

# Foundations of AI

## 11. Knowledge Representation: Modeling with Logic

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Concepts, Actions, Time, & All the Rest

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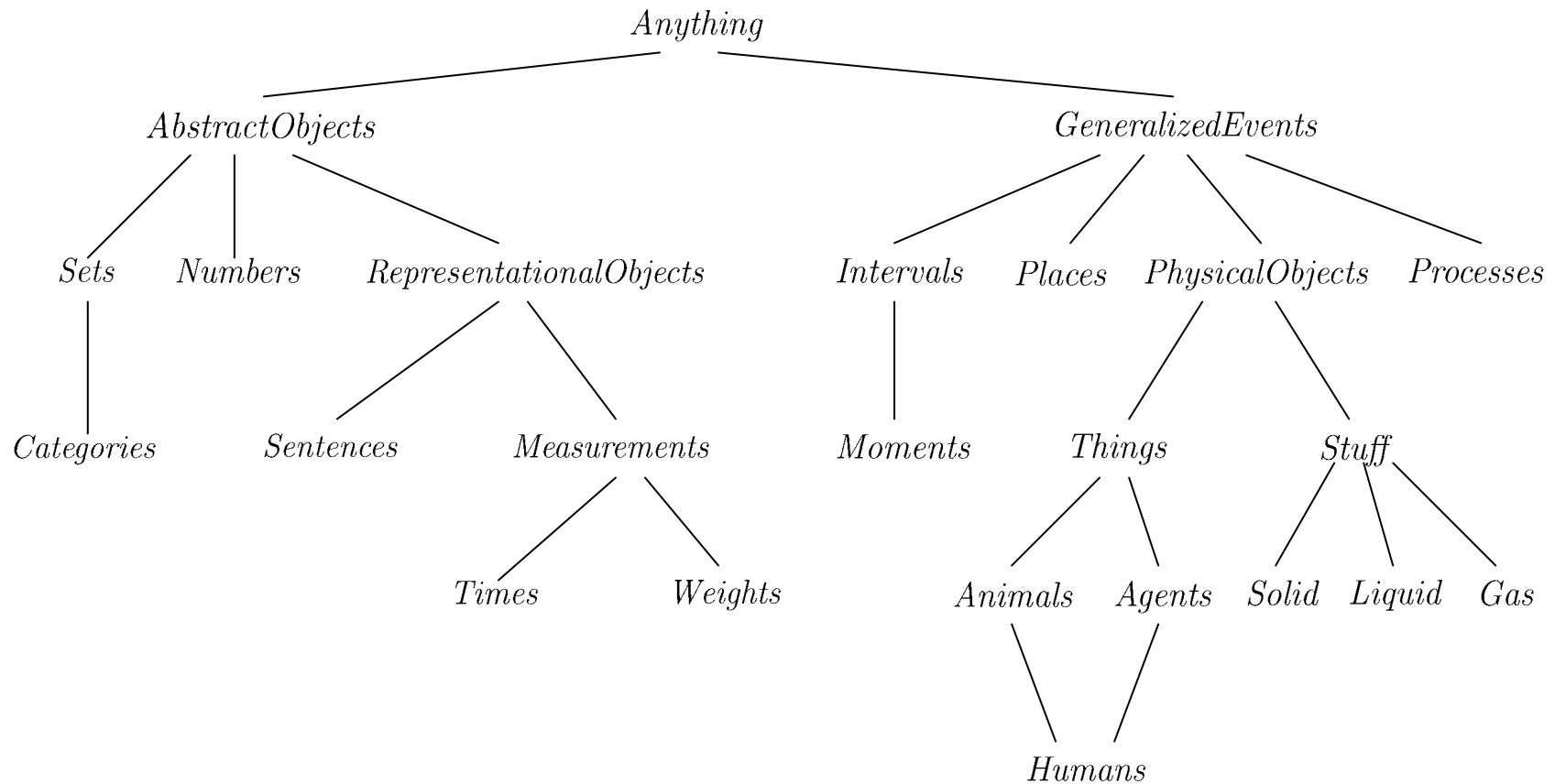
# Knowledge Representation and Reasoning

- 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):  $\exists x \text{Action}(x, t)$

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

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

...

**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.,  $Portable(gold)$ .

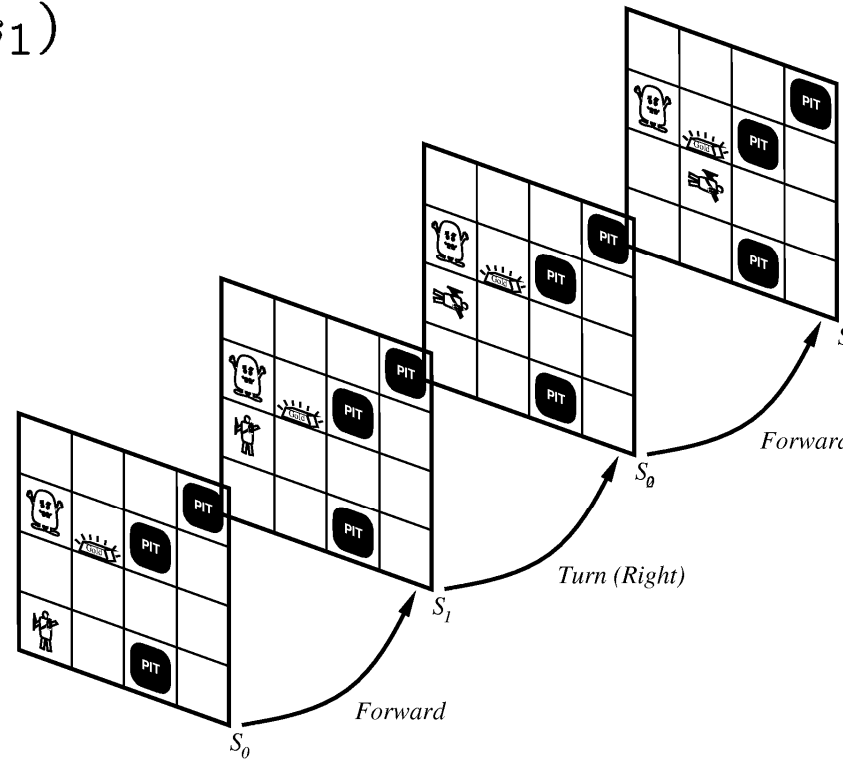
# Example: WUMPUS-World

Let  $s_0$  be the initial situation and

$$s_1 = do(\text{forward}, s_0)$$

$$s_2 = do(\text{turn}(\text{right}), s_1)$$

$$s_3 = do(\text{forward}, s_2)$$



## Description of Actions

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

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

In the WUMPUS-World:

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

**Positive effect axiom:**

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

**Negative effect axiom:**

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

## 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

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

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

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  $\Leftrightarrow$  [ action made it true  $\vee$  already true and the action did not *falsify* it ]

Example for *grab* :

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

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

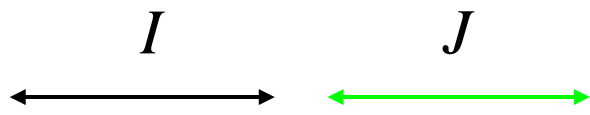
We can describe the temporal occurrence of event/actions:

- **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)

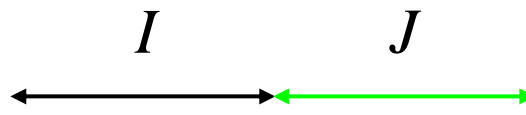
# Allen's Interval Calculus

- 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



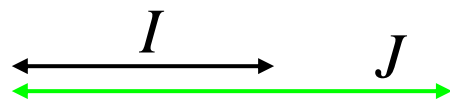
$I < J, J > I$   
*before/after*



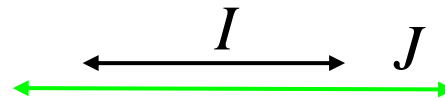
$I m J, J m^{-1} I$   
*meets*



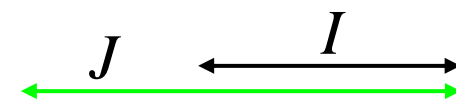
$I o J, J o^{-1} I$   
*overlaps*



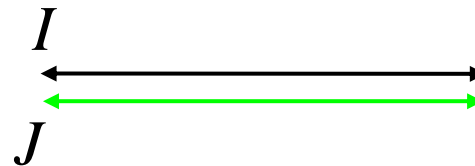
$I s J, J s^{-1} I$   
*starts*



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

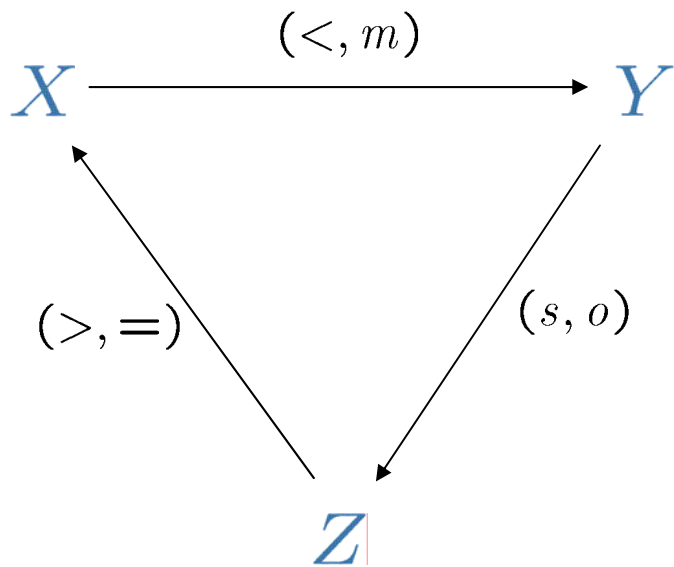
- $X(<, m)Y, Y(o, s)Z, Z > X$

# 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



$$\begin{aligned} X < Y \text{ s } Z &= X \quad Z \\ X < Y \text{ o } Z &= X \quad Z \\ X \text{ m } Y \text{ s } Z &= X \quad Z \\ X \text{ m } Y \text{ o } Z &= X \quad Z \end{aligned}$$

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.
- Generality vs. efficiency
- In every case, logical semantics is important!