Principles of Knowledge Representation and Reasoning

Predicate Logic

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Why First-Order Logic (FOL)?

- In propositional logic, the only building blocks are atomic propositions.
- We cannot talk about the internal structures of these propositions.
- Example:
  - *All CS students know formal logic*
  - *Peter is a CS student*
  - Therefore, *Peter knows formal logic*
  - Not possible in propositional logic
- Idea: We introduce predicates, functions, object variables and quantifiers.

Syntax

- variable symbols: $x, y, z, \ldots$
- n-ary function symbols: $f, g, \ldots$
- constant symbols: $a, b, c, \ldots$
- n-ary predicate symbols: $P, Q, \ldots$
- logical symbols: $\forall$, $\exists$, $=$, $\neg$, $\wedge$, ...

Terms	t	$\longrightarrow$	x	variable
		$\mid$	$f(t_1, \ldots, t_n)$	function application
		$\mid$	a	constant
Formulae	φ	$\longrightarrow$	$P(t_1, \ldots, t_n)$	atomic formulae
		$\mid$	$t = t'$	identity formulae
		$\mid$	$\ldots$	propositional connectives
		$\mid$	$\forall x \varphi'$	universal quantification
		$\mid$	$\exists x \varphi'$	existential quantification

ground term, etc.: term, etc. without variable occurrences

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ground term, etc.: term, etc. without variable occurrences

Semantics: Idea

- In FOL, the universe of discourse consists of objects, functions over these objects, and relations over these objects.
- Function symbols are mapped to functions, predicate symbols are mapped to relations, and terms to objects.
- Notation: Instead of $\mathcal{I}(x)$ we write $x^{\mathcal{I}}$.
- Note: Usually one considers all possible non-empty universes. (However, sometimes the interpretations are restricted to particular domains, e.g. integers or real numbers.)
- Satisfiability and validity is then considered wrt all these universes.

Formal Semantics: Interpretations

Interpretations: $\mathcal{I} = \langle \mathcal{D}, \cdot^{\mathcal{I}} \rangle$ with $\mathcal{D}$ being an arbitrary non-empty set and $\cdot^{\mathcal{I}}$ being a function which maps

- n-ary function symbols f to n-ary functions $f^{\mathcal{I}} \in [\mathcal{D}^n \rightarrow \mathcal{D}]$,
- constant symbols a to objects $a^{\mathcal{I}} \in \mathcal{D}$, and
- n-ary predicates P to n-ary relations $P^{\mathcal{I}} \subseteq \mathcal{D}^n$.

Interpretation of ground terms:

$$(f(t_1, \ldots, t_n))^{\mathcal{I}} \;=\; f^{\mathcal{I}}({t_1}^{\mathcal{I}}, \ldots, {t_n}^{\mathcal{I}}) \;(\in \mathcal{D})$$

Truth of ground atoms:

$$\mathcal{I} \models P(t_1, \ldots, t_n) \quad \text{iff} \quad \langle {t_1}^{\mathcal{I}}, \ldots, {t_n}^{\mathcal{I}} \rangle \in P^{\mathcal{I}}$$

Examples

$$\begin{aligned}
\mathcal{D} &= \{d_1, \dots, d_n\}, n \geq 2 \\
\mathrm{a}^{\mathcal{I}} &= d_1 \\
\mathrm{b}^{\mathcal{I}} &= d_2 \\
\mathrm{eye}^{\mathcal{I}} &= \{d_1\} \\
\mathrm{red}^{\mathcal{I}} &= \mathcal{D} \\
\mathcal{I} &\models \mathrm{red}(\mathrm{b}) \\
\mathcal{I} &\not\models \mathrm{eye}(\mathrm{b})
\end{aligned}$$

$$\begin{aligned}
\mathcal{D} &= \{1, 2, 3, \dots\} \\
1^{\mathcal{I}} &= 1 \\
2^{\mathcal{I}} &= 2 \\
&\vdots \\
\mathrm{even}^{\mathcal{I}} &= \{2, 4, 6, \dots\} \\
\mathrm{succ}^{\mathcal{I}} &= \{(1 \mapsto 2), (2 \mapsto 3), \dots\} \\
\mathcal{I} &\not\models \mathrm{even}(3) \\
\mathcal{I} &\models \mathrm{even}(\mathrm{succ}(3))
\end{aligned}$$

Formal Semantics: Variable Maps

V is the set of variables. Function $\alpha \colon V \to \mathcal{D}$ is a variable map.
Notation: $\alpha[x/d]$ is identical to α except for x where $\alpha[x/d](x) = d$.
Interpretation of terms under $\mathcal{I}, \alpha$:

$$\begin{aligned} x^{\mathcal{I},\alpha} &= \alpha(x) \\ a^{\mathcal{I},\alpha} &= a^{\mathcal{I}} \\ (f(t_1, \dots, t_n))^{\mathcal{I},\alpha} &= f^{\mathcal{I}}({t_1}^{\mathcal{I},\alpha}, \dots, {t_n}^{\mathcal{I},\alpha}) \end{aligned}$$

Truth of atomic formulae:

$$\mathcal{I}, \alpha \models P(t_1, \dots, t_n) \quad \text{iff} \quad \langle {t_1}^{\mathcal{I},\alpha}, \dots, {t_n}^{\mathcal{I},\alpha} \rangle \in P^{\mathcal{I}}$$

Example (cont'd):
$\alpha = \{x \mapsto d_1, y \mapsto d_2\}$ $\quad \mathcal{I}, \alpha \models \mathsf{red}(x)$ $\quad \mathcal{I}, \alpha[y/d_1] \models \mathsf{eye}(y)$

Formal Semantics: Truth

Truth of φ by $\mathcal{I}$ under α ($\mathcal{I}, \alpha \models \varphi$) is defined as follows.

$\mathcal{I}, \alpha \models P(t_1, \ldots, t_n)$	iff $\langle {t_1}^{\mathcal{I},\alpha}, \ldots, {t_n}^{\mathcal{I},\alpha} \rangle \in P^{\mathcal{I}}$
$\mathcal{I}, \alpha \models t_1 = t_2$	iff ${t_1}^{\mathcal{I},\alpha} = {t_2}^{\mathcal{I},\alpha}$
$\mathcal{I}, \alpha \models \neg\varphi$	iff $\mathcal{I}, \alpha \not\models \varphi$
$\mathcal{I}, \alpha \models \varphi \land \psi$	iff $\mathcal{I}, \alpha \models \varphi$ and $\mathcal{I}, \alpha \models \psi$
$\mathcal{I}, \alpha \models \varphi \lor \psi$	iff $\mathcal{I}, \alpha \models \varphi$ or $\mathcal{I}, \alpha \models \psi$
$\mathcal{I}, \alpha \models \varphi \rightarrow \psi$	iff if $\mathcal{I}, \alpha \models \varphi$, then $\mathcal{I}, \alpha \models \psi$
$\mathcal{I}, \alpha \models \varphi \leftrightarrow \psi$	iff $\mathcal{I}, \alpha \models \varphi$, iff $\mathcal{I}, \alpha \models \psi$
$\mathcal{I}, \alpha \models \forall x\, \varphi$	iff $\mathcal{I}, \alpha[x/d] \models \varphi$ for all $d \in \mathcal{D}$
$\mathcal{I}, \alpha \models \exists x\, \varphi$	iff $\mathcal{I}, \alpha[x/d] \models \varphi$ for some $d \in \mathcal{D}$

Examples

$$\Theta = \left\{ \begin{array}{l} \text{eye}(a), \text{eye}(b) \\ \forall x(\text{eye}(x) \rightarrow \text{red}(x)) \end{array} \right\}$$

$$\mathcal{D} = \{d_1, \ldots, d_n\}, \; n > 1$$

$$\mathrm{a}^{\mathcal{I}} = d_1$$

$$\mathrm{b}^{\mathcal{I}} = d_1$$

$$\text{eye}^{\mathcal{I}} = \{d_1\}$$

$$\text{red}^{\mathcal{I}} = \mathcal{D}$$

$$\alpha = \{(x \mapsto d_1), (y \mapsto d_2)\}$$

Questions:

$\mathcal{I}, \alpha \models \text{eye}(b) \vee \neg\text{eye}(b)$? Yes

$\mathcal{I}, \alpha \models \text{eye}(x) \rightarrow \text{eye}(x) \vee \text{eye}(y)$? Yes

$\mathcal{I}, \alpha \models \text{eye}(x) \rightarrow \text{eye}(y)$? No

$\mathcal{I}, \alpha \models \text{eye}(a) \wedge \text{eye}(b)$? Yes

$\mathcal{I}, \alpha \models \forall x(\text{eye}(x) \rightarrow \text{red}(x))$? Yes

$\mathcal{I}, \alpha \models \Theta$? Yes

Examples

$$\Theta = \left\{ \begin{array}{l} \mathsf{eye}(a), \mathsf{eye}(b) \\ \forall x(\mathsf{eye}(x) \rightarrow \mathsf{red}(x)) \end{array} \right\}$$

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Questions:

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$\mathcal{I}, \alpha \models \mathsf{eye}(x) \rightarrow \mathsf{eye}(x) \vee \mathsf{eye}(y)$? Yes

$\mathcal{I}, \alpha \models \mathsf{eye}(x) \rightarrow \mathsf{eye}(y)$? No

$\mathcal{I}, \alpha \models \mathsf{eye}(a) \wedge \mathsf{eye}(b)$? Yes

$\mathcal{I}, \alpha \models \forall x(\mathsf{eye}(x) \rightarrow \mathsf{red}(x))$? Yes

$\mathcal{I}, \alpha \models \Theta$? Yes

Examples

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Questions:

$\mathcal{I}, \alpha \models \text{eye}(b) \vee \neg\text{eye}(b)$? Yes

$\mathcal{I}, \alpha \models \text{eye}(x) \rightarrow \text{eye}(x) \vee \text{eye}(y)$? Yes

$\mathcal{I}, \alpha \models \text{eye}(x) \rightarrow \text{eye}(y)$? No

$\mathcal{I}, \alpha \models \text{eye}(a) \wedge \text{eye}(b)$? Yes

$\mathcal{I}, \alpha \models \forall x(\text{eye}(x) \rightarrow \text{red}(x))$? Yes

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\Theta &= \left\{ \begin{array}{l} \text{eye}(a), \text{eye}(b) \\ \forall x(\text{eye}(x) \rightarrow \text{red}(x)) \end{array} \right\} \\
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\end{aligned}$$

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$\mathcal{I}, \alpha \models \text{eye}(x) \rightarrow \text{eye}(y)$? No

$\mathcal{I}, \alpha \models \text{eye}(a) \wedge \text{eye}(b)$? Yes

$\mathcal{I}, \alpha \models \forall x(\text{eye}(x) \rightarrow \text{red}(x))$? Yes

$\mathcal{I}, \alpha \models \Theta$? Yes

Examples

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Questions:

$\mathcal{I}, \alpha \models \text{eye}(b) \lor \neg\text{eye}(b)$?
Yes

$\mathcal{I}, \alpha \models \text{eye}(x) \rightarrow \text{eye}(x) \lor \text{eye}(y)$? Yes

$\mathcal{I}, \alpha \models \text{eye}(x) \rightarrow \text{eye}(y)$?
No

$\mathcal{I}, \alpha \models \text{eye}(a) \land \text{eye}(b)$?
Yes

$\mathcal{I}, \alpha \models \forall x(\text{eye}(x) \rightarrow \text{red}(x))$? Yes

$\mathcal{I}, \alpha \models \Theta$? Yes

Examples

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$\mathcal{I}, \alpha \models \mathsf{eye}(x) \rightarrow \mathsf{eye}(y)$? No

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Examples

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$\mathcal{I}, \alpha \models \forall x(\text{eye}(x) \rightarrow \text{red}(x))$? Yes

$\mathcal{I}, \alpha \models \Theta$? Yes

Terminology

$\mathcal{I}, \alpha$ is a model of φ iff

$$\mathcal{I}, \alpha \models \varphi.$$

A formula can be satisfiable, unsatisfiable, falsifiable, valid, ...

Two formulae φ and ψ are logically equivalent (symb.: $\varphi \equiv \psi$) iff for all $\mathcal{I}, \alpha$:

$$\mathcal{I}, \alpha \models \varphi \text{ iff } \mathcal{I}, \alpha \models \psi.$$

Note: $\mathrm{P(x)} \not\equiv \mathrm{P(y)}$!

Logical implication is also analogous to propositional logic:

$$\Theta \models \varphi \quad \text{iff} \quad \text{for all } \mathcal{I}, \alpha \text{ s.t. } \mathcal{I}, \alpha \models \Theta \text{ also } \mathcal{I}, \alpha \models \varphi.$$

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Free and Bound Variables

Variables can be free or bound (by a quantifier) in a formula:

$$
\begin{aligned}
\text{free}(x) &= \{x\} \\
\text{free}(f(t_1, \ldots, t_n)) &= \text{free}(t_1) \cup \cdots \cup \text{free}(t_n) \\
\text{free}(t_1 = t_2) &= \text{free}(t_1) \cup \text{free}(t_2) \\
\text{free}(P(t_1, \ldots, t_n)) &= \text{free}(t_1) \cup \cdots \cup \text{free}(t_n) \\
\text{free}(\neg\varphi) &= \text{free}(\varphi) \\
\text{free}(\varphi * \psi) &= \text{free}(\varphi) \cup \text{free}(\psi), \text{ for } * = \vee, \wedge, \rightarrow, \leftrightarrow \\
\text{free}(\Xi x \varphi) &= \text{free}(\varphi) \setminus \{x\}, \text{ for } \Xi = \forall, \exists
\end{aligned}
$$

Example: $\forall x\, (R(\boxed{y}, \boxed{z}) \wedge \exists y\, (\neg P(y,x) \vee R(y, \boxed{z})))$

Framed occurrences are free, all others are bound.

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\text{free}(P(t_1,\ldots,t_n)) &= \text{free}(t_1) \cup \cdots \cup \text{free}(t_n) \\
\text{free}(\neg\varphi) &= \text{free}(\varphi) \\
\text{free}(\varphi * \psi) &= \text{free}(\varphi) \cup \text{free}(\psi), \;\; \text{for } * = \vee, \wedge, \rightarrow, \leftrightarrow \\
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Open & Closed Formulae

- Formulae without free variables are called closed formulae or sentences. Formulae with free variables are called open formulae.
- Closed formulae are all we need when we want to state something about the world. Open formulae (and variable maps) are only necessary for technical reasons (semantics of $\forall$ and $\exists$).
- Note that *logical equivalence*, *satisfiability*, and entailment are independent from variable maps if we consider only closed formulae.
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Important Theorems

Theorem (Compactness)

Let $\Phi \cup \{\psi\}$ be a set of closed formulae.

(a) $\Phi \models \psi$ *iff there exists a finite subset* $\Phi' \subseteq \Phi$ *s. t.* $\Phi' \models \psi$.

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