AUTOMATED PLANNING

Automated Planning is an important problem solving activity which consists in synthesizing a ***sequence of actions*** performed by an agent that leads from an initial state of the world to a given target state (**goal**)

AUTOMATED PLANNING

Given:

- an initial state
- a set of actions you can perform
- a state to achieve (**goal**)

Find:

a plan: a partially or totally ordered set of actions needed to achieve the goal from the initial state

Planning is:

- one application per se
- A common activity in many applications such as
  - diagnosis: test plans and actions to repair (reconfigure) a system
  - scheduling
  - robotics

AUTOMATED PLANNING: basics

An **automated planner** is an *intelligent agent* that operates in a certain domain described by:

1. ***a representation of the initial state***
2. ***a representation of a goal***
3. ***a formal description of the executable actions (also called operators)***

It dynamically defines the plan of actions needed to reach the goal from the initial state.

ACTION REPRESENTATION

- A planner relies on a formal description of the executable actions. It is called ***Domain Theory***.

- Each action is identified by a name and declaratively modeled through ***preconditions*** is ***postconditions***.

- Preconditions are the conditions which must hold to ensure that the action can be executed;
- Postconditions represent the effects of the action on the world.

- Often the Domain Theory consists of operators containing variables that define **classes of actions**. A different instantiation of the variables corresponds to a different action.

EXAMPLE: THE BLOCK WORLD

Actions:

STACK (X, Y)

IF: holding (X) and clear (Y)

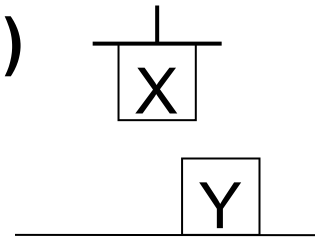
THEN: handempty and clear (X) and on (X, Y);

UNSTACK (X, Y)

IF: handempty and clear (X) and on (X, Y)

THEN: holding (X) and clear (Y);

(1)



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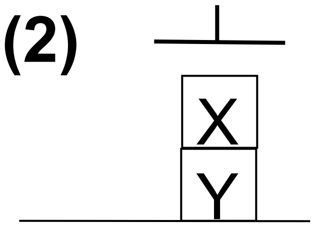

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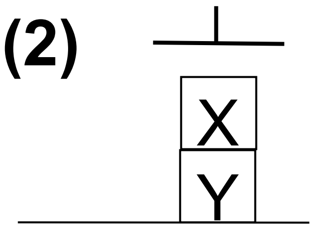

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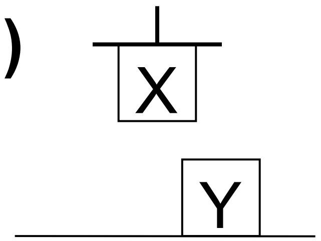


EXAMPLE: THE BLOCK WORLD

PICKUP (X)

IF: ontable (X) and clear (X) and handempty

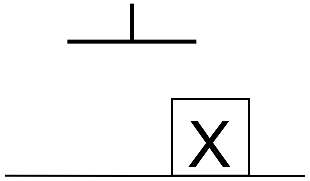
THEN: holding (X);

Putdown (X)

IF: holding (X)

THEN: ontable (X) and clear (X) and handempty.

(1')



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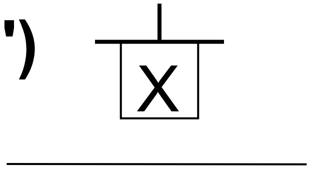

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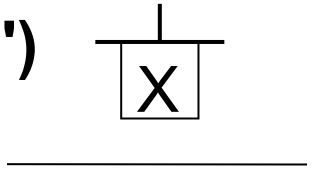

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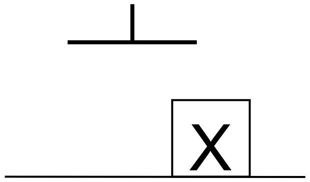


PLANNING

Solving process for deciding the steps (actions) that solve a planning problem:

- *non decomposable*

  There can be interaction between subgoals

- *reversible*

  the choices made during the plan generation are backtrackable.

A planner is **complete** if it always finds a plan when it exists.

A planner is **correct** when the solution found leads from the initial state to the goal.

EXECUTION

The execution is the implementation of the plan

- *irreversible*

  often the execution of an action is not backtrackable

- *non deterministic*

  the plan can have effects that are different from what we expect. Working in the real world pertains uncertainty. In some cases the plan may fail. Then we can in principle find a recovery plan from scratch or partially.

PLANNING TECHNIQUES

- Deductive planning
- Planning as search
- Linear planning
- Nonlinear planning - Partial Order Planning (POP)
- Hierarchical planning
- Conditional planning
- Graph-based planning

GENERATIVE PLANNING

It is an off-line planning that produces the whole plan before execution. It works on a *snapshot* of the current state.

It is based on some (often unrealistic) assumptions

- Atomic time: actions are not interruptible
- Deterministic effects
- The initial state is a priori fully known
- The plan execution is the only cause of changing in the world.

It is opposed to reactive planning

PLANNING AS SEARCH

Planning can be seen as a search activity.

Many different views of planning as search: states and operators change.

- Deductive planning as theorem proving: states are sets of propositions that are true in a given state of the world, operators are deductive rules
- Planning as search in the state space: states are sets of propositions that are true in a given state of the world, operators are actions
- Planning as search in the plan space: states are partial plans and operators are plan refinement/completion moves

LINEAR PLANNING

- A linear planner formulates the planning problem as a search in the state space and uses classical search strategies.

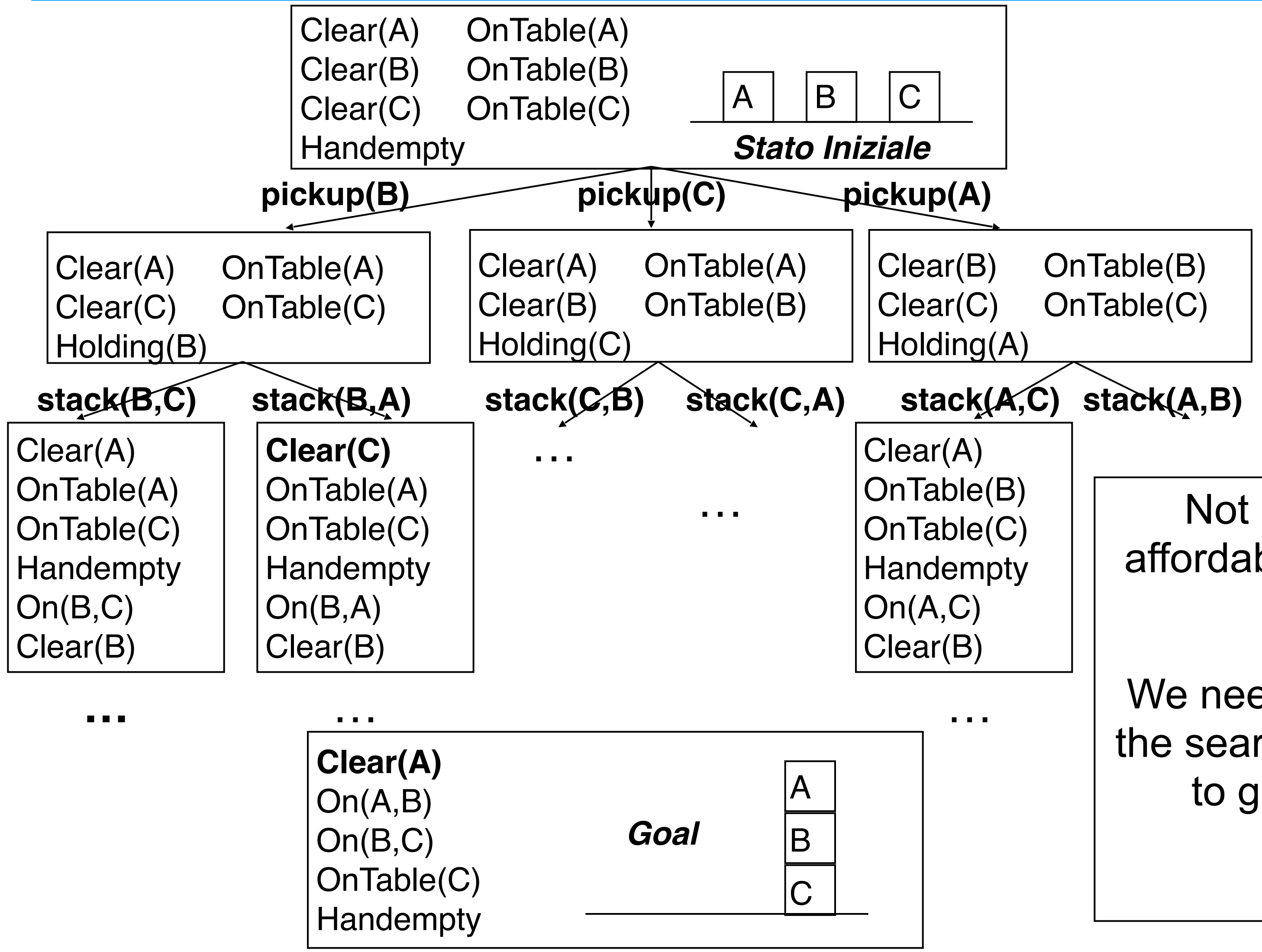
The search algorithm could proceed

➢ **Forward**: if search starts from the initial state and proceeding when it finds a state that is a superset of the goal

➢ **Backward**: if search starts from the goal and proceeds backward until it finds a state that is a subset of the initial state.

$\downarrow$

PLANNING AS FORWARD SEARCH



Not computationally affordable for large search spaces.

We need ways for pruning the search space/heuristics to guide the search

PLANNING AS BACKWARD SEARCH

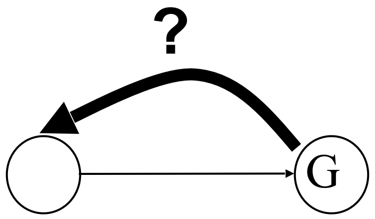
Goal regression: it is a mechanism to reduce a goal in subgoals during search by applying rules (actions)

Given a goal *G* and a rule *R*

PRECOND: *Plist*
DELETE: *Dlist*
ADD: *Alist*

Regression of G through R ***Regr[G, R]*** is:

- Regr[G,R] = true if G∈Alist
- Regr[G,R] = false if G∈Dlist
- Regr[G,R] = G altrimenti



EXAMPLE

Given R1:*unstack(X,Y)*

PRECOND: handempty, on(X,Y), clear(X)

DELETE: handempty, on(X,Y), clear(X)

ADD: holding(X), clear(Y)

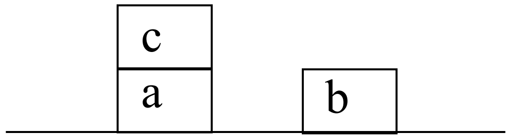
We have:

- Regr[holding(b), R1] = true
- Regr[handempty,R1]=false
- Regr[ontable(c),R1]=ontable(c)
- Regr[clear(c), R1] =

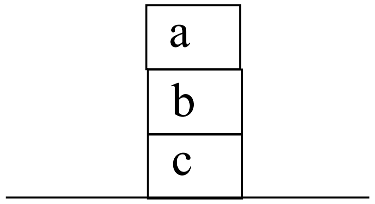
$$\begin{tikzcd} {} \arrow[r] \arrow[dr] & Y=c \\ & \mathrm{clear}(c) \end{tikzcd} \quad = \; Y = c \vee \mathrm{clear}(c)$$

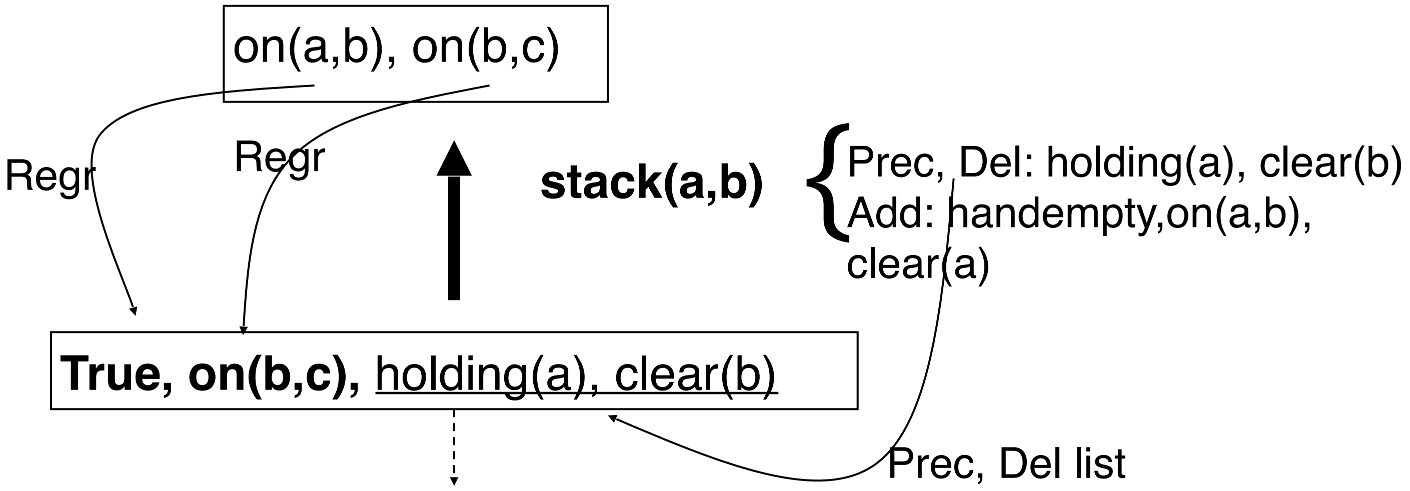
EXAMPLE

Stato iniziale: clear(b), clear(c), on(c,a), handempty, ontable(a), ontable(b)



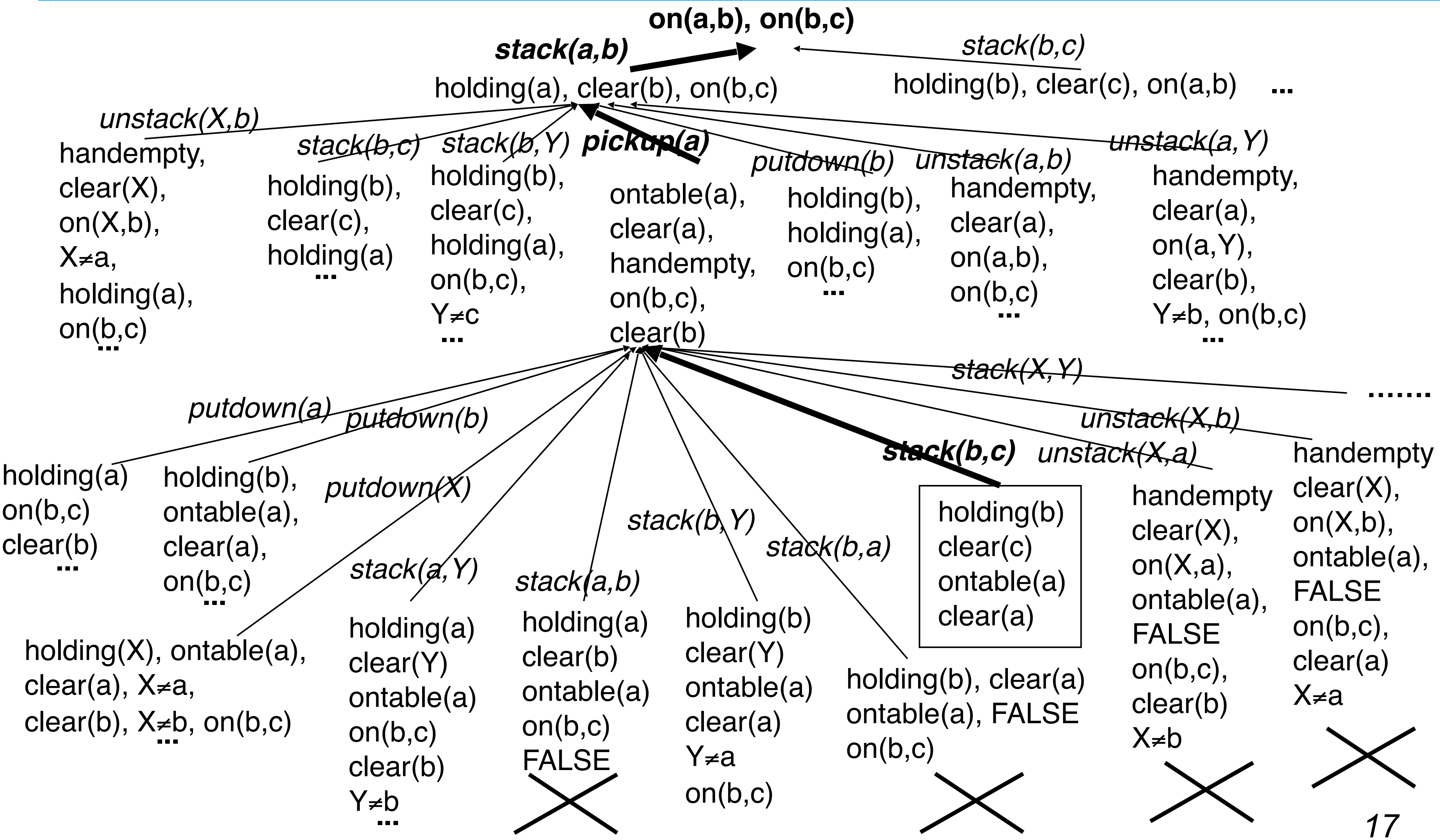
Goal: on(a,b), on(b,c)




on(a,b), on(b,c)
Regr
Regr
stack(a,b)
Prec, Del: holding(a), clear(b)
Add: handempty,on(a,b), clear(a)
True, on(b,c), holding(a), clear(b)
Prec, Del list

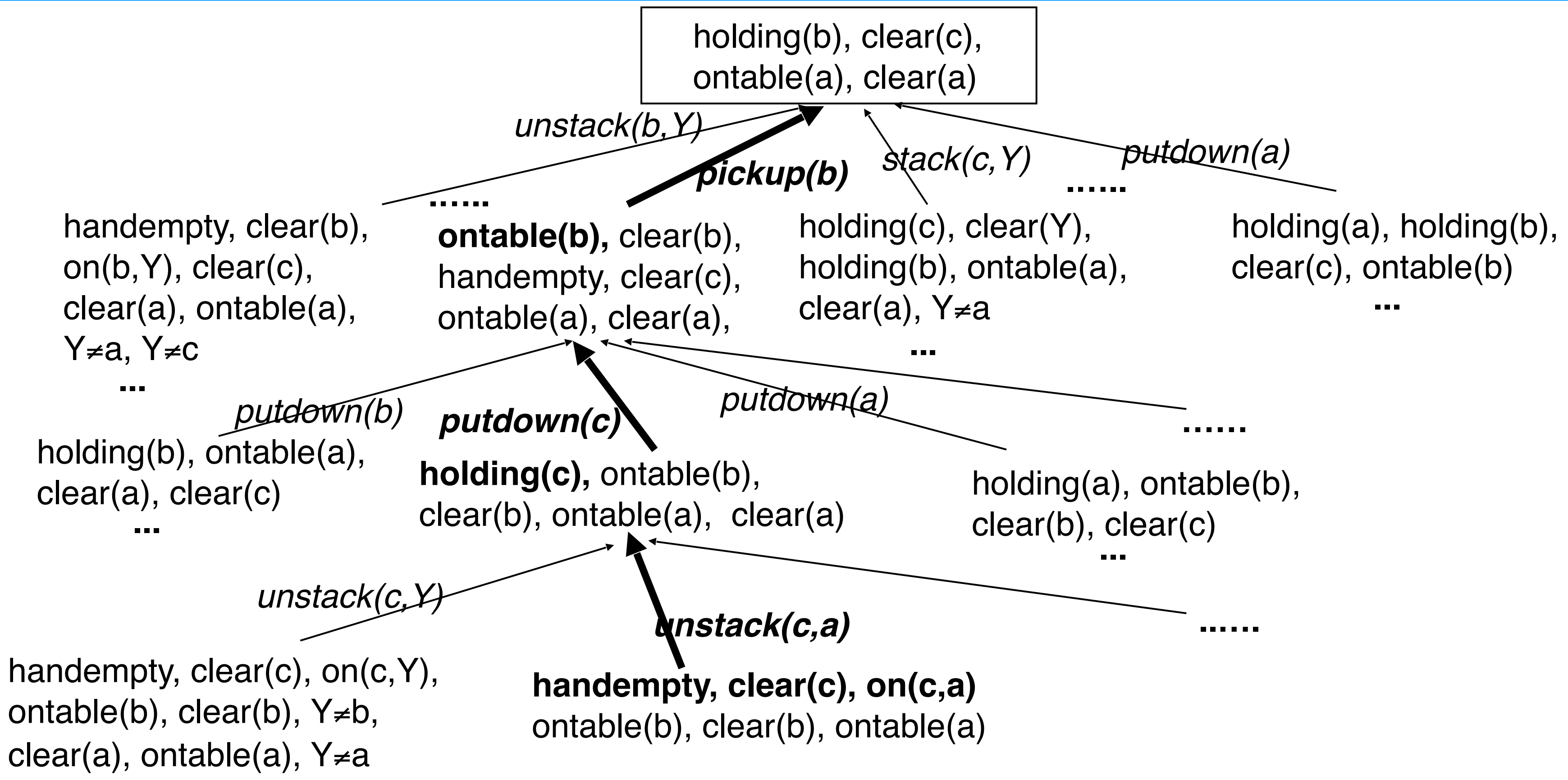
Nuova lista di goal da soddisfare

BACKWARD ALGORITHM



on(a,b), on(b,c)
stack(a,b)
holding(a), clear(b), on(b,c)
stack(b,c)
holding(b), clear(c), on(a,b) ...
unstack(X,b)
handempty, clear(X), on(X,b), X≠a, holding(a), on(b,c) ...
stack(b,c)
holding(b), clear(c), holding(a) ...
stack(b,Y)
holding(b), clear(c), holding(a), on(b,c), Y≠c ...
pickup(a)
ontable(a), clear(a), handempty, on(b,c), clear(b)
putdown(b)
holding(b), holding(a), on(b,c) ...
unstack(a,b)
handempty, clear(a), on(a,b), on(b,c) ...
unstack(a,Y)
handempty, clear(a), on(a,Y), clear(b), Y≠b, on(b,c) ...
stack(X,Y)
....
putdown(a)
holding(a) on(b,c) clear(b) ...
putdown(b)
holding(b), ontable(a), clear(a), on(b,c) ...
putdown(X)
holding(X), ontable(a), clear(a), X≠a, clear(b), X≠b, on(b,c) ...
stack(a,Y)
holding(a) clear(Y) ontable(a) on(b,c) clear(b) Y≠b ...
stack(a,b)
holding(a) clear(b) ontable(a) on(b,c) FALSE
stack(b,Y)
holding(b) clear(Y) ontable(a) clear(a) Y≠a on(b,c)
stack(b,a)
holding(b), clear(a) ontable(a), FALSE on(b,c)
stack(b,c)
holding(b) clear(c) ontable(a) clear(a)
unstack(X,a)
handempty clear(X), on(X,a), ontable(a), FALSE on(b,c), clear(b) X≠b
unstack(X,b)
handempty clear(X), on(X,b), ontable(a), FALSE on(b,c), clear(a) X≠a

BACKWARD ALGORITHM


holding(b), clear(c), ontable(a), clear(a)
unstack(b,Y)
pickup(b)
stack(c,Y)
putdown(a)
......
......
handempty, clear(b), on(b,Y), clear(c), clear(a), ontable(a), Y≠a, Y≠c
...
ontable(b), clear(b), handempty, clear(c), ontable(a), clear(a),
holding(c), clear(Y), holding(b), ontable(a), clear(a), Y≠a
...
holding(a), holding(b), clear(c), ontable(b)
...
putdown(b)
putdown(c)
putdown(a)
......
holding(b), ontable(a), clear(a), clear(c)
...
holding(c), ontable(b), clear(b), ontable(a), clear(a)
holding(a), ontable(b), clear(b), clear(c)
...
unstack(c,Y)
unstack(c,a)
......
handempty, clear(c), on(c,Y), ontable(b), clear(b), Y≠b, clear(a), ontable(a), Y≠a
handempty, clear(c), on(c,a) ontable(b), clear(b), ontable(a)

Questo coincide con lo stato iniziale

DEDUCTIVE PLANNING

Deductive planning uses logics for representing states, goals and actions and generates a plan as a theorem proof.

Green and Kowalsky formulations

SITUATION CALCULUS

First order logic to describe states and clauses to describe actions

- **Situation**: world snapshot describing properties (*fluents*) that hold in a given state s
  - Example: block world

    on(b,a,s)

    ontable(c,s)

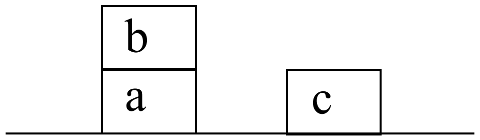
We are saying that on state S, a and b are ture

- **Actions**: define which fluents are true as a consequence of an action

precondition *on(X,Y,S) and clear(X,S)* $\rightarrow$

(ontable(X,do(putOnTable(X),S))) *and*

(clear(Y,do(putOnTable(X),S)))



DEDUCTIVE PLANNING

Green uses *situation calculus* to build a planning based on logic resolution.

$$\downarrow$$

He finds a proof of a formula containing a state variable. At the end of the proof the state variable will be instantiated to the plan to reach the objective

SITUATION CALCULUS

- ***Plan construction*** *: deduction, goal proof*
  - *Example*

    :- ontable(b,S). Means: does a state S exist in which ontable(b) is true?

    YES with S=putOntable(b,s)

- ***Advantages****: high expressivity, can describe complex problems*

- ***Limitations****: frame problem*

FRAME PROBLEM

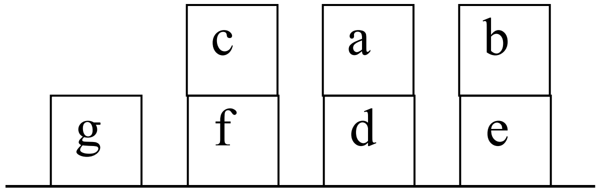
- Knowledge representation problem
- We have to explicitly list all fluents that change and that DO NOT change after a state transition.
- If we have a complex domain the number of these axioms grows enormously.

EXAMPLE

- These axioms describe propositions that are true in the initial state s0

A.1 on(a,d,s0).
A.2 on(b,e,s0).
A.3 on(c,f,s0).
A.4 clear(a,s0).
A.5 clear(b,s0).
A.6 clear(c,s0).
A.7 clear(g,s0).
A.8 diff(a,b)
A.9 diff(a,c)
A.10 diff(a,d)…

G is clear because it hasn't block on top of it



EXAMPLE

➢ Actions are clauses

Diff means X and Z are different from each other

Action *move(X,Y,Z)*

The precondition are X and Z should be cleare

clear(X,S) and clear(Z,S) and on(X,Y,S) and diff(X,Z)

$\rightarrow$ *clear(Y,do(move(X,Y,Z),S)), on(X,Z,do(move(X,Y,Z),S))*.

X from Y to Z

we clear the lock Y and we put X over Z, this is a double move --> unstack and stack

moves a block X from Y to Z, starting from a state S and ending in a state *do(move(X,Y,Z),S)*) that translates in the following axioms (*effect axioms)*

From the previous action, we can write the opposite negatation and divide it in two part

A.11 *~clear(X,S)* or *~clear(Z,S)* or *~on(X,Y,S)* or *~diff(X,Z) or clear(Y,do(move(X,Y,Z),S)).*

A.12 *~clear(X,S)* or *~clear(Z,S)* or *~on(X,Y,S)* or *~diff(X,Z) or on(X,Z,do(move(X,Y,Z),S))*.

EXAMPLE

Given a goal we find a proof through the resolution process:

GOAL:- on(a,b,S1)

l'obiettivo è posizionare A sopra B

~on(a,b,S1)

(A.12) {X/a,Z/b,S1/do(move(a,Y,b),S)}

~clear(a,S) or ~clear(b,S) or ~on(a,Y,S) or ~diff(a,b)

(A.4)	*(A.5)*	*(A.1)*	*(A.8)*
{S/s0},	*{S/s0},*	*{S/s0, Y/d}*	*true*

~on(a,b,S1) leads to a contraddiction to we have a proof for on(a,b,S1) with the substitution **S1/do(move(a,d,b),s0).** This is our plan!!

Now suppose we want to solve a more complex problem

Goal: on(a,b,S), on(b,g,S).

Solution*:* ***S/do(move(a,d,b),do(move(b,e,g),s0)).***

Frame problem: it is that everything that it is not written in outr theory it is not true

To solve this problem we need a complete description of the state after each move.

In every new state we need frame action for every possibible proprieties of our problem. Because it underlines that axioms untouched in the previous state (S0) are still valid and true also in the new state (S1). Example in this case G remains clear also after the move of A from d to b.

EXAMPLE

To describe an action, beside effect axioms we have to specify all fluents that would not change by the execution of an action (*frame axioms*). In our example we would need:

on(U,V,S) and diff(U,X) → on(U,V,do(move(X,Y,Z),S))

clear(U,S) and diff(U,Z) → clear(U,do(move(X,Y,Z),S))

We need a frame axiom for each condition that is not changed by each action.

$\Downarrow$

<u>If the problem is complex, too many axioms</u>

KOWALSKY FORMULATION

- We use the predicate *holds(rel, s/a)* to describe all the relations rel that are true in a given state s or made true by the eecution of an action.
- Predicate *poss(s)* that indicates if a state *s is possible* (namely reachable).
- Predicate *pact(a,s)* to indicate that it is possible to execute an action A in a state s, namely the preconditions of a are true in s.

If a stateA is possible S and the preconditions of an action A are satisfied, then it is possible the state produced by S after the execution of A:

poss(S) and pact(A,S) → poss(do(A,S))

The nice part of kowalsky formulation is that we can solve the problem using logic programming (like Prolog)

KOWALSKY FORMULATION

We need **one frame assertion per action** (advantage w.r.t Green)

In the previous example we would have

holds(V,S) ∧ *diff(V,clear(Z))* ∧ *diff(V,on(X,Y))* → *holds(V,do(move(X,Y,Z),S)))*

that states that every term different from clear(Z) and on (X,Y) (**delete list**) are true after the eecution of the action move.

EXAMPLE

Goal

:- *poss(S), holds(on(a,b),S), holds(on(b,g),S)*.

Use PROLOG to solve it

Initial State

poss(s0).

holds(on(a,d),s0).

holds(on(b,e),s0).

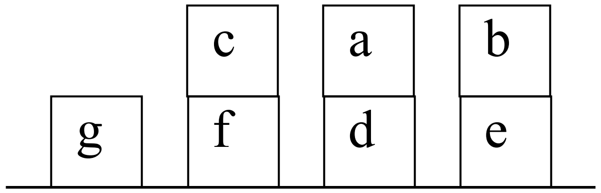
holds(on(c,f),s0).

holds(clear(a),s0).

holds(clear(b),s0).

holds(clear(c),s0).

holds(clear(g),s0).



In the exame there will be the question to take an action and to use the kowalsky formulation,
For Example:
Stack (X,Y) PreCondition holding(X), clear(Y) Effect: Add on(X,Y), handempty, clear(X) Delete holding(X) Clear (Y)

EXAMPLE

Solution: holds(on (X,Y)), do(stack(X,Y),S)
holds(handempty, do(stack(X,Y), S))
holds(clear(X), do(Stack(X,Y),S))

These 3 are effects

pact(stack(X,Y), S) :- holds(holding(x), S), holds (clear(Y), S) These are preconditions

holds(V, do (stack(X,Y), S) :- holds (V, S), V\= holding(X), V\= clear(X)

these are frame actions

Effects of move(X,Y,Z):

holds(clear(Y),do(move(X,Y,Z),S)).

holds(on(X,Z),do(move(X,Y,Z),S)).

Preconditions of move(X,Y,Z):

pact(move(X,Y,Z),S):-

holds(clear(X),S), holds(clear(Z),S), holds(on(X,Y),S), X\=Z.

Frame conditions: We have frame action per action not like for each proprieties like before

holds(V,do(move(X,Y,Z),S)):- holds(V,S), V\=clear(Z), V\=on(X,Y).

It says that every proprieties V in S except clear Z and on X,Y (these are proprieties deleted by the action) are true in the new state S1

Clause for state reachability

poss(do(A,S)):- poss(S), pact(A,S).

Goal :- *poss(S), holds(on(b,g),S), holds(on(a,b),S)*.

Yes per *S* = ***do(move(a, d, b), do(move(b, e, g), s0)***) This is the plan

STRIPS

STRIPS - Stanford Research Institute Problem Solver

- Specific language for the actions. Easier syntax than the situation calculus (less expressive more efficient).
- Ad hoc algorithm for the plan construction

STRIPS: Language for states

- State representation
  - fluent that are true in a given state

    Esempio: *on(b,a), clear(b), clear(c), ontable(c)*
- Goal representation
  - fluent that are true in the goal state
  - We can have variables

    Ex: *on(X,a)*

STRIPS: Language for actions

- Action representation (3 lists)
  - PRECONDITIONS: fluents that should be true for applying the move
  - DELETE List: fluents that become false after the move
  - ADD List: fluents that become true after the move

Example *Move(X, Y, Z)*

Preconditions*: on(X,Y), clear(X), clear(Z)*

Delete List*: clear(Z), on(X,Y)*

Add list*: clear(Y), on(X,Z)*

Sometimes ADD e DELETE list are glued in an **EFFECT** list with positive and negative axioms

Esempio *Move(X, Y, Z)*

Precondizioni*: on(X,Y), clear(X), clear(Z)*

Effect List*: ¬clear(Z), ¬on(X,Y), clear(Y), on(X,Z)*

Frame problem solved with the **Strips Assumption**:

everything which is not in the ADD and DELETE list is unchanged

STRIPS: Language for actions

pickup(X)
PRECOND: ontable(X), clear(X), handempty
DELETE: ontable(X), clear(X), handempty
ADD: holding(X)

putdown(X)
PRECOND: holding(X)
DELETE: holding(X)
ADD: ontable(X), clear(X), handempty

STRIPS: Language for actions

stack(X,Y)
PRECOND: holding(X), clear(Y)
DELETE: holding(X), clear(Y)
ADD: handempty, on(X,Y), clear(X)

unstack(X,Y)
PRECOND: handempty, on(X,Y), clear(X)
DELETE: handempty, on(X,Y), clear(X)
ADD: holding(X), clear(Y)

STRIPS: Algorithm

- Linear planner based on backward search
- Initial state fully known (**Closed World Assumption**) Everything that is not decleared is false
- Two data structures
  - Goal stack LIFO
  - Description of the current state
- Algorithm
  - Initialise the stack with the goals to reach
  - <u>while</u> stack not empty <u>do</u>

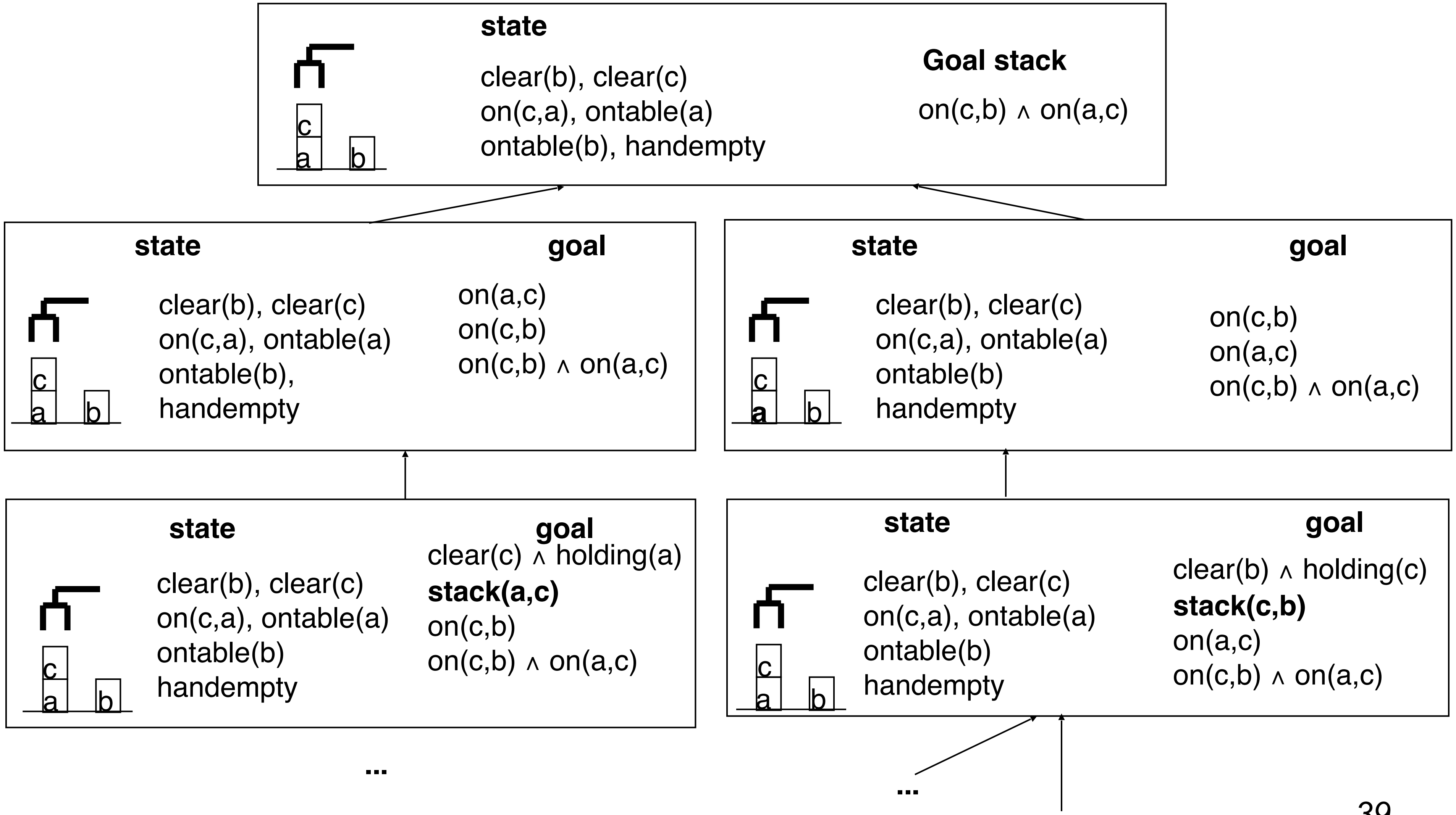
```
        if  top(stack) = A  and $A\theta \subseteq S$ (note that A can be an and of goals or a single one)
                then pop(a) and execute substitution $\theta$ on the  stack
                else  if  top(stack) = a
                          then
                - Select a rule R with a $\in$ Addlist(R),
                - pop(a), push(R), push(Precond(R));
                 else  if  top(stack) = a1 $\wedge$ a2 $\wedge$ … $\wedge$ an
                          (*) then push(a1),…, push(an)
                      else if top(stack) = R
                 then pop(R) e apply  R on S
```

(*) Note that the order in which subgoals are inserted in stack is a non-deterministic choice point. The end of goals should be verified afterword - interacting goals)

STRIPS: Algorithm – some notes

- The problem is divided into subgoals which might interact
- Many possible goal orderings.
- At each step we select one subgoal from the goal stack.
- When we have a set of actions that reach a goal, we execute them on the state that proceeds forward.
- The process goes on until the stack is empty
- When at the top of the stack we find an **and of goals**, we need to check that this is still satisfied in the current state before removing it. If it is not, we have to reinsert the and and change order.

EXAMPLE



state

clear(b), clear(c)
on(c,a), ontable(a)
ontable(b), handempty

Goal stack

on(c,b) ∧ on(a,c)

state

clear(b), clear(c)
on(c,a), ontable(a)
ontable(b),
handempty

goal

on(a,c)
on(c,b)
on(c,b) ∧ on(a,c)

state

clear(b), clear(c)
on(c,a), ontable(a)
ontable(b)
handempty

goal

on(c,b)
on(a,c)
on(c,b) ∧ on(a,c)

state

clear(b), clear(c)
on(c,a), ontable(a)
ontable(b)
handempty

goal

clear(c) ∧ holding(a)
stack(a,c)
on(c,b)
on(c,b) ∧ on(a,c)

state

clear(b), clear(c)
on(c,a), ontable(a)
ontable(b)
handempty

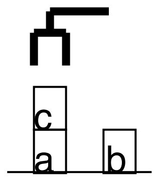
goal

clear(b) ∧ holding(c)
stack(c,b)
on(a,c)
on(c,b) ∧ on(a,c)

...

...

EXAMPLE

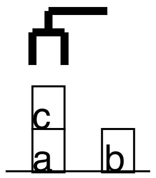


state

clear(b), clear(c)
on(c,a), ontable(a)
ontable(b)
handempty

goal

holding(c),
clear(b)
clear(b) ∧ holding(c)
stack(c,b)
on(a,c)
on(c,b) ∧ on(a,c)



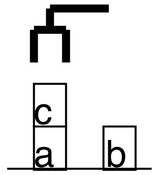
state

clear(b)
clear(c)
on(c,a), ontable(a)
ontable(b)
handempty

goal

handempty ∧ clear(c)
∧ on(c,Y)
unstack(c,Y), clear(b)
clear(b) ∧ holding(c)
stack(c,b), on(a,c)
on(c,b) ∧ on(a,c)

with {a/Y} the end is true in S (avoid orderings)



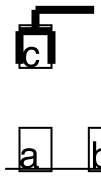
state

clear(b), clear(c)
on(c,a), ontable(a)
ontable(b)
handempty

goal

unstack(c,a),
clear(b)
clear(b) ∧ holding(c)
stack(c,b), on(a,c)
on(c,b) ∧ on(a,c)

Execute unstack(c,a)



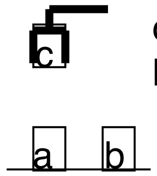
state

clear(b), clear(a)
ontable(a), ontable(b)
holding(c)

goal

clear(b)
clear(b) ∧ holding(c)
stack(c,b)
on(a,c)
on(c,b) ∧ on(a,c)

Verified goal and conjunction.



state

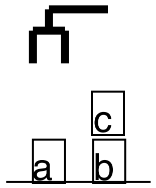
clear(b), clear(a)
ontable(a), ontable(b)
holding(c)

goal

stack(c,b)
on(a,c)
on(c,b) ∧ on(a,c)

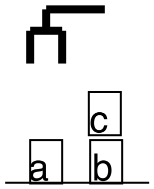
execute stack

EXAMPLE



state
clear(c), clear(a)
ontable(a) ontable(b)
on(c,b), handempty

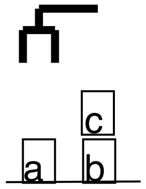
goal
on(a,c)
on(c,b) ∧ on(a,c)



state
clear(c), clear(a)
ontable(a), ontable(b)
on(c,b), handempty

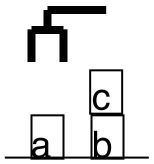
goal
clear(c) ∧ holding(a)
stack(a,c)
on(c,b) ∧ on(a,c)

clear(c) true in S



state
clear(c), clear(a)
ontable(a), ontable(b)
on(c,b), handempty

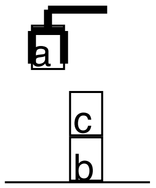
goal
holding(a)
clear(c) ∧ holding(a)
stack(a,c)
on(c,b) ∧ on(a,c)



state
clear(c), clear(a)
ontable(a)
ontable(b)
on(c,b), handempty

goal
ontable(a) ∧ clear(a)
∧ handempty
pickup(a)
clear(c) ∧ holding(a)
stack(a,c)
on(c,b) ∧ on(a,c)

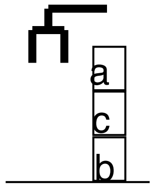
cong OK execute pickup



state
clear(c), ontable(b)
on(c,b), holding(a)

goal
clear(c) ∧ holding(a)
stack(a,c)
on(c,b) ∧ on(a,c)

cong OK execute stack



state
clear(a), ontable(b)
on(c,b), on(a,c)

goal
on(c,b) ∧ on(a,c)

Empty stack
END

The solution is :

1. unstack(c,a) 2. stack(c,b) 3. pickup(a) 4. stack(a,c)

STRIPS PITTFALLS

1. **Very large search space.** In the example we have seen a single path but there are many alternatives
    - Non deterministich choice in the ordering
    - More actions applicable to reduce a goal

Solution: Heuristic strategies

- To select the goal
- To select the action

- **MEANS-ENDS ANALYSIS**
    - Find the most significant difference between the state and the goal
    - Reduce that different before

STRIPS PITTFALLS

2. Interacting goals.

Interacting goals G1, G2
- Plan actions for reaching G2
- Then to solve G1 we destroy what we have done for G2
- At the end of the planning G2 is not true anymore.

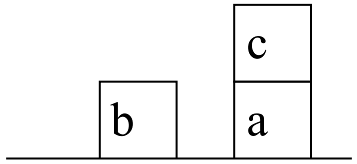
➢ Complete solution:
  - Try all possible orderings of goals and subgoals.

➢ Practical solution (Strips):
  - Solve them independently
  - Verify afterward
  - If the conjunction is not true, change ordering

SUSSMAN ANOMALY

Initial State:

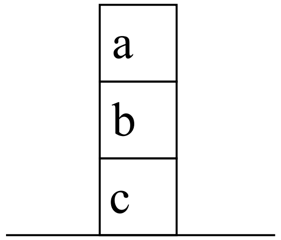
clear(b),
clear(c),
on(c,a),
ontable(a),
ontable(b),
handempty



Goal: on(a,b),on(b,c)

Two possible initial stacks

(1)	(2)
on(a,b)	on(b,c)
on(b,c)	on(a,b)
on(a,b) ∧ on(b,c)	on(a,b) ∧ on(b,c)



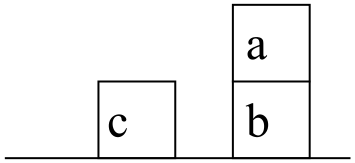
We chose (1)

SUSSMAN ANOMALY

We apply the STRIPS algorithm for the first goal and obtain:

1. unstack(c,a)
2. putdown(c)
3. pickup(a)
4. stack(a,b)

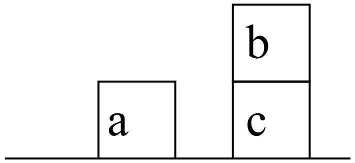
Current state:



Now we plan for the second goal on(b,c).

5. unstack(a,b)
6. putdown(a)
7. pickup(b)
8. stack(b,c)

Current state:



The conjunction

on(a,b) ∧ on(b,c)

is not valid

SUSSMAN ANOMALY

The conjunction on(a,b) $\wedge$ on(b,c) is not valid

So we reinsert on(a,b) in the goal stack

and obtain:

9. pickup(a)
10. stack(a,b)

We have obtained what we need, <u>but not that efficiently</u>.

Search in the space of Plans

- Linear planners are search algorithms that explore the state space.
  - The plan is a linear sequence of actions to achieve the goals.

- Non-linear planners are search algorithms that generate a plan as a search problem in the space of plans.
  - In the search tree each node is a partial plan and operators are plan refinement operations.

- A non-linear generative planner assumes that the initial state is fully known **Closed World Assumption**: Everything that is not explicitly stated in the initial state is considered as false

- **Least Commitment planning**: never impose more restrictions than those that are strictly necessary.
  - Avoid making decisions when they are not required. This avoids many backtracking.

NON-LINEAR PLANNING

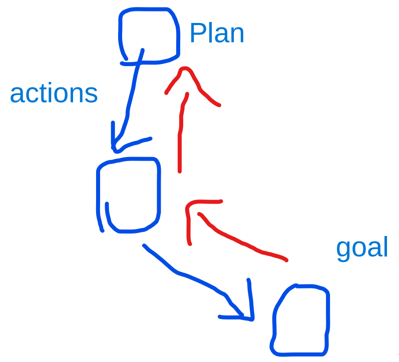
- A non-linear plan is represented as
  - a set of **actions** (instances of operators)
  - a (not exhaustive) set of **orderings** between actions
  - a set of "**causal links**" (Described later)

- Initial plan: it is an empty plan with two fake actions
  - **start**: No preconditions. Its effects match the initial state
  - **stop**: No effects. Its pre-conditions match the goal
  - Ordering: start <stop

In the non-linear planning, in every node i have a plan, the root node is an empy plan.
So it is different from linear plan where we have States.

From the root nodes we have to start add actions in order to reach the goal (every arch is an action but also we can call each one a plan refinment operator)

We proced backward, we start form the goal, and we try to add action backwards to reach the goal.



NON-LINEAR PLANNING

- At each step either the set of operators or the set of orderings or the set of causal links is increased until all goals are met.
  - Non required orderings are not posted

- A solution is a set of partially specified and partially ordered operators.

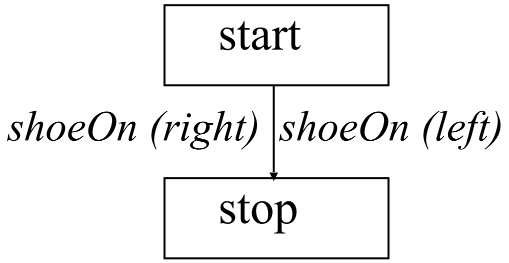
- To obtain a real plan the partial order should be linearized in one of the possible total orders (*linearization operation*).

Example: plan to wear shoes

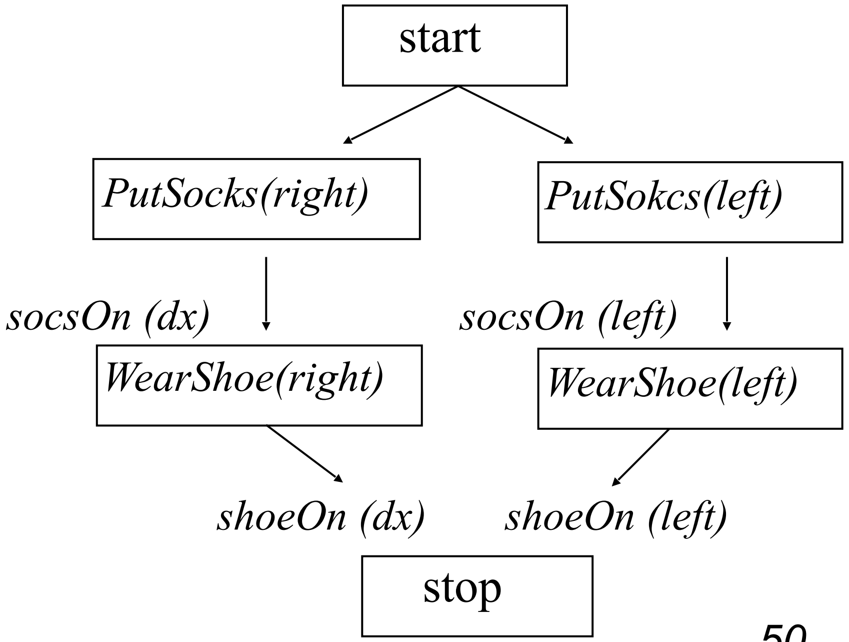
- Goal: shoeOn (dX), shoeOn (sX)

- actions
  - WearShoe(Foot)
    PRECOND: socksOn (Foot)
    EFFECT: shoeOn (Foot)
  - PutSocks(Foot)
    PRECOND: ¬ socksOn (Foot)
    EFFECT: socksOn (Foot)

Initial plan



Partial plans Finals



Partial Order Planning: intuitive algorithm

```
While (plan not complete) do
    – select an action SN that has a precondition not satisfied;
    – select an action S (new or already in the plan) that has C among its effects;
    – add the order constraint S <SN;
    – if S is a new action add the constraint Start <S <Stop;
    – add the causal link <S, SN, C>;
    – solve any threat on causal links
end
```

➢ In case of failure if choice points exist, the algorithm backtracks and it explores alternatives.

➢ A **causal link** is a triple that consists of two operators Si, Sj and a subgoal c . C should be precondition of Sj and effect of Si

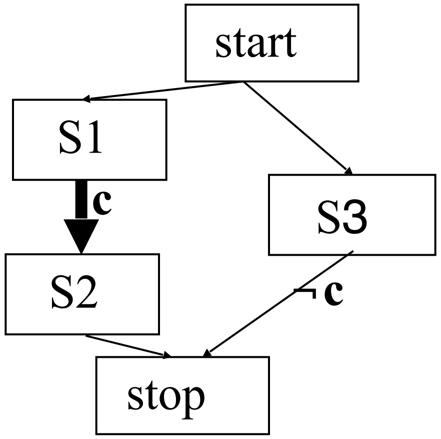
➢ A causal link stores the causal relations between actions: it traces why a given operator has been introduced in the plan.

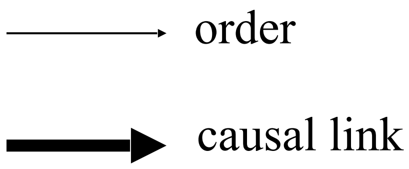
➢ Causal links help tackling the problem of *interacting goals*.

$$S_i \xrightarrow{c} S_j$$

Causal links and threats

An action *S3* is a **threat** for a causal link <*S1, S2, c*> if it has an effect that negates *c* and no ordering constraint exists that prevents *S3* to be performed between *S1* and *S2*.



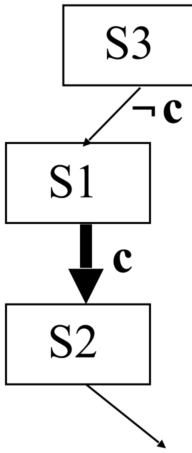


Possible solutions

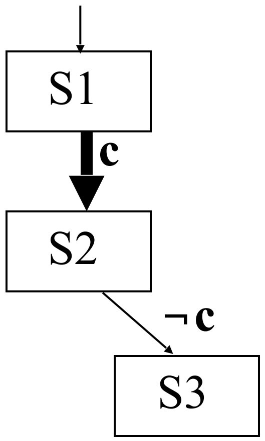
- Demotion: The constraint *S3 <S1 is imposed* before S1
- Promotion: The constraint *S2 <S3 is imposed* After S1

There are 2 ways to protect casual links

Demotion



Promotion



Example: Purchasing Schedule

- Initial state:
  at (home), sells (HWS, drill), sells (sm, milk), sells (sm, banana)
- Goal:
  at (home), have (drill), have (milk), have (banana)
- actions:

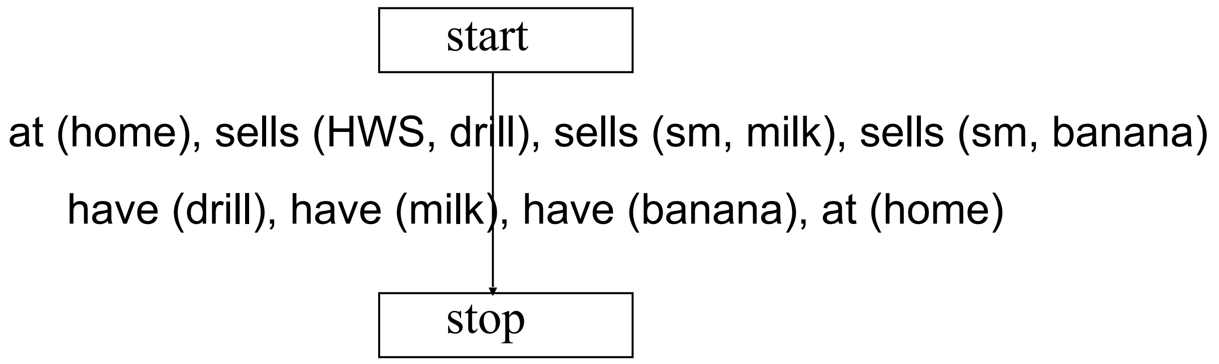
  Go (X, Y):

  PRECOND: at (X)
  EFFECT: at (Y), ¬ at (X)

  buy (S, Y):

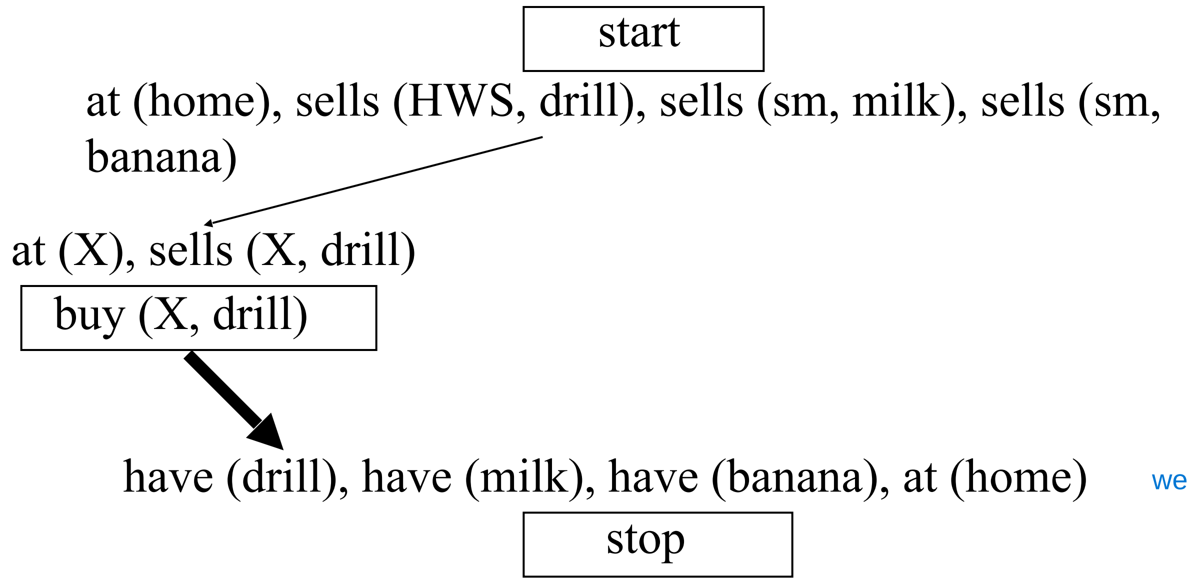
  PRECOND: at (S), sells (S, Y)
  EFFECT: have (Y)

- initial plan (known *null*):


start
at (home), sells (HWS, drill), sells (sm, milk), sells (sm, banana)
have (drill), have (milk), have (banana), at (home)
stop

Example: Purchasing Schedule

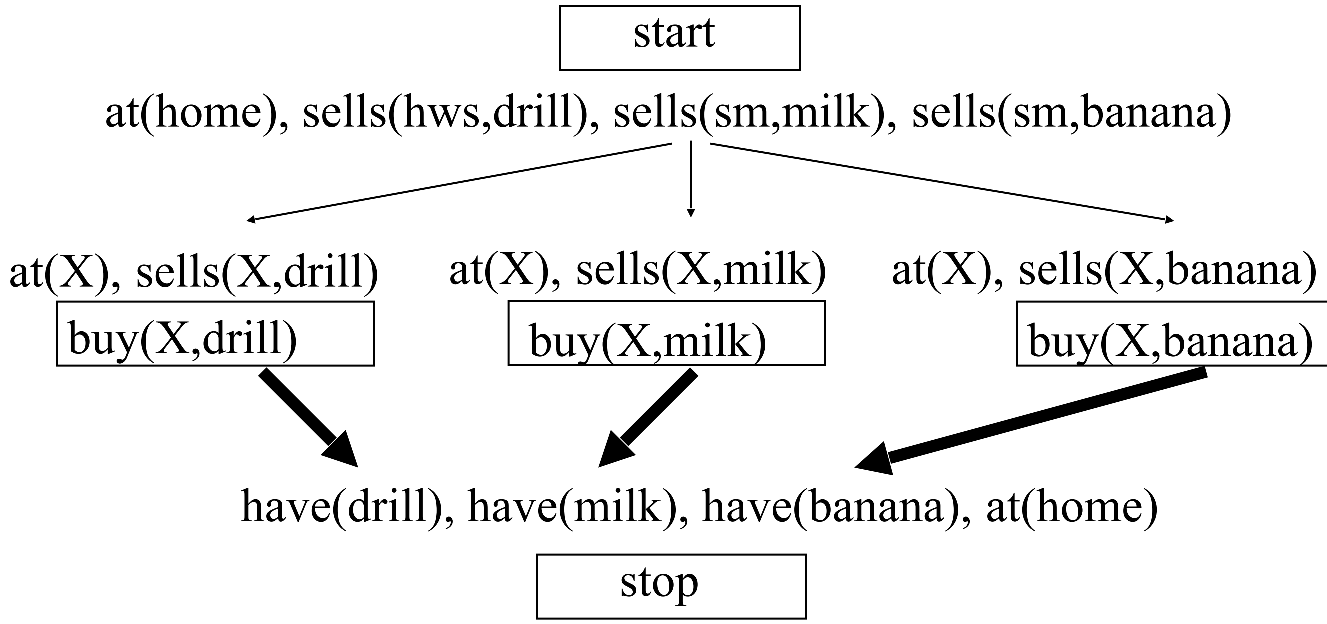
- First step:
  - select a precondition (goal) to be fulfilled: *have (drill)*
  - select an action that has *have(drill)* as an effect: *buy (X, Y)*
  - Plan refinement:
    - Link variable Y with the term *drill*
    - Impose ordering constraints *Start <buy <Stop*
    - Insert the causal link <*buy (X, drill), stop, have (drill)*>


start
at (home), sells (HWS, drill), sells (sm, milk), sells (sm, banana)
at (X), sells (X, drill)
buy (X, drill)
have (drill), have (milk), have (banana), at (home)
stop

we can select each of this goal to reach

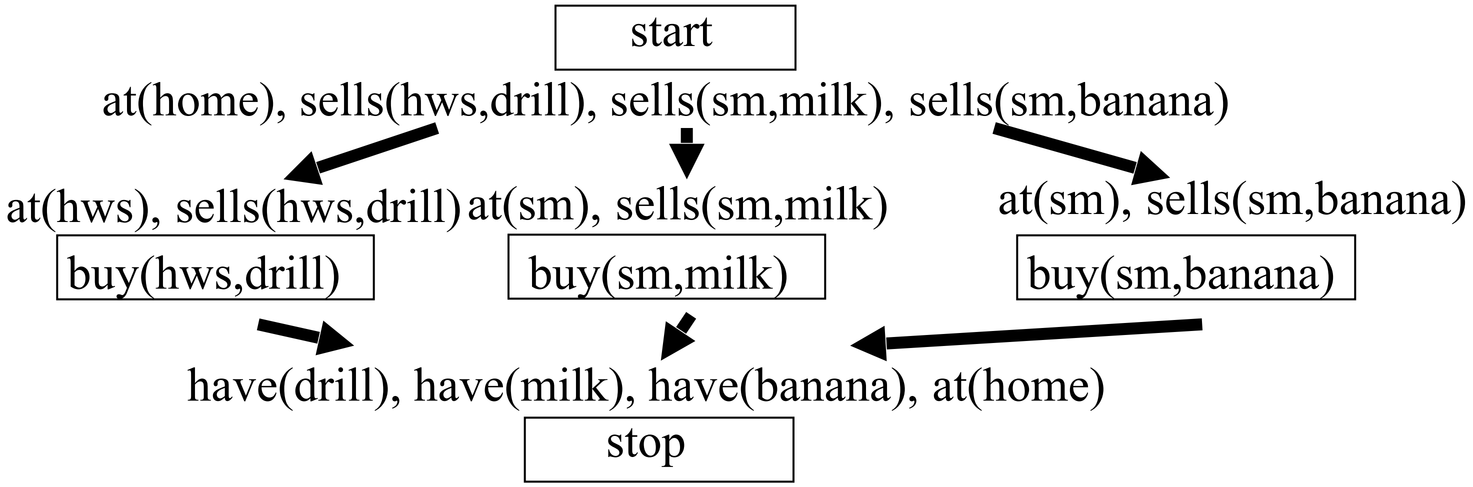
Example: Purchasing Schedule

- Same procedure for
  - *have (milk)*
  - *have (banana)*

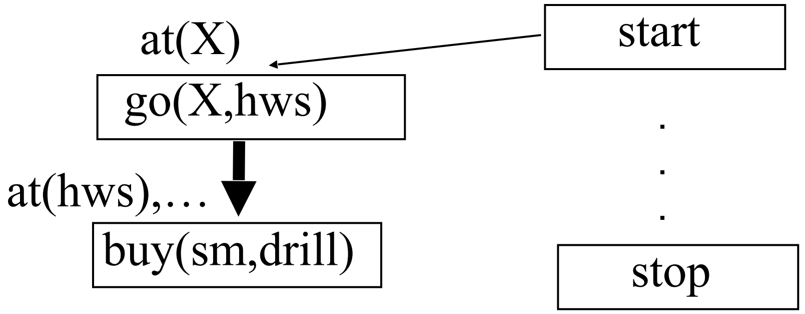


Example: Purchasing Schedule

- Select *sells(X,drill)*, true in the initial state imposing *X=hws*. The same happens for *sells(X,milk)* and *sells(X,banana)* with *X=sm*. Add causal links.

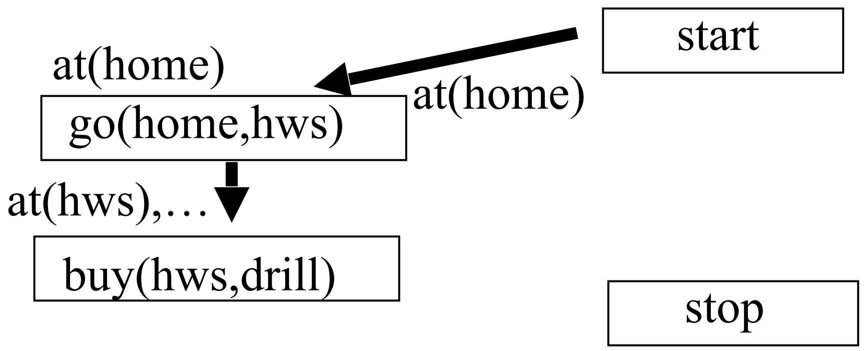

start
at(home), sells(hws,drill), sells(sm,milk), sells(sm,banana)
at(hws), sells(hws,drill)
buy(hws,drill)
at(sm), sells(sm,milk)
buy(sm,milk)
at(sm), sells(sm,banana)
buy(sm,banana)
have(drill), have(milk), have(banana), at(home)
stop

- Select
  - *at(hws)* precondition of *buy(hws,drill)*
  - Add *go(X,hws)* in the plan along with orderings and causal links.

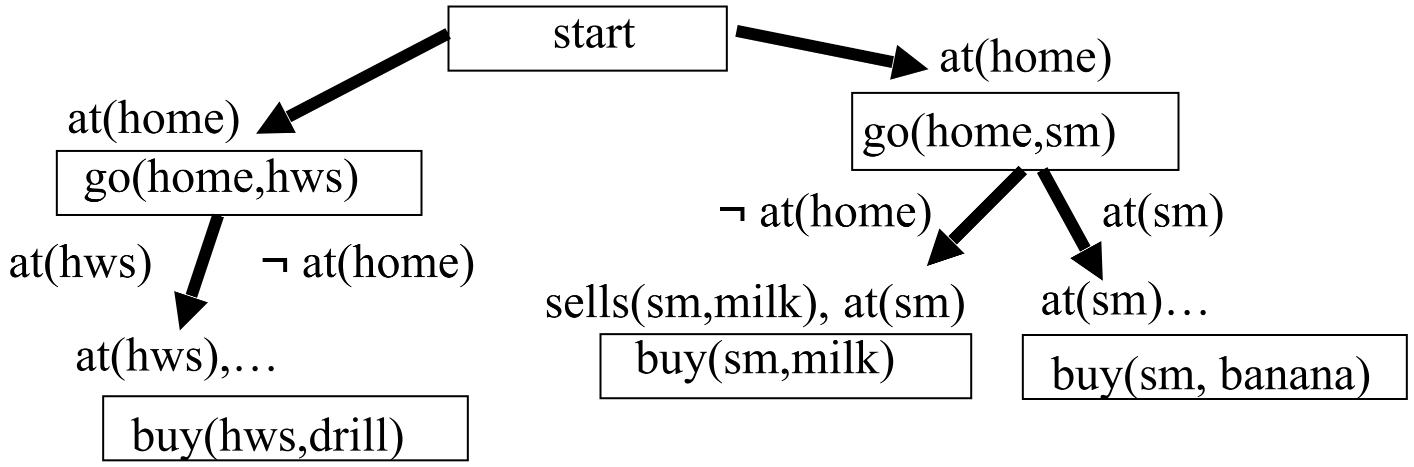


Example: Purchasing Schedule

- Select *at(X)* as precondition of *go(X, hws), true in Start* with *X = home* and protect the causal link.

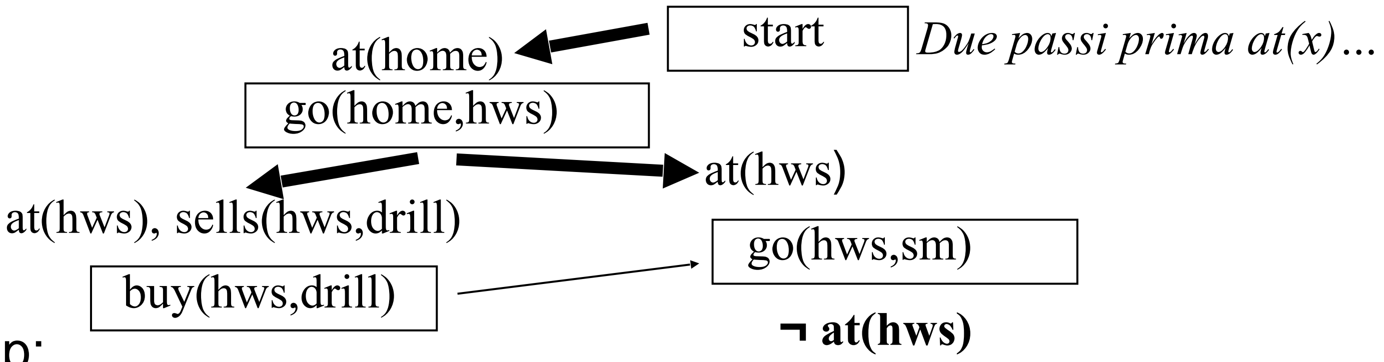


- Same procedure for *at (sm)*

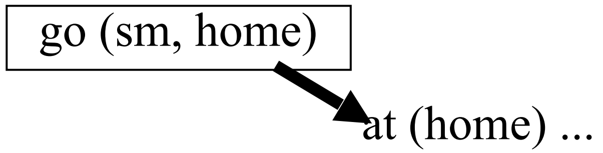


Example: Purchasing Schedule

- ➢ Solve the conflict between actions *go(home, hws)* and *go(home, sm)*
  - If the agent performs *go(home, hws)* it cannot be *at(home)* to perform *go(home, sm)* and viceversa
  - **imposing ordering constraints does not work**
  - backtracking on the solution step of *at(X)* (Precondition of *go(X,sm))*
  - use *go(home, hws)* instead of *Start* with *X = home to satify at(X) with X= hws*
  - So we have *buy(hws, drill) < go(hws, sm). This way at (hws)* is protected by the causal link between *go (home, HWS) and buy (HWS, drill)* (**promotion)**

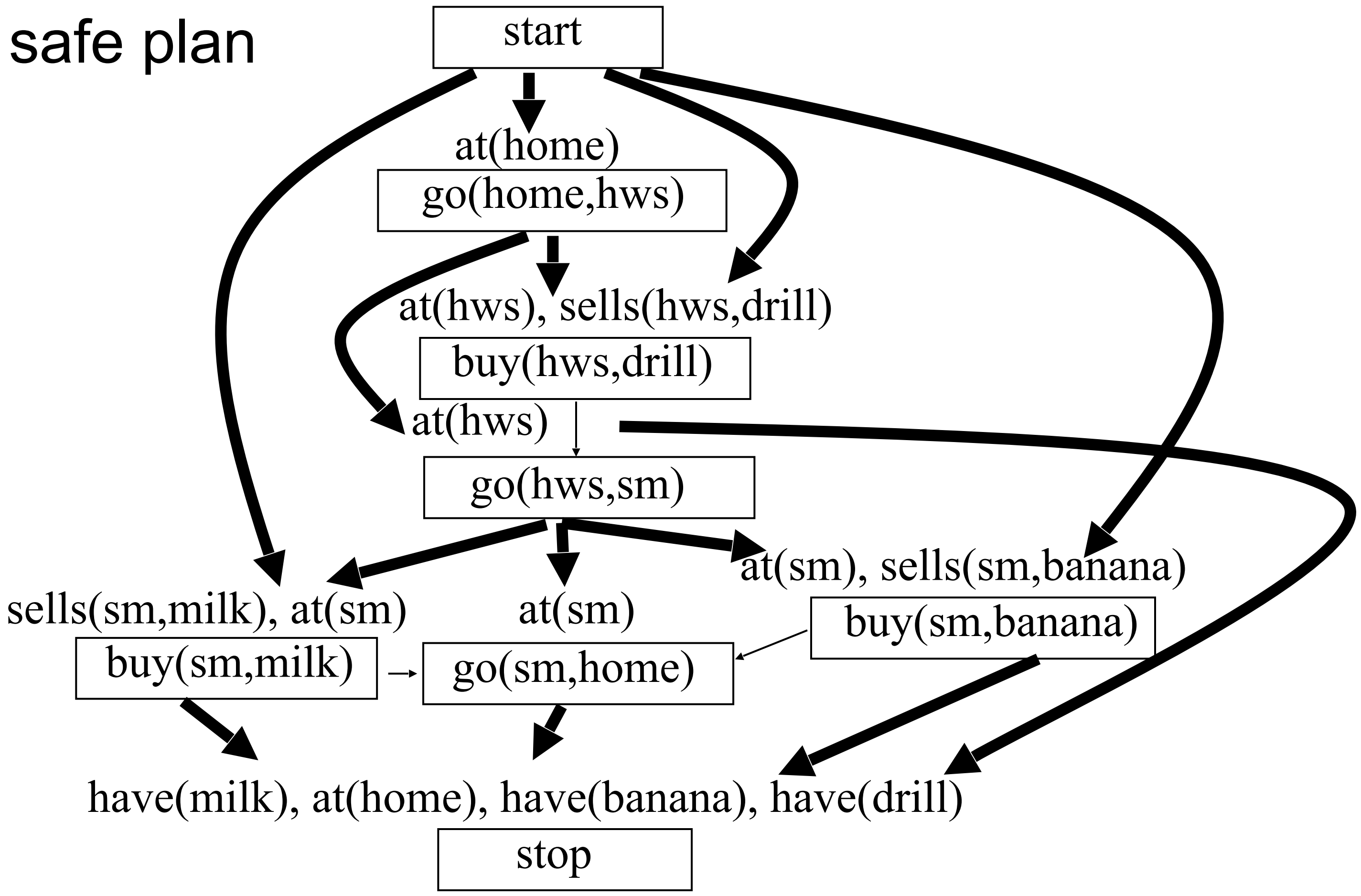


- ➢ Last step:
  - solve *at(home)* of *stop*: the only way is to put the action *go(home)* before *stop*



Example: Purchasing Schedule

- Complete and safe plan



A final plan is obtained by ordering all actions:

1) go (home, hws) 2) buy (hws, drill) 3) Go (hws, sm)

4) buy (sm, milk) 5) buy (sm, banana) 6) go (sm, home)

Partial Order Planning Algorithm (POP)

```
function POP (initialGoal Operators) returns plan
    plan: = INITIAL_PLAN (start, stop, initialGoal)
    loop
        if  SOLUTION (plan) then return plan;
        SN, C: = SELECT_SUBGOAL (plan);
        CHOOSE_OPERATOR (plan, operators, SN, C);
        RESOLVE_THREATS (plan)
    end

function SELECT_SUBGOAL (plan)
    select SN from STEPS (plan) with unsolved precondition C;
    return SN, C
```

Partial Order Planning Algorithm (POP)

```
procedure CHOOSE_OPERATOR (plan, ops, SN, C)
    pick an S with effect C from ops or from STEPS (plan);
    if S does not exist then fail;
    add the causal link <S, SN, C>
    add the ordering constraint S <SN
    if S is a new action added to the plan
    then  add S to STEPS(plan)
                    add the constraint Start <S <Stop
procedure SOLVE_THREAT (plan)
    for each action S that threats a causal link between Si and Sj,
    choose either
        demotion: add the constraint  S < Si
        promotion: add the constraint  Sj <S
        if NOT_CONSISTENT (plan) then fail
```

Modal Truth Criterion (MTC)

Promotion and *demotion* alone are not enough to ensure the completeness of the planner. A planner is complete if it always finds a solution if a solution exists.

The *Modal Truth Criterion* is a construction process that guarantees planner completeness.

A Partial Order Planning algorithm interleaves goal achievement steps with threat protection steps.

The MTC provides five plan refinement methods (one for the open goal achievement and 4 for threat protection) that ensure the completeness of the planner.

Modal Truth Criterion (MTC)

1. ***Establishment***, open goal achievement by means of: (1) a new action to be inserted in the plan, (2) an ordering constraint with Action already in the plan or simply (3) of a variable assignment.
2. ***Promotion***, ordering constraint that imposes the threatening action before the first of the causal link;
3. ***Demotion***, ordering constraint that imposes the threatening action after the second of the causal link;
4. ***White knight***, insert a new operator or use one already in the plan between to S1 and S3 such that it establishes the precondition of S3 threatened by S1.
5. ***Separation***, insert *non codesignation constraints* between the variables of the negative effect and the threatened precondition so to avoid unification.
   This is useful when variables have not yet been instantiated.

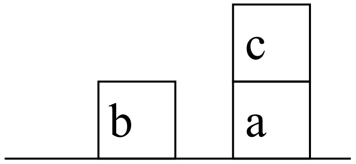
Ex. Given the causal link

any threat imposed by stack(Y,c) can be solved by imposing X ≠ Y

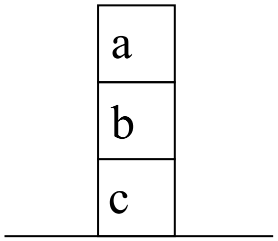
$$\mathit{pickups}\ (X) \xrightarrow{\mathit{holding}\ (X)} \mathit{stack}\ (X, b)$$

Example: Sussmann Anomaly

Initial state ([*IS*]):
clear (b), clear (c), on (c, a), ontable (a)
ontable (b), handempty.



Goal ([*G*]):
on (a,b), on (b, c).



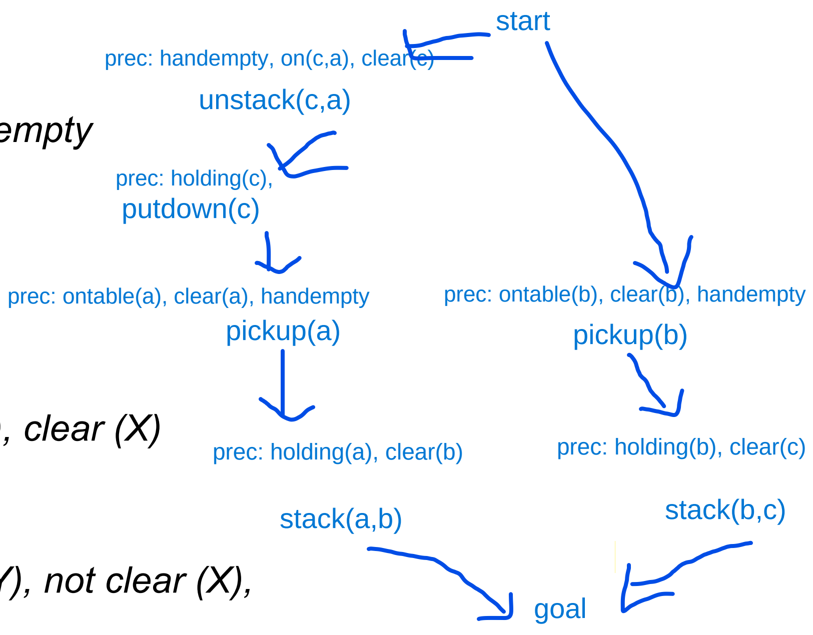
actions

pickup (X)
PRECOND: *ontable (X), clear (X), handempty*
POSTCOND: *holding (X) not ontable (X), not clear (X), not handempty*

putdown (X)
PRECOND: *holding (X)*
POSTCOND: *ontable (X), clear (X), handempty*

stack (X, Y)
PRECOND: *holding (X), clear (Y)*
POSTCOND: *not holding (X), not clear (Y), handempty, on (X, Y), clear (X)*

unstack (X, Y)
PRECOND: *handempty, on (X, Y), clear (X)*
POSTCOND: *holding (X), clear (Y) ,. not handempty, not on (X, Y), not clear (X),*


start
prec: handempty, on(c,a), clear(c)
unstack(c,a)
prec: holding(c),
putdown(c)
prec: ontable(a), clear(a), handempty
pickup(a)
prec: holding(a), clear(b)
stack(a,b)
prec: ontable(b), clear(b), handempty
pickup(b)
prec: holding(b), clear(c)
stack(b,c)
goal

now we have to find threats

Example: Sussmann Anomaly

initial plan:

Orderings: [start <stop]
List of Causal links: [].
Goal agenda:[on(a, b), on(b, c)]

Establishment: chose two actions (without orders) that meet the goals
stack (a, b)
PRECOND: *holding (a), clear (b)*
POSTCOND: *handempty, on (a, b), not clear (b), not holding (a)*

stack (b, c)
PRECOND: *holding (b), clear (c)*
POSTCOND: *handempty, on (b, c), not clear (c), not holding (b)*

Orderings: [start <stop, start < stack (a, b), start <stack (b, c), stack (b, c) <stop]
List of Causal links: [<stack (a, b), stop, on (a, b)>, <stack (b, c), stop, on (b, c)>].
Goal agenda: [holding (a), clear (b), holding (b), clear (c)]

The actions are not ordered. At the moment we only know that both of them will occur.

Example: Sussmann Anomaly

Some of the preconditions on the agenda (*clear (b) and clear (c))* are already met in the initial state: just add the causal link.

Orderings: [see. above]
List of causal link: [..., <start, stack (a, b), clear (b)>, <start, stack (b, c), clear (c)>].
Goal Agenda: [holding (a), holding (b)]

Now we proceed with the establishment of: holding(a), holding (b)

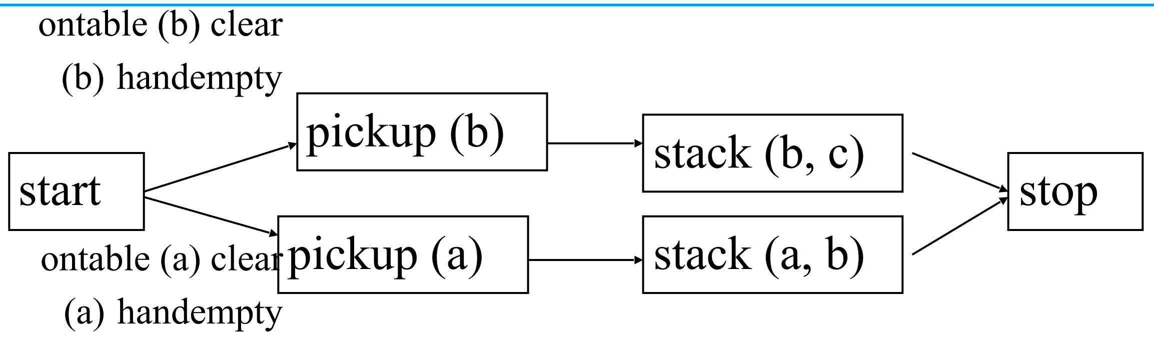
pickup (a)
PRECOND: *ontable (a), clear (a), handempty*
POSTCOND: *not ontable (a), not clear (a), holding (a), not handempty,*

pickup (b)
PRECOND: *ontable (b), clear (b), handempty*
POSTCOND: *not ontable (b), not clear (b), holding (b), not handempty*

List of orders : [..., pickup (a) < stack (a, b), pickup (b) < stack (b, c)]
Causal links: [...,<pickup(a), stack(a,b), holding(a)>, <pickup(b), stack(b,c), holding (b)>]
Goal Agenda: [ontable (a), clear (a), ontable(b), clear(b), handempty]

Example: Sussmann Anomaly

Partial current plan:



ontable(b), ontable(a) clear(b) are met in the initial state.

Orderings: [see. above]
Causal links: [..., <start, pickup(a), ontable (a)>, <start, pickup (b), ontable (b)>,
<start, pickup (b), clear (b)>]
Goal Agenda: *[handempty, clear(a)]*

stack(a, b) threats <*start, pickup(b), clear (b)*> as *not clear(b) is one of its effects* and nothing prevents it to precede *pickup (b)* and invalidate its precondition *clear (b)*.

↓

impose (**promotion**) *pickup (b) < stack (a, b)*

Example: Sussmann Anomaly

handempty is true in the initial state.

The new causal link <*start, pickup (b), handempty*> is threatened by *pickup(a)*:

$\downarrow$

Impose (promotion) *pickup (b) < pickup(a)*

The precondition *handempty* of *pickup(a)* cannot be satisfied from the start because *pickup(b) preceding pickup(a) would negate it*.

$\downarrow$

we apply the **white knight** using the plan action *stack(b,c)* that reinforces *handempty*:

pickup(b) < stack (b, c) <pickup(a)

in this case the white knigth is not a new action is an action that is already in the planning, we should search always before ig the action for the knight is alreafdy in the plan (better)

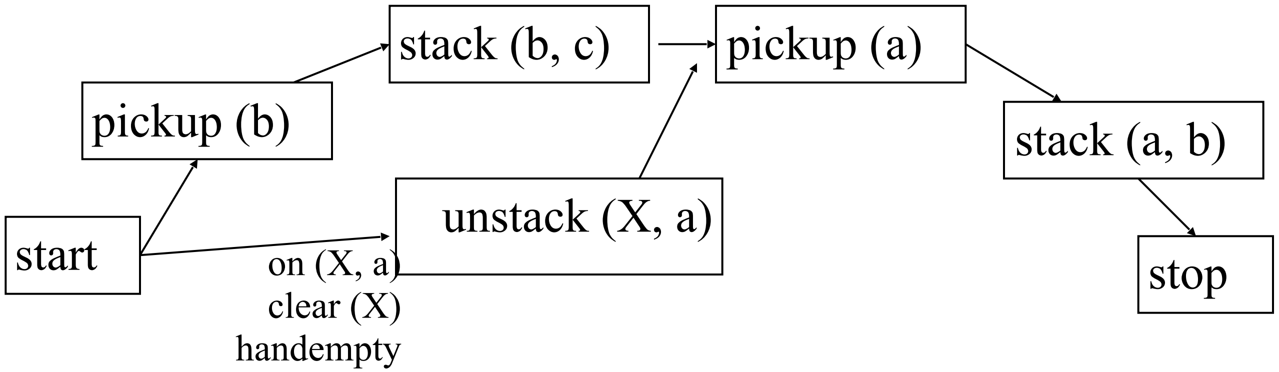
Orderings: [..., pickup(b)< stack (a,b), pickup(b) < pickup(a), stack (b,c) <pickup (a)]
Causal Links: [..., <start, pickup(b), handempty>, <stack (b,c), pickup(a), handempty>].
Goal Agenda: [clear(a)]

Example: Sussmann Anomaly

To satisfy *clear (a)* we can add the action:

unstack (X, a)
PRECOND: *handempty, on (X, a), clear (X)*
POSTCOND: *handempty not, clear (a), holding (X) not on (X, a)*

current partial plan:



Orderings: [..., start < unstack (X, a), unstack (X, a) < stop, unstack (X, a) <pickup (a)]
the causal link list: [..., <unstack(X, a), pickup(a), clear (a)>
Agenda of goals: [On (X, a), clear (X), handempty]

The three preconditions are met on the agenda in the initial state by imposing *X* = *c* in the move *unstack (X, a).*

Example: Sussmann Anomaly

unstack (c, a) is a threat to the causal link *<start, pickup(b), handempty>*

Add a new move **white knight**

putdown (c)
PRECOND: *holding (c)*
POSTCOND: *ontable (c), clear (c), handempty, not holding (c)*

ordering as well:
unstack (c, a) <putdown (c) <pickup (b)

We then used two types of white knights, one using an action which is already in the plan, and one introducing a new action.

Now all the preconditions are met so we can linearize the plan (add the ordering constraints) and possibly instantiating not yet instantiated variables, to get a concrete plan.

1) unstack (c, a) 2) putdown (c) 3) pickup (b)
4) stack (b, c) 5) pickup(a) 6) stack (a, b)

CLOSING REMARKS

- It is always preferable to apply promotion and demotion before white knight (in particular when the action inserted is a new action not belonging to the plan).
- Unfortunately non-linear planners can generate very inefficient plans, even if correct.
- Planning is semi-decidable: if there is a plan that solves a problem the planner finds it, but if there is not, the planner can work indefinitely.
- In domains of increasing complexity it is hard to use a correct and complete planner, which is efficient and domain independent. Often we use ad-hoc methods.

Planning in practice

- Many applications in complex domains:
  - Planners for the Internet (search for information)
  - Softbots

  https://www.washington.edu/research/pathbreakers/1991a.html

Management of space missions

http://ti.arc.nasa.gov/tech/asr/planning-and-scheduling/

  - Robotics

http://www.robocup.org/

  - Graphplan developed by Carnegie Mellon University

http://www.cs.cmu.edu/~avrim/graphplan.html

  - Industrial production plans
  - Logistics

- Classical algorithms have efficiency problems in case of complex domains

- There are techniques that make the algorithms more efficient

$\downarrow$

HIERARCHICAL PLANNING

HIERARCHICAL PLANNING

Hierarchical planners are search algorithms that manage the creation of complex plans at **different levels of abstraction**, by considering the simplest details only after finding a solution for the most difficult ones.

➢ We need a language that enables operators at different levels of abstraction:
  – *Values of criticality assigned to the preconditions*
  – *Atomic operators vs. Marco operators*

All operators are again defined by PRECONDITIONS and EFFECTS.

➢ Popular hierarchical planning algorithms:
  – *STRIPS-Like*
  – *Partial-Order*

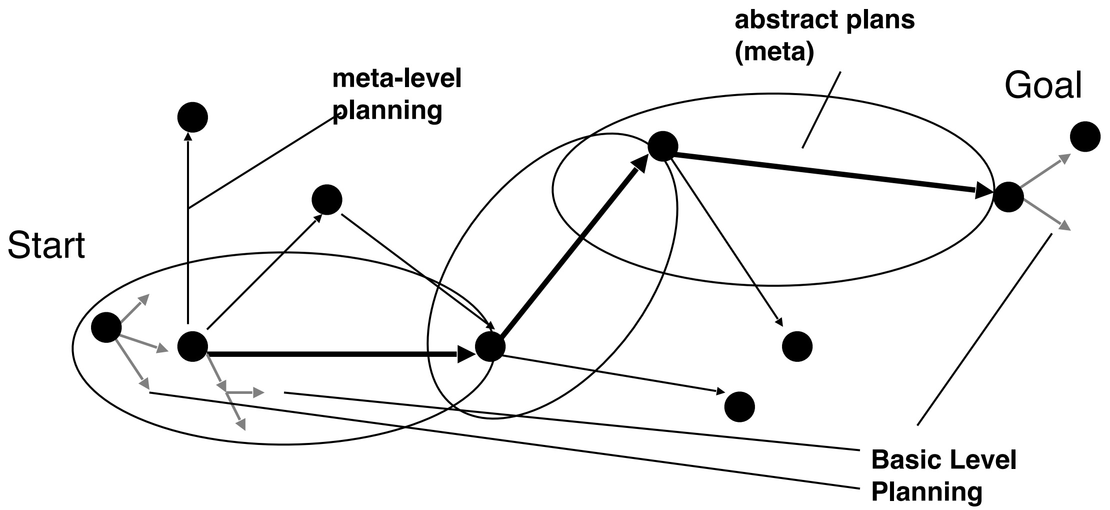
Given a goal, the hierarchical planner performs a ***meta-level search*** to generate a ***meta-level plan*** which leads from a state that is very close to the initial one to a state which is very close to the goal.

HIERARCHICAL PLANNING

The plan is then completed with a lower level search, taking account of details omitted at the previous level.

So a hierarchical algorithm must be able to:

- organize high (*meta-level*)
- expand abstract plans into concrete plans
  - planning abstract parts in terms of more specific actions (planning *basic level*)
  - expanding already prebuilt plans



ABSTRIPS

Hierarchical planner who enhances the Strips definition of actions with a **criticality value** (proportional to the complexity of its achievement) to each precondition.

The planning algorithm proceeds at different levels of abstraction spaces. At each level, lower level preconditions are ignored.

ABSTRIPS fully explores the space of a certain level of abstraction before moving on to a more detailed level: **length search**

At every level of abstraction, it generates a complete plan

Application examples:

- ➢ construction of a building,
- ➢ organization of a trip,
- ➢ draft a top-down program.

ABSTRIPS: Methodology of solution

1. A threshold value is fixed.
2. All the preconditions whose criticality value is less than the threshold value are considered true.
3. STRIPS(*) finds a plan that meets all the preconditions whise value is greater or equal to the threshold value.
4. It then uses the full plan pattern obtained as a guide and lowers the value of the threshold.
5. It extends the plan with operators that meet the preconditions whose level of criticality is higher than or equal to the new threshold value.
6. It lowers the threshold value until all the preconditions of the original rules have been considered.

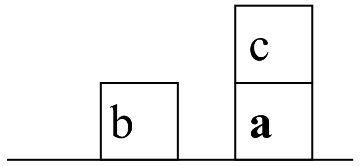
It is important to give good values critical preconditions !!!

(*) At every level we can use a different planner, not necessarily STRIPS.

Example (Algorithm Strips-Like)

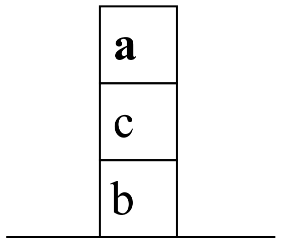
➢ Initial state:

clear (b)
clear (c)
on (c, a)
handempty
ontable (a)
ontable (b)



➢ Goal:

on (c, b) ∧ *on (a, c)*



We specify a hierarchy of goals and preconditions assigning criticality values (that reflect the degree of difficulty in satisfying them):

on **(3)**
ontable, clear, holding **(2)**
handempty **(1)**

Example (Algorithm Strips-Like)

We use the STRIPS rules:

pickup (X)
PRECOND: *ontable (X), clear (X), handempty*
DELETE: *ontable (X), clear (X), handempty*
ADD: *holding (X)*

putdown (X)
PRECOND: *holding (X)*
DELETE: *holding (X)*
ADD: *ontable (X), clear (X), handempty*

stack (X, Y)
PRECOND: *holding (X), clear (Y)*
DELETE: *holding (X), clear (Y)*
ADD: *handempty, on (X, Y), clear (X)*

unstack (X, Y)
PRECOND: *handempty, on (X, Y), clear (X)*
DELETE: *handempty, on (X, Y), clear (X)*
ADD: *holding (X), clear (Y)*

Example (Algorithm Strips-Like)

- **First level** of abstraction: we consider only the preconditions with criticality value 3 and you get the following goal stack:

on (c, b)
on (a, c)
on (c, b) ∧ on (a, c)

- The action *stack (c, b)* is added to the plan to meet *on (c, b)*.
- Since its preconditions are all less critical than 3 they are considered to be met.

A new state is generated by simulating the execution of action *stack (c, b)*.

state description	**goal stack**
clear (b)	on (a, c)
clear (c)	on (c, b) ∧ on (a, c)
ontable (a)	
ontable (b)	
on (c, b)	
handempty	
on (c, a)	

Note: in the description of the state only effects with criticality greater than or equal to 3 are added/deleted. There may be inconsistencies, but this is fine!!

Example (Algorithm Strips-Like)

- The action *stack (a, c)* is added following the same process for *stack (c, b)*. The complete plan at Level 1 is:

  1. ***stack (a, c)***
  2. ***stack (c, b)***

- **Second level** of abstraction: we restart from initial state and in the goal stack we insert the initial goals, the actions computed at level 1 and their preconditions (along with a goal ordering):

  holding (c)
  clear (b)
  holding (c) ∧ clear (b)
  stack (c, b)
  holding (a)
  clear (c)
  holding (a) ∧ clear (c)
  stack (a, c)
  on (c, b) ∧ on (a, c)

Example (Algorithm Strips-Like)

- The condition *holding(c)* is satisfiable with the action *unstack(c, X)* and the stack becomes

  clear (c)
  on (c, X)
   clear (c) and on (c, X)
  unstack (c, X)
  clear (b)
  holding (c) ∧ clear (b)
  stack (c, b)
  holding (a)
  clear (c)
  holding (a) ∧ clear (c)
  stack (a, c)
  on (c, b) ∧ on (a, c)

- the preconditions of *unstack (c, X)* to be considered at level 2 (*clear(c)* and *on(c, X)*) are all met in the initial state with the substitution *X / a*.

Example (Algorithm Strips-Like)

Executing the action *unstack (c, a)* on the initial state results in:

state description	**goal stack**
clear (b)	clear (b)
clear (a)	holding (c) ∧ clear (b)
ontable (a)	**stack (c, b)**
ontable (b)	holding (a)
handempty	clear (c)
holding (c)	holding (a) ∧ clear (c)
	stack (a, c)
	on (c, b) ∧ on (a, c)

And so on until you get the full plan of level 2:

1. ***unstack (c, a)***
2. ***stack (c, b)***
3. ***pickup (a)***
4. ***stack (a, c)***

Example (Algorithm Strips-Like)

➢ **Third level** of abstraction: we have the following goal stack

handempty ∧ clear (c) ∧ on (c, a)
unstack (c, a)
holding (c) ∧ clear (b)
stack (c, b)
handempty ∧ clear (a) ∧ ontable (a)
pickup (a)
holding (a) ∧ clear (c)
stack (a, c)
on (c, b) ∧ on (a, c)

Only the precondition *handempty* still needs to be considered.
The search for a solution to level 3 in this case is simply a check: the solution at level 2 is also correct for level 3 and the search stops.

Note: A level 1 the valid plan

1. ***stack (a, c)***
2. ***stack (c, b)***

would fail causing backtracking.

⇦ ***Homework: check it!!***

HIERARCHICAL PLANNING *MACRO-OPERATORS*

Two types of operators:

- ***Atomic*** operators
- ***Macro*** operators

- ➢ **Atomic** operators represent elementary actions typically defined as STRIPS rules.
  - ➢ Atomic operators can be directly executed by an agent
- ➢ **Macro** operators in turn represent a set of elementary actions: they are decomposable into atomic operators
  - ➢ Macro operators before execution should be further decomposed
  - ➢ Their decomposition can be *precompiled* or from *plan*.

HIERARCHICAL PLANNING
MACRO-OPERATORS

Precompiled decomposition: the description of the macro operator also contains the DECOMPOSITION - the sequence of basic operators to be executed at run-time.

ACTION: ***Cook (X)***

PRECOND: *have (X), have (pot), have (salt) in (water, pot)*

EFFECT: *cooked*(X)

DECOMPOSITION: *S1: boil (water), S2: put (salt, water),*
S3: put (X, pot), S4: boilinWater (X)

ORDER: S1 <S2, S1 < S3, S2 < S4, S3 < S4

$$\begin{tikzcd}
 & S2 \arrow[dr] & \\
S1 \arrow[ur] \arrow[dr] & & S4 \\
 & S3 \arrow[ur] &
\end{tikzcd}$$

Planned decomposition: the planner must perform a low-level search for synthesising the atomic action plan that implements the macro action.

HIERARCHICAL PLANNING *MACRO-OPERATORS*

The planning algorithm can be either linear or non-linear

A hierarchical non-linear algorithm is similar to POP where at each step one can choose between:

- Reach an open goal with an operator (including macro operators)
- expand a macro step of the plan (the decomposition method can be precompiled or schedule).

```
function HD_POP (initialGoal, methods, operators) returns plan
 plan: = INITIAL_PLAN (start, stop, initialGoal)
 loop
   if  SOLUTION (plan) then return plan;
   choose between
     •   SN, C: = SELECT_SUBGOAL (plan);
         CHOOSE_OPERATOR (plan, operators, SN, C);
     •   SnonPrim: = SELECT_MACRO_STEP (plan)
         CHOOSE_DECOMPOSITION (SnonPrim, methods, plan)
   SOLVE_THREATS (plan)
 end
```

Example (POP-like Algorithm)

Initial state

have (pot), have (pan), have (oil), have (onion)

have (pasta), have (tomato), have (salt), have (water)

Goal

made (pasta, tomato)

ATOMIC ACTIONS

ACTION ***makePasta (X)***

PRECOND: *have (pasta), cooked(pasta), Sauce (X)*

EFFECT: *made(pasta, X)*

ACTION ***boil (X)***

PRECOND: *have (X), have (pot), in (X, pot), plain (X)*

EFFECT: *boiled (X)*

ACTION ***boilinWater (X)***

PRECOND: *have (X), have (pot), in (water, pot), boiled (water), in (salt, water), in (X, water)*

EFFECT: *cooked (X)*

ACTION ***cookSauce (X)***

PRECOND: *have (X), have (pan), in (onion, pan), fried (onion), in (X, oil)*

EFFECT: *sauce (X)*

Example (POP-like Algorithm)

ACTION ***fry (X)***

PRECOND: *have (X), have (pan), have (oil), in (oil pan), in (X, pan), plain (oil)*

EFFECT: *fried (X)*

ACTION: ***put (X, Y)***

PRECOND: *have (X), have (Y)*

EFFECT: *in (X, Y),¬ plain (Y)*

ACTIONS MACRO

ACTION: ***Cook (X)***

PRECOND: *have (X), have (pot), have (salt) in (water, pot)*

EFFECT: *cooked*(X)

DECOMPOSITION: *S1: boil (water), S2: put (salt, water), S3: put (X, pot), S4: boilinWater (X)*

ORDER: S1 < S2, S1 < S3, S2 < S4, S3 < S4

$$\begin{tikzcd}
 & S2 \arrow[dr] & \\
S1 \arrow[ur] \arrow[dr] & & S4 \\
 & S3 \arrow[ur] &
\end{tikzcd}$$

ACTION: ***MakeSauce (X)***

PRECOND: *have (X), have (oil), have (onion), have (pan)*

EFFECT: *sauce (X)*

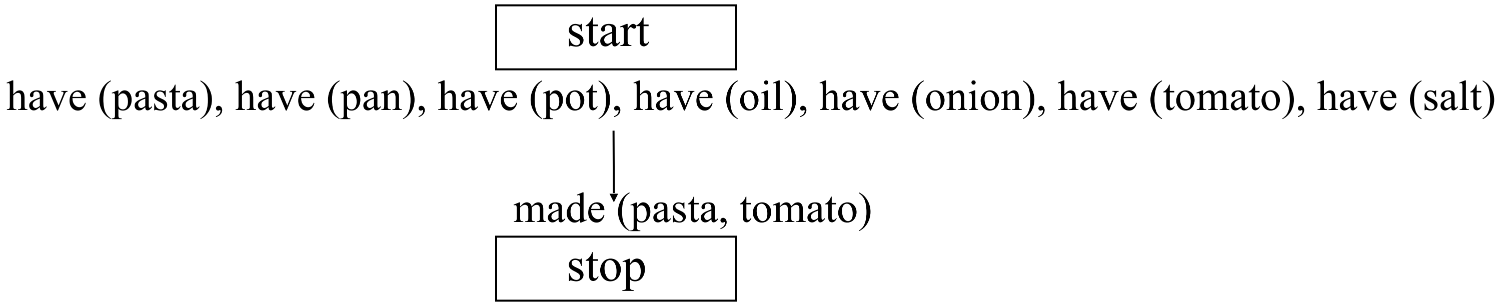
DECOM: *S4: put (oil pan), S5: put (onion, pan), S6: fry (onion), S7: put (X, oil), S8: cookSauce (X)*

ORDER: S4 < S6, S5 < S6, S6 < S7, S7 < S8

$$\begin{tikzcd}
S4 \arrow[r] & S6 \arrow[r] & S7 \arrow[r] & S8 \\
S5 \arrow[ur] & & &
\end{tikzcd}$$

Example (POP-like Algorithm)

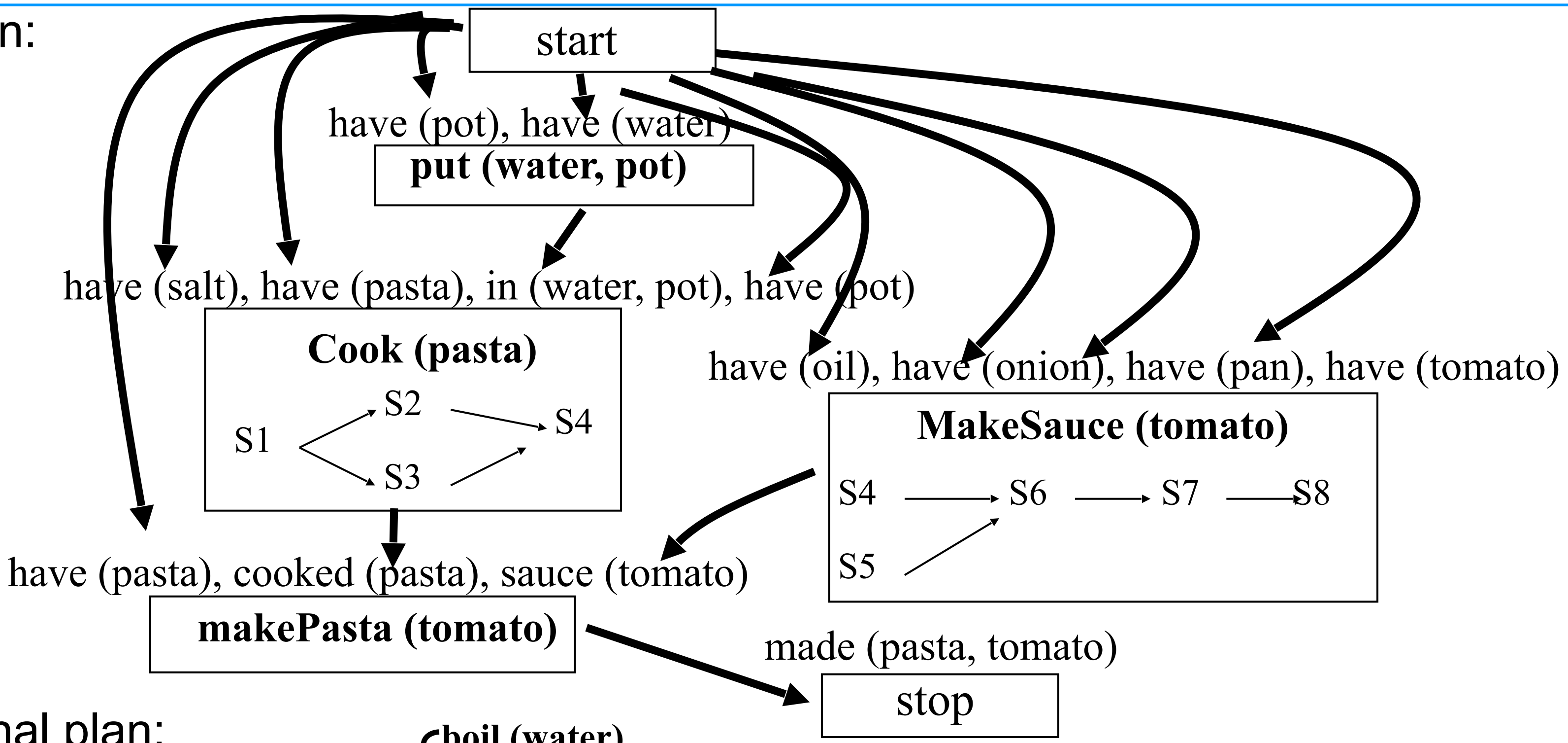
- Initial empty plan


start
have (pasta), have (pan), have (pot), have (oil), have (onion), have (tomato), have (salt)
made (pasta, tomato)
stop

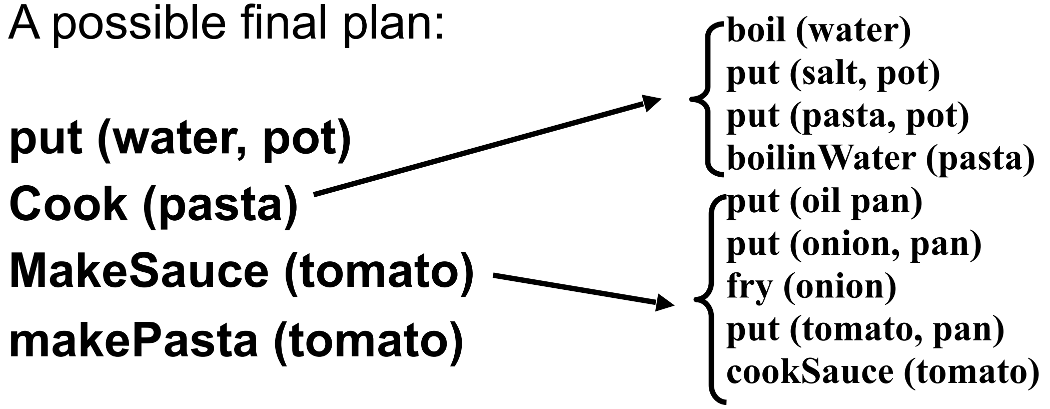
- At every step you can choose between
  - Reach an open goal with an operator (including macro operators)
  - Expand a macro step of the plan (the decomposition method can be precompiled or already planned).

Example (POP-like Algorithm)

Complete plan:


start
have (pot), have (water)
put (water, pot)
have (salt), have (pasta), in (water, pot), have (pot)
Cook (pasta)
S1
S2
S3
S4
have (oil), have (onion), have (pan), have (tomato)
MakeSauce (tomato)
S4
S5
S6
S7
S8
have (pasta), cooked (pasta), sauce (tomato)
makePasta (tomato)
made (pasta, tomato)
stop

A possible final plan:



DECOMPOSITION

To ensure the decomposition is safe, some properties must be guaranteed:

Constraints on the decomposition

- If the A macro action has the effect X and is expanded with the plan P
  - X must be the effect of at least one of the actions in which A is decomposed and it should be protected until the end of the plan P
  - each precondition of the actions in P must be guaranteed by the previous actions in P or it must be a precondition of A
  - the P action must not threat any causal link when P is substituted for A in the plan

Only under these conditions you can replace the macro action A with the plan P

DECOMPOSITION

Replacing A with P

➢ When replacing A with P, the orderings and causal links should be added

– **Orderings**

- for each B such that B <A then B <first(P) is imposed (first action of P)
- for each B such that A <B then last (P) <B is imposed (last action of P)

– **Causal links**

- if <S, A, C> is a causal link in the initial plan, then it must be replaced by a set of causal links <S, Si, C> where Si are the actions of P that have C as a precondition and no other step of A before it has a C as a precondition
- if <A, S, C> is a causal link in the initial plan, then it must be replaced by a set of causal links <Si, S, C> where Si are the actions that have C as an effect and no other step of P after it has the effect C

EXECUTION

Generative planners build plans that are then executed by an **executing agent**.

Possible problems encountered during execution:

- ➢ An action should be executed and its preconditions are not satisfied
  - – incomplete or incorrect knowledge
  - – unexpected conditions
  - – the world changes indipendently from the planner

- ➢ Action effects are not the one expected
  - – Errors of the executing agent
  - – Non deterministic/unpredictable effects

While executing, the agent should *perceive* the changes in the world and *Act* accordingly

EXECUTION

- Some planners run under the hypothesis of **Open World Assumption** as opposed to the *Closed World Assumption***:** they consider that the information that is not explicitly stated in a state is not false, but **unknown**
- The unknown information can be retrieved via **sensing actions** added to the plan.
- ***Sensing actions*** are modeled as causal actions.
- The preconditions are the conditions that must be true to perform a certain observation, while postconditions are the result of the observation.
- Two possible approaches:
  - Conditional Planning
  - Integration between Planning and Execution

CONDITIONAL PLANNING

A **conditional planner** is a search algorithm that generates various alternative plans for each source of uncertainty of the plan.

A **conditional plan** it is therefore constituted by:

- causal actions
- Sensing actions for retrieving unknown information
- Several alternative partial plans of which only one will be executed depending on the results of the observations.

Example: Conditional Planning

Causal actions:

remove (X, Y)
PRECOND: *on (X, Y), ¬* ***intact (X)***
EFFECT: ¬ *on (X, Y), off (X), clearHub (Y)*

puton (X, Y)
PRECOND: *off (X), clearHub (Y)*
EFFECT: *on (X, Y), ¬ off (X), ¬ clearHub (Y)*

inflate (X)
PRECOND: ***intact (X)****, flat (X)*
EFFECT: *inflated (X), ¬flat (X)*

Sensing action*:*

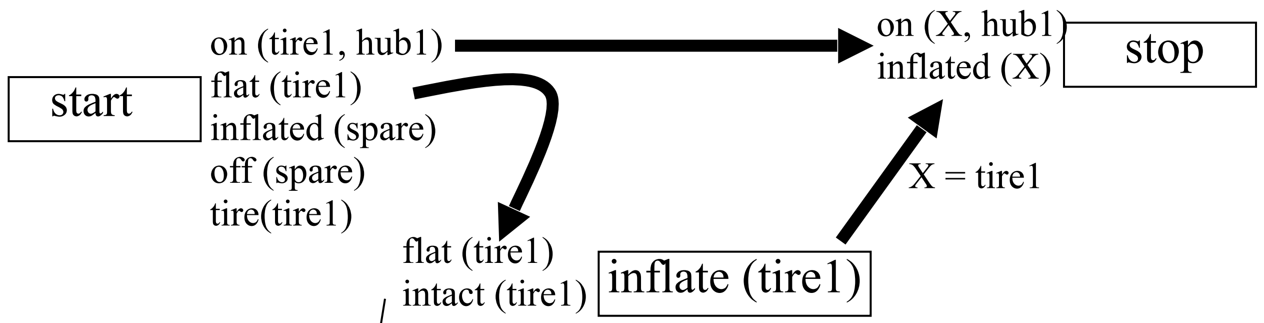
check(X)
PRECOND: tire (X)
EFFECT: knowsWhether (intact (X))

initial state*: on (tire1, hub1), flat (tire1), inflated (spare), off (spare), tire(tire1)*

Goal*: on(X, hub1), inflated (X)*

Example: Conditional Planning

A traditional planner (without sensing actions) would produce the following plan:

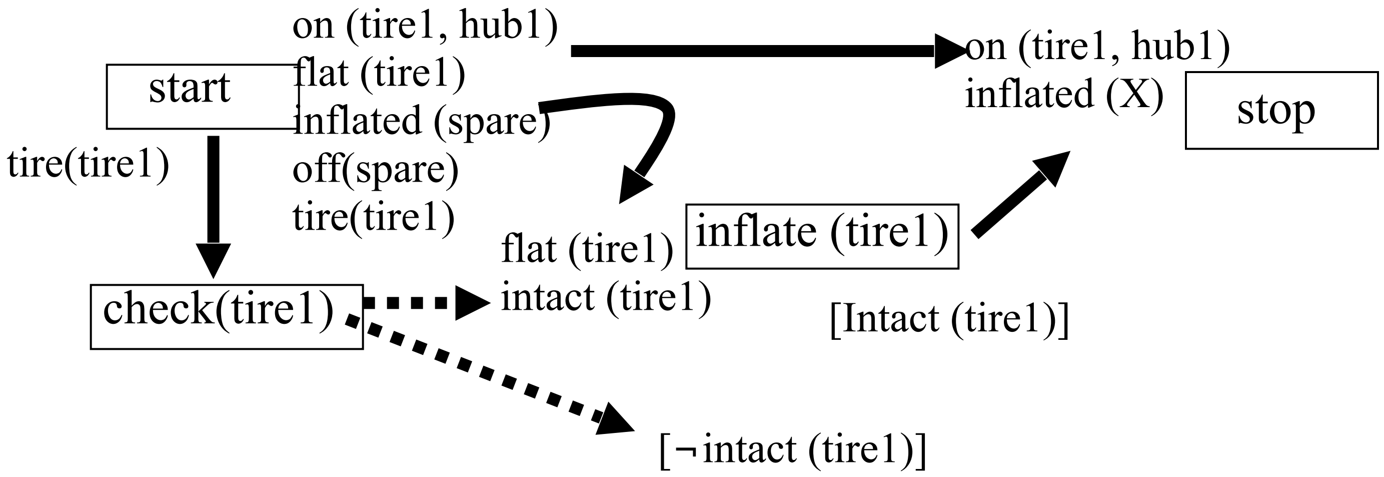


The condition *intact (tire1)* does not appear in the description of the initial state and cannot be obtained as an effect of any action: **failure** of the plan.

Upon backtracking the plan fails again as we get *X* = *spare*: *remove (tire1, hub1)* - *puton (spare, hub1)* as the precondition ¬ *intact (tire1)* cannot be achieved in any way.

Example: Conditional Planning

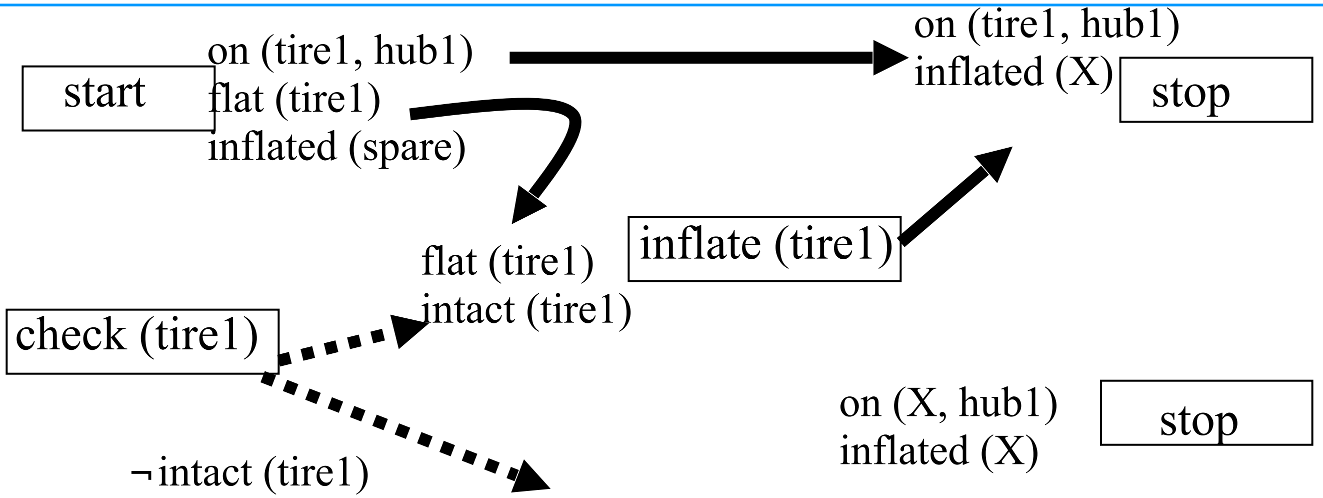
Using the sensing action one can build a **conditional plan**:



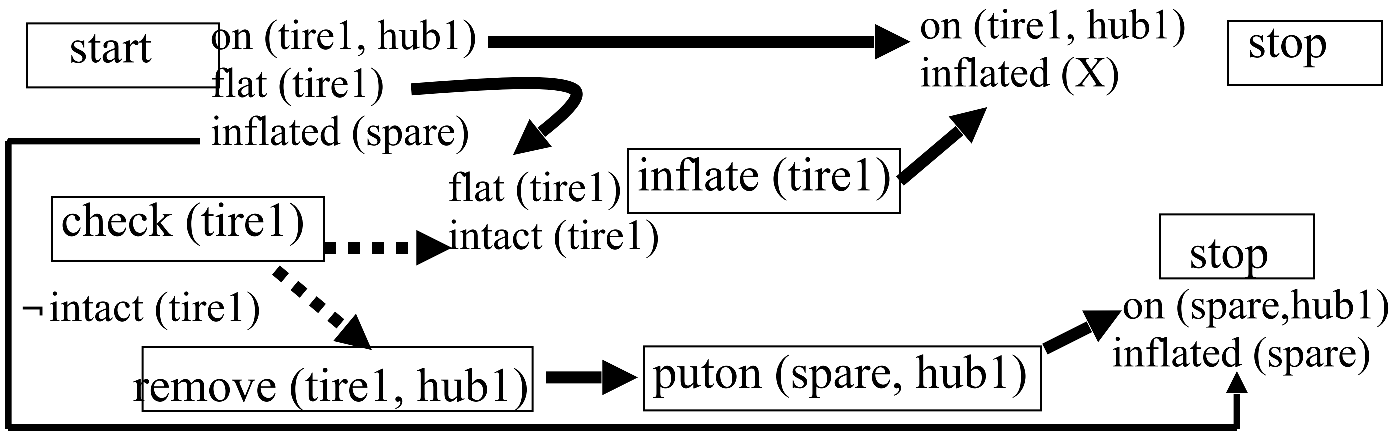
- ➢ *inflate(tire1)* is the correct plan in only one executing scenario: a **context** in which *intact (tire1)* is true in the initial state

- ➢ We should generate a copy of the goal for every other executing scenario and generate a corresponding plan for each of them.
- ➢ **We have an exponential number of plans**

Example: Conditional Planning



Conditional plan



Conditional Planning: limitations

- Combinatorial **explosion of the search tree** with high numbers of alternative contexts.
- A comprehensive plan which takes account every possible contingency might require a lot of **memory**.
- Not always all alternative contexts are known in advance
- Often conditional planners are associated with **probabilistic planners** that plan only for the most probable contexts.

Contingency planners

- Cassandra deterministic contingency planner
- Buridan builds plans that have a probability greater than a certain threshold
- **C.BURIDAN**
- **Algorithm https: //www.aaai.org/Papers/AIPS/1994/AIPS94-006.pdf**
- **Action representation Draper et al. 1994a**A probabilistic model of action for least-commitment planning with information gathering. In Proceedings of the Tenth International Conference on Uncertainty in Artificial Intelligence, pp. 178-186 Seattle, WA Morgan Kauffman.

- Systems interleaving planning and execution
- IPEM
- SAGE
- XII

REACTIVE PLANNING (Brooks - 1986)

We have described a deliberative planning process where the plan is built before execution

Reactive planners are on-line algorithms, capable of interacting with the world to deal with the dynamicity and the non-determinism of the environment:

- ➢ They observe the world in the planning stage
- ➢ They acquire unknown information
- ➢ They monitor the implementation of actions and check the effects
- ➢ They interleave planning and execution

Pure reactive systems do not plan, they only react as triggers to world variations.

PURE REACTIVE SYSTEMS

They have access to a knowledge base that describes what actions must be carried out and under what circumstances. Choose one action at a time, without any lookahead activicy.

- A thermostat uses the simple rules:

1) If the temperature T of the room is K degrees above the threshold T0, turn the air conditioner on;
2) If the room temperature is below T0 K degrees, turn the air conditioner off.

Advantages:

- They are able to interact with the real system. They are robust in domains for which it is difficult to provide complete and accurate models.
- They do not use models, but perceive world changes. That's why they are also extremely fast in responding.

Downside:

Their performance in predictable domains that require reasoning and deliberate is quite low (eg. Chess) as they are not able to generate plans.

HYBRID SYSTEMS

Modern responsive planners are **hybrids** integrate a **generative approach** and a **reactive approach** in order to exploit the computational capacity of the first and the ability to interact with the system of the second thus addressing the problem of the execution.

A **hybrid planner:**

- ➢ generates a plan to achieve the goal
- ➢ checks the preconditions of the action that is about to run, and the effects of the action that just executed
- ➢ backtracks the effects of action (importance of action reversibility) and reschedules in case of failures
- ➢ corrects the plans if unforeseen external events occur.