AI Planning
State-space planning

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Acknowledgements

Most of the slides used in this course are taken or are modifications from Dana Nau's lecture slides for the textbook *Automated Planning,* licensed under the Creative Commons Attribution-NonCommercial-ShareAlike License:

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State-space planning. Motivation.

- Nearly all planning procedures are search procedures
- Different planning procedures have different search spaces
  - Two examples:
- *State-space planning*
  - Each node represents a state of the world
    - A plan is a path through the space
- *Plan-space planning*
  - Each node is a set of partially-instantiated operators, plus some constraints
    - Impose more and more constraints, until we get a plan

State-space planning. Outline.

- State-space planning
  - Forward search
  - Backward search
  - Lifted backward search
  - STRIPS

Forward-search(O, s_0, g)

$s \leftarrow s_0$

$\pi \leftarrow$ the empty plan

loop

  if s satisfies g then return π

  $E \leftarrow \{a | a$ is a ground instance an operator in O,

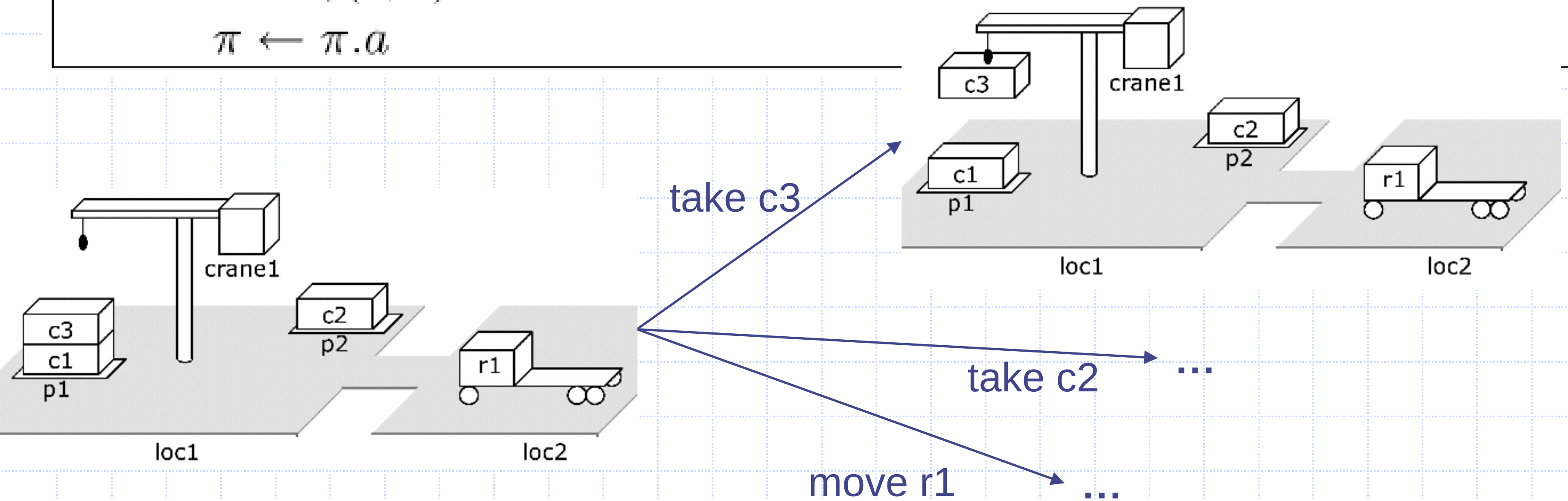
    and $\mathrm{precond}(a)$ is true in $s\}$

  if $E = \emptyset$ then return failure

  nondeterministically choose an action $a \in E$

  $s \leftarrow \gamma(s, a)$

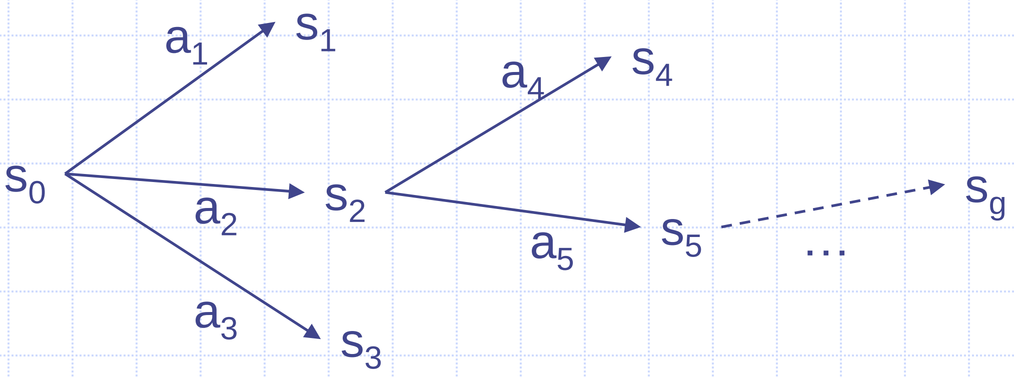
  $\pi \leftarrow \pi.a$



Forward search. Properties

- Forward-search is *sound*
  - for any plan returned by any of its nondeterministic traces, this plan is guaranteed to be a solution
- Forward-search also is *complete*
  - if a solution exists then at least one of Forward-search's nondeterministic traces will return a solution.

Forward search. Deterministic Implementations.

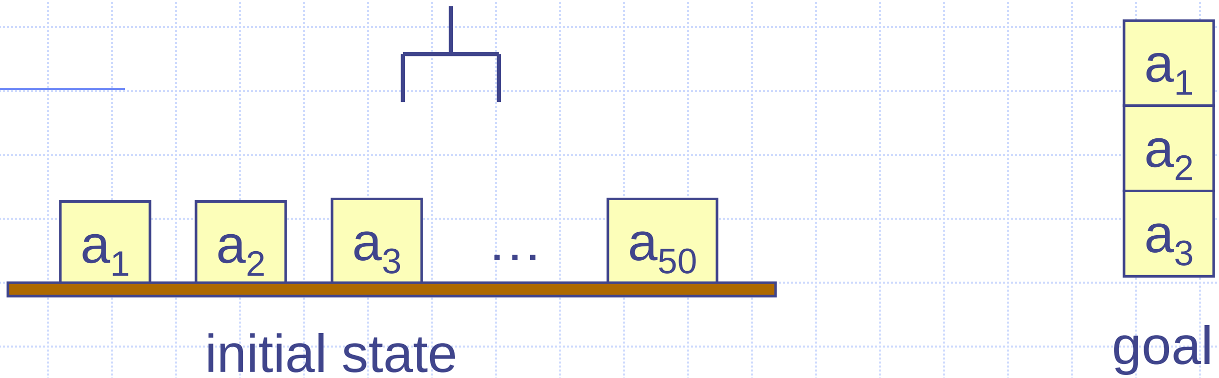


- Some deterministic implementations of forward search:
  - breadth-first search
  - depth-first search
  - best-first search (e.g., A*)
  - greedy search
- Breadth-first and best-first search are sound and complete
  - But they usually aren't practical because they require too much memory
  - Memory requirement is exponential in the length of the solution

Forward search. Deterministic Implementations.

- In practice, more likely to use depth-first search or greedy search
  - Worst-case memory requirement is linear in the length of the solution
  - In general, sound but not complete
    - But classical planning has only finitely many states
    - Thus, can make depth-first search complete by doing loop-checking

Branching Factor of Forward Search



- Forward search can have a very large branching factor
  - E.g., many applicable actions that don't progress toward goal
- Why this is bad:
  - Deterministic implementations can waste time trying lots of irrelevant actions
- Need a good heuristic function and/or pruning procedure

Backward Search

- For forward search, we started at the initial state and computed state transitions
  - new state = $\gamma(s,a)$
- For backward search, we start at the goal and compute inverse state transitions
  - new set of subgoals = $\gamma^{-1}(g,a)$
- To define $\gamma^{-1}(g,a)$, must first define *relevance*:
  - An action *a* is relevant for a goal *g* if
    - *a* makes at least one of *g*'s literals true
      - $g \cap \text{effects}(a) \neq \emptyset$
    - *a* does not make any of *g*'s literals false
      - $g^+ \cap \text{effects}^-(a) = \emptyset$ and $g^- \cap \text{effects}^+(a) = \emptyset$

Backward search. Inverse State Transitions.

- If *a* is relevant for *g*, then
  - $\gamma^{-1}(g,a) = (g - \text{effects}(a)) \cup \text{precond}(a)$
- Otherwise $\gamma^{-1}(g,a)$ is undefined

- Example: suppose that
  - g = {on(b1,b2), on(b2,b3)}
  - a = stack(b1,b2)
- What is $\gamma^{-1}(g,a)$?

Backward-search(O, s_0, g)

$\pi \leftarrow$ the empty plan

loop

if s_0 satisfies g then return π

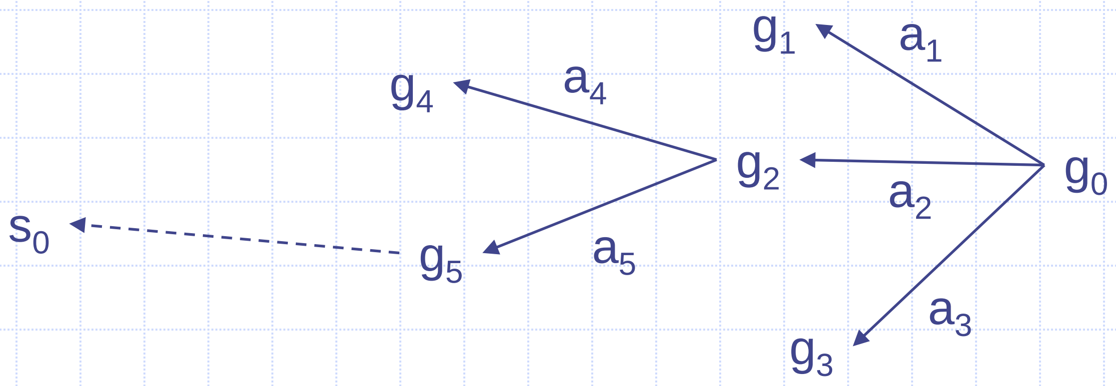
$A \leftarrow \{a | a$ is a ground instance of an operator in O and $\gamma^{-1}(g, a)$ is defined$\}$

if $A = \emptyset$ then return failure

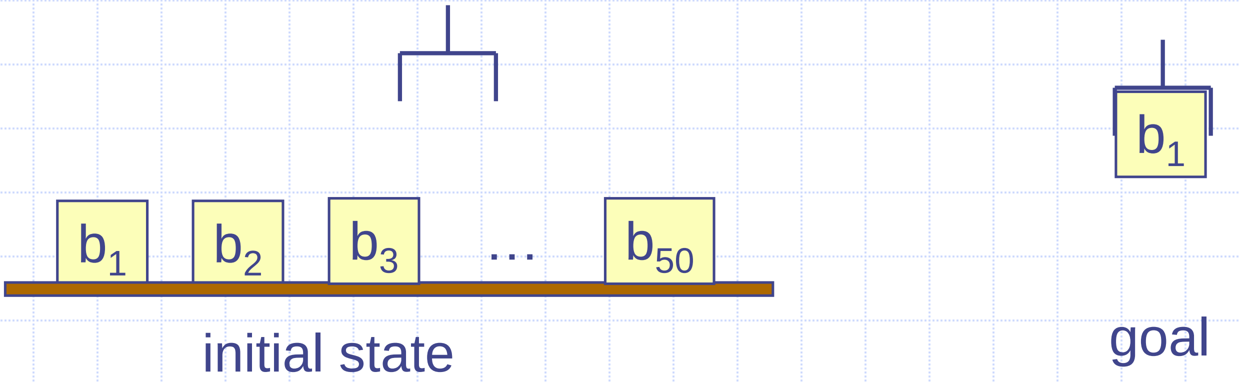
nondeterministically choose an action $a \in A$

$\pi \leftarrow a.\pi$

$g \leftarrow \gamma^{-1}(g, a)$



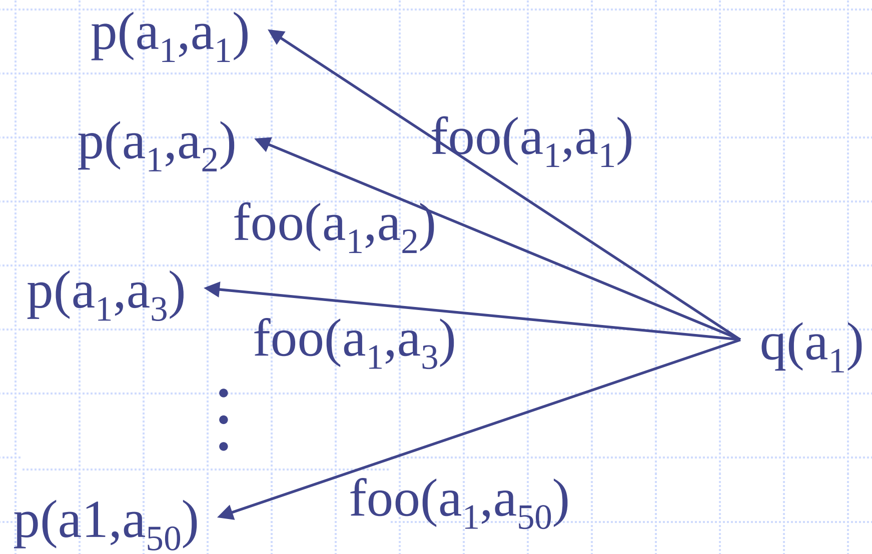
Efficiency of Backward Search



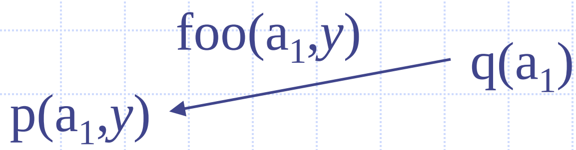
- Backward search can *also* have a very large branching factor
  - E.g., an operator o that is relevant for g may have many ground instances $a_1, a_2, \ldots, a_n$ such that each a_i's input state might be unreachable from the initial state
- As before, deterministic implementations can waste lots of time trying all of them

Lifting

foo(x,y)
    precond: p(x,y)
    effects: q(x)



- Can reduce the branching factor of backward search if we *partially* instantiate the operators
  - this is called *lifting*



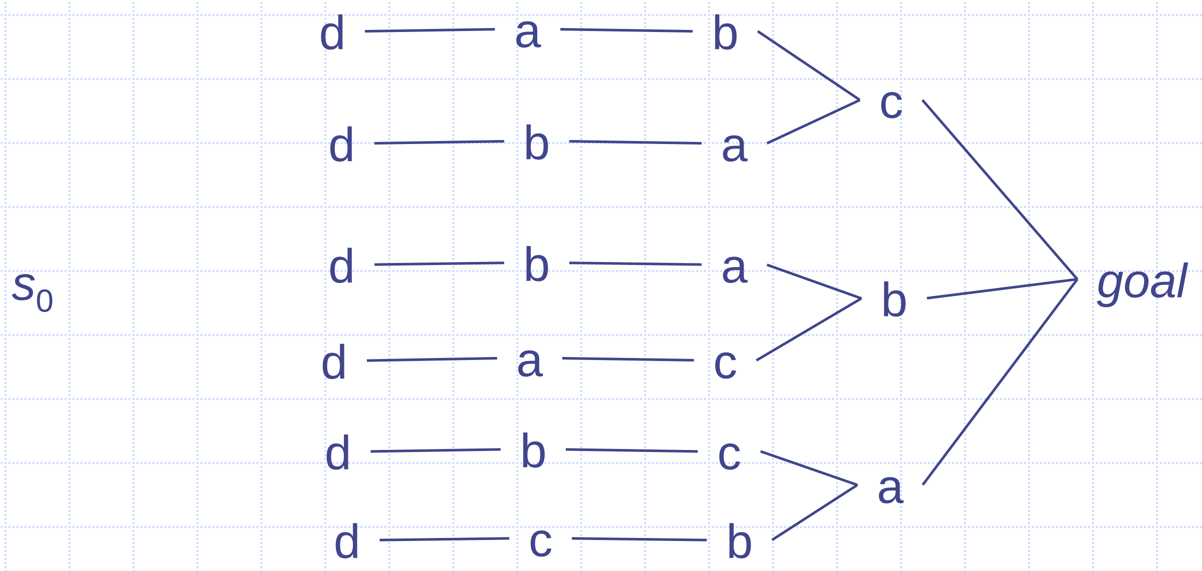
Lifted Backward Search

- More complicated than Backward-search
  - Have to keep track of what substitutions were performed
- But it has a much smaller branching factor

```
Lifted-backward-search(O, s_0, g)
    π ← the empty plan
    loop
        if s_0 satisfies g then return π
        A ← {(o,θ)|o is a standardization of an operator in O,
                θ is an mgu for an atom of g and an atom of effects⁺(o),
                and γ⁻¹(θ(g), θ(o)) is defined}
        if A = ∅ then return failure
        nondeterministically choose a pair (o,θ) ∈ A
        π ← the concatenation of θ(o) and θ(π)
        g ← γ⁻¹(θ(g), θ(o))
```

The Search Space is Still Too Large

- Lifted-backward-search generates a smaller search space than Backward-search, but it still can be quite large
  - Suppose actions *a*, *b*, and *c* are independent, action *d* must precede all of them, and there's no path from s_0 to *d*'s input state
  - We'll try all possible orderings of *a*, *b*, and *c* before realizing there is no solution



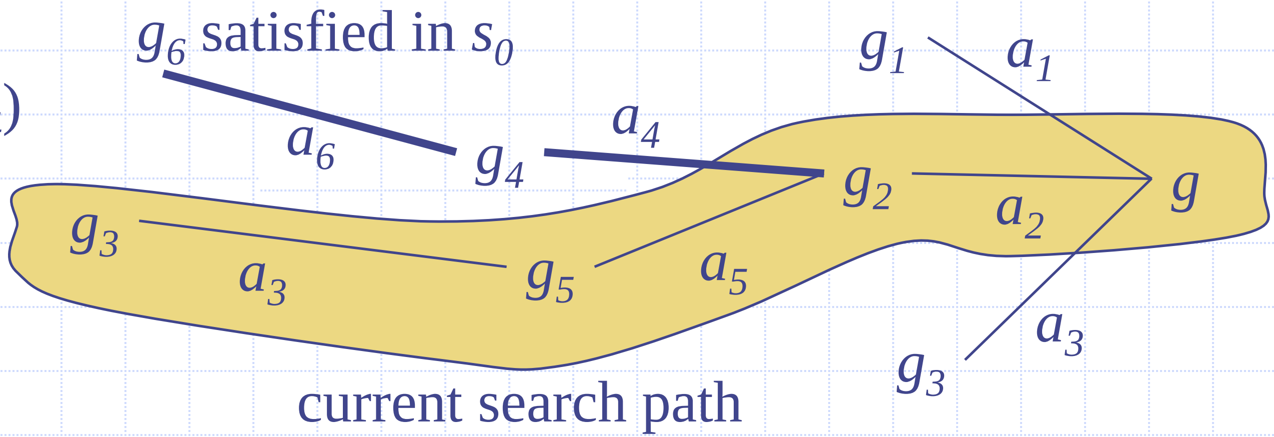
Pruning the Search Space: STRIPS

- $\pi \leftarrow$ the empty plan
- do a modified backward search from *g*
  - instead of $\gamma^{-1}(s,a)$, each new set of subgoals is just precond(*a*)
  - whenever you find an action that's executable in the current state, then go forward on the current search path as far as possible, executing actions and appending them to π
  - repeat until all goals are satisfied

STRIPS

$\pi = \langle a_6, a_4 \rangle$

$s = \gamma(\gamma(s_0, a_6), a_4)$



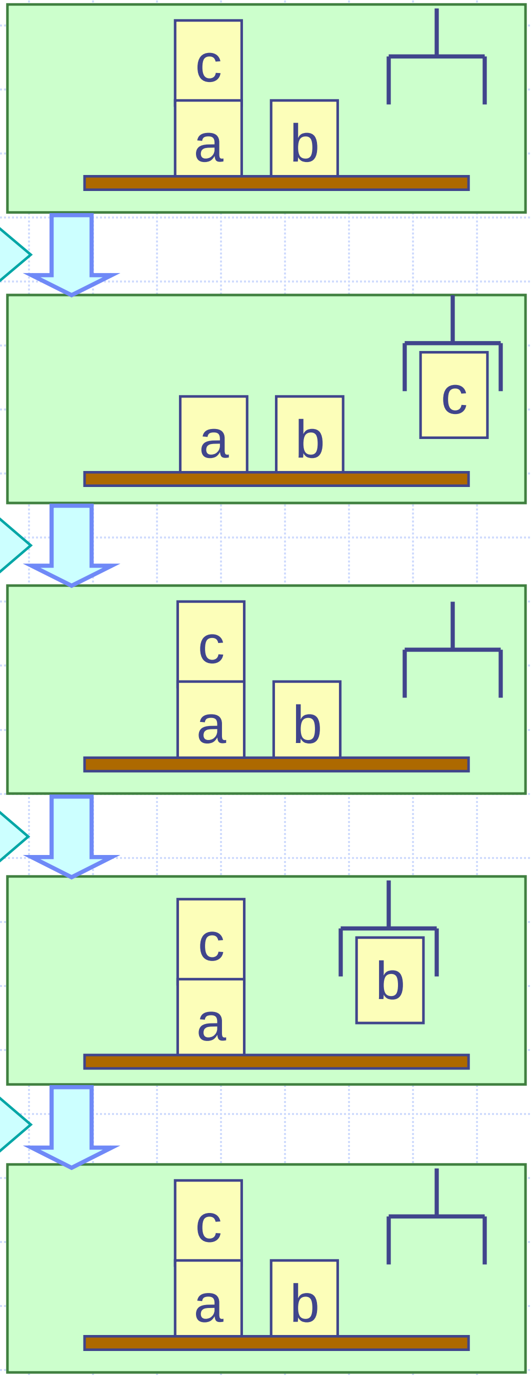
Quick Review of Blocks World

unstack(x,y)
- Precond: on(x,y), clear(x), handempty
- Effects: $\neg$on(x,y), $\neg$clear(x), $\neg$handempty, holding(x), clear(y)

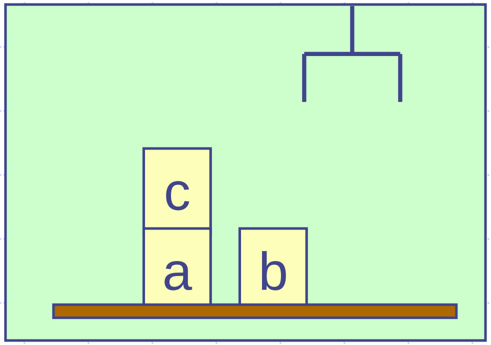
stack(x,y)
- Precond: holding(x), clear(y)
- Effects: $\neg$holding(x), $\neg$clear(y), on(x,y), clear(x), handempty

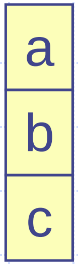
pickup(x)
- Precond: ontable(x), clear(x), handempty
- Effects: $\neg$ontable(x), $\neg$clear(x), $\neg$handempty, holding(x)

putdown(x)
- Precond: holding(x)
- Effects: $\neg$holding(x), ontable(x), clear(x), handempty



The Sussman Anomaly





Initial state goal

- On this problem, STRIPS can’t produce an irredundant solution
  - Try it and see

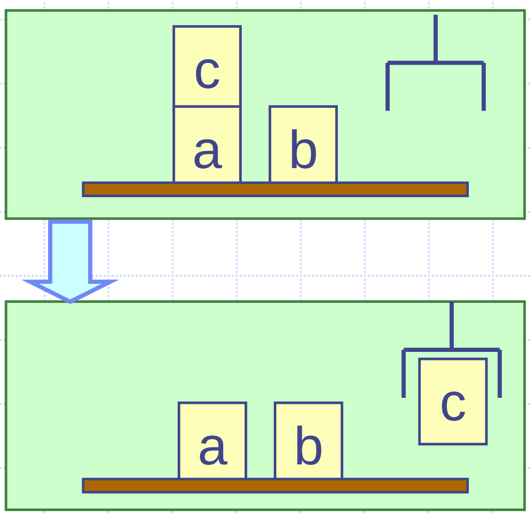
STRIPS solving the Sussman Anomaly

handempty
clear(c)
on(c,a)
unstack(c,a)

clear(a) →
ontable(a)
handempty
pickup(a)

holding (a) →
clear (b)
stack(a,b)

on(a,b) →
on(b,c)



unstack(c,a)

New current state of the problem

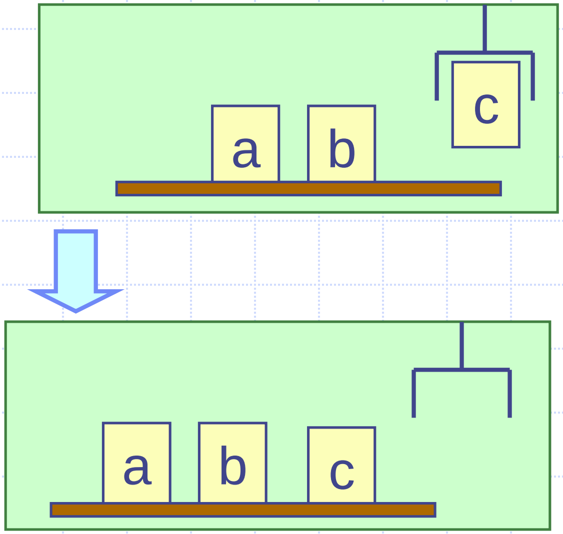
STRIPS solving the Sussman Anomaly

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

holding (a)
clear (b)
stack(a,b)

clear(a)
ontable(a)
handempty
pickup(a)

holding(c)
putdown(c)



Current state of the problem

putdown(c)

New current state of the problem

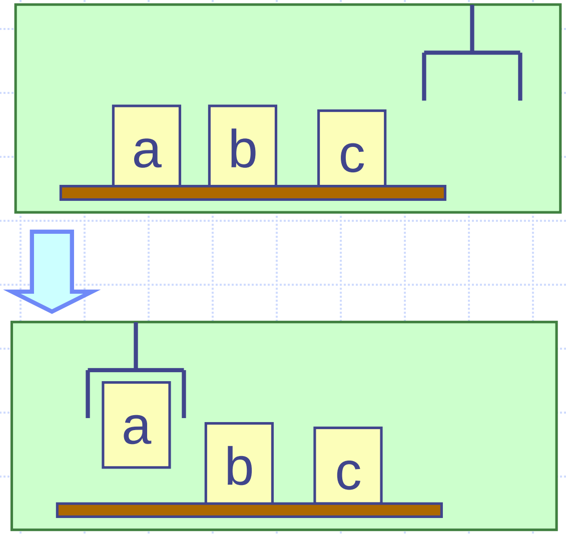
c

STRIPS solving the Sussman Anomaly

<u>clear(a)</u>
<u>ontable(a)</u>
<u>handempty</u>
pickup(a)

holding (a) →
<u>clear (b)</u>
stack(a,b)

on(a,b) →
on(b,c)



Current state of the problem

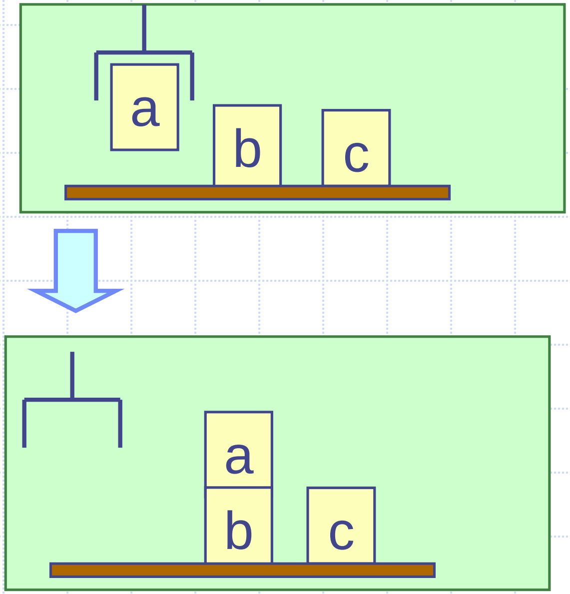
pickup(a)

New current state of the problem

STRIPS solving the Sussman Anomaly

holding (a)
clear (b)
stack(a,b)

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



Current state of the problem

stack(a,b)

New current state of the problem

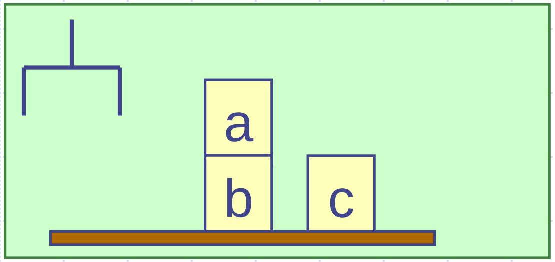
STRIPS solving the Sussman Anomaly

clear(a)
on(a,b)
unstack(a,b)

clear(b)
ontable(b)
handempty
pickup(b)

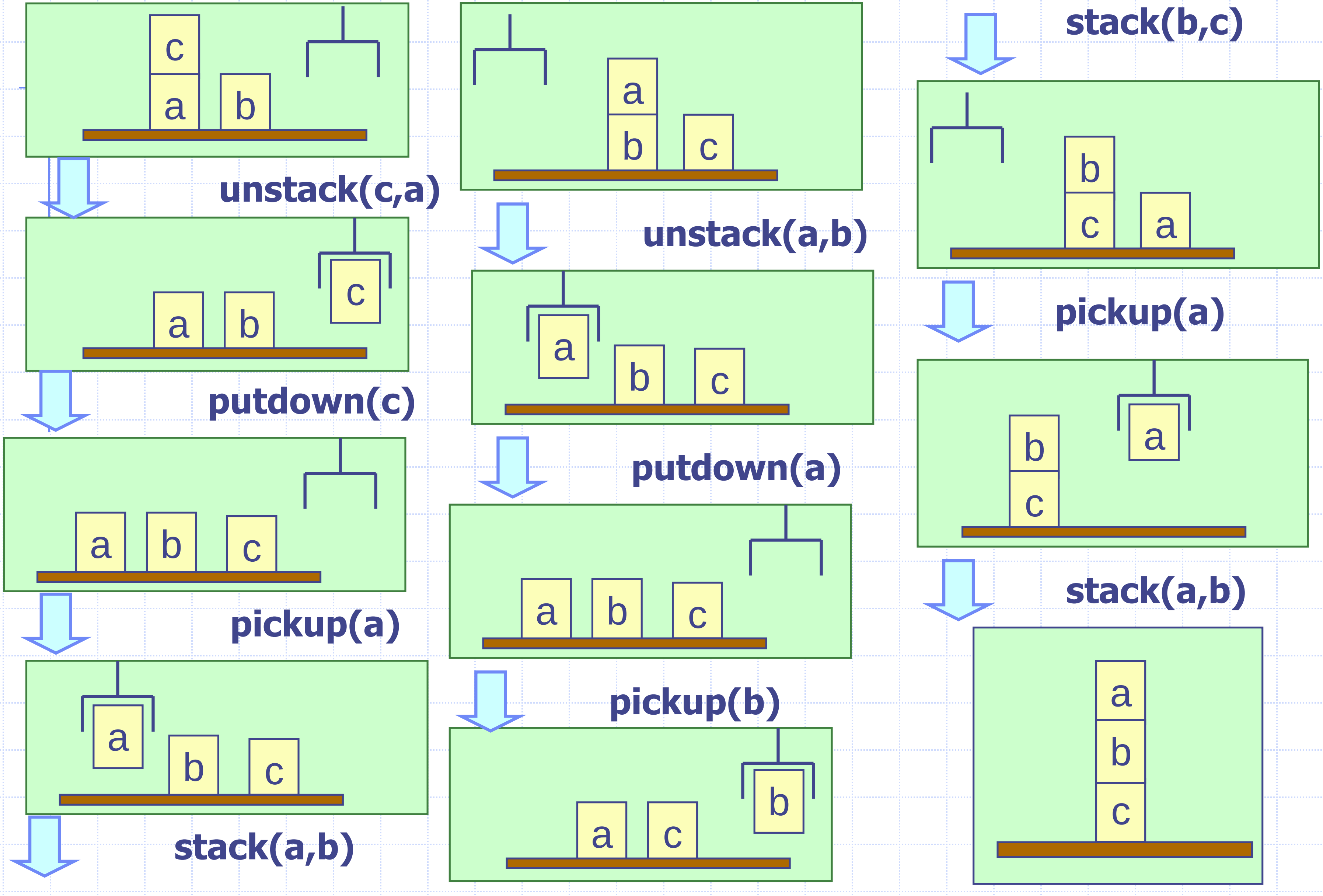
holding(b)
clear(c)
stack(b,c)

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



Current state of the problem

STRIPS solving the Sussman Anomaly



The Register Assignment Problem

- State-variable formulation:

Initial state:	{value(r1)=3, value(r2)=5, value(r3)=0}
Goal:	{value(r1)=5, value(r2)=3}
Operator:	assign(r,v,r',v')
	precond: value(r)=v, value(r')=v'
	effects: value(r)=v'

- STRIPS cannot solve this problem at all

How to Handle Problems like These?

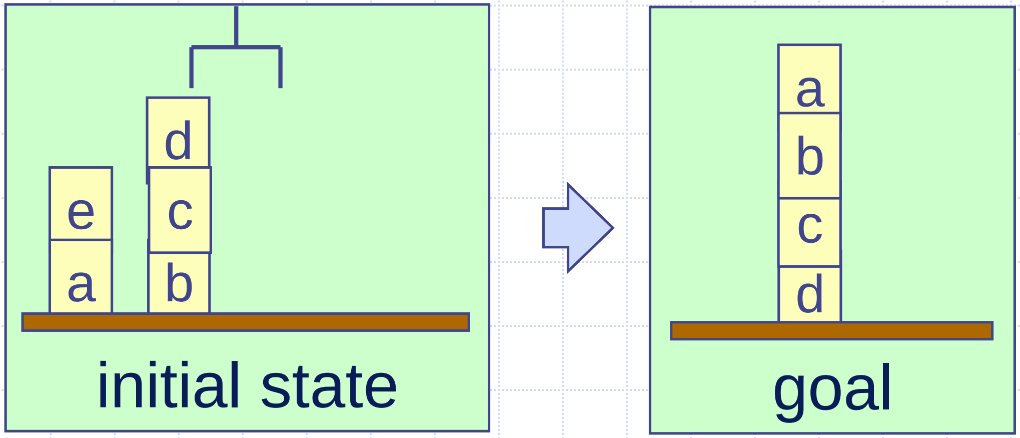
- Several ways:
  - Do something other than state-space search
    - Plan-space search
  - Use forward or backward state-space search, with *domain-specific* knowledge to prune the search space
    - Can solve both problems quite easily this way

Domain-Specific Knowledge

- A blocks-world planning problem $P = (O,s_0,g)$ is solvable if s_0 and g satisfy some simple consistency conditions
  - g should not mention any blocks not mentioned in s_0
  - a block cannot be on two other blocks at once
  - etc.
    - Can check these in time $O(n \log n)$
- If P is solvable, can easily construct a solution of length $O(2m)$, where m is the number of blocks
  - Move all blocks to the table, then build up stacks from the bottom
    - Can do this in time $O(n)$
- With additional domain-specific knowledge can do even better …

Additional Domain-Specific Knowledge

- A block *x* needs to be moved if any of the following is true:
  - *s* contains ontable(*x*) and *g* contains on(*x*,*y*) (block a)
  - *s* contains on(*x*,*y*) and *g* contains ontable(*x*) - (block d)
  - *s* contains on(*x*,*y*) and *g* contains on(*x*,*z*) for some *y*≠*z* (block c)
  - *s* contains on(*x*,*y*) and *y* needs to be moved - (block e)



Domain-Specific Algorithm

loop
if there is a clear block *x* such that
x needs to be moved **and**
x can be moved to a place where it won't need to be moved
then move *x* to that place
else if there is a clear block *x* such that
x needs to be moved
then move *x* to the table
else if the goal is satisfied
then return the plan
else return failure
repeat