Classical Planning

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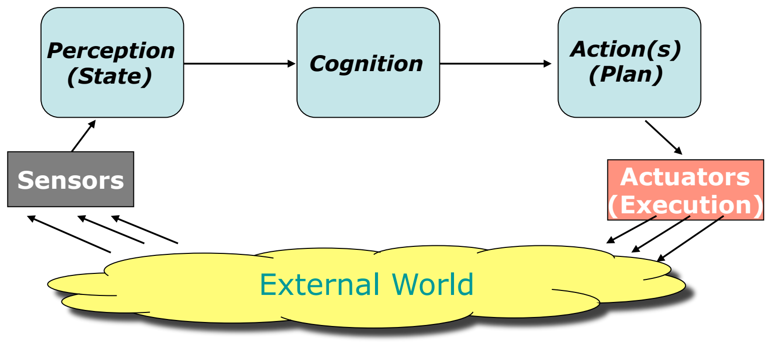
Readings:
- Chapter 10, Russell & Norvig
- Integrating planning and learning: The Prodigy architecture, (Sections 1 and 2)
  M M. Veloso, J. Carbonell, M. Perez, D. Borrajo, E. Fink, and J. Blythe.
  Journal of Experimental and Theoretical Artificial Intelligence, 7(1):81--120, 1995 (see pdf file off course website or www.cs.cmu.edu/~mmv/)

Planning – Problem Solving

Newell and Simon 1956

- Given the *actions* available in a task domain.
- Given a problem specified as:
  – an initial *state* of the world,
  – goal statement - a set of *goals* to be achieved.
- Find a *solution* to the problem, i.e., a *way* to transform the initial state into a new state of the world where the goal statement is true.
- Planning is *"thinking…"*

Intelligent Agents: Planning, Execution, and Learning



Outline (2 lectures)

- Introduction: Search and Planning
- State, Actions, and Goal Representation
- Planning Algorithms
  - State-space Planning – GPS, Prodigy
  - Plan-space Planning – SNLP
  - GraphPlan
  - SATPlan
- Heuristics for Planning Algorithms
- Planning and Execution
  - Conditional Planning
    - Representation and algorithms
  - Information gathering actions
  - Replanning

Planning - Search

- Search agent - issues
  - Atomic state representations
  - Instantiated actions
  - Domain-specific heuristics
  - Number of actions and states
- Planning agent
  - Factored state representation
    - Collection of variables
  - Actions schemas
    - Changes to the state

Models of World State

- **"Information-less" numerical identification (s1, s2,...)**
- **Symbolic – factored**
  - **Features**
  - **Predicates**
- **Conjunctive, enumerative, observable**
- **Complete, correct, deterministic**
- **Probabilistic, approximate, incremental, on-demand**

Classical Deterministic Planning

- Action Model
  - complete, deterministic, correct, STRIPS/PDDL representation, typed variables, CWA
- Single initial state, fully known
- Goal statement – set of goals

Several different planning algorithms

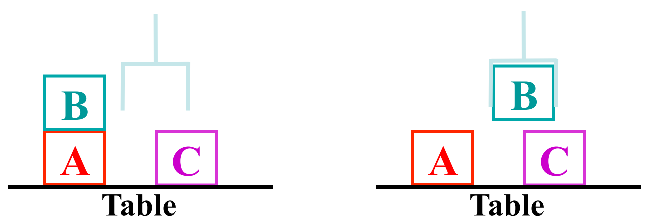
STRIPS Representation

- Implicit Solution to Frame Problem
  - ***State*** is database of ground literals
  - If literal is not in database, assumed to be ***false***
  - Effects of actions represented using ***add*** and ***delete*** lists (insert and remove literals from database)
  - No explicit representation of time
  - No logical inference rules
- Action representation
  - Conjunctive preconditions
  - Effects as *add* and *delete* lists

The Blocks World - States

- Objects
  - Blocks: *A, B, C*
  - Table: *Table*
- Predicates
  - *On(A, B), On(C, Table), Clear(B), Handempty, Holding(C)*
  - *On-table(A), On(A,B), Top(B),…*
  - *Tower(A,B,C,…)*
- States – Conjunctive
  - On(A,B) and On(B,C) and Clear(A) and Handempty

The Blocks World Definition – Actions

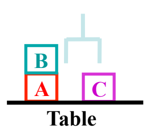


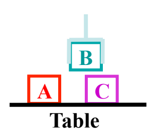
- Blocks are picked up and put down by the arm
- Blocks can be picked up only if they are clear, i.e., without any block on top
- The arm can pick up a block only if the arm is empty, i.e., if it is not holding another block, i.e., the arm can be pick up only one block at a time
- The arm can put down blocks on blocks or on the table

Action Schema

- Action Name
- All variables used in the schema
  - Universally quantified
  - Can choose values *to instantiate* the variables
- Precondition
- Effect
  - Positive effects – adds effect to state
  - Negative effects – deletes effects from state (if in state)

STRIPS – The Blocks World





Pickup_from_table(b)
- Pre: Block(b), Handempty
  Clear(b), On(b, Table)
- Add: Holding(b)
- Delete: Handempty,
  On(b, Table)

Putdown_on_table(b)
- Pre: Block(b), Holding(b)
- Add: Handempty,
  On(b, Table)
- Delete: Holding(b)

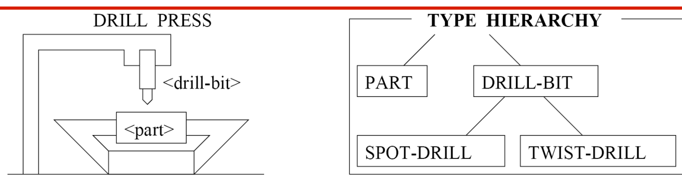
Pickup_from_block(b, c)
- Pre: Block(b), Handempty
  Clear(b), On(b, c), Block(c)
- Add: Holding(b), Clear(c)
- Delete: Handempty,
  On(b, c)

Putdown_on_block(b, c)
- Pre: Block(b), Holding(b)
  Block(c), Clear(c), b $\neq$ c
- Add: Handempty, On(b, c)
- Delete: Holding(b), Clear(c)

Actions

- An action *a* is **applicable** in *s* if all the preconditions of action *a are satisfied by s*.
- RESULT(s,a) = (s – Del (a)) U Add (a)
- No explicit mention of *time*
  - The precondition always refers to time *t*
  - The effect always refers to time *t+1*

Example – Action Model



drill-spot (<part>, <drill-bit>)
<part>: type PART
<drill-bit>: type SPOT-DRILL
Pre: (holding-tool <drill-bit>)
(holding-part <part>)
Add: (has-spot <part>)

put-drill-bit (<drill-bit>)
<drill-bit>: type DRILL-BIT
Pre: tool-holder-empty
Add: (holding-tool <drill-bit>)
Del: tool-holder-empty

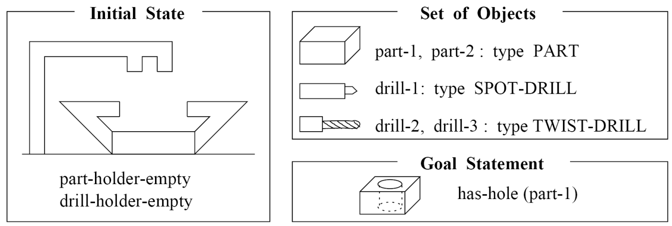
put-part(<part>)
<part>: type PART
Pre: part-holder-empty
Add: (holding-part <drill-bit>)
Del: part-holder-empty

drill-hole(<part>, <drill-bit>)
<part>: type PART
<drill-bit>: type TWIST-DRILL
Pre: (has-spot <part>)
(holding-tool <drill-bit>)
(holding-part <part>)
Add: (has-hole <part>)

remove-drill-bit(<drill-bit>)
<drill-bit>: type DRILL-BIT
Pre: (holding-tool <drill-bit>)
Add: tool-holder-empty
Del: (holding-tool <drill-bit>)

remove-part(<part>)
<part>: type PART
Pre: (holding-part <drill-bit>)
Add: part-holder-empty
Del: (holding-part <drill-bit>)

Example – Problem and Plan




```
put-part(part-1)
put-drill=bit(drill-1)
drill-spot(part-1, drill-1)
remove-drill-bit(drill-1)
put-drill-bit(drill-2)
drill-hole(part-1, drill-2)
```


Initial State, Goal, Actions Example-1

$Init(At(C_1, SFO) \land At(C_2, JFK) \land At(P_1, SFO) \land At(P_2, JFK)$
$\quad \land Cargo(C_1) \land Cargo(C_2) \land Plane(P_1) \land Plane(P_2)$
$\quad \land Airport(JFK) \land Airport(SFO))$
$Goal(At(C_1, JFK) \land At(C_2, SFO))$
$Action(Load(c, p, a),$
 PRECOND: $At(c, a) \land At(p, a) \land Cargo(c) \land Plane(p) \land Airport(a)$
 EFFECT: $\neg At(c, a) \land In(c, p))$
$Action(Unload(c, p, a),$
 PRECOND: $In(c, p) \land At(p, a) \land Cargo(c) \land Plane(p) \land Airport(a)$
 EFFECT: $At(c, a) \land \neg In(c, p))$
$Action(Fly(p, from, to),$
 PRECOND: $At(p, from) \land Plane(p) \land Airport(from) \land Airport(to)$
 EFFECT: $\neg At(p, from) \land At(p, to))$

Figure 10.1 A PDDL description of an air cargo transportation planning problem.

Questions

- Instantiated actions?
- Applicable actions?
- Result of applying an action?

Domain and Actions

- A *domain* can be represented by many possible choices of literals, variables, actions, preconditions, effects.
- Choice of domain
  - Granularity of representation
  - Detail of reasoning
  - Effectiveness of search

Initial State, Goal, Actions Example-2

$Init(On(A, Table) \land On(B, Table) \land On(C, A)$
$\quad \land Block(A) \land Block(B) \land Block(C) \land Clear(B) \land Clear(C))$
$Goal(On(A, B) \land On(B, C))$
$Action(Move(b, x, y),$
$\quad$ PRECOND: $On(b, x) \land Clear(b) \land Clear(y) \land Block(b) \land Block(y) \land$
$\qquad (b \neq x) \land (b \neq y) \land (x \neq y),$
$\quad$ EFFECT: $On(b, y) \land Clear(x) \land \neg On(b, x) \land \neg Clear(y))$
$Action(MoveToTable(b, x),$
$\quad$ PRECOND: $On(b, x) \land Clear(b) \land Block(b) \land (b \neq x),$
$\quad$ EFFECT: $On(b, Table) \land Clear(x) \land \neg On(b, x))$

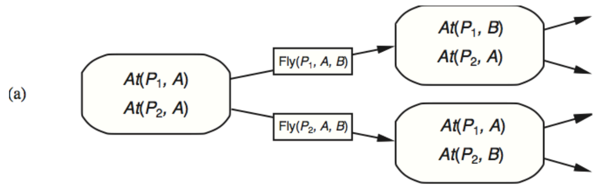
Figure 10.3 A planning problem in the blocks world: building a three-block tower. One solution is the sequence $[MoveToTable(C, A), Move(B, Table, C), Move(A, Table, B)]$.

Domain Representation – Blocksworld

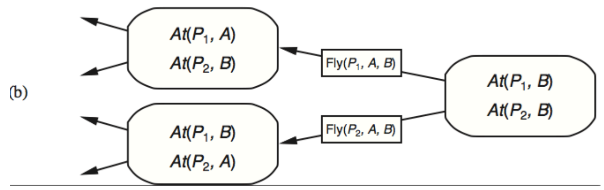
```
(OPERATOR MOVE
 :preconds
   ?block BLOCK
   ?from OBJECT
   ?to OBJECT
  (and (clear ?block)
         (clear ?to)
         (on ?block ?from)
 :effects
  add (on ?block ?to)
  del (on ?block ?from)
  (if (block-p ?from)
      add (clear ?from))
  (if (block-p ?to)
      del (clear ?to)))
```

Planning Algorithms

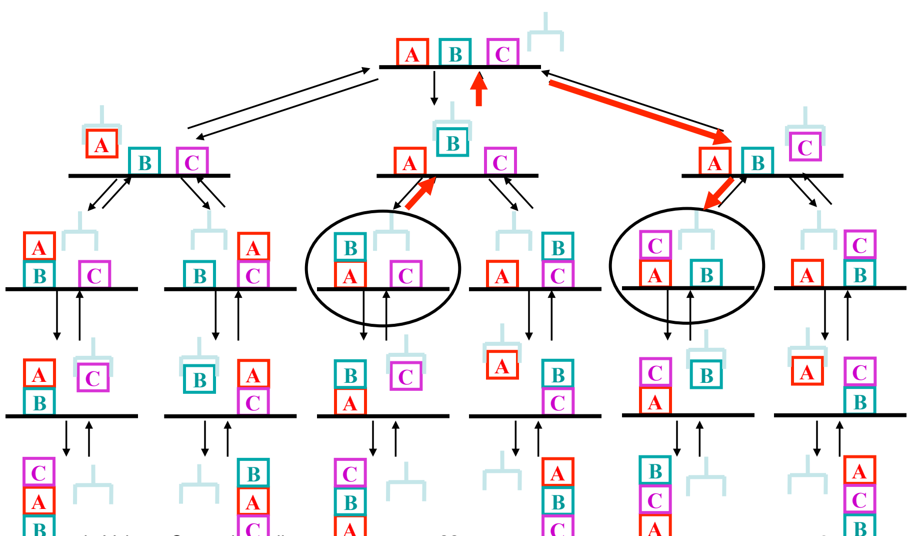
- Progression: Forward state-space search



- Regression: Backward state-space search



Search Transitions Complete State



Finding a Plan – Plan Generation

- ***Backtracking Search*** Through a ***Search Space***
  - How to conduct the search
  - How to represent the search space
  - How to evaluate the solutions
- Non-Deterministic ***Choice Points*** Determine Backtracking
  - Choice of actions
  - Choice of variable bindings
  - Choice of temporal orderings
  - Choice of subgoals to work on

Properties of Planning Algorithms

- **Soundness**
  - A planning algorithm is ***sound*** if all solutions are *legal* plans
    - All preconditions, goals, and any additional constraints are satisfied
- **Completeness**
  - A planning algorithm is ***complete*** if a solution can be found whenever one actually exists
  - A planning algorithm is ***strictly complete*** if all solutions are included in the search space
- **Optimality**
  - A planning algorithm is ***optimal*** if it maximizes a predefined measure of plan quality

Linear Planning

- Basic Idea – Goal **stack**
  - *Work* ***on one goal until completely solved*** *before moving on to the next goal*

Means-Ends Analysis

- Basic Idea
  - ***Search by reducing the difference between the state and the goals***
  - What ***means*** (operators) are available to achieve the desired ***ends*** (goal)

Means-ends Analysis in Linear Planning

(*Newell and Simon 60s*)

GPS Algorithm (*state*, *goals, plan*)

- If *goals* ⊆ *state*, then return *(state,plan)*
- **Choose** a difference $d \in$ *goals* between *state* and *goals*
- **Choose** an operator o to reduce the difference d
- If no applicable operators, then return *False*
- *(state,plan)* = **GPS** (*state*, preconditions(o), *plan*)
- If *state*, then return **GPS** (apply (o, *state*), *goals, [plan,o]*)

Initial call: GPS (initial-state, initial-goals, [])

GPS Blocks-World Example

1. Search Stack

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

State

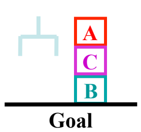
Clear(B)
Clear(C)
On(C, A)
On(A, Table)
On(B, Table)
Handempty

2. Search Stack

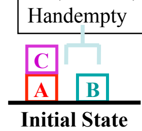
On(A, C) On(C, B)
On(A, C)
On(C, B)

State

Clear(B)
Clear(C)
On(C, A)
On(A, Table)
On(B, Table)
Handempty



Goal



Initial State

3. Search Stack

On(A, C) On(C, B)
On(A, C)
Put_Block(C, B)
Holding(C) Clear(B)

State

Clear(B)
Clear(C)
On(C, A)
On(A, Table)
On(B, Table)
Handempty

4. Search Stack

On(A, C) On(C, B)
On(A, C)
Put_Block(C, B)
Holding(C) Clear(B)
Holding(C)
Clear(B)

State

Clear(B)
Clear(C)
On(C, A)
On(A, Table)
On(B, Table)
Handempty

GPS Blocks-World Example

5. Search Stack

On(A, C) On(C, B)
On(A, C)
Put_Block(C, B)
Holding(C) Clear(B)
Holding(C)

State

Clear(B)
Clear(C)
On(C, A)
On(A, Table)
On(B, Table)
Handempty

6. Search Stack

On(A, C) On(C, B)
On(A, C)
Put_Block(C, B)
Holding(C) Clear(B)
Pick_Block(C)
Handempty Clear(C) On(C, ?b)

State

Clear(B)
Clear(C)
On(C, A)
On(A, Table)
On(B, Table)
Handempty

7. Search Stack

On(A, C) On(C, B)
On(A, C)
Put_Block(C, B)
Holding(C) Clear(B)
Pick_Block(C)

State

Clear(B)
Clear(C)
On(C, A)
On(A, Table)
On(B, Table)
Handempty

8. Search Stack

On(A, C) On(C, B)
On(A, C)
Put_Block(C, B)
Holding(C) Clear(B)

[Pick_Block(C)]

State

Clear(B)
Clear(C)
On(A, Table)
On(B, Table)
Holding(C)
Clear(A)

GPS Blocks-World Example

9. Search Stack

On(A, C) On(C, B)
On(A, C)
Put_Block(C, B)

[Pick_Block(C)]

State

Clear(B)
Clear(C)
On(A, Table)
On(B, Table)
Holding(C)
Clear(A)

10. Search Stack

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

[Pick_Block(C); Put_Block(C, B)]

State

Clear(C)
On(A, Table)
On(B, Table)
Clear(A)
Handempty
On(C, B)

11. Search Stack

On(A, C) On(C, B)
Put_Block(A, C)
Holding(A) Clear(C)

[Pick_Block(C)
Put_Block(C, B)]

State

Clear(C)
On(A, Table)
On(B, Table)
Clear(A)
Handempty
On(C, B)

12. Search Stack

On(A, C) On(C, B)
Put_Block(A, C)
Holding(A) Clear(C)
Holding(A)
Clear(C)

[Pick_Block(C)
Put_Block(C, B)]

State

Clear(C)
On(A, Table)
On(B, Table)
Clear(A)
Handempty
On(C, B)

GPS Blocks-World Example

13. Search Stack

On(A, C) On(C, B)
Put_Block(A, C)
Holding(A) Clear(C)
Holding(A)

[Pick_Block(C);
Put_Block(C, B)]

State

Clear(C)
On(A, Table)
On(B, Table)
Clear(A)
Handempty
On(C, B)

14. Search Stack

On(A, C) On(C, B)
Put_Block(A, C)
Holding(A) Clear(C)
Pick_Table(A)
Handempty Clear(A) On(A, Table)

[Pick_Block(C); Put_Block(C, B)]

State

Clear(C)
On(A, Table)
On(B, Table)
Clear(A)
Handempty
On(C, B)

15. Search Stack

On(A, C) On(C, B)
Put_Block(A, C)
Holding(A) Clear(C)
Pick_Table(A)

[Pick_Block(C);
Put_Block(C, B)]

State

Clear(C)
On(A, Table)
On(B, Table)
Clear(A)
Handempty
On(C, B)

16. Search Stack

On(A, C) On(C, B)
Put_Block(A, C)
Holding(A) Clear(C)

[Pick_Block(C);
Put_Block(C, B);
Pick_Table(A)]

State

Clear(C)
On(B, Table)
Clear(A)
On(C, B)
Holding(A)

GPS Blocks-World Example

17. Search Stack

On(A, C) On(C, B)
Put_Block(A, C)

[Pick_Block(C);
Put_Block(C, B);
Pick_Table(A)]

State

Clear(C)
On(B, Table)
Clear(A)
On(C, B)
Holding(A)

18. Search Stack

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

[Pick_Block(C);
Put_Block(C, B);
Pick_Table(A);
Put_Block(A, C)]

State

On(B, Table)
Clear(A)
On(C, B)
Handempty
On(A, C)

19. Search Stack

[Pick_Block(C);
Put_Block(C, B);
Pick_Table(A);
Put_Block(A, C)]

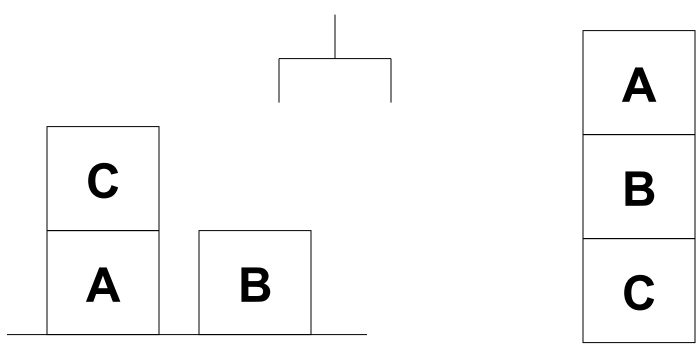
State

On(B, Table)
Clear(A)
On(C, B)
Handempty
On(A, C)

Linear Planning with MEA

- Sound?
- Optimal?
- Complete?

The Sussman Anomaly



4-Action Blocks World Domain

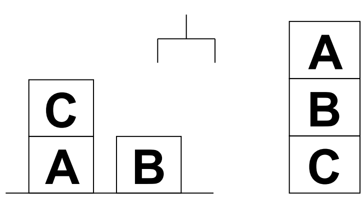
Pickup (?b)
Pre: (handempty)
(clear ?b)
(on-table ?b)
Add: (holding ?b)
Delete: (handempty)
(on-table ?b)
(clear ?b)

Putdown (?b)
Pre: (holding ?b)
Add: (handempty)
(on-table ?b)
Delete: (holding ?b)

Unstack (?a, ?b)
Pre: (handempty)
(clear ?a) (on ?a ?b)
Add: (holding ?a) (clear ?b)
Delete: (handempty)
(on ?a ?b) (clear ?a)

Stack (?a, ?b)
Pre: (holding ?a) (clear ?b)
Add: (handempty)
(on ?a ?b)
Delete: (holding ?a)
(clear ?b)

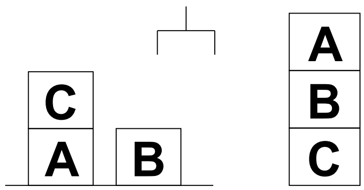
The Sussman Anomaly



Linear Solution:
- *(on B C)*
  - *Pickup (B)*
  - *Stack (B, C)*
- *(on A B)*
  - *Unstack (B, C)*
  - *Putdown (B)*
  - *Unstack (C, A)*
  - *Putdown (C)*
  - *Stack (A, B)*
- *(on B C)*
  - *Unstack (A, B)*
  - *Putdown (A)*
  - *Pickup (B)*
  - *Stack (B, C)*
- *(on A B)*
  - *Pickup (A)*
  - *Stack (A,B)*

Linear Solution:
- *(on A B)*
  - *Unstack (C, A)*
  - *Putdown (C)*
  - *Stack (A, B)*
- *(on B C)*
  - *Unstack (A, B)*
  - *Putdown (A)*
  - *Pickup (B)*
  - *Stack (B, C)*
- *(on A B)*
  - *Pickup (A)*
  - *Stack (A,B)*

NonLinear Solution – Optimal



NonLinear Solution:
- *(on A B)*
  - *Unstack (C, A)*
  - *Putdown (C)*
- *(on B C)*
  - *Pickup (B)*
  - *Stack (B, C)*
- *(on A B)*
  - *Pickup (A)*
  - *Stack (A, B)*

Linear Planning – Goal Stack

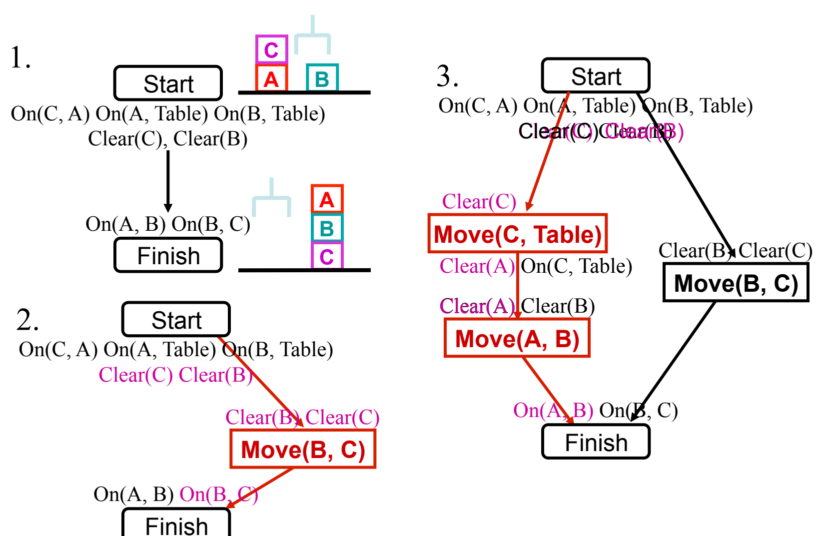
- **Advantages**
  - Reduced search space, since goals are solved one at a time, and not all possible goal orderings are considered
  - Advantageous if goals are (mainly) independent
  - Linear planning is ***sound***
- **Disadvantages**
  - Linear planning may produce ***suboptimal*** solutions (based on the number of operators in the plan)
  - Planner's efficiency is sensitive to goal orderings
    - Control knowledge for the "right" ordering
    - Random restarts
    - Iterative deepening
- Completeness?

Plan-Space, Partial-Order Planning

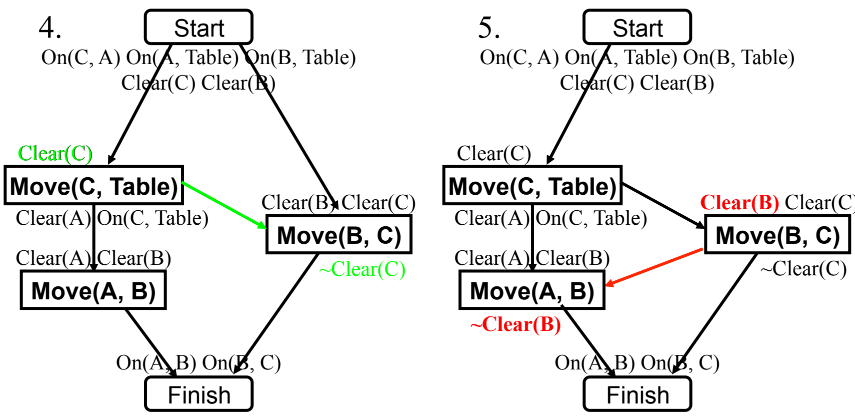
- General Approach
  - Find unachieved precondition
    - Add new action ***or*** connect to existing action
  - Determine if conflicts occur
    - Previously achieved precondition is "clobbered"
    - Fix conflicts (reorder, bind, …)
- Partial-order planning can easily (and optimally) solve blocks world problems that involve goal interactions (e.g., the "Sussman Anomaly" problem)

Initial State **Goal**

POP and Sussman's Anomaly



POP and Sussman's Anomaly



Least Commitment

- Basic Idea
  - ***Make choices that are relevant only to solving the current part of the problem***
- Least Commitment Choices
  - **Orderings**: Leave actions unordered, unless they must be sequential
  - **Bindings**: Leave variables unbound, unless needed to unify with conditions being achieved
  - **Actions**: Usually not subject to "least commitment"

POP – The Details

- ***Causal Links***
  - *Adding new actions or connecting to existing actions*
  - The "purpose" of an action (which condition it supports)
  - $a_i \rightarrow^c a_j$, where a_i, a_j are actions and c is an effect of a_i
  - Plan = <A, O, B, L>
- ***Threats***
  - *Finding and fixing conflicts*
  - Action a_k with an effect c' that might "clobber" a causal link
  - ***Promotion***: Order a_k after a_j
  - ***Demotion*** : Order a_k before a_i
  - ***Separation*** : Constrain c' so that it does not unify with c (non-codesignation constraint)

Partial Order Planning: Discussion

- **Advantages**
  - Partial order planning is ***sound*** and ***complete***
  - Typically produces better solutions (shorter), but not guaranteed ***optimal***
  - Least commitment ***may*** lead to shorter search times
- **Disadvantages**
  - Significantly more complex algorithms (higher *per-node* cost)
  - Hard to determine what is true in a state
  - Larger search space (**infinite**!)

Plan Terminology

- ***Totally Ordered*** Plan
  - There exists sufficient orderings O such that all actions in A are ordered with respect to each other
- ***Fully Instantiated*** Plan
  - There exists sufficient constraints in B such that all variables are constrained to be equal to some constant
- ***Consistent*** Plan
  - There are no contradictions in O or B
- ***Complete*** Plan
  - Every precondition p of every action a_i in A is ***achieved***: There exists an effect of an action a_j that comes before a_i and unifies with p, and no action a_k that deletes p comes between a_j and a_i
- Partial plans are typically ***not*** executable ***nor*** consistent

Example: One-Way Rocket (Veloso 89)

```
(OPERATOR LOAD-ROCKET
 :preconds
  ?roc ROCKET
  ?obj OBJECT
  ?loc LOCATION
 (and (at ?obj ?loc)
      (at ?roc ?loc))
 :effects
  add (inside ?obj ?roc)
  del (at ?obj ?loc))
```

```
(OPERATOR UNLOAD-ROCKET
 :preconds
  ?roc ROCKET
  ?obj OBJECT
  ?loc LOCATION
 (and (inside ?obj ?roc)
      (at ?roc ?loc))
 :effects
  add (at ?obj ?loc)
  del (inside ?obj ?roc))
```

```
(OPERATOR MOVE-ROCKET
 :preconds
  ?roc ROCKET
  ?from-l LOCATION
  ?to-l LOCATION
 (and (at ?roc ?from-l)
      (has-fuel ?roc))
 :effects
  add (at ?roc ?to-l)
  del (at ?roc ?from-l)
  del (has-fuel ?roc))
```

Incompleteness of Linear Planning

```
Initial state:
          (at obj1 locA)
          (at obj2 locA)
          (at ROCKET locA)
          (has-fuel ROCKET)
```

```
Goal statement:
   (and
     (at obj1 locB)
     (at obj2 locB))
```

Goal	*Plan*
(at obj1 locB)	(LOAD-ROCKET obj1 locA) (MOVE-ROCKET) (UNLOAD-ROCKET obj1 locB)
(at obj2 locB)	*failure*

State-Space Nonlinear Planning

Extend linear planning:

- From **stack** to **set** of goals.
- Include in the search space all possible interleaving of goals.

State-space nonlinear planning is **complete**.

Goal	*Plan*
(at obj1 locB)	(LOAD-ROCKET obj1 locA)
(at obj2 locB)	(LOAD-ROCKET obj2 locA)
(at obj1 locB)	(MOVE-ROCKET) (UNLOAD-ROCKET obj1 locB)
(at obj2 locB)	(UNLOAD-ROCKET obj1 locB)

Prodigy Planner

- Extension to GPS
  - Set of goals, instead of stack of goals
  - Means-ends analysis for selection of “pending goals”
  - Choice point for applying an operator when applicable and continue backward-chaining (subgoaling)

Prodigy4.0 (Veloso et al. 90)

1. Terminate if the goal statement is satisfied in the current state.

2. Compute the **SET** of *pending goals G*, and the **set** of *applicable operators A*.

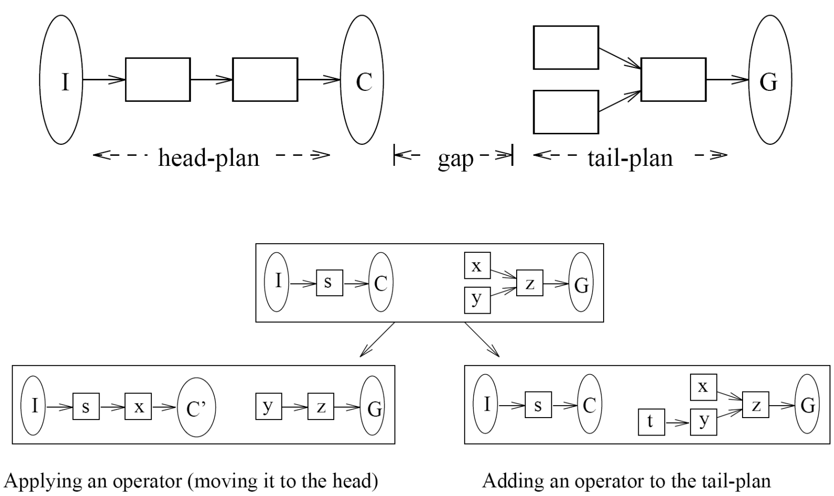
   - A goal is pending if it is a precondition, not satisfied in the current state, of an operator already in the plan.
   - An operator is applicable when all its preconditions are satisfied in the state.

1. Choose a goal G in *G* or choose an operator A in *A*.

Prodigy4.0 Planning Algorithm

4. If G has been chosen, then
   - *Expand goal* G, i.e., get the set *O* of *relevant instantiated operators* that could achieve G,
   - Choose an operator O from *O*,
   - Go to step 1.
5. If an operator A has been selected as directly applicable, then
   - *Apply* A,
   - Go to step 1.

Prodigy4.0 – Search Representation



Why is Planning Hard?

Planning involves a complex search:

- Alternative operators to achieve a goal
- Multiple goals that interact
- Solution optimality, quality
- Planning efficiency, soundness, completeness

Many Issues in Planning

- State representation
  - The frame problem
  - The "choice" of predicates
    - On-table (x), On (x, table), On-table-A, On-table-B,…
- Action representation
  - Many alternative definitions
  - Reduce to "needed" definition
  - Conditional effects
  - Uncertainty
  - Quantification
  - Functions
- Generation – planning algorithm(S)

Many Planning "Domains"

- Web management agents
- Robot planning
- Manufacturing planning
- Image processing management
- Logistics transportation
- Crisis management
- Bank risk management
- Blocksworld
- Puzzles
- Artificial domains

Summary

- **Planning:** selecting one sequence of actions (operators) that transform (apply to) an initial state to a final state where the goal statement is true.
- **Means-ends analysis:** identify and reduce, as soon as possible, *differences* between state and goals.
- **Linear planning:** backward chaining with means-ends analysis using a stack of goals - potentially efficient, possibly unoptimal, incomplete; GPS, STRIPS.
- **Plan-space planning**: least commitment search; causal links and threat resolution; effective management of goal interactions
- **Nonlinear planning with means-ends analysis:** backward chaining using a set of goals; reason about *when* "to reduce the differences;" Prodigy4.0.