CS 1571 Introduction to AI
Lecture 13

Planning

Milos Hauskrecht
milos@cs.pitt.edu
5329 Sennott Square

Administration

- **PS-5 due today**:
  - **Report**
  - **No programming assignment**
- **No homework out**
- **Midterm:**
  - **Tuesday, October 15, 2002**
  - **In-class, closed book**
  - **Material covered till (including) Thursday, October 10**

Planning

Propositional and first-order logic

- Give formalisms for representing the knowledge about the world and ways of reasoning
- Statements about the world are either **true** or **false**

The real-world:

- Is **dynamic**; i.e. it can change over time
  - Things that are true now may not be true in the future

  Example: *Age(John, 17)* *Age(John, 18)*
- An intelligent **agent can actively change** the world through actions.

  Example: action of painting car12 blue causes:

  color(car12, white) becomes **false** and *color(car12, blue*) **true**

Planning problem: find a sequence of actions that lead to a goal

Planning

Planning problem:

- find a sequence of actions that lead to a goal
- is a special type of a **search problem**

Search problem:

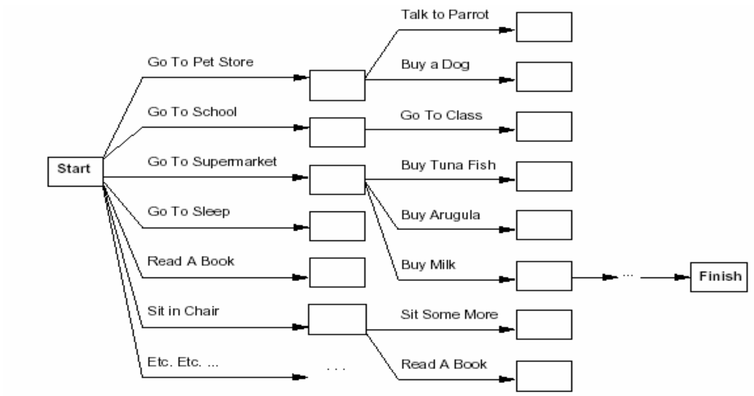
- **State space** – a set of states of the world among which we search for the solution.
- **Initial state**. A state we start from.
- **Operators**. Map states to new states.
- **Goal condition**. Test whether the goal is satisfied.

Challenges:

- Build a representation language for modeling action and change
- Design of special search algorithms for a given representation

Planning search. Example.

- Assume a simple problem of buying things:
  - **Get a quarter of milk, bananas, cordless drill**



A huge branch factor !!! Goals can take multiple steps to reach!!!

Planning

How to address the problems?

- **Open state, action and goal representations** to allow selection, reasoning. Make things visible and expose the structure.
  - Use FOL or its restricted subset to do the reasoning.
- **Add actions** to the plan sequence **wherever and whenever it is needed**
  - Drop the need to construct solutions sequentially from the initial state.
- **Apply divide and conquer strategies to sub-goals** if these are independent.

Challenges:

- Build a representation language for modeling action and change
- Design of special search algorithms for a given representation

Planning systems design.

Two planning systems designs:

- **Situation calculus**
  - based on first-order logic,
  - a situation variable models new states of the world
  - use inference methods developed for FOL to do reasoning
- **STRIPS – like planners**
  - STRIPS – Stanford research institute problem solver
  - Restricted language as compared to the situation calculus
  - Allows for more efficient planning algorithms

Situation calculus

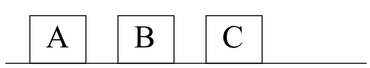
- Logic for reasoning about changes in the state of the world
- **The world is described by:**
  - Sequences of situations of the current state
  - Changes from one situation to another are caused by actions
- **The situation calculus allows us to:**
  - Describe the initial state and goal state
  - Build the KB that describes the effect of actions (operators)
  - Prove that the KB implies the goal state
    - and thereby allow us to extract a plan

Situation calculus

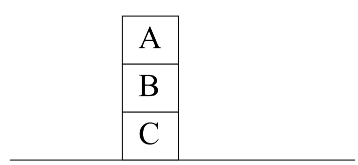
Language:

- **Special variables:** *s,a* – objects of type situation and action
- **Action functions** that return actions.
  - E.g. *Move(A, TABLE, B)* represents a move action
  - *Move(x,y,z)* represents an action schema
- **Two special function symbols of type situation**
  - s_0 – initial situation
  - *DO(a,s)* – denotes the situation obtained after performing an action a in situation s
- **Situation-dependent functions and relations** (also called fluents)
  - **Relation:** *On(x,y,s)* – object x is on object y in situation s;
  - **Function:** Above(x,s) – object that is above x in situation s.

Situation calculus. Blocks world example.



Initial state

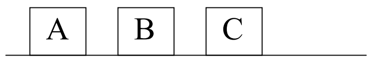


Goal

$On(A,Table, s_0)$
$On(B,Table, s_0)$
$On(C,Table, s_0)$
$Clear(A, s_0)$
$Clear(B, s_0)$
$Clear(C, s_0)$
$Clear(Table, s_0)$

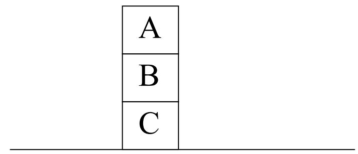
On(A,B, s)
On(B,C, s)
On(C,Table, s)

Blocks world example.



Initial state

On(A,Table, s_0*)*
On(B,Table, s_0*)*
On(C,Table, s_0*)*
Clear(A, s_0*)*
Clear(B, s_0*)*
Clear(C, s_0*)*
Clear(Table, s_0*)*



Goal

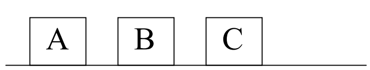
On(A,B, s)
On(B,C, s)
On(C,Table, s)

Note: It is not necessary that the goal describes all relations

Clear(A, s)

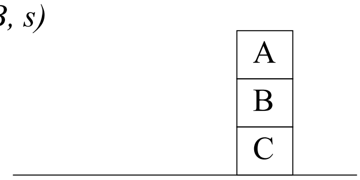
Blocks world example.

Assume a simpler goal *On(A,B, s)*



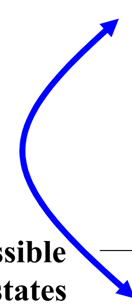
Initial state

On(A,Table, s_0*)*
On(B,Table, s_0*)*
On(C,Table, s_0*)*
Clear(A, s_0*)*
Clear(B, s_0*)*
Clear(C, s_0*)*
Clear(Table, s_0*)*

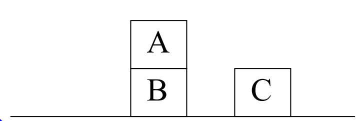


Goal

On(A,B, s)



2 possible goal states



Goal

On(A,B, s)

Knowledge about the world. Axioms.

Knowledge in the KB

- represents changes in the world due to actions.

Two types of axioms:

- **Effect axioms**
  - changes in situations that result from actions
- **Frame axioms**
  - things preserved from the previous situation

Blocks world example. Effect axioms.

Effect axioms:

Moving x from y to z. $MOVE(x, y, z)$

Effect of move changes on **On** relations

$$On(x, y, s) \wedge Clear(x, s) \wedge Clear(z, s) \rightarrow On(x, z, DO(MOVE(x, y, z), s))$$

$$On(x, y, s) \wedge Clear(x, s) \wedge Clear(z, s) \rightarrow \neg On(x, y, DO(MOVE(x, y, z), s))$$

Effect of move changes on **Clear** relations

$$On(x, y, s) \wedge Clear(x, s) \wedge Clear(z, s) \rightarrow Clear(y, DO(MOVE(x, y, z), s))$$

$$On(x, y, s) \wedge Clear(x, s) \wedge Clear(z, s) \wedge (z \neq Table) \rightarrow \neg Clear(z, DO(MOVE(x, y, z), s))$$

Blocks world example. Frame axioms.

- **Frame axioms.**
  - Represent things that remain unchanged after an action.

On relations:

$$On(u,v,s) \wedge (u \neq x) \wedge (v \neq y) \rightarrow On(u,v,DO(MOVE(x,y,z),s))$$

Clear relations:

$$Clear(u,s) \wedge (u \neq z) \rightarrow Clear(u,DO(MOVE(x,y,z),s))$$

Planning in situation calculus.

Planning problem:

- find a sequence of actions that lead to a goal

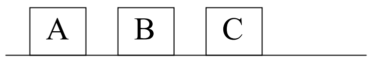
Planning in situation calculus is converted to theorem proving.

Goal state:

$$\exists s\ On(A,B,s) \wedge On(B,C,s) \wedge On(C,Table,s)$$

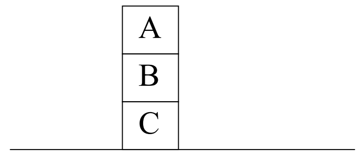
- Possible inference approaches:
  - **Inference rule approach**
  - **Conversion to SAT**
- **Plan** (solution) is a byproduct of theorem proving.
- **Example:** blocks world

Planning in a blocks world.



Initial state

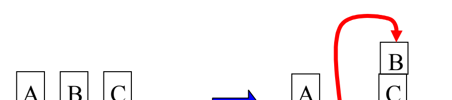
$On(A,Table,\ s_0)$
$On(B,Table,\ s_0)$
$On(C,Table,\ s_0)$
$Clear(A,\ s_0)$
$Clear(B,\ s_0)$
$Clear(C,\ s_0)$
$Clear(Table,\ s_0)$



Goal

$On(A,B,\ s)$
$On(B,C,\ s)$
$On(C,Table,\ s)$

Planning in the blocks world.



Initial state (s0)

s1

$s_0 =$

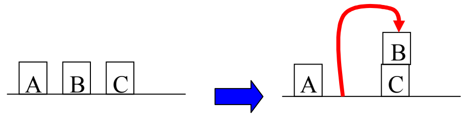
$On(A,Table,s_0)$ $Clear(A,s_0)$ $Clear(Table,s_0)$
$On(B,Table,s_0)$ $Clear(B,s_0)$
$On(C,Table,s_0)$ $Clear(C,s_0)$

Action: $MOVE(B,Table,C)$

$s_1 = DO(MOVE(B,Table,C),s_0)$

?

Planning in the blocks world.



Initial state (s0) **s1**

$s_0 =$

$On(A, Table, s_0)$ $Clear(A, s_0)$ $Clear(Table, s_0)$

$On(B, Table, s_0)$ $Clear(B, s_0)$

$On(C, Table, s_0)$ $Clear(C, s_0)$

Action: $MOVE(B, Table, C)$

$s_1 = DO(MOVE(B, Table, C), s_0)$

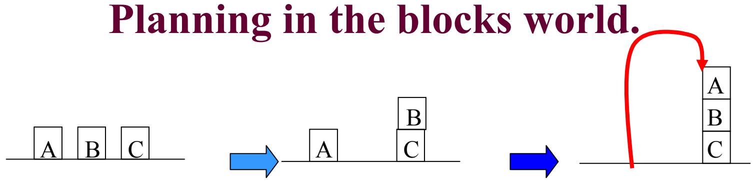
$On(A, Table, s_1)$ $Clear(A, s_1)$ $Clear(Table, s_1)$

$On(B, C, s_1)$ $Clear(B, s_1)$

$\neg On(B, Table, s_1)$ $\neg Clear(C, s_1)$

$On(C, Table, s_1)$

Planning in the blocks world.



Initial state (s0) **s1** **s2**

$s_1 = DO(MOVE(B, Table, C), s_0)$

$On(A, Table, s_1)$ $Clear(A, s_1)$ $Clear(Table, s_1)$

$On(B, C, s_1)$ $Clear(B, s_1)$

$\neg On(B, Table, s_1)$ $\neg Clear(C, s_1)$

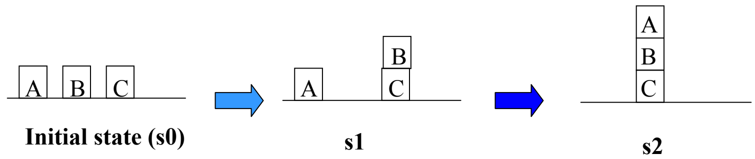
$On(C, Table, s_1)$

Action: $MOVE(A, Table, B)$

$s_2 = DO(MOVE(A, Table, B), s_1)$

$= DO(MOVE(A, Table, B), DO(MOVE(B, Table, C), s_0))$

Planning in the blocks world.



$s_1 = DO(MOVE(B, Table, C), s_0)$

$On(A, Table, s_1)$

$On(B, C, s_1)$

$\neg On(B, Table, s_1)$

$On(C, Table, s_1)$

$Clear(A, s_1)$

$Clear(B, s_1)$

$\neg Clear(C, s_1)$

$Clear(Table, s_1)$

Action: $MOVE(A, Table, B)$

$s_2 = DO(MOVE(A, Table, B), s_1)$

$= DO(MOVE(A, Table, B), DO(MOVE(B, Table, C), s_0))$

$On(A, B, s_2)$

$On(B, C, s_2)$

$On(C, Table, s_2)$

$\neg On(A, Table, s_2)$

$\neg On(B, Table, s_2)$

$Clear(A, s_2)$

$\neg Clear(B, s_2)$

$\neg Clear(C, s_2)$

$Clear(Table, s_2)$

Planning in situation calculus.

Planning problem:

- find a sequence of actions that lead to a goal

Planning in situation calculus is converted to theorem proving.

Goal state:

$\exists s\; On(A, B, s) \wedge On(B, C, s) \wedge On(C, Table, s)$

- Possible inference approaches:
  - **Inference rule approach**
  - **Conversion to SAT**
- **Plan** (solution) is a byproduct of theorem proving.
- **Problem:**
  - Large search space.
  - Proof may not lead to the best plan.

Frame problem

Frame problem refers to:

- The need to represent a large number of frame axioms

Solution: combine positive and negative effects in one rule

$$On(u,v,DO(MOVE(x,y,z),s)) \Leftrightarrow (\neg((u=x)\wedge(v=y))\wedge On(u,v,s))\vee$$
$$\vee(((u=x)\wedge(v=z))\wedge On(x,y,s)\wedge Clear(x,s)\wedge Clear(z,s))$$

Inferential frame problem:

– We still need to derive properties that remain unchanged

Other problems:

- **Qualification problem** – enumeration of all possibilities under which an action holds
- **Ramification problem** – enumeration of all inferences that follow from some facts