Knowledge Representation

Lecture 2: Classical Logics

Patrick Koopmann

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What is a Knowledge Representation?

after [Davis, Shrobe and Szolovits, 1993]:

1. Surrogate
2. Expression of ontological commitment
3. Theory of intelligent reasoning
4. Medium of efficient computation
5. Medium of human expression

Today we look at two examples: propositional logic and first-order logic

Propositional Logic

Propositional logic is an example of a simple KR

- Propositional variables abstract atoms of information
  - a: Tom comes to the VU.
  - c: Tom takes the bike.
  - b: Tom takes the tram.
  - d: It is sunny.
  - e: It is raining.
  - f: The bike is broken.
  - g: The tram company is on strike.
- Operators allow to build complex formulas
  1. $d \rightarrow \neg e$
  2. $a \leftrightarrow (b \vee c)$
  3. $(e \vee f) \rightarrow \neg b$
  4. $(d \wedge \neg f) \rightarrow b$
  5. $g \rightarrow \neg c$
  6. $e \wedge \neg g$
- A clear semantics defines what these formulas mean
- Automated reasoning can be used to infer implicit information
  - *Does Tom come to the VU?*

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- Atomic sentences as building blocks
  - Represent facts we want to reason about
  - No inner structure
- We can build more complex sentences using operators
- Every sentence is either true or false

Propositional Logics: Reasoning Problems

What do we want to do with such sentences?

- Entailment
  - What does logically follow from my knowledge?
  - Example: *Does it follow from my knowledge that Tom comes to the VU?*

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- Entailment
  - What does logically follow from my knowledge?
  - Example: *Does it follow from my knowledge that Tom comes to the VU?*
- Consistency
  - Is my knowledge consistent?
  - Does it describe a possible situation?
  - Example: "It rains", "It is sunny", "If it rains, it is not sunny" $\Rightarrow$ not consistent
  - In context of propositional logic, usually called satisfiability

Propositional Logic: Vocabulary

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Our vocabulary V consists of an infinite set of propositional variables:

$$V = \{a, b, c, \ldots\}$$

These are our basic building blocks:

- Represent sentences we reason about
- Using letters makes it easier to write complex formulas
- But we could also use strings: "It rains", "It is sunny".

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- These interpret the value of the propositional variables
- and represent different possibilities.

Interpretations in Propositional Logic

An interpretation in propositional logic is a function $I : V \to \{\textbf{true}, \textbf{false}\}$

Examples:

- $I_1(\text{“Es regnet”}) = \textbf{true}$, $I_1(\text{“Die Sonne scheint”}) = \textbf{false}$

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Propositional formulas restrict the space of interpretations to those that are models (abstract representations) of possible alternatives of the described situation.

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Examples:

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  “Es regnet” $\rightarrow \neg$“Die Sonne scheint”

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Examples:

- *"Wenn es regnet, scheint die Sonne nicht."*
  "Es regnet" $\rightarrow \neg$"Die Sonne scheint"
- $(c \wedge d) \leftrightarrow (a \vee \neg b)$

Exercise: Formalization in Propositional Logic

Assume we have the following propositional variables:

- a: "The post brings a parcel."
- b: "I am at home."
- c: "My neighbour is at home."
- d: "I take the parcel."
- e: "My neighbour takes the parcel."
- f: "The parcel goes back."

Formalize the following facts into propositional logic:

"I am not at home, and the post brings a parcel."	
"My neighbour is at home."	
"If I am at home and the post brings a parcel, I take the parcel."	
"If I am not at home, I don't take the parcel."	
"If the post brings a parcel, and neither me nor the neighbour take the parcel, it goes back."	
"If the post brings a parcel and the neighbour is at home, the neighour takes the parcel if and only if I am not at home."	

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F	$\neg F$
false	**true**
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- $I((a \land b) \to c) = \mathbf{true}$

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- Try to find an interpretation I that satisfies some of the formulas you have written down in the previous exercise.
- Of course, you only need to specify the variables that are relevant
- Example: $I(a) =$ **true** and $I(b) =$ **false** satisfies the first formula

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We can therefore leave out brackets for nested conjunctions/disjunctions:

- $(F \vee G) \vee H = F \vee (G \vee H) = F \vee G \vee H$
- $(F \wedge G) \wedge H = F \wedge (G \wedge H) = F \wedge G \wedge H$

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Having a method for satisfiability is sufficient:

- $F \models G$ if and only if $F \land \neg G$ is not satisfiable

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Termination For each instance of P, the algorithm stops after a finite number of steps.

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- Many decision problems are decidable:
  - Example: *Is X a prime number?*
- But there are also problems that are undecidable:
  - Example *Does program P eventually stop?*
  - This corresponds to the famous halting problem
  - It is impossible to devise an algorithm that always answers this correctly.

Reasoning in Propositional Logic in Practice

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In practice:

- SAT-solvers are tools to determine satisfiability of propositional formulas
- Modern SAT-solvers are highly optimized, and can often deal with very large formulas in short time
- Examples of SAT solvers: MiniSAT, PicoSAT, CaDiCaL, ...

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What we cannot do well is reason using the inner structure of sentences:

- "Socrates is a human."
- "All humans are mortal."
- Entails: "Socrates is mortal."

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- Every parent has a child: $\forall x : (\mathit{Parent}(x) \rightarrow \exists y : \mathit{hasChild}(x, y))$

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The vocabulary is now more involved:

- constants a, b, c, ... denote specified objects
- variables x, y, z, ... denote unspecified objects
- function names f, g, h, ... denote functions
  - Every function name f has an arity $ar(f) \in \mathbb{N}^+$
  - The arity determines how many arguments the function takes
  - *Examples:* successor, sum $\quad ar(\text{successor}) = 1, \quad ar(\text{sum}) = 2$

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The vocabulary is now more involved:

- constants a, b, c, ... denote specified objects
- variables x, y, z, ... denote unspecified objects
- function names f, g, h, ... denote functions
  - Every function name f has an arity $ar(f) \in \mathbb{N}^+$
  - The arity determines how many arguments the function takes
  - *Examples:* successor, sum $\quad ar(\text{successor}) = 1, \quad ar(\text{sum}) = 2$
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Again, interpretations determine what these mean

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- Then, we define atoms:
  - if P is a predicate name of arity n, and $t_1, \ldots, t_n$ are terms, then $P(t_1, \ldots, t_n)$ is an atom
  - Example: $EvenNumber(x)$, $Neighbours(sister(anna), peter)$
  - atoms are like the propositional variables in propositional logic

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  - $\forall x : F$ ("for all", universal quantification)

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Some examples:

- $\forall x : (\mathit{EvenNumber}(x) \leftrightarrow \mathit{OddNumber}(\mathit{sum}(x, 1)))$
- $\forall x : (\mathit{Parent}(x) \rightarrow \exists y : \mathit{HasChild}(x, y))$
- $\forall x : \forall y : (\exists z : \mathit{DeliversParcelTo}(z, y, x) \wedge \mathit{AtHome}(x)) \rightarrow \mathit{ReceivedParcel}(x, y))$

First-Order Logic: Example

We can use first-order logic to model the parcel example a bit better:

$$\neg AtHome(patrick)$$
$$DeliversParcelTo(mailMan, patrick, parcel)$$
$$Neighbour(patrick, lucia)$$
$$\forall x : \forall y : \forall z : ((BringsParcelTo(x, y, z) \wedge AtHome(y)) \rightarrow Receives(x, z))$$
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- $\cdot^I$ is a function that interprets constants, functions and variables
- We then write their interpretations as c^I, f^I, P^I, etc.

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  - It maps tuples of elements to elements
- Every predicate name P with arity n is assigned a relation $P \in \Delta^n$
  - This means, P is a set of tuples
  - For example, if P has arity 1, it is a subset of Δ
  - If P has arity 3, it contains tuples $\langle a, b, c \rangle$, where a, b and c are from Δ

Example: First-Order Interpretation

$$\Delta^I = \{a, b, c, d\}$$

$$patrick^I = a \qquad mailMan^I = b \qquad parcel^I = c$$

$$Neighbour^I = \{\langle a, d\rangle, \langle d, a\rangle\} \qquad AtHome^I = \{a, d\}$$

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Which formulas hold in this interpretation?

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Using variable assigments, we can now define what it means for a first-order formula to be satisfied in an interpretation.

Satisfaction of First-Order Formulas

- Satisfaction of formulas F is first defined relative to a variable assigment σ_I for the interpretation in question.
- We write this as $\sigma_I \models F$ (F is satisfied under σ_I).

We define satisfaction under a variable assignment *inductively*:

- For any atom $P(t_1, \ldots, t_n)$: $\quad \sigma_I \models P(t_1, \ldots, t_n) \quad$ if $\langle t_1, \ldots, t_n \rangle \in P^I$

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Satisfaction of First-Order Formulas

Now observe:

- If all variables are bound, the variable assignment is not relevant anymore
- We can then write $I \models F$ instead of $\sigma_I \models F$
- This is how *satisfaction of sentences* is defined
  - Recall: every variable in a sentence is bound

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- In particular, it is only semi-decidable

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This limits the usefulness of FOL as KR drastically!

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- Restrict the number of variables to 2
- Restrict the use of quantifiers
- Or more involved restrictions on formulas

From First-Order to Propositional Logic

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- Ground formulas are like propositional formulas:
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- We can thus use SAT-solvers to reason with them.

From First-Order to Proposition Logic: Grounding

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  - All quantifiers are universal quantifiers
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  - $\forall x : (Student(x) \rightarrow Person(x))$
  - $\forall x : \forall y : (Neighbour(x, y) \leftrightarrow Neighbour(y, x))$
  - $\forall x : \forall y : ((Person(x) \wedge hasChild(x, y)) \rightarrow Parent(x)$

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- Idea: use all groundings of quantified variables:
  - $\forall x : (\mathit{Student}(x) \rightarrow \mathit{Person}(x))$
    $\Longrightarrow \mathit{Student}(\mathit{tom}) \rightarrow \mathit{Person}(\mathit{tom}) \ \land \ \mathit{Student}(\mathit{peter}) \rightarrow \mathit{Person}(\mathit{peter}) \ \land \ \ldots$
  - We use only the constants that occur in our formulas.
  - If we have no constant, we use an arbitrary one (e.g. a)

From First-Order to Proposition Logic: Grounding

- This trick fails once we have functions or existential quantifiers
  - refer to new objects
  - there may be many: $\forall x : A(x) \rightarrow A(f(x)) \quad \Rightarrow \quad A(a), \quad A(f(a)), \quad A(f(f(a))), \quad \ldots$

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Conclusion

Propositional Logic

- Limited expressivity
- Reasoning may take exponential time
- Efficient SAT-solvers

First-Order Logic

- High expressivity
- Semantics a bit involved
- Only semi-decidable
- But there are syntactical restrictions that makes it decidable

Friday

Next: A family of fragments of first-order logic that

- can deal with existential and universal quantification
- is decidable
- has a more readable syntax (optimized for its use case)
- has easier semantics
- allows for efficient reasoning in practical applications

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Meet the Description Logics!