Planning

Some material adopted from notes
by Andreas Geyer-Schulz
and Chuck Dyer

Planning problem

- Find a **sequence of actions** that achieves a given **goal** when executed from a given **initial world state**. That is, given
  - a set of operator descriptions (defining the possible primitive actions by the agent),
  - an initial state description, and
  - a goal state description or predicate,

  compute a plan, which is
  - a sequence of operator instances, such that executing them in the initial state will change the world to a state satisfying the goal-state description.
- Goals are usually specified as a conjunction of goals to be achieved

Planning vs. problem solving

- Planning and problem solving methods can often solve the same sorts of problems
- Planning is more powerful because of the representations and methods used
- States, goals, and actions are decomposed into sets of sentences (usually in first-order logic)
- Search often proceeds through *plan space* rather than *state space* (though there are also state-space planners)
- Subgoals can be planned independently, reducing the complexity of the planning problem

Typical assumptions

- Atomic time: Each action is indivisible
- No concurrent actions are allowed (though actions do not need to be ordered with respect to each other in the plan)
- Deterministic actions: The result of actions are completely determined—there is no uncertainty in their effects
- Agent is the sole cause of change in the world
- Agent is omniscient: Has complete knowledge of the state of the world
- Closed World Assumption: everything known to be true in the world is included in the state description. Anything not listed is false.

Blocks world

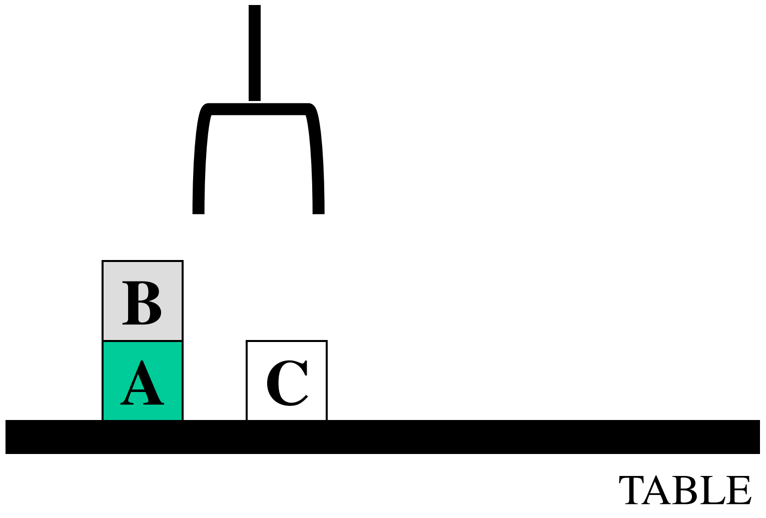
The **blocks world** is a micro-world that consists of a table, a set of blocks and a robot hand.

Some domain constraints:

- Only one block can be on another block
- Any number of blocks can be on the table
- The hand can only hold one block

Typical representation:

ontable(A)
ontable(C)
on(B,A)
handempty
clear(B)
clear(C)



General Problem Solver

- The General Problem Solver (GPS) system was an early planner (Newell, Shaw, and Simon)
- GPS generated actions that reduced the difference between some state and a goal state
- GPS used Means-Ends Analysis
  - Compare what is given or known with what is desired and select a reasonable thing to do next
  - Use a table of differences to identify procedures to reduce types of differences
- GPS was a state space planner: it operated in the domain of state space problems specified by an initial state, some goal states, and a set of operations

Situation calculus planning

- Intuition: Represent the planning problem using first-order logic
  - Situation calculus lets us reason about changes in the world
  - Use theorem proving to "prove" that a particular sequence of actions, when applied to the situation characterizing the world state, will lead to a desired result

Situation calculus

- **Initial state**: a logical sentence about (situation) S_0

  At(Home, S_0) ^ ~Have(Milk, S_0) ^ ~ Have(Bananas, S_0) ^ ~Have(Drill, S_0)

- **Goal state**:

  ($\exists$s) At(Home,s) ^ Have(Milk,s) ^ Have(Bananas,s) ^ Have(Drill,s)

- **Operators** are descriptions of how the world changes as a result of the agent's actions:

  $\forall$(a,s) Have(Milk,Result(a,s)) <=> ((a=Buy(Milk) ^ At(Grocery,s)) $\vee$
  (Have(Milk, s) ^ a~=Drop(Milk)))

- Result(a,s) names the situation resulting from executing action a in situation s.
- Action sequences are also useful: Result'(l,s) is the result of executing the list of actions (l) starting in s:

  ($\forall$s) Result'([],s) = s

  ($\forall$a,p,s) Result'([a|p]s) = Result'(p,Result(a,s))

Situation calculus II

- A solution is a plan that when applied to the initial state yields a situation satisfying the goal query:

  At(Home,Result'(p,S_0))

  ^ Have(Milk,Result'(p,S_0))

  ^ Have(Bananas,Result'(p,S_0))

  ^ Have(Drill,Result'(p,S_0))

- Thus we would expect a plan (i.e., variable assignment through unification) such as:

  p = [Go(Grocery), Buy(Milk), Buy(Bananas), Go(HardwareStore), Buy(Drill), Go(Home)]

Situation calculus: Blocks world

- Here's an example of a situation calculus rule for the blocks world:
  - Clear (X, Result(A,S)) ↔
    [Clear (X, S) ∧
    (¬(A=Stack(Y,X) ∨ A=Pickup(X))
    ∨ (A=Stack(Y,X) ∧ ¬(holding(Y,S))
    ∨ (A=Pickup(X) ∧ ¬(handempty(S) ∧ ontable(X,S) ∧ clear(X,S))))]
    ∨ [A=Stack(X,Y) ∧ holding(X,S) ∧ clear(Y,S)]
    ∨ [A=Unstack(Y,X) ∧ on(Y,X,S) ∧ clear(Y,S) ∧ handempty(S)]
    ∨ [A=Putdown(X) ∧ holding(X,S)]
- English translation: A block is clear if (a) in the previous state it was clear and we didn't pick it up or stack something on it successfully, or (b) we stacked it on something else successfully, or (c) something was on it that we unstacked successfully, or (d) we were holding it and we put it down.
- Whew!!! There's gotta be a better way!

Situation calculus planning: Analysis

- This is fine in theory, but remember that problem solving (search) is exponential in the worst case
- Also, resolution theorem proving only finds *a* proof (plan), not necessarily a good plan
- So we restrict the language and use a special-purpose algorithm (a planner) rather than general theorem prover

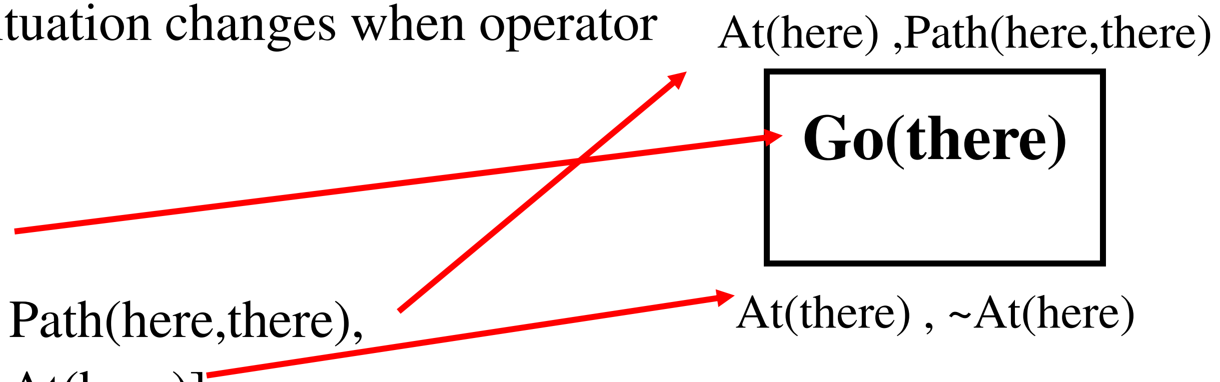
Basic representations for planning

- Classic approach first used in the **STRIPS** planner circa 1970
- States represented as a conjunction of ground literals
  - at(Home) ^ ~have(Milk) ^ ~have(bananas) ...
- Goals are conjunctions of literals, but may have variables which are assumed to be existentially quantified
  - at(x) ^ have(Milk) ^ have(bananas) ...
- Do not need to fully specify state
  - Non-specified either don't-care or assumed false
  - Represent many cases in small storage
  - Often only represent changes in state rather than entire situation
- Unlike theorem prover, not seeking whether the goal is true, but is there a sequence of actions to attain it

Operator/action representation

- Operators contain three components:
  - **Action description**
  - **Precondition** - conjunction of positive literals
  - **Effect** - conjunction of positive or negative literals which describe how situation changes when operator is applied
- Example:

Op[Action: Go(there),
  Precond: At(here) ^ Path(here,there),
  Effect: At(there) ^ ~At(here)]



- All variables are universally quantified
- Situation variables are implicit
  - preconditions must be true in the state immediately before operator is applied; effects are true immediately after

Blocks world operators

- Here are the classic basic operations for the blocks world:
  - stack(X,Y): put block X on block Y
  - unstack(X,Y): remove block X from block Y
  - pickup(X): pickup block X
  - putdown(X): put block X on the table
- Each will be represented by
  - a list of preconditions
  - a list of new facts to be added (add-effects)
  - a list of facts to be removed (delete-effects)
  - optionally, a set of (simple) variable constraints
- For example:

```
preconditions(stack(X,Y), [holding(X),clear(Y)])
deletes(stack(X,Y), [holding(X),clear(Y)]).
adds(stack(X,Y), [handempty,on(X,Y),clear(X)])
constraints(stack(X,Y), [X\==Y,Y\==table,X\==table])
```

Blocks world operators II

```
operator(stack(X,Y),
        Precond [holding(X),clear(Y)],
        Add [handempty,on(X,Y),clear(X)],
        Delete [holding(X),clear(Y)],
        Constr [X\==Y,Y\==table,X\==table]).
```

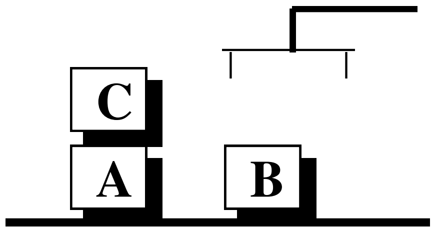
```
operator(unstack(X,Y),
      Pre [on(X,Y), clear(X), handempty],
       ADD[holding(X),clear(Y)],
       Del [handempty,clear(X),on(X,Y)],
       [X\==Y,Y\==table,X\==table]).
```

```
operator(pickup(X),
        [ontable(X), clear(X), handempty],
        [holding(X)],
        [ontable(X),clear(X),handempty],
        [X\==table]).
```

```
operator(putdown(X),
        [holding(X)],
        [ontable(X),handempty,clear(X)],
        [holding(X)],
        [X\==table]).
```

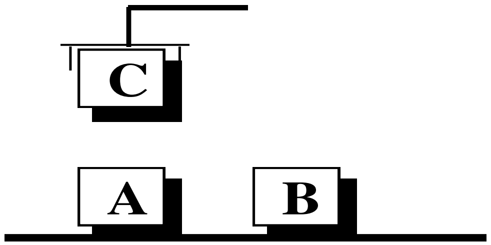
STRIPS planning

- STRIPS maintains two additional data structures:
  - **State List** - all currently true predicates.
  - **Goal Stack** - a push down stack of goals to be solved, with current goal on top of stack.
- If current goal is not satisfied by present state, examine add lists of operators, and push operator and preconditions list on stack. (Subgoals)
- When a current goal is satisfied, POP it from stack.
- When an operator is on top stack, record the application of that operator on the plan sequence and use the operator’s add and delete lists to update the current state.



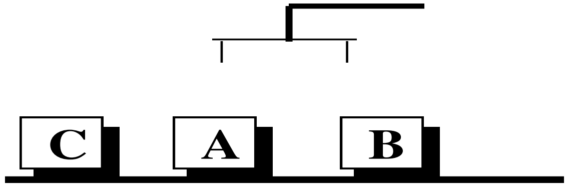
CLEAR(B)
ON(C,A)
CLEAR(C)
ONTABLE(A)
ONTABLE(B)
HANDEMPTY

<u>UNSTACK(x,y)</u>
P & D: HANDEMPTY,
CLEAR(x), ON(x,y)
A: HOLDING(x),
CLEAR(y)



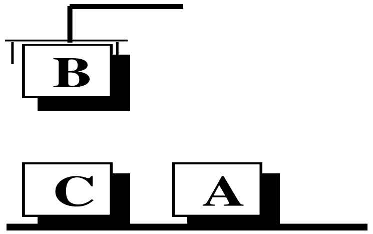
CLEAR(A)
CLEAR(B)
HOLDING(C)
ONTABLE(A)
ONTABLE(B)

<u>PUTDOWN(x)</u>
P & D: HOLDING(x)
A: ONTABLE(x),
CLEAR(x),
HANDEMPTY



CLEAR(A)
CLEAR(B)
ONTABLE(A)
ONTABLE(B)
ONTABLE(C)
CLEAR(C)
HANDEMPTY

<u>PICKUP(x)</u>
**P & D: ONTABLE(x),
CLEAR(x), HANDEMPTY**
A: HOLDING(x)



CLEAR(A)
ONTABLE(A)
ONTABLE(C)
CLEAR(C)
HOLDING(B)

<u>STACK(x,y)</u>
**P & D: HOLDING(x),
CLEAR(y)**
A: HANDEMPTY, ON(x,y), CLEAR(x)

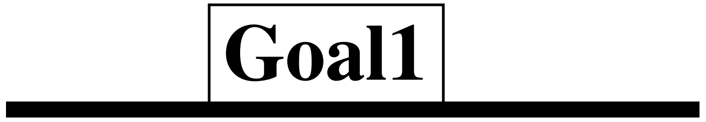
etc.

The original STRIPS system used a *goal stack* to control its search.

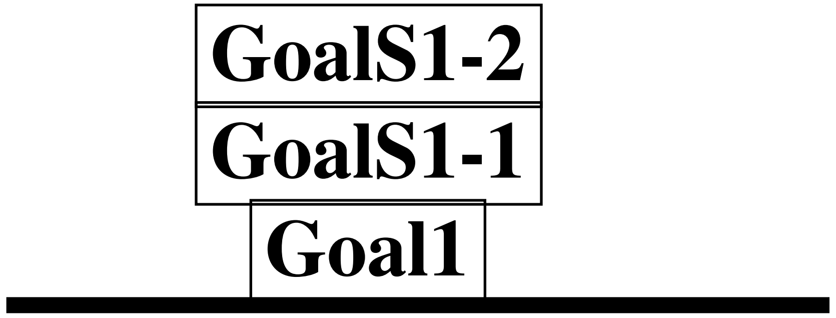
The system has a database and a goal stack, and it focuses attention on solving the top goal (which may involve solving sub-goals, which are then pushed onto the stack, etc.)

The basic idea

Place goal in goal stack:



Considering top Goal1, place onto it its sub-goals:



Then try to solve sub-goal GoalS1-2, and continue…

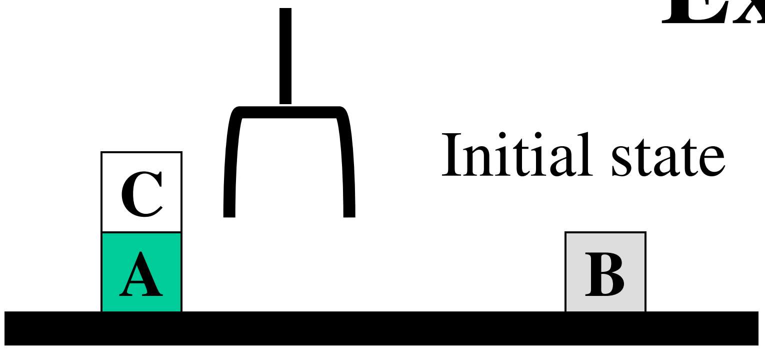
Stack Manipulation Rules I

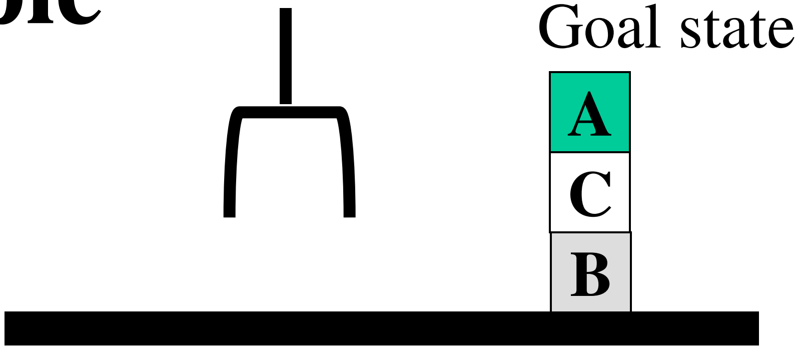
If on top of goal stack	Than do:
• Compound or single goal matching the current state description	• Remove it
• Compound goal not matching the current state description	1. Keep original compound goal on stack; 2. List the unsatisfied component goals on the stack in some new order

Stack Manipulation Rules II

If on top of goal stack	Than do:
• Single-literal goal not matching the current state description.	• Find new rule whose instantiated add-list includes the goal, and 1. Replace the goal with the instantiated rule; 2. Place the rule's instantiated precondition formula on top of stack
• Rule	1. Remove rule from stack; 2. Update database using rule; 3. Keep track of rule (for solution)
• Nothing	• Stop

Example





1. Place on stack original goal:

Stack:

On(A,C) & On(C,B)

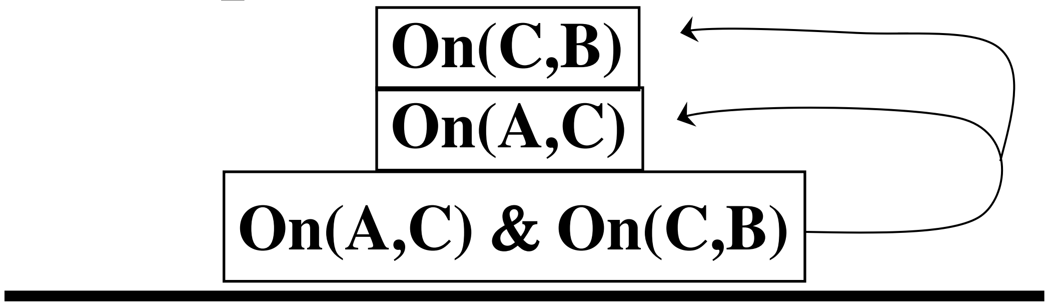
Database:

CLEAR(B)
ON(C,A)
CLEAR(C)
ONTABLE(A)
ONTABLE(B)
HANDEMPTY

Example

2. Since top goal is unsatisfied compound goal, list its unsatisfied subgoals on top of it:

Stack:

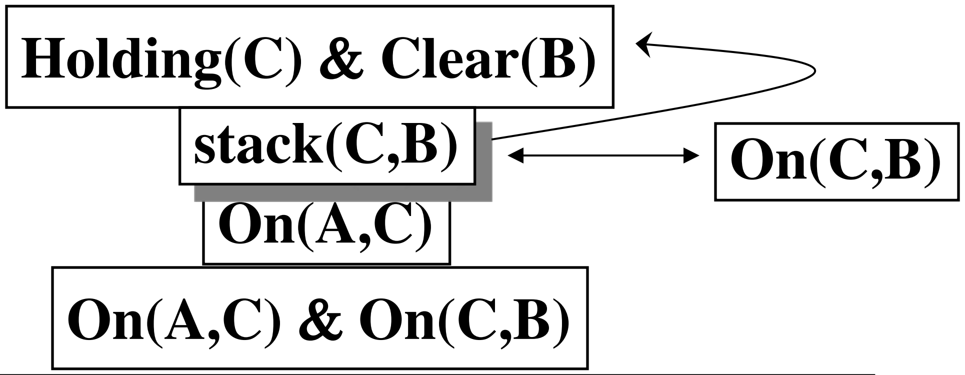


Database (unchanged):

CLEAR(B)
ON(C,A)
CLEAR(C)
ONTABLE(A)
ONTABLE(B)
HANDEMPTY

Example

3. Since top goal is unsatisfied single-literal goal, find rule whose instantiated add-list includes the goal, and: a. Replace the goal with the instantiated rule; b. Place the rule's instantiated precondition formula on top of stack



Stack:

Database (unchanged):

CLEAR(B)
ON(C,A)
CLEAR(C)
ONTABLE(A)
ONTABLE(B)
HANDEMPTY

Example

4. Since top goal is unsatisfied compound goal, list its subgoals on top of it:

Stack:

Clear(B)

Holding(C)

Holding(C) & Clear(B)

stack(C,B)

On(A,C)

On(A,C) & On(C,B)

Database (unchanged):

CLEAR(B)
ON(C,A)
CLEAR(C)
ONTABLE(A)
ONTABLE(B)
HANDEMPTY

Example

5. Single goal on top of stack matches data base, so remove it:

Stack:

~~**Clear(B)**~~
Holding(C)
Holding(C) & Clear(B)
stack(C,B)
On(A,C)
On(A,C) & On(C,B)

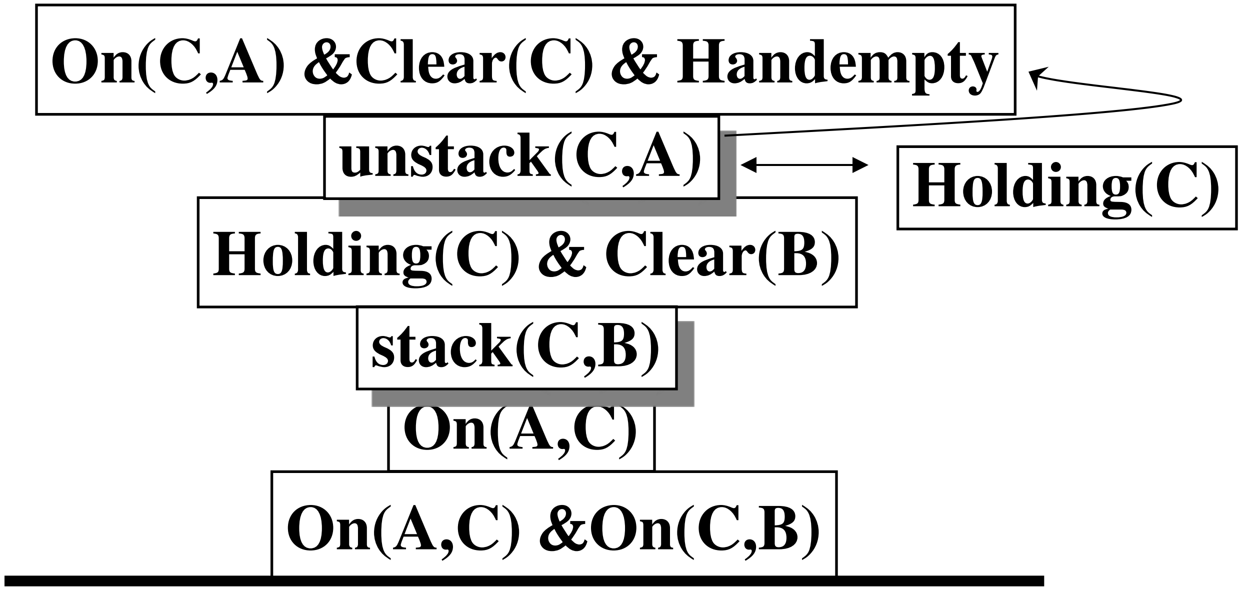
Database (unchanged):

CLEAR(B)
ON(C,A)
CLEAR(C)
ONTABLE(A)
ONTABLE(B)
HANDEMPTY

Example

6. Since top goal is unsatisfied single-literal goal, find rule whose instantiated add-list includes the goal, and: a. Replace the goal with the instantiated rule; b. Place the rule's instantiated precondition formula on top of stack

Stack:



Database: (unchanged)

Example

7. Compound goal on top of stack matches data base, so remove it:

Stack:

~~**On(C,A) &Clear(C) & Handempty**~~

unstack(C,A)

Holding(C) & Clear(B)

stack(C,B)

On(A,C)

On(A,C) &On(C,B)

Database (unchanged):

CLEAR(B)
ON(C,A)
CLEAR(C)
ONTABLE(A)
ONTABLE(B)
HANDEMPTY

Example

8. Top item is rule, so:
   a. Remove rule from stack;
   b. Update database using rule;
   c. Keep track of rule (for solution)

Stack:

~~unstack(C,A)~~

Holding(C) & Clear(B)

stack(C,B)

On(A,C)

On(A,C) &On(C,B)

Database:

unstack(X,Y):

Add - [holding(X),clear(Y)]

Delete -[handempty,clear(X),on(X,Y)]

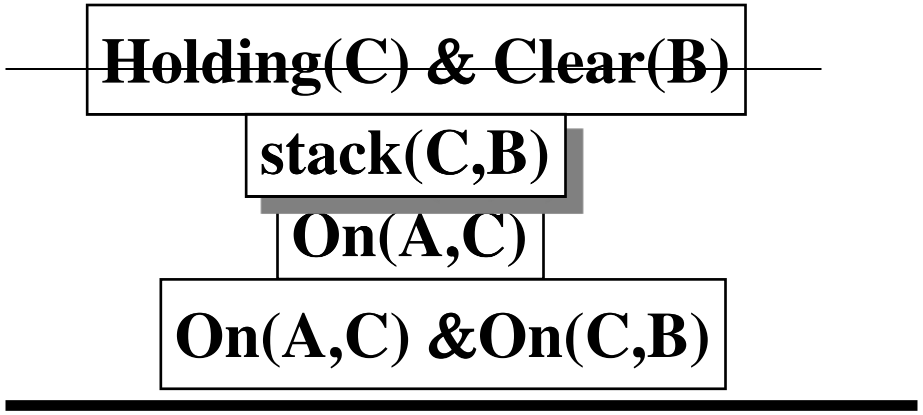
CLEAR(B)
ONTABLE(A)
ONTABLE(B)
HOLDING(C)
CLEAR(A)

Solution: {unstack(C,A)}

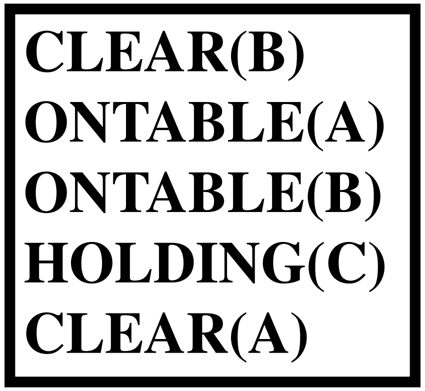
Example

9. Compound goal on top of stack matches data base, so remove it:

Stack:



Database:
(unchanged)



Solution: {unstack(C)}

Example

10. Top item is rule, so:
    a. Remove rule from stack;
    b. Update database using rule;
    c. Keep track of rule (for solution)

Stack:

~~stack(C,B)~~

On(A,C)

On(A,C) &On(C,B)

ONTABLE(A)
ONTABLE(B)
HANDEMPTY
CLEAR(A)
CLEAR(C)
ON(C,B)

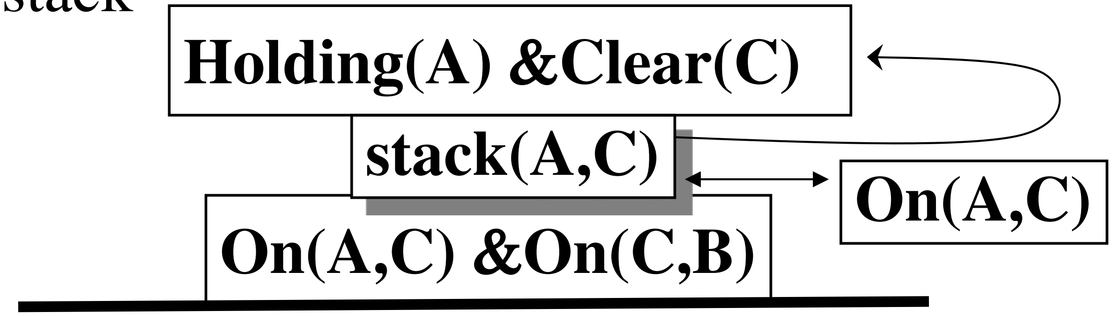
Database:
stack(X,Y):
Add - [handempty,on(X,Y),clear(X)]
Delete - [holding(X),clear(Y)]

Solution: {unstack(C), stack(C,B)}

Example

11. Since top goal is unsatisfied single-literal goal, find rule whose instantiated add-list includes the goal, and: a. Replace the goal with the instantiated rule; b. Place the rule's instantiated precondition formula on top of stack

Stack:



Database:
(unchanged)

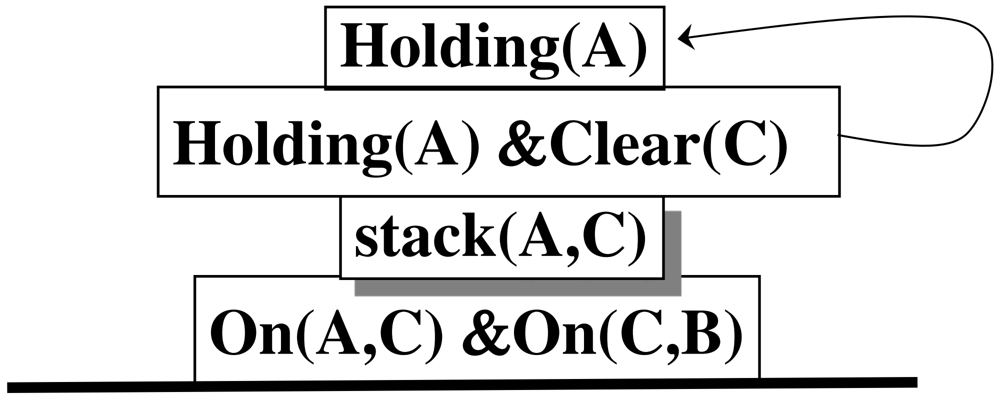
ONTABLE(A)
ONTABLE(B)
HANDEMPTY
CLEAR(A)
CLEAR(C)
ON(C,B)

Solution: {unstack(C), stack(C,B)}

Example

12. Since top goal is unsatisfied compound goal, list its unsatisfied sub-goals on top of it:

Stack:



Database:
(unchanged)

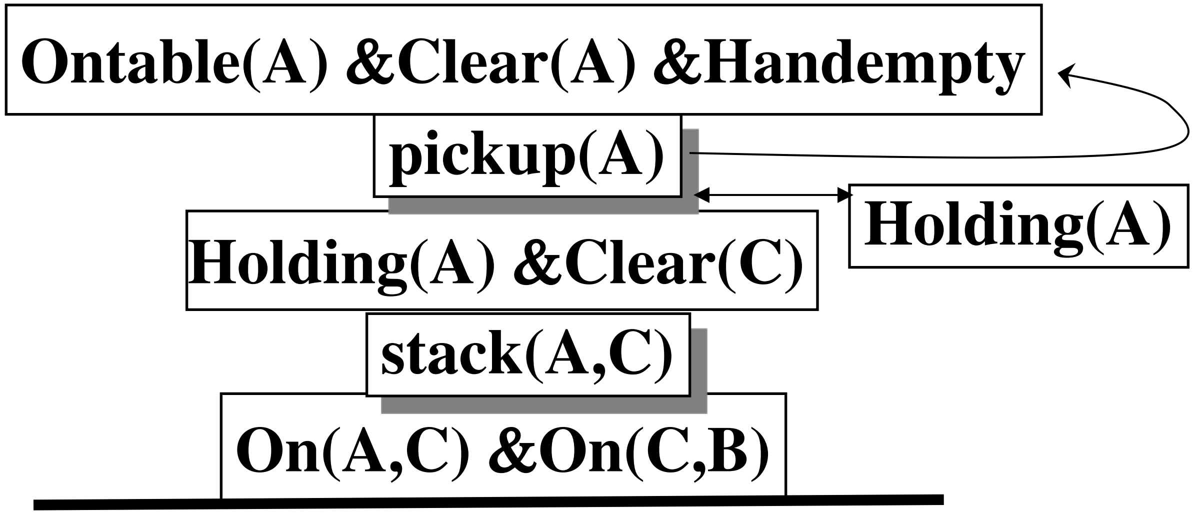
ONTABLE(A)
ONTABLE(B)
HANDEMPTY
CLEAR(A)
CLEAR(C)
ON(C,B)

Solution: {unstack(C), stack(C,B)}

Example

13. Since top goal is unsatisfied single-literal goal, find rule whose instantiated add-list includes the goal, and: a. Replace the goal with the instantiated rule; b. Place the rule's instantiated precondition formula on top of stack

Stack:



Database:
(unchanged)

Solution: {unstack(C), stack(C,B)}

Example

14. Compound goal on top of stack matches data base, so remove it:

Stack:

~~Ontable(A) &Clear(A) &Handempty~~

pickup(A)

Holding(A) &Clear(C)

stack(A,C)

On(A,C) &On(C,B)

Database:
(unchanged)

ONTABLE(A)
ONTABLE(B)
HANDEMPTY
CLEAR(A)
CLEAR(C)
ON(C,B)

Solution: {unstack(C), stack(C,B)}

Example

15. Top item is rule, so:
    a. Remove rule from stack;
    b. Update database using rule;
    c. Keep track of rule (for solution)

Stack:

~~**pickup(A)**~~

Holding(A) &Clear(C)

stack(A,C)

On(A,C) &On(C,B)

Database:

pickup(X):
Add - [holding(X)]
Delete - [ontable(X),clear(X),handempty]

ONTABLE(B)
ON(C,B)
CLEAR(C)
HOLDING(A)

Solution: {unstack(C), stack(C,B),pickup(A)}

Example

16. Compound goal on top of stack matches data base, so remove it:

Stack:

~~Holding(A) &Clear(C)~~

stack(A,C)

On(A,C) &On(C,B)

Database:
(unchanged)

ONTABLE(B)
ON(C,B)
CLEAR(C)
HOLDING(A)

Solution: {unstack(C), stack(C,B),pickup(A)}

Example

17. Top item is rule, so:
    a. Remove rule from stack;
    b. Update database using rule;
    c. Keep track of rule (for solution)

Stack:

~~**stack(A,C)**~~

On(A,C) &On(C,B)

Database:

stack(X,Y):
Add - [handempty,on(X,Y),clear(X)]
Delete - [holding(X),clear(Y)]

ONTABLE(B)
ON(C,B)
ON(A,C)
CLEAR(A)
HANDEMPTY

Solution: {unstack(C), stack(C,B),pickup(A), stack(A,C)}

Example

18. Compound goal on top of stack matches data base, so remove it:

Stack:

~~On(A,C) &On(C,B)~~

Database:

stack(X,Y):

Add - [handempty,on(X,Y),clear(X)]

Delete - [holding(X),clear(Y)]

ONTABLE(B)
ON(C,B)
ON(A,C)
CLEAR(A)
HANDEMPTY

Solution: {unstack(C), stack(C,B),pickup(A), stack(A,C)}

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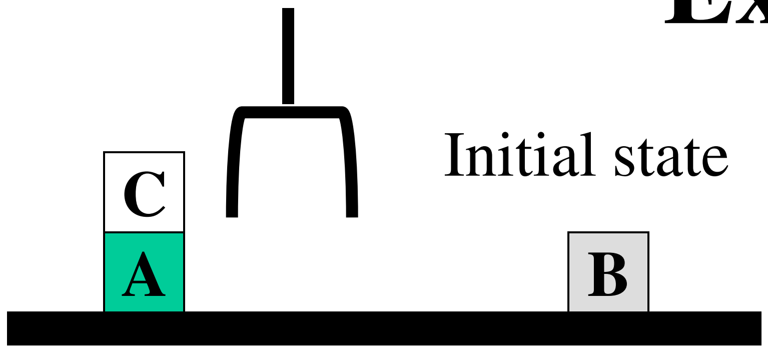
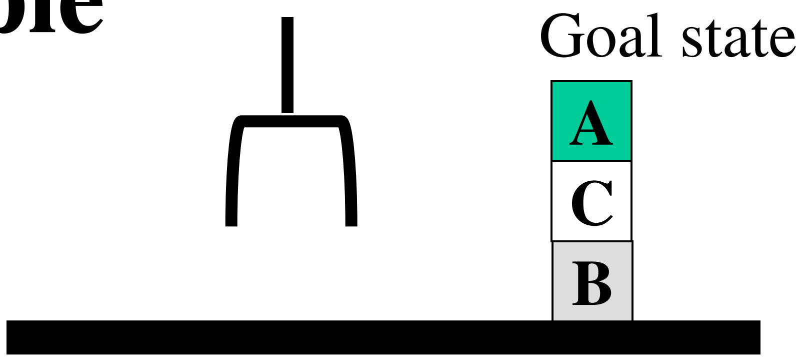
19. Stack is empty, so stop. $\Longrightarrow$

Solution: {unstack(C), stack(C,B),pickup(A), stack(A,C)}

Example





In solving this problem, we took some shortcuts—we branched in the right direction every time.

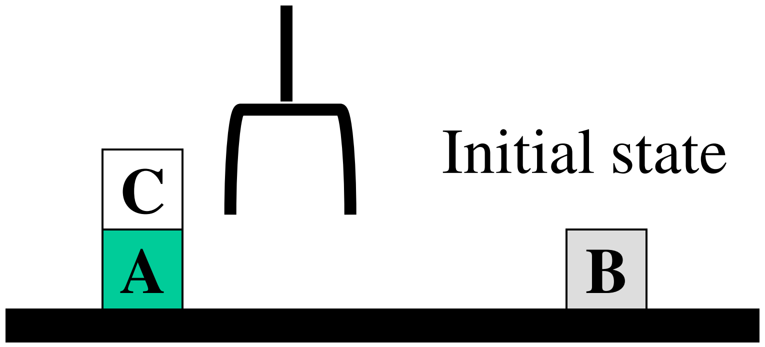
In practice, searching can be guided by

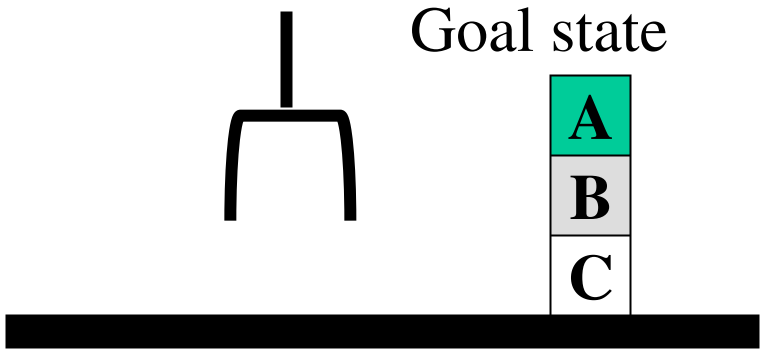
1. Heuristic information (e.g., try to achieve "HOLDING(x)" last)

2. Detecting unprofitable paths (e.g., when the newest goal set has become a superset of the original goal set)

3. Considering useful operator side effects (by scanning down the stack).

Sussman Anomaly





I: **ON(C,A)**
ONTABLE(A)
ONTABLE(B)
ARMEMPTY

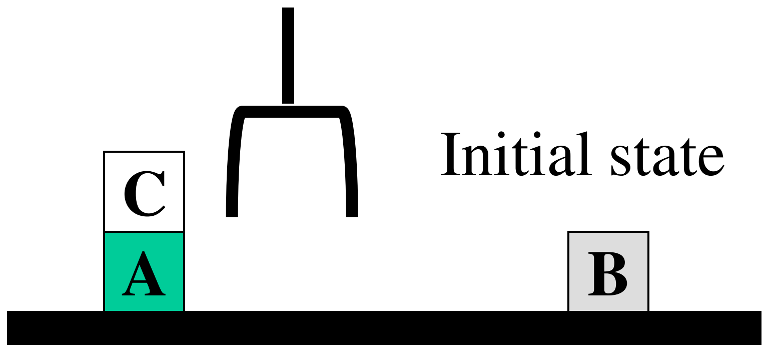
G: **ON(A,B)**
ON(B,C)

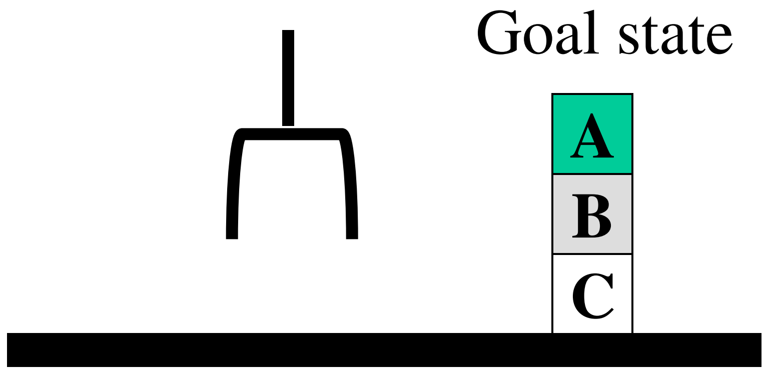
It could try ON(B,C) first, then ON(A,B)—but it will find that the first goal has been undone. So the first goal will be added back onto the stack and solved.

Sussman Anomaly

The final sequence is inefficient:

PICKUP(B)
STACK(B,C)
UNSTACK(B,C)
PUTDOWN(B)
UNSTACK(C,A)
PUTDOWN(C)
PICKUP(A)
STACK(A,B)
UNSTACK(A,B)
PUTDOWN(A)
PICKUP(B)
STACK(B,C)
PICKUP(A)
STACK(A,B)



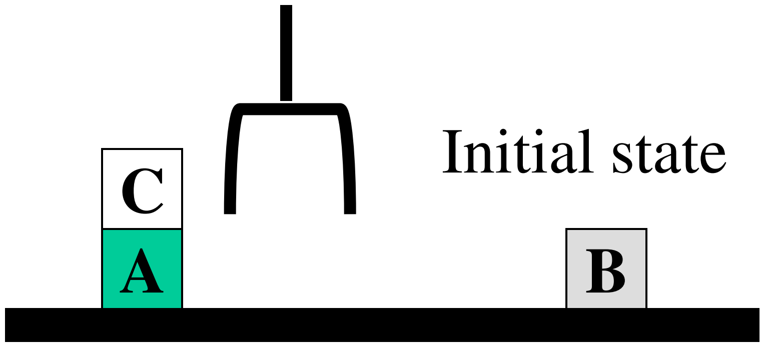


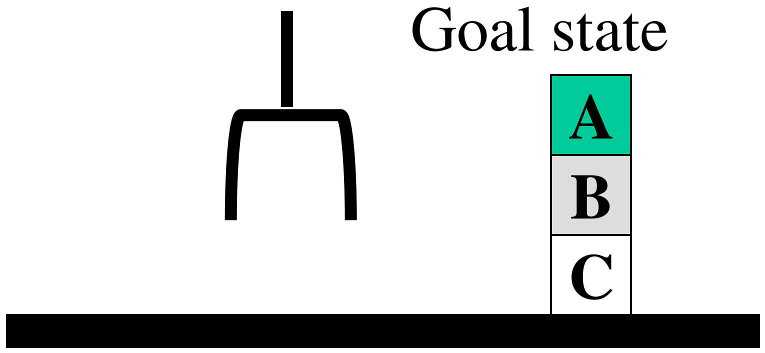
1. Trying the goals in the other order doesn't help much.

2. We can remove adjacent operators that undo each other.

What we really want is to:

1. Begin work on ON(A,B) by clearing A (i.e., putting C on table)
2. Achieve ON(B,C) by stacking B on C
3. Achieve [finish] ON(A,B) by stacking A on B.





We couldn’t do this using a <u>stack</u>, but we can if we use a <u>set</u> of goals.

STRIPS cannot solve all goals

Ex (from Nilsson, p. 305):

"We have two memory registers X and Y whose initial contents are A and B respectively."

I: Contents(X,A) &Contents(Y,B)

We have one operation,

<u>Assign</u>(u,r,t,s) P: Contents(r,s)

D: Contents(u,t) A: Contents(u,s)

Our goal state is:

G: Contents(X,B) &Contents(Y,A)

STRIPS cannot defer its solution of either subgoal long enough not to erase the other register's contents.