Foundations of AI

13. Knowledge Representation: Modeling with Logic

Concepts, Actions, Time, & all the rest

Wolfram Burgard, Bernhard Nebel, and Luc De Raedt

Contents

- Knowledge Representation and Reasoning
- Concepts & Description logics
- Logical agents for the WUMPUS World
- Situation calculus
- The frame problem
- Time intervals and their description

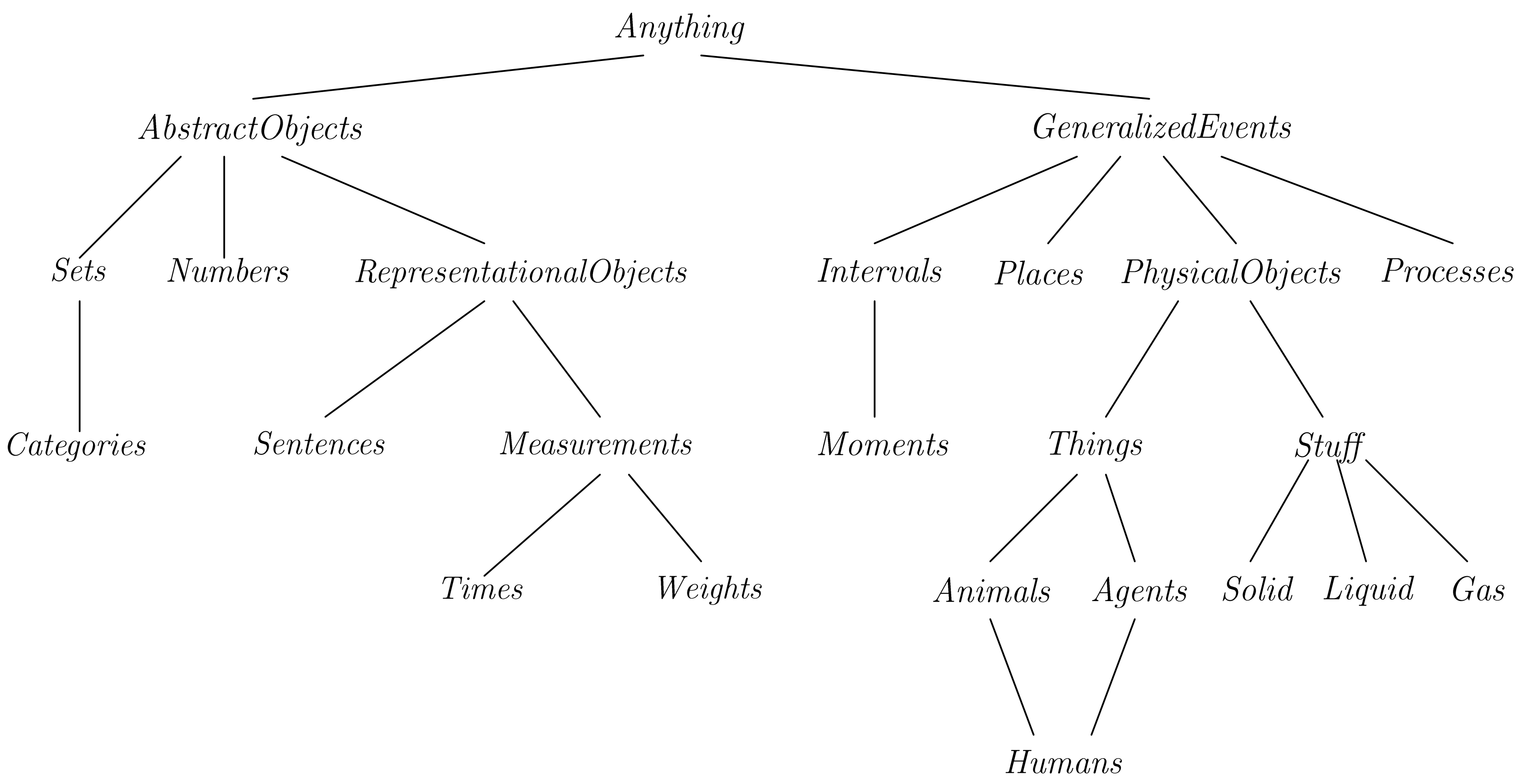
Knowledge Representation and Reasoning

- Often, our agents need knowledge before they can start to act intelligently
- They then also need some reasoning component to exploit the knowledge they have
- Examples:
  - Knowledge about the important concepts in a domain
  - Knowledge about actions one can perform in a domain
  - Knowledge about temporal relationships between events
  - Knowledge about the world and how properties are related to actions

Categories and Objects

- We need to describe the objects in our world using categories
- Necessary to establish a common category system for different applications (in particular on the web)
- There are a number of quite general categories everybody and every application uses

The Upper Ontology:
A General Category Hierarchy



Description Logics

- How to describe more specialized things?
- Use definitions and/or necessary conditions referring to other already defined *concepts*:
  - a parent is a human with at least one child
- More complex description:
  - a proud-grandmother is a human, which is female with at least two children that are in turn parents whose children are all doctors

Reasoning Services in Description Logics

- Subsumption: Determine whether one description is more general than (subsumes) the other
- Classification: Create a subsumption hierarchy
- Satisfiability: Is a description satisfiable?
- Instance relationship: Is a given object instance of a concept description?
- Instance retrieval: Retrieve all objects for a given concept description

Special Properties of Description Logics

- Semantics of description logics (DLs) can be given using ordinary PL1
- Alternatively, DLs can be considered as modal logics
- Reasoning for most DLs is much more efficient than for PL1
- Nowadays, W3C standards such as OWL (formerly DAML+OIL) are based on description logics

Logic-Based Agents That Act

```
function KB-AGENT(percept) returns an action
   static: KB, a knowledge base
           t, a counter, initially 0, indicating time

   TELL(KB, MAKE-PERCEPT-SENTENCE(percept, t))
   action ← ASK(KB, MAKE-ACTION-QUERY(t))
   TELL(KB, MAKE-ACTION-SENTENCE(action, t))
   t ← t + 1
   return action
```

Query (Make-Action-Query): $\exists x Action(x, t)$

A variable assignment for x in the WUMPUS world example should give the following answers:

$turn(right), turn(left), forward, shoot, grab, release, climb$

Reflex Agents

… only react to percepts.

Example of a percept statement (at time 5):

$$Percept(stench, breeze, glitter, none, none, 5)$$

1. $\forall b, g, u, c, t[Percept(stench, b, g, u, c, t) \Rightarrow Stench(t)]$
   $\forall s, g, u, c, t[Percept(s, breeze, g, u, c, t) \Rightarrow Breeze(t)]$
   $\forall s, b, g, u, c, t[Percept(s, b, glitter, u, c, t) \Rightarrow AtGold(t)]$
   $\ldots$
2. Step: Choice of action

$$\forall t[AtGold(t) \Rightarrow Action(grab, t)]$$

$$\ldots$$

Note: Our reflex agent does not know when it should climb out of the cave and cannot avoid an infinite loop.

Model-Based Agents

… have an internal model

- of all basic aspects of their environment,
- of the executability and effects of their actions,
- of further basic laws of the world, and
- of their own goals.

Important aspect: How does the world change?

→ Situation calculus: (McCarthy, 63).

Situation Calculus

- A way to describe dynamic worlds with PL1.
- States are represented by terms.
- The world is in state s and can only be altered through the execution of an action: $do(a, s)$ is the resulting situation, if a is executed.
- Actions have preconditions and are described by their effects.
- Relations whose truth value changes over time are called fluents. Represented through a predicate with two arguments: the fluent and a state term. For example, $At(x, s)$ means, that in situation s, the agent is at position x. $Holding(y, s)$ means that in situation s, the agent holds object y.
- Atemporal or eternal predicates, e.g., $Portable(gold)$.

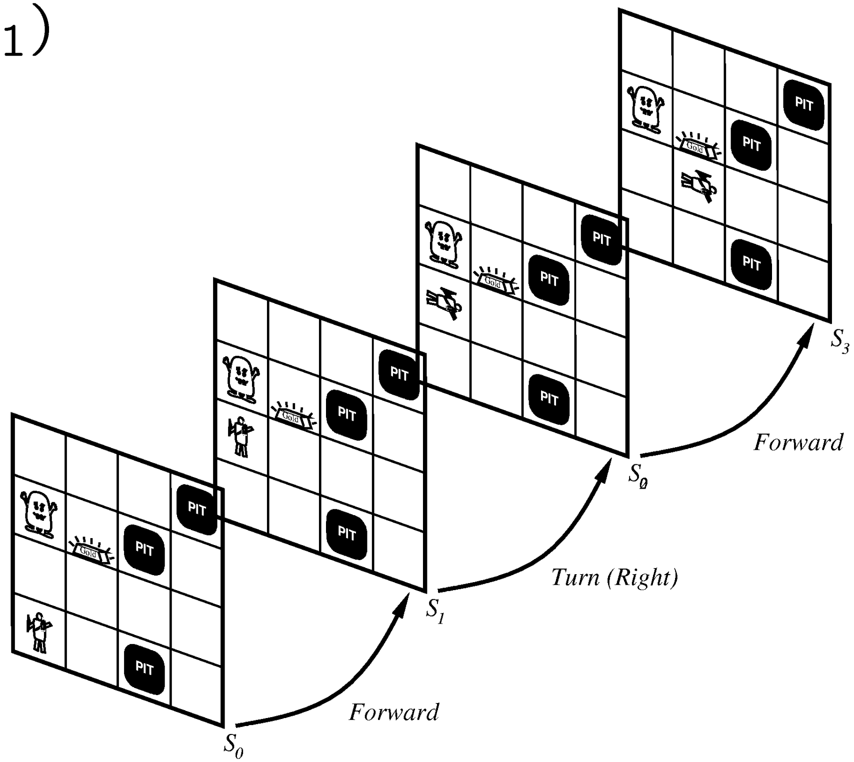
Example: WUMPUS-World

Let s_0 be the initial situation and

$s_1 = do(forward, s_0)$

$s_2 = do(turn(right), s_1)$

$s_3 = do(forward, s_2)$



Description of Actions

Preconditions: In order to pick something up, it must be both present and portable:

$$\forall x, s[Poss(grab(x), s) \Leftrightarrow Present(x, s) \wedge Portable(x)]$$

In the WUMPUS-World:

$$Portable(gold), \forall s[AtGold(s) \Rightarrow Present(gold, s)]$$

Positive effect axiom:

$$\forall x, s[Poss(grab(x), s) \Rightarrow Holding(x, do(grab(x), s))]$$

Negative effect axiom:

$$\forall x, s \neg Holding(x, do(release(x), s))$$

The Frame Problem

We had: $Holding(gold, s_0)$.

Following situation: $\neg Holding(gold, do(release(gold), s_0))$?

We had: $\neg Holding(gold, s_0)$.

Following situation: $\neg Holding(gold, do(turn(right), s_0))$?

- We must also specify which *fluents* remain unchanged!
- The frame problem: Specification of the properties that *do not* change as a result of an action.

→ Frame axioms must also be specified.

Number of Frame Axioms

$$\forall a, x, s[Holding(x, s) \wedge (a \neq release(x)) \Rightarrow Holding(x, do(a, s))]$$

$$\forall a, x, s[\neg Holding(x, s) \wedge \{(a \neq grab(x)) \vee \neg Poss(grab(x), s)\} \\ \Rightarrow \neg Holding(x, do(a, s))]$$

Can be very expensive in some situations, since $O(|F| \times |A|)$ axioms must be specified, F being the set of fluents and A being the set of actions.

Successor-State Axioms

A more elegant way to solve the frame problem is to fully describe the successor situation:

true after action ⇔ [action made it true ∨ already true and the action did not *falsify* it]

Example for $grab$:

$$\forall a, x, s[Holding(x, do(a, s))$$
$$\Leftrightarrow \{(a = grab(x) \wedge Poss(a, s)) \vee (Holding(x, s) \wedge a \neq release(x))\}]$$

Can also be automatically compiled by only giving the effect axioms (and then applying *explanation closure*). Here we suppose that only certain effects can appear.

Limits of this Version of Situation Calculus

- No explicit time. We cannot discuss how long an action will require, if it is executed.
- Only one agent. In principle, however, several agents can be modeled.
- No parallel execution of actions.
- Discrete situations. No continuous actions, such as moving an object from A to B.
- Closed world. Only the agent changes the situation.
- Determinism. Actions are always executed with absolute certainty.

→ Nonetheless, sufficient for many situations.

Qualitative Descriptions of Temporal Relationships

We can describe the temporal occurrence of event/actions:

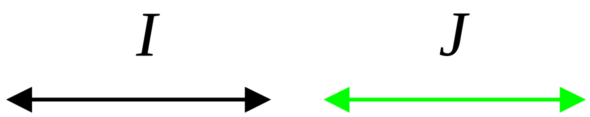
- absolute by using a date/time system
- relative with respect to other event occurrences
- quantitatively, using time measurements (5 secs)
- qualitatively, using comparisons (before/overlaps)

Allen's Interval Calculus

- Allen proposed a calculus about relative order of *time intervals*
- Allows us to describe, e.g.,
  - Interval I occurs before interval J
  - Interval J occurs before interval K
- and to conclude
  - Interval I occurs before interval K

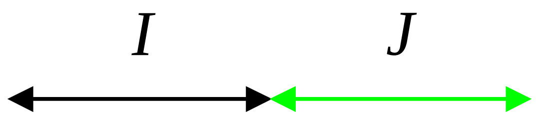
→ 13 jointly exhaustive and pair-wise disjoint relations between intervals

Allen's 13 Interval Relations



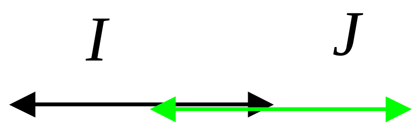
$I < J, J > I$

$before/after$



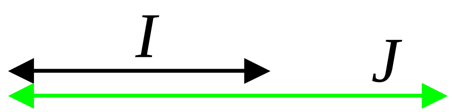
$I m J, J m^{-1} I$

$meets$



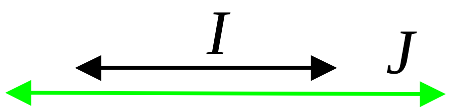
$I o J, J o^{-1} I$

$overlaps$



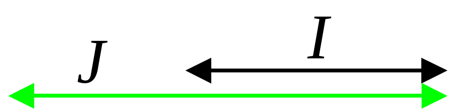
$I s J, J s^{-1} I$

$starts$



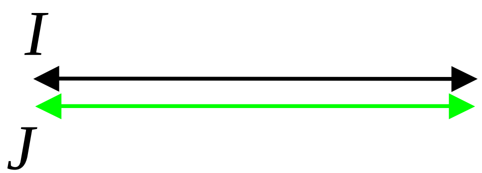
$I d J, J d^{-1} I$

$during$



$I f J, J f^{-1} I$

$finishes$



$I = J$

Examples

- Using Allen's relation system one can describe temporal configurations as follows:
  - $X < Y, Y\, o Z, Z > X$

- One can also use disjunctions (unions) of temporal relations:
  - $X(<, m)Y, Y(o, s)Z, Z > X$

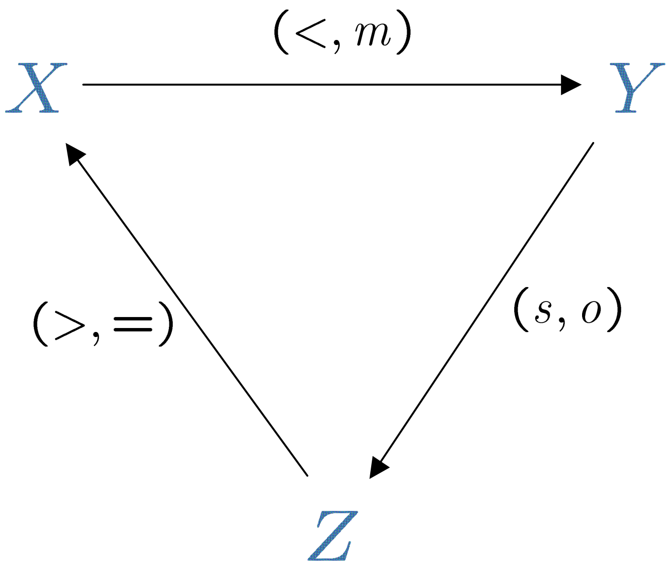
Reasoning in Allen's Relations System

How do we reason in Allen's system

- Checking whether a set of formulae is satisfiable
- Checking whether a temporal formula follows logically

➢ Use a constraint propagation technique for CSPs with infinite domains (3-consistency), based on *composing relations*

Constraint Propagation



$$
\begin{array}{lcll}
X < Y \, s \, Z & = & X & \quad Z \\
X < Y \, o \, Z & = & X & \quad Z \\
X \, m \, Y \, s \, Z & = & X & \quad Z \\
X \, m \, Y \, o \, Z & = & X & \quad Z
\end{array}
$$

Do that for every triple until nothing changes anymore, then CSP is 3-consistent

Concluding Remarks: Use of Logical Formalisms

- In many (but not all) cases, full inference in PL1 is simply too slow (and therefore too unreliable).
- Often, special (logic-based) representational formalisms are designed for specific applications, for which specific inference procedures can be used. Examples:
  - Description logics for representing conceptual knowledge.
  - James Allen’s time interval calculus for representing qualitative temporal knowledge.
  - Planning: Instead of situation calculus, this is a specialized calculus (STRIPS) that allows us to address the frame problem.

$\rightarrow$ Generality vs. efficiency

$\rightarrow$ In every case, logical semantics is important!