Situation Calculus

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(slides adapted from Robert Wilensky)

Using Logic to Plan

- We need ways of:
  - representing the world.
  - representing the goal.
  - representing how actions change the world.
- We haven't said much about the last.
  - Difficulty: After an action, new things are true, and some previously true facts are no longer true.

Situations

Idea:

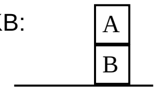
- Introduce a notion of *situations*, which are logical terms
  - Consist of initial situation (usually called S_0) and all situations generated by applying an action to a situation.
- State facts about situations.
  - By relativizing predications to situations.
  - E.g., instead of saying just **On(A,B)**, say (somehow) **On(A,B)** in situation $\mathbf{S_0}$
- Actions are thus
  - performed in a situation, and
  - produce new situations with new facts.
  - Examples: Forward and Turn(Right)

Representing Predications Relative to a Situation

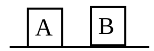
- Can add an argument for a situation to each predicate that can change.
  - E.g., instead of **On(A,B)**, write $\mathbf{On(A,B,S_0)}$
- Alternatively, introduce a predicate **Holds** and turn **On**, etc., into *functions*:
  - E.g., $\mathbf{Holds(On(A,B),S_0)}$
  - What do things like **On(A,B)** now mean?
    - Either a category of situations, in which **A** is on **B**, or a set of those situations.

How This Will Work

- Before some action, we might have in our KB:
  On(A,B,S_0)
  On(B,Table,S_0)
  ....



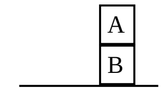
- After an action that moves A to the table, say, we add
  Clear(B,S_1)
  On(A,Table,S_1)



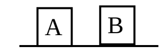
- All these propositions are true. We have dealt with the issue of change, by keeping track of what is true when.

Same Thing, Slightly Different Notation

- Before :
  Holds(On(A,B),S_0)
  Holds(On(B,Table),S_0)
  ...



- After, add
  Holds(Clear(B),S_1)
  Holds(On(A,Table),S_1)



Representing Actions

- Need to represent:
  - Results of doing an action
  - Conditions that need to be in place to perform an action.
- For convenience, we will define *functions* to abbreviate actions:
  - E.g., **Move(A,B)** denotes the *action type* of moving **A** onto **B**.
  - These are action *types*, because actions themselves are specific to time, etc.
- Now, introduce a *function* **Result**, designating "the situation resulting from doing an action type in some situation".
  - E.g., **Result(Move(A,B),S_0)** means "the situation resulting from doing an action of type **Move(A,B)** in situation **S_0**".

How This Works

- Keep in mind that things like
  Result(Move(A,B),S_0)
  are *terms*, and denote *situations*.
  They can appear anywhere we would expect a situation.
- So we can say things like
  S_1=Result(Move(A,B),S_0),
  On(A,B,Result(Move(A,B),S_0)),
  On(A,B,S_1), etc.
  (Alternatively, **Holds(On(A,B),Result(Move(A,B),S_0))**, etc.)

Axiomatizing Actions

- Now, we can describe the results of actions, together with their preconditions.
- E.g., 'If nothing is on x and y, then one can move x to on top of y, in which case x will then be on y.'

  ∀x,y,s Clear(x,s) ∧ Clear(y,s)
  ⇒ On(x,y,Result(Move(x,y),s))
- Alternatively:

  ∀x,y,s
  Holds(Clear(x),s) ∧ Holds(Clear(y),s)
  ⇒ Holds(On(x,y), Result(Move(x,y),s))
- This is an *effect axiom*.
  - It includes a precondition as well.

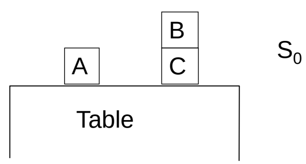
Situation Calculus

- This approach is called the *situation calculus*.
- We axiomatize all our actions, then use a general theorem prover to prove that a situation exists in which our goal is true.
- The actions in the proof would comprise our plan.

A Very Simple Example

- KB:

  On(A,Table,S_0)
  On(B,C,S_0)
  On(C,Table,S_0)
  Clear(A,S_0)
  Clear(B,S_0)
  and axioms about actions, etc.



- Goal:

  ∃s'. On(A,B,s')

What happens?

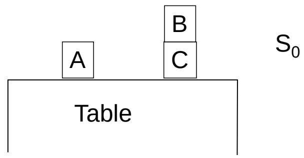
- We try to prove **On(A,B,s')** for some s'
  - Find axiom

    ∀x,y,s. Clear(x,s) ∧ Clear(y,s)
    ⇒ On(x,y,Result(Move(x,y),s))
  - By chaining, e.g., goal would be true if we could prove **Clear(A,s) ∧ Clear(B,s)** by backward chaining.
  - But both are true in **S_0**, so we can conclude **On(A,B,Result(Move(A,B),S_0))**
- We are done!
- We look in the proof and see only one action, **Move(A,B)**, which is executed in situation **S_0**, so this is our plan.

Tougher Example: Same Initial World, Harder Goal

- KB:

  On(A,Table,S_0)
  On(B,C,S_0)
  On(C,Table,S_0)
  Clear(A,S_0)
  Clear(B,S_0)
  and axioms about actions, etc.



- Goal:

  ∃s' On(A,B,s') ∧ On(B,C,s')

(Intuitively, really not harder: B already on C, and we just showed how to make A on B.)

With Goal **On(A,B,s') ∧ On(B,C,s')**

- Suppose we try to prove the first subgoal, **On(A,B,s')**.
  - Use same axiom
    ∀x,y,s. Clear(x,s) ∧ Clear(y,s)
    ⇒ On(x,y, Result(Move(x,y),s))
  - Again, by chaining, we can conclude
    On(A,B,Result(Move(A,B),S_0)).
  - Abbreviating **Result(Move(A,B),S_0)** as **S_1**, we have **On(A,B,S_1)**.
- Substituting for s' in our other subgoal makes that **On(B,C,S_1)**. If this is true, we're done.
- But we have no reason to believe this is true!
- Sure, **On(B,C,S_0)**, but how does the planner know this is still true, i.e., **On(B,C,S_1)**?
- In fact, it doesn't, so it fails to find an answer!

The Frame Problem

- We have failed to express the fact that everything that isn't changed by an action stays the same.
- Can fix by adding *frame axioms*. E.g.:

  ∀x,y,z,s.
  Clear(x,s) ⇒ Clear(x, Result(Paint(x,y),s))
  ...
- There are *lots* of these!
- Is this a big problem?

Better Frame Axioms

- Can fix with neater formulation:

  ∀x,y,s,a.
  On(x,y,s) ∧ (∀z. a=Move(x,z) ⇒ y=z)
  ⇒ On(x,y,Result(a,s))
- Can combine with effect axioms to get *successor-state axioms*:

  ∀x,y,s,a.
  On(x,y,Result(a,s)) ⇔
  On(x,y,s) ∧ (∀z. a=Move(x,z) ⇒ y=z)
  ∨ (Clear(x,s) ∧ Clear(y,s) ∧ a=Move(x,y))

How Does This Help Our Example?

- We want to prove

  On(B,C,Result(Move(A,B),S_0)) given that **On(B,C,S_0)**

  Axiom says

  ∀x,y,s,a. On(x,y,Result(a,s)) ⇔
  On(x,y,s) ∧ (∀z. a=Move(x,z) ⇒ y=z)
  ∨ (Clear(x,s) ∧ Clear(y,s) ∧ a=Move(x,y))

- So need to show

  On(B,C,S_0) ∧ (∀z. Move(A,B)=Move(B,z) ⇒ C=z) is true, which is easy

  – The first conjunct is in the KB.

  – The second one is true since actions are the same only if they have the same name and involve the exact same objects i.e.

$$A(x_1, \cdots, x_m) = A(y_1, \cdots, y_m) \text{ iff } x_1 = y_1 \wedge \cdots \wedge x_m = y_m$$

so **Move(A,B)=Move(B,z)** is false.

Note: Another assumption in KB: $A(x_1, \cdots, x_m) \neq B(y_1, \cdots, y_n)$

These are known as Unique Action Axioms

For Refutation Theorem Proving: (Dual) Skolemisation

- Suppose ∀x. ∃y. G(x,y) is goal in resolution refutation.
- So, we need to negate the goal:

  ¬ ∀x. ∃y. G(x,y) ≡ ∃x. ∀y. ¬G(x,y)

- Then skolemise (i.e drop existential quantifier):

  ¬G(X_0,y)

- Intuition:
  – y is to be unified to construct *witness*.
  – X_0 must not be instantiated.

- Similar story for GMP, but goal not negated, i.e. G(X_0,y), for some y, is used as the goal.

KB and Axioms as Clauses

Constants: A, B, C, S0
Variables: a, x, y, s

Initial State

On(A,Table,S0)
On(B,C,S0)
On(C,Table,S0)
Clear(A,S0)
Clear(B,S0)

Goal

¬On(A,B,s') ∨ ¬On(B,C,s')

Effect Axiom

¬Clear(x,s) ∨ ¬Clear(y,s) ∨
On(x,y, Result(Move(x,y),s))

Frame Axioms

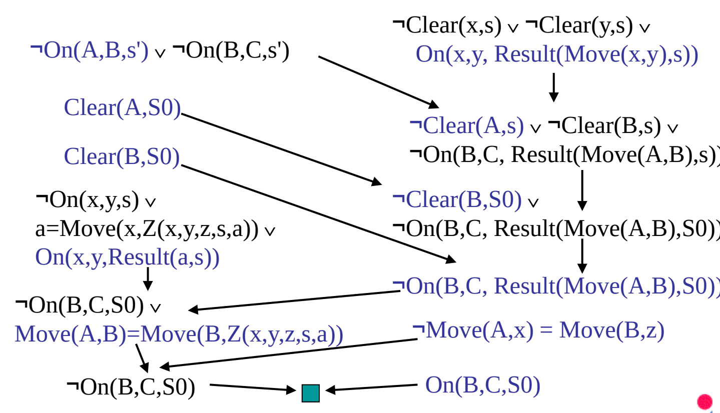
¬On(x,y,s) ∨ a=Move(x,Z(x,y,z,s,a)) ∨ On(x,y,Result(a,s))
¬On(x,y,s) ∨ ¬y=Z(x,y,z,s,a) ∨ On(x,y,Result(a,s))

(Skolem function: Z)

Unique Action Axioms: ¬ Move(A,B)=Move(B,z), etc

Unique Name Axiom: disequality for every pair of constants in KB

Resolution Refutation



Frame problem partially solved

- This solves the representational part of the frame problem.
- Still have to compute that everything that was true that wasn't changed is still true. Inefficient (as is general theorem proving).
- Solution: Special purpose representations, special purpose algorithms, called *Planners*.

Summary

- Planning
- Situations
- Frame problem