Foundations of Artificial Intelligence
10. Knowledge Representation: Modeling with Logic
Concepts, Actions, Time, and all the Rest

Joschka Boedecker and Wolfram Burgard and Marco Ragni

Albert-Ludwigs-Universität Freiburg

June 10th & 15th, 2016
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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.
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.
Typical questions of interest:

- **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
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
function KB-AGENT(\textit{percept}) \textbf{returns} an action

\textbf{persistent}: \textit{KB}, a knowledge base

\hspace{1cm} \textit{t}, a counter, initially 0, indicating time

\begin{align*}
\text{T} & \text{ELL}(\textit{KB}, \text{MAKE-PERCEPT-SENTENCE(} \textit{percept}, \textit{t})) \\
\textit{action} & \leftarrow \text{ASK}(\textit{KB}, \text{MAKE-ACTION-QUERY(} \textit{t})) \\
\text{T} & \text{ELL}(\textit{KB}, \text{MAKE-ACTION-SENTENCE(} \textit{action}, \textit{t})) \\
\textit{t} & \leftarrow \textit{t} + 1 \\
\textbf{return} & \textit{action}
\end{align*}

\textbf{Query (MAKE-ACTION-QUERY):} \exists \textit{x} \text{Action}(\textit{x}, \textit{t})

A variable assignment for \textit{x} in the WUMPUS world example should give the following answers: \textit{turn(}right\textit{)}, \textit{turn(}left\textit{)}, \textit{forward}, \textit{shoot}, \textit{grab}, \textit{release}, \textit{climb}. 
Reflex Agents

... only react to percepts.

Example of a percept statement (at time 5):

\[\text{Percept}(\text{stench}, \text{breeze}, \text{glitter}, \text{none}, \text{none}, 5)\]

1. \(\forall b, g, u, c, t[\text{Percept}(\text{stench}, b, g, u, c, t) \Rightarrow \text{Stench}(t)]\)
   
   \(\forall s, g, u, c, t[\text{Percept}(s, \text{breeze}, g, u, c, t) \Rightarrow \text{Breeze}(t)]\)

   \(\forall s, b, g, u, c, t[\text{Percept}(s, b, \text{glitter}, u, c, t) \Rightarrow \text{AtGold}(t)]\)

   ...

2. Step: Choice of action

   \(\forall t[\text{AtGold}(t) \Rightarrow \text{Action}(\text{grab}, t)]\)

   ...

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

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

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

$$s_3 = do(\text{forward}, s_2)$$
Preconditions: In order to pick something up, it must be both present and portable:

\[ \forall x, s [ \text{Poss}(\text{grab}(x), s) \iff \text{Present}(x, s) \land \text{Portable}(x)] \]

In the WUMPUS-World:

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

Positive effect axiom:

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

Negative effect axiom:

\[ \forall x, s \neg \text{Holding}(x, \text{do}(\text{release}(x), s)) \]
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.
∀a, x, s[\text{Holding}(x, s) \land (a \neq \text{release}(x)) \Rightarrow \text{Holding}(x, \text{do}(a, s))]

∀a, x, s[\neg\text{Holding}(x, s) \land \{(a \neq \text{grab}(x)) \lor \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.
A more elegant way to solve the frame problem is to fully describe the successor situation:

true after action
⇔ [ action made it true or, already true and the action did not falsify it ]

Example for *grab*:

\[ \forall a, x, s [ \text{Holding}(x, \text{do}(a, s)) ] \]

\[ \iff \{ (a = \text{grab}(x) \land \text{Poss}(a, s)) \lor (\text{Holding}(x, s) \land a \neq \text{release}(x)) \} \]

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.
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 Relation

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

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

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

  \[ X < Y, \ Y \circ Z, \ Z > X \]

- 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

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, there is a specialized calculus (STRIPS) that allows us to address the frame problem efficiently.

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