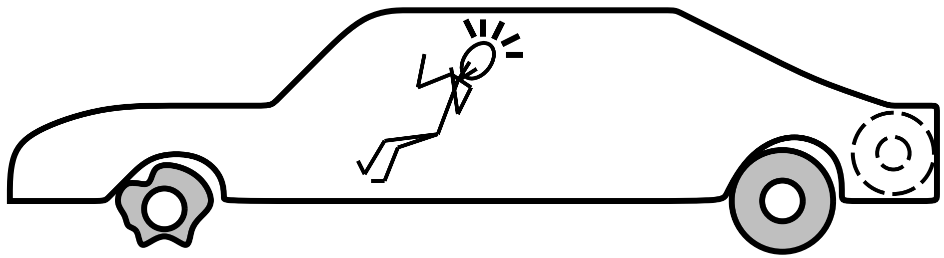
  But: very sensitive to subgoal ordering
- Good for problems with loosely related subgoals

The Real World



On(x) ~Flat(x)

FINISH

START

~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** **Example:** $\mathit{Intact}(\mathit{Spare})$**?**
- **Disjunctive effects**

  Example: $\mathit{Inflate}(x)$ **causes**

  $\mathit{Inflated}(x) \vee \mathit{SlowHiss}(x) \vee \mathit{Burst}(x) \vee \mathit{BrokenPump} \vee \ldots$

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Incorrect information

- **Current state incorrect** **Example:** **spare NOT intact**
- **Missing/incorrect postconditions in operators**

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Incorrect information

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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: $[\mathit{Check}(\mathit{Tire1}), \mathbf{If}(\mathit{Intact}(\mathit{Tire1}), [\mathit{Inflate}(\mathit{Tire1})], [\mathit{CallHelp}])]$

  Disadvantage: **Expensive because it plans for many unlikely cases**

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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

$$[\ldots, \mathbf{If}(\mathit{p}, [\mathit{thenPlan}], [\mathit{elsePlan}]), \ldots]$$

Check *p* **against current knowledge base, execute** *thenPlan* **or** *elsePlan*

Conditional Planning

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Conditional planning

Just like POP **except:**

If an open condition can be established by observation action

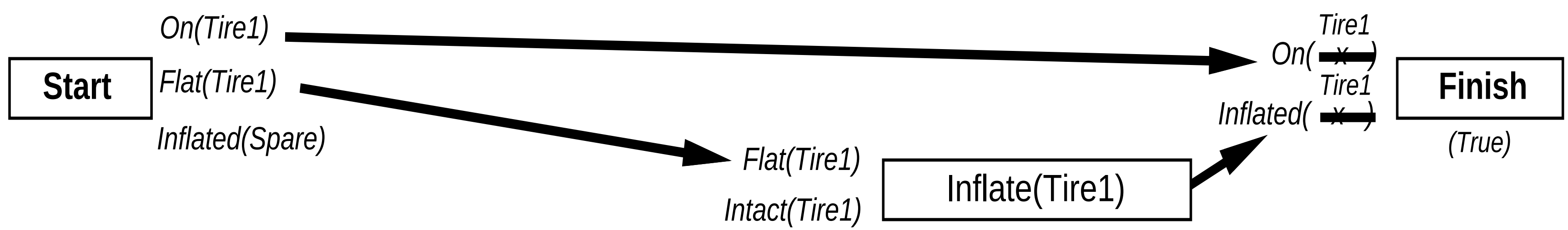
- **add the action to the plan**
- **complete plan for each possible observation outcome**
- **insert conditional step with these subplans**

CheckTire(x)

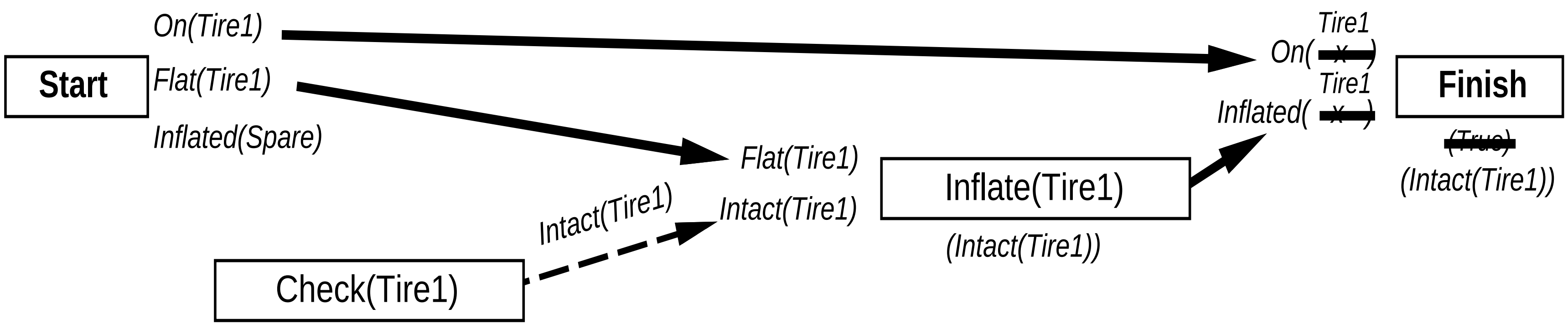
KnowsIf(Intact(x))

Conditional Planning Example

Conditional Planning Example



Conditional Planning Example



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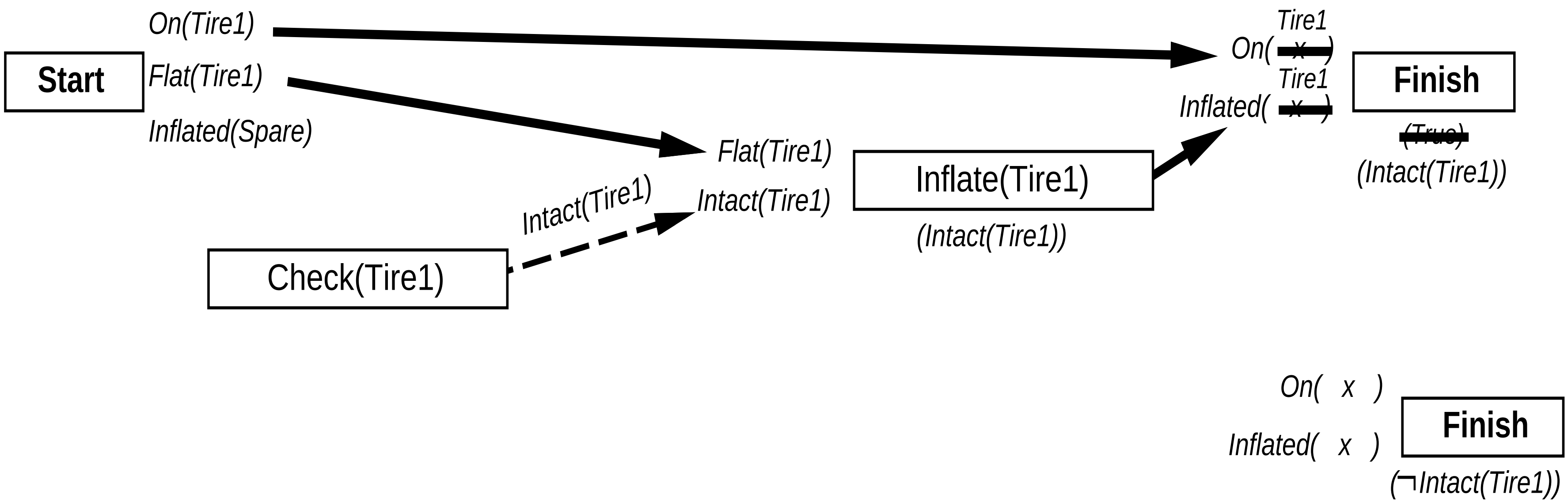

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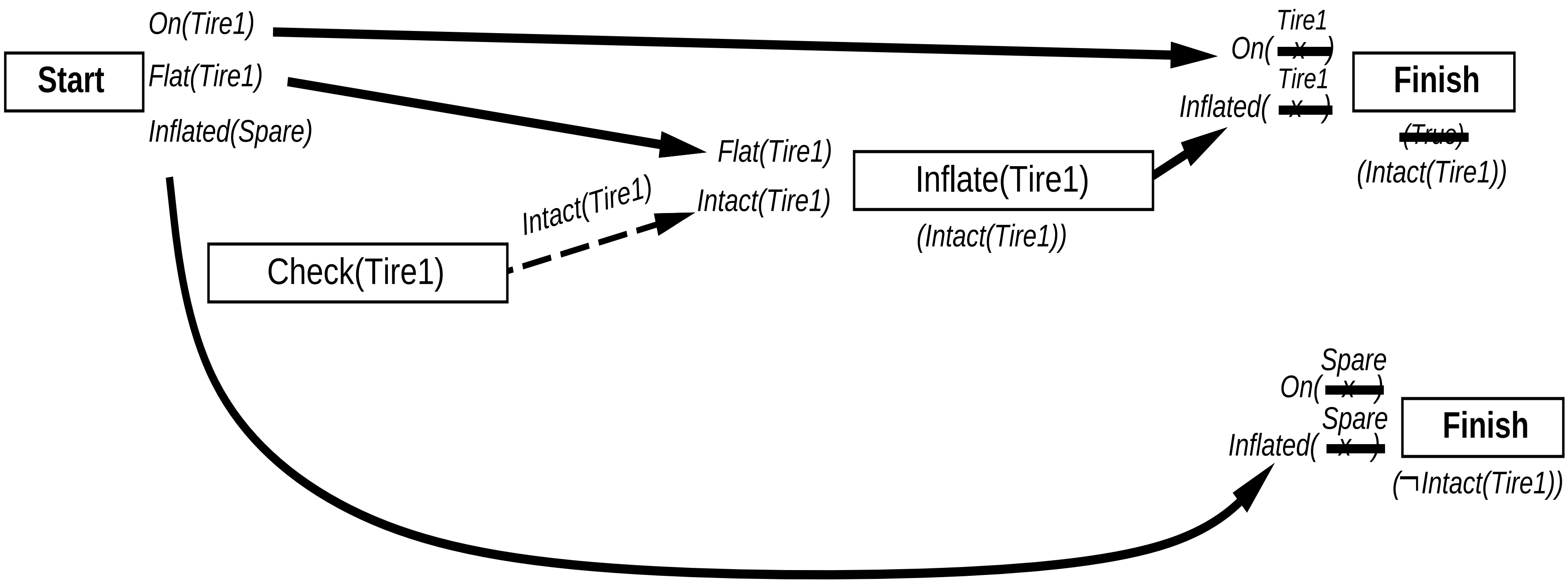

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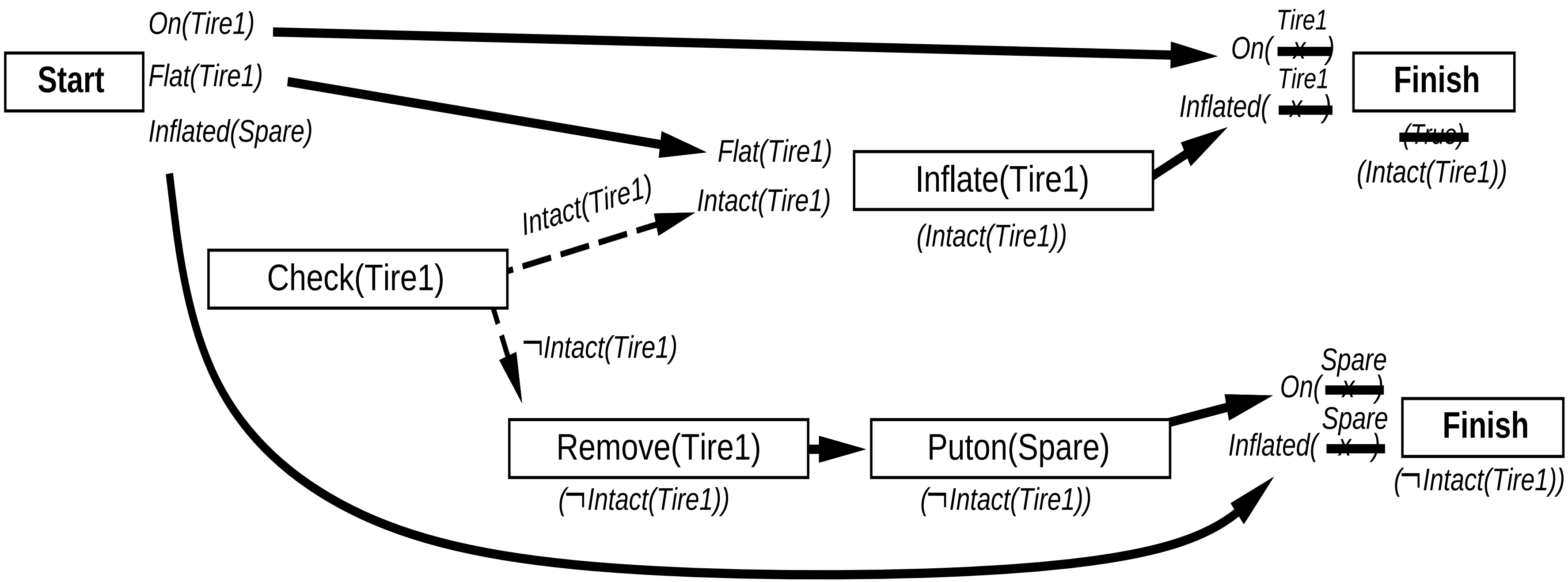

Monitoring

Execution monitoring

Failure: **Preconditions of remaining plan not met**

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Action monitoring

Failure: Preconditions of next action not met

(or action itself fails, e.g., robot bump sensor)

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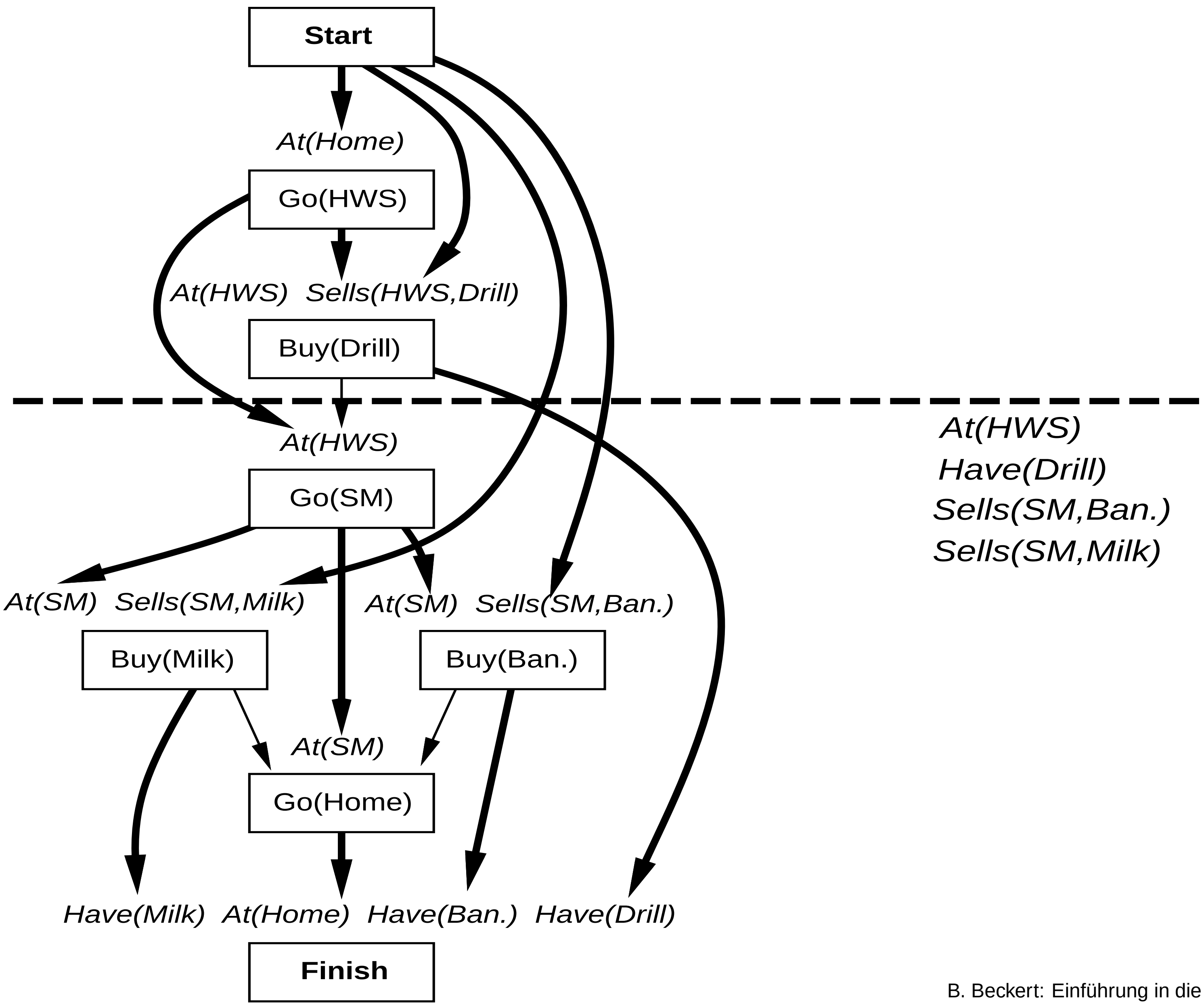
Consequence of failure

Need to replan

Preconditions for Remaining Plan



Replanning

Simplest

On failure, replan from scratch

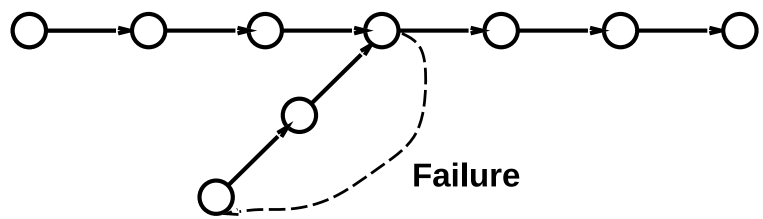
Replanning

Simplest

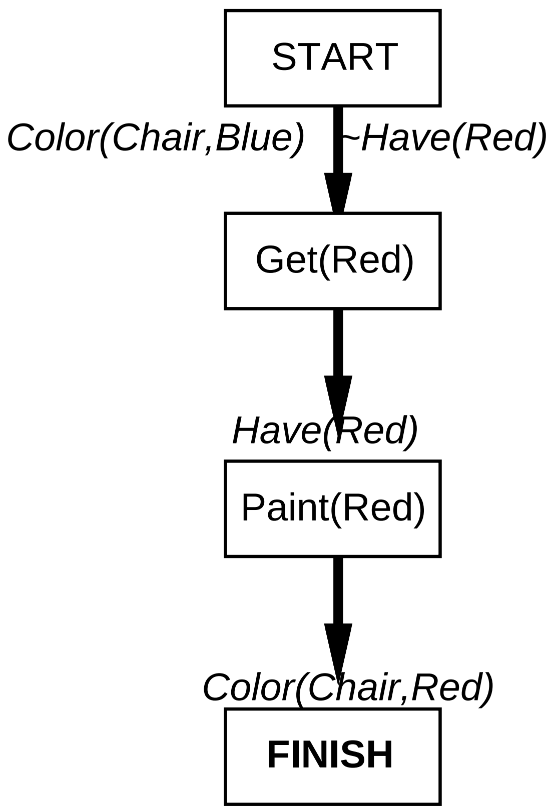
On failure, replan from scratch

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**