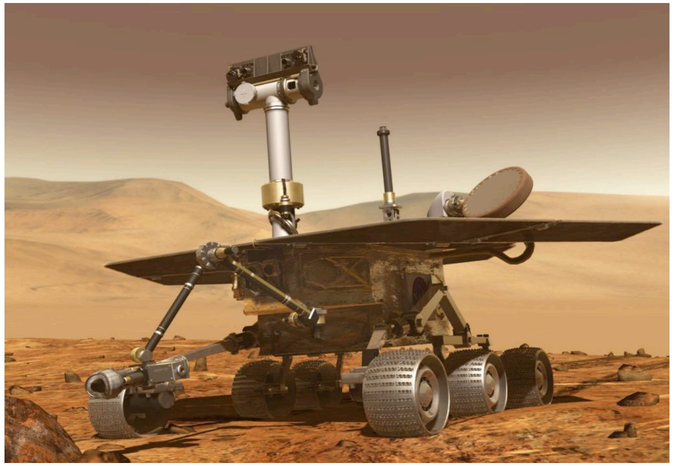
Introduction: What is planning?

Deciding what to, how and when

- We want to achieve something
- We have things we can do
- We know when we can do each thing
- We know what happens when we do things
- We know what we cannot or are not allowed to do
- We know where we are now
- So, what do we do, when and how to achieve what we want?

Example: Decide what a rover does



What can a rover do?

- Drive, turn, stop, etc.
- Operate sensors (cameras, etc.)
- Operate arm
- Operate internal systems (storage, etc.)
- Communicate with Earth and orbiters

What limits rover operations?

- Rules of the worls – cannot be in two places at once
- Rules about operations – no moving arm while driving
- Temporal limits – moving takes time
- Resource limits – have only limited energy budget
- etc.

But, isn’t this easy?

We humans do it all the time, right?

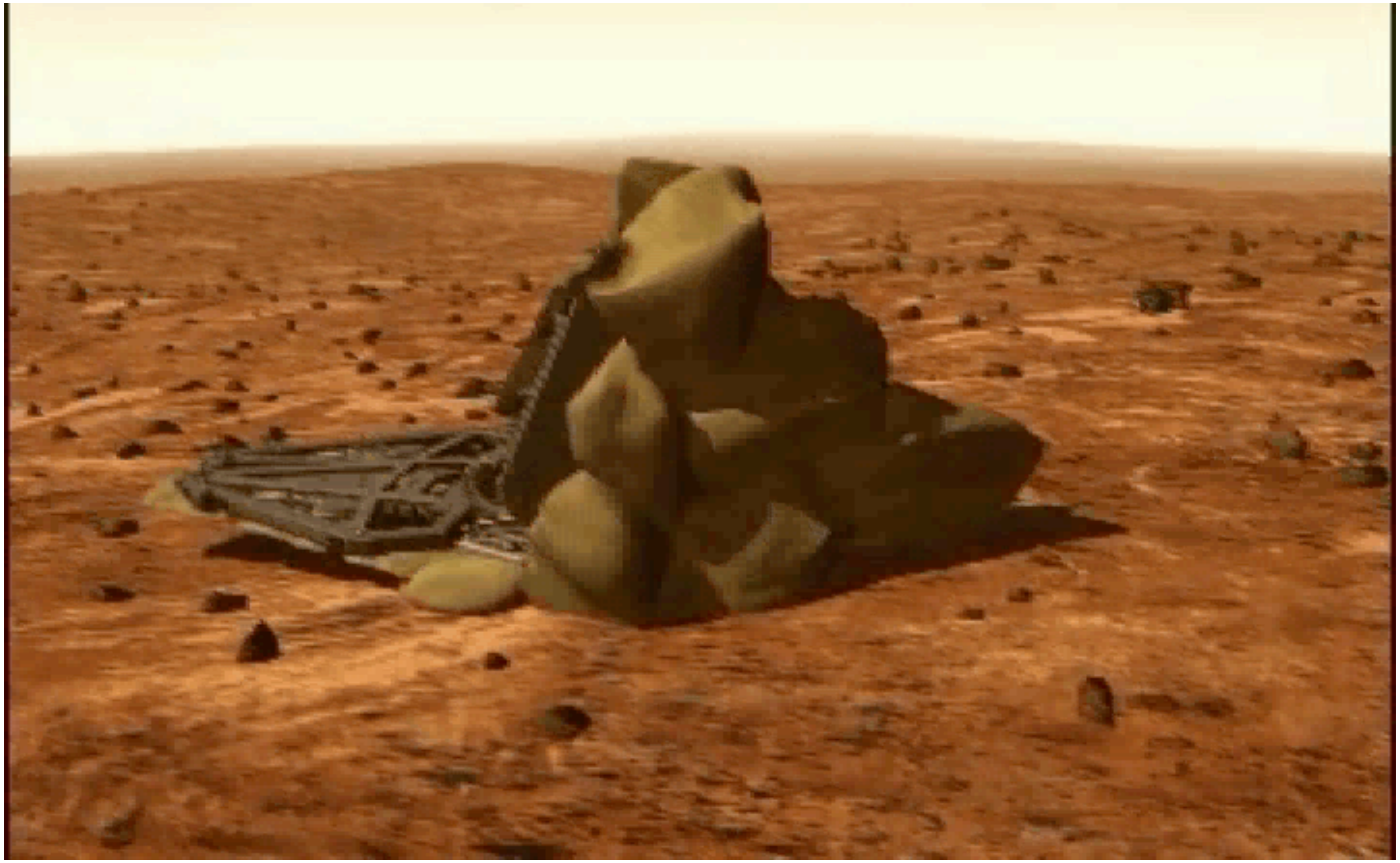
- Yes, but not always well or correctly – and certainly not optimally
  - Example:
- Also, we are not very good at large problems
  - Example:

Not as easy as it looks!

- Humans often end up needing help with planning
- Machines often have hard time with planning

But, lots of fun!

Planning for rover operations



Rover planning on board

Planning

Ubiquitous in Artificial Intelligence

- Basic idea in rational agent is ability to achieve goals
- To achieve goals you invariably have to plan

Planning is in fact a search problem

- Given: Current state, possible actions and goals
- Actions: Map one state to another, if applicable
- Result: Sequence of actions to achieve goal
- Method: Search for a path, using actions as steps, to get from current state to goal

Planning and Search

Planning sounds familiar, right?

- Sliding tiles (8 puzzle) is a planning problem

Planning is key to AI

- Rational agents, seeking to achieve goals, have to plan
- Rational agents must work in many different areas

Special purpose search not reusable

- Search for 8-puzzle solutions not good for controlling rover

General planning

- Methods to solve arbitrary planning problems
- Often built on general search methods, but there is more to it
- Look at representation, reasoning and search for planning

Planning: Plan

Logical representation

- Situation calculus

STRIPS representation

- States and Actions
- Examples

Simple search methods

- Forward search
- Backward search
- Heuristic search

Planning: Outline of lectures

Logical representation

- Situation calculus

STRIPS representation

- States and Actions
- Examples

Simple search methods

- Forward search
- Backward search
- Heuristic search

Planning: Outline (cont)

Partial Order Planning

- Search with grounded values
- Search with variables
- Heuristics

Planning with Graphs

- Planning graphs
- Heuristics
- “Graphplan” methods

Planning

Planning in the "Real World"

- Time, Resources, Complex Relations, Constraints, etc.
- Hierarchical Task Network Planning
- Planning in a non-deterministic world
- Plan execution and re-planning

Decisions in an uncertain world

- Basic notions in probability
- Basic axioms and Bays rule
- Probabilistic methods for decision-making

Situation Calculus

Basic Idea: Use logic and theorem proving

- Describe each situation with a set of logical sentences
- Describe actions and effects with logical axioms

Planning

- "Prove" the goal as a new sentence
- Or, "ask" whether goal can be proven from given sentences

Logical representation

Time in planning

- Would assume **time** is key element in planning
- but, many planners use “steps” not actual time
- We will use steps for now - okay as long as actions are sequential

Situations (steps)

- Use basic sentences from predicate logic
- Situation typically defined by a set of propositions that are true:
  - isLinked(mac,epson)
  - isLinked(mac,laserjet)
  - canPrint(mac,laserjet)
  - isBroken(epson)
- Assume propositions not in set are false (closed-world assumption)

Situations changing over “time”

Situations change between steps

- Need to connect step and situations

Want to describe different situations

- Could say: afterStep(s) = { isLinked(mac,epson), isLinked (mac,laserjet),...}
- Problem: Does not fit predicate logic

So, we describe a relation between s and literal:

- holds(isLinked(mac,epson),s)
- holds(isLinked(mac,laserjet,s)
- ...

Describing actions

Basic idea is to describe what changes

- Assume s is situation and a is an action
- Use result(a,s) to describe result of applying a in s
- Example: s' = result(printFile(mac,epson,foo), s0)

Example description:

- If printer is connected and not broken, and print command is given for a file, then the result is that file has been printed

$$\text{holds(isLinked(mac,epson),s)} \wedge \neg\text{holds(isBroken(epson),s)}$$
$$\rightarrow \text{holds(havePrintout(foo), result(printFile(mac,epson,foo), s))}$$

Lýsing einstakra vandamála

Upphafsstaða

- Staðan í upphafi áætlunar
- Gerum ráð fyrir að stöðu sé lýst til fullnustu
  - T.d. með forsendu um lokaðan heim (closed world assumption)

Lýsing á markmiði

- Skilyrði sem lýsa markmiði áætlunar
- Yfirleitt er stöðu ekki lýst til fullnustu
  - Margar stöður fullnægja skilyrðinu

Dæmi:

- Upphafsstaða:
  - holds(linked(mac,epson),s_0), holds(hasFile(mac,foo), s_0),...
- Markmiðsskilyrði:
  - holds(havePrintout(foo),s_{final})

Example

Actions

- ¬holds(have(fork),s) → holds(have(fork), result grab(fork), s))
- ¬holds(have(knife),s) → holds(have(knife), result grab(knife), s))

Initial state

- ¬holds(have(fork),s0) ∧ ¬holds(have(knife),s0)

Goal

- holds(have(fork),s) ∧ holds(have(knife),s)

Can now solve with any logical theorem prover

Or, can we?

Small Problem

Describing an action:

- holds(isLinked(mac,epson),s) $\wedge$ ¬holds(isBroken(epson),s)
  $\rightarrow$ holds(havePrintout(foo), result printFile(mac,epson,foo), s)

The Frame Problem:

- How do we know that the printer does not get disconnected?
  - Would rather not have to add every possible thing, such as:
    holds(isLinked(mac,epson), result printFile(mac,epson,foo), s)
- How do we know this does not turn on the projector?
  - Definitely don't want to have to add:
    holds(isLinked(mac,epson),s) $\wedge$ ¬holds(isBroken(epson),s)
    $\wedge$ ¬holds(isOn(projector),s)
    $\rightarrow$ holds(havePrintout(foo), result printFile(mac,epson,foo), s)
    $\wedge$ ¬holds(isOn(projector), result printFile(mac,epson,foo), s)

Related problems are: Qualification and Ramification Prob's

Classical planning (STRIPS)

Simpler method

- Instead of general logic, use special “planning” representation
- Build on logic ideas – use propositional literals
- Define directly mapping of state and action to new state
- Solves the frame problem

Simplification also adds limits

- Less representational power
  - Cannot use complex logical relations
  - Cannot have conditional effects
  - Cannot extend to handle time, arithmetic, continuous resources,
  - Cannot do a lot of things
- But, sufficient to handle simple planning problems

STRIPS Actions

Each action has two parts:

- Condition on applicability (Preconditions)
- Description of result when it is applied (Effects)

Preconditions:

- Set of literals that must hold in current state
- print(file,mac,epson) has preconditions:
  - hasFile(mac,file)
  - linked(mac,epson)
  - -broken(epson)
  - hasPaper(epson)
- Common usage:
  - print(file,mac,epson):
    - pre: hasFile(mac,file), linked(mac,epson), -broken(epson), ...

STRIPS actions

Effects:

- Sets of positive and negated literals
- Positive ones are "Add effects"
- Negated ones are "Delete effects"
- Example: printFile(file,mac,epson) has the effects:
  - havePrintout(file)
  - -hasPaper(epson)
    - Silly printer can only fit one page at a time
- Common representation for effects
  - printFile(file,mac,epson):
    - add: havePrintout(file)
    - del: hasPaper(epson)

Example: Blocks World

The BlocksWorld problem

- Have blocks, e.g., A,B,C,D,…
- Have a table (infinite and without specific locations)
- Can move a block from atop a block to another
- Can move a block from table to atop of another block
- Can move block from atop of a block on to table

State descriptions:

- loc(x,y): Block x is on top of y (or on table if y is "table")
- clear(x): No block is on top of x

Example: Blocks World

Action: move(x,y,z)

- pre: clear(x), loc(x,y), clear(z)
- add: loc(x,z), clear(y)
- del: loc(x,y), clear(z)

Action: move-to-table(x,y)

- pre: clear(x), loc(x,y)
- add: loc(x,table), clear(y)
- del: loc(x,y)

Action: move-from-table(x,y)

- pre: clear(x), loc(x,y)
- add: loc(x,table), clear(y)
- del: loc(x,y)

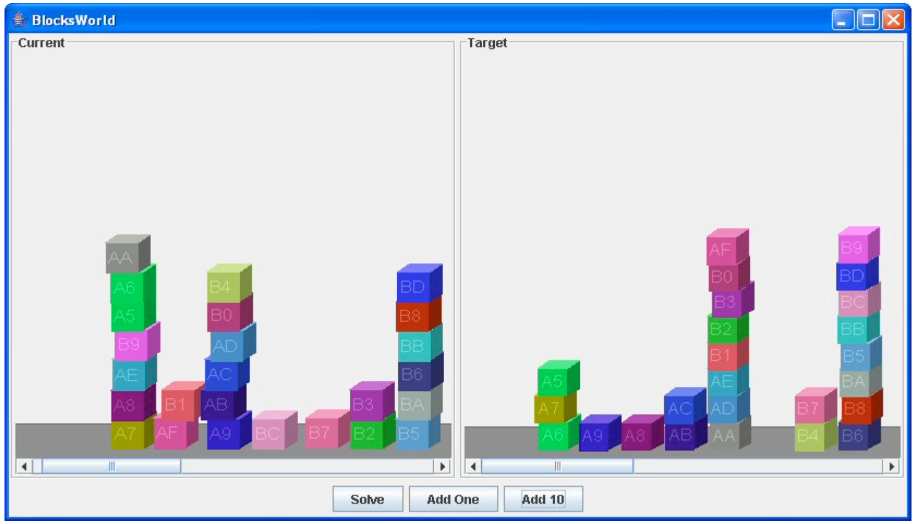


Photo: Univ. Hamburg

Classical state space planning

Initial state

- The state at the beginning
- Described as a set of positive literals
  - Assume other propositions are false

Goal condition

- Condition that defines the goal
- Set of literals (positive or negative)
  - Other propositions can be either true or false

Example:

- Initial state:
  - linked(mac,epson), hasFile(mac,foo), hasFile(mac,file),...
- Goal condition:
  - havePrintout(foo)

STRIPS properties

Solves the frame problem

- Literals that do not appear in effects are unchanged

Does not solve the ramification problem

- Hard to describe effects of complex actions
- Example: Airplane full of people flies to London – the action needs to describe effect on each person

Does not solve the qualification problem

- Difficult to exhaustively list all conditions
- Example: Car will start only if there is no potato in the tailpipe

Still, permits state space search for planning

Example: Transport problem

Objects

- Packages
- Airplanes
- Airports

Actions

- Load a package into airplane
- Fly airplane from one airport to another
- Unload package from airplane

Forward state space search

Basic idea:

- Search starts from initial state
- Applicable actions determine possible next states
- Next states defined by states and action effects
- Use any favorite search technique to find a goal state

Breadth-First Search:

- L is the initial state and an empty path
- Repeat:
  - If L is empty, we are done and no solution can be found
  - Pick first state s from list L
  - If s satisfies goal condition, retun s with path to s
  - Find all applicable actions in s and for each action a, add the result of applying a to s to end of L (with path to s + a)

Example: Blind search in Blocks World

Initial state:

- loc(A,table)
- loc(B,C)
- loc(C,table)
- clear(A)
- clear(B)

Goal:

- loc(B,A)
- loc(A,C)

Blind forward state space search in planning

Unfocussed and often impractical method

- All possible actions examined
  - Even those having nothing to do with initial state or goal
- Search space is very large

However, heuristic version is getting better

- With recent advances in heuristics has forward search become a reasonable technique

Regression planning (“Backwards search”)

Basic Idea:

- Start with the goal condition
- Select an action that achieves some element in goal condition
- Find a state that permits action and gives goal condition
- Apply recursively to the state found
- Use search method of choice

Finding regression state of given state S:

- Select a literal in S, say it is L (and L is either p or –p)
- Find action A that achieves L
  - has p in add effects if L=p
  - has p in del effects if L= -p
- Regressed state is (s \ L ∪ pre(A))

Example:

Initial state:

- loc(A,table)
- loc(B,C)
- loc(C,table)
- clear(A)
- clear(B)

Goal condition:

- loc(B,A)
- loc(A,C)

About regression planning

More focused than forward search

- Only examines actions that in some way relate to the goal

Blind regression is impractical

- Blind search is invariably exponential in length of plan

Heuristics more complex than for forward search

- But, some promising techniques based on heuristic regression

Heuristic state space search

Blind search does not work in planning

- Branching factor is way too large
- Without heuristics, even small planning problems are unsolvable

Basic ideas for heuristics in state space search for planning

- Simplify preconditions – ignore some of them
- Simplify effects – ignore some of them

Heuristics from ignoring preconditions

Extreme version: Ignore all preconditions

- Assume every action can be applied in any state
- Find a plan from given state to a goal state
  - Easier problem to solve, but additions and effects still make it nontrivial
- Length of plan is heuristic evaluation of s

Variations

- Assume effects of actions are independent
  - Length of plan then becomes number of literals in goal different from s
- Assume actions of have no delete effects
  - Finding plan then becomes very easy

Heuristics from ignoring effects

Basic idea

- Assume actions have no delete effects
- Solve the simplified planning problem from state s to goal state
- Length of plan is heuristic evaluation of state s

Implementation

- Solving a planning problem to get heuristics
- But, problem is much simpler and easier to solve

Separating subgoals

Basic idea

- Find a plan for each literal in goal condition
- Combine the plans to generate a complete plan

Problem!

- Initial state: loc(B,table), loc(A,table), loc(C,A), clear(B), clear(C)
- Goal: loc(A,B), loc(B,C)
- Called the Sussman anamoly