COMP4418: Knowledge Representation and Reasoning

First-Order Logic

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First-Order Logic

- First-order logic furnishes us with a much more expressive knowledge representation language than propositional logic
- We can directly talk about objects, their properties, relations between them, etc. …
- Here we discuss first-order logic and resolution
- However, there is a price to pay for this expressiveness in terms of decidability
- References:

  - Ivan Bratko, Prolog Programming for Artificial Intelligence, Addison-Wesley, 2001. (Chapter 15)
  - Stuart J. Russell and Peter Norvig, Artificial Intelligence: A Modern Approach, Prentice-Hall International, 1995. (Chapter 6)

Overview

- Syntax of First-Order Logic
- Semantics of First-Order Logic
- Conjunctive Normal Form
- Unification
- First-Order Resolution
- Soundness and Completeness
- Decidability
- Conclusion

Syntax of First-Order Logic

- **Constant Symbols:** a, b, $\ldots$, $Mary$ (objects)
- **Variables:** x, y, $\ldots$
- **Function Symbols:** f, $mother\_of$, $sine$, $\ldots$
- **Predicate Symbols:** $Mother$, $likes$, $\ldots$
- **Quantifiers:** $\forall$ (universal); $\exists$ (existential)

Terms: constant, variable, functions applied to terms (refer to objects)

- **Atomic Sentences:** predicate applied to terms (state facts)
- **Ground (closed) term:** a term with no variable symbols

Syntax of First-Order Logic

Sentence ::= AtomicSentence $\parallel$ Sentence Connective Sentence
$\parallel$ Quantifier Variable Sentence $\parallel$ $\neg$ Sentence $\parallel$ (Sentence)

AtomicSentence ::= Predicate (Term*)

Term ::= Function (Term*) $\parallel$ Constant $\parallel$ Variable

Connective ::= $\rightarrow \parallel \wedge \parallel \vee \parallel \leftrightarrow$

Quantifier ::= $\forall \parallel \exists$

Constant ::= **a** $\parallel$ **John** $\parallel$ ...

Variable ::= x $\parallel$ *men* $\parallel$ ...

Predicate ::= P $\parallel$ **Red** $\parallel$ **Between** $\parallel$ ...

Function ::= f $\parallel$ **Father** $\parallel$ ...

Converting English into First-Order Logic

- Everyone likes lying on the beach — $\forall x\; Beach(x)$
- Someone likes Fido — $\exists x\; Likes(x, Fido)$
- No one likes Fido — $\neg\exists x\; Likes(x, Fido)$
- Fido doesn't like everyone — $\neg\forall x\; Likes(Fido, x)$
- All cats are mammals — $\forall x\; (Cat(x) \rightarrow Mammal(x))$
- Some mammals are carnivorous — $\exists x\; (Mammal(x) \land Carnivorous(x))$

Nested Quantifiers

Note that the order of quantification is very important

- Everything likes everything — $\forall x\ \forall y\ Likes(x,\ y)$
- Something likes something — $\exists x\ \exists y\ Likes(x,\ y)$
- Everything likes something — $\forall x\ \exists y\ Likes(x,\ y)$
- There is something liked by everything — $\exists y\ \forall x\ Likes(x,\ y)$

Scope of Quantifiers

- The scope of a quantifier in a formula ϕ is that subformula ψ of ϕ of which that quantifier is the main logical operator
- Variables belong to the innermost quantifier that mentions them
- Examples:
  - $Q(x) \rightarrow \forall y\, P(x, y)$ — scope of $\forall y$ is $P(x, y)$
  - $\forall z\, P(z) \rightarrow \neg Q(z)$ — scope of $\forall z$ is $P(z)$ but not $Q(z)$
  - $\exists x(P(x) \rightarrow \forall x\, P(x))$
  - $\forall x(P(x) \rightarrow Q(x)) \rightarrow (\forall x\, P(x) \rightarrow \forall x\, Q(x))$

Terminology

- Free-variable occurrences in a formula —
  - All variables in an atomic formula
  - The free-variable occurrences in $\neg\phi$ are those in ϕ
  - The free-variable occurrences in $\phi \oplus \psi$ are those in ϕ and ψ for any connective $\oplus$
  - The free-variable occurrences in $\forall x\ \Phi$ and $\exists x\ \Phi$ are those in Φ except for occurrences of x
- Open formula — A formula in which free variables occur
- Closed formula — A formula with no free variables
- Closed formulae are also known as sentences

Semantics of First-Order Logic

- A world in which a sentence is true under a particular interpretation is known as a model of that sentence under the interpretation
- **Constant symbols** an interpretation specifies which object in the world a constant refers to

  Predicate symbols an interpretation specifies which relation in the model a predicate refers to

  Function symbols an interpretation specifies which function in the model a function symbol refers to

  Universal quantifier is true iff all all instances are true

  Existential quantifier is true iff one instance is true

Conversion into Conjunctive Normal Form

1. Eliminate implication

$$\phi \rightarrow \psi \equiv \neg\phi \vee \psi$$

2. Move negation inwards (negation normal form)

$$\neg(\phi \wedge \psi) \equiv \neg\phi \vee \neg\psi$$
$$\neg(\phi \vee \psi) \equiv \neg\phi \wedge \neg\psi$$
$$\neg\, \forall x\, \phi \equiv \exists x\, \neg\phi$$
$$\neg\, \exists x\, \phi \equiv \forall x\, \neg\phi$$
$$\neg\neg\phi \equiv \phi$$

3. Standardise variables

   $(\forall x\, P(x)) \vee (\exists x\, Q(x))$
   becomes $(\forall x\, P(x)) \vee (\exists y\, Q(y))$

Conversion into Conjunctive Normal Form

4. Skolemise
   $\exists x\, P(x) \Rightarrow P(a)$
   $\forall x \exists y\, P(x, y) \Rightarrow \forall x\, P(x, f(x))$
   $\forall x \forall y \exists z\, P(x, y, z) \Rightarrow \forall x \forall y\, P(x, y, f(x, y))$

5. Drop universal quantifiers

6. Distribute $\wedge$ over $\vee$

$$(\phi \wedge \psi) \vee \chi \equiv (\phi \vee \chi) \wedge (\psi \vee \chi)$$

7. Flatten nested conjunctions and disjunctions

$$(\phi \wedge \psi) \wedge \chi \equiv \phi \wedge \psi \wedge \chi; (\phi \vee \psi) \vee \chi \equiv \phi \vee \psi \vee \chi$$

(8. In proofs, rename variables in separate clauses — standardise apart)

CNF — Example 1

$\forall x[(\forall y\, P(x,\, y)) \rightarrow \neg\forall y(Q(x,\, y) \rightarrow R(x,\, y))]$

1. $\forall x[\neg(\forall y\, P(x,\, y)) \vee \neg\forall y(\neg Q(x,\, y) \vee R(x,\, y))]$

2. $\forall x[(\exists y\, P(x,\, y)) \vee \exists y(Q(x,\, y) \wedge \neg R(x,\, y))]$

3. $\forall x[(\exists y\, \neg P(x,\, y)) \vee \exists z(Q(x,\, z) \wedge \neg R(x,\, z))]$

4. $\forall x[\neg P(x,\, f(x)) \vee (Q(x,\, g(x)) \wedge \neg R(x,\, g(x)))]$

5. $\neg P(x,\, f(x)) \vee (Q(x,\, g(x)) \wedge \neg R(x,\, g(x)))$

6. $(\neg P(x,\, f(x)) \vee Q(x,\, g(x))) \wedge (\neg P(x,\, f(x)) \vee \neg R(x,\, g(x)))$

8. $\neg P(x,\, f(x)) \vee Q(x,\, g(x))$
   $\neg P(y,\, f(y)) \vee \neg R(y,\, g(y))$

CNF — Example 2

$\neg\exists x\forall y\forall z((P(y)\vee Q(z))\rightarrow(P(x)\vee Q(x)))$

$\neg\exists x\forall y\forall z(\neg(P(y)\vee Q(z))\vee(P(x)\vee Q(x)))$ [Eliminate $\rightarrow$]

$\forall x\neg\forall y\forall z(\neg(P(y)\vee Q(z))\vee(P(x)\vee Q(x)))$ [Move $\neg$ inwards]

$\forall x\exists y\neg\forall z(\neg(P(y)\vee Q(z))\vee(P(x)\vee Q(x)))$ [Move $\neg$ inwards]

$\forall x\exists y\exists z\neg(\neg(P(y)\vee Q(z))\vee(P(x)\vee Q(x)))$ [Move $\neg$ inwards]

$\forall x\exists y\exists z(\neg\neg(P(y)\vee Q(z))\wedge\neg(P(x)\vee Q(x)))$ [Move $\neg$ inwards]

$\forall x\exists y\exists z((P(y)\vee Q(z))\wedge(\neg P(x)\wedge\neg Q(x)))$ [Move $\neg$ inwards]

$\forall x((P(f(x))\vee Q((g(x)))\wedge(\neg P(x)\wedge\neg Q(x)))$ [Skolemise]

$(P(f(x))\vee Q((g(x)))\wedge\neg P(x)\wedge\neg Q(x)$ [Drop $\forall$]

Unification

- Unification takes two atomic formulae and returns a substitution that makes them look the same
- Example:

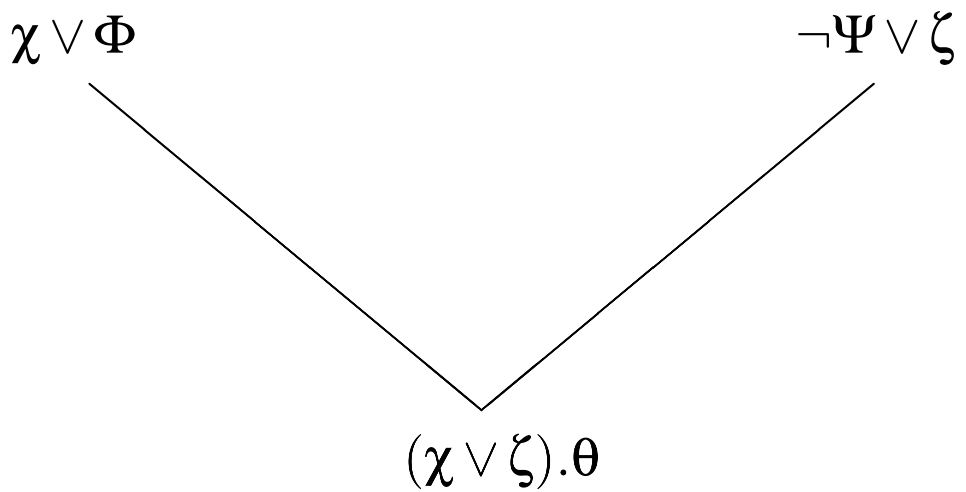
$$\{x/a,\ y/z,\ w/f(b,\ c)\}$$

- Note:
  1. Each variable has at most one associated expression
  2. No variable with an associated expression occurs within any associated expression
- $\{x/g(y),\ y/f(x)\}$ is not a substitution
- Substitution σ that makes a set of expressions identical known as a unifier
- Substitution σ_1 is a more general unifier than a substitution σ_2 if for some substitution τ, $\sigma_2 = \sigma_1\tau$.

First-Order Resolution

- Generalised Resolution Rule:

  For clauses $\chi \vee \Phi$ and $\neg\Psi \vee \zeta$



- Where θ is a unifier for atomic formulae Φ and Ψ
- $\chi \vee \zeta$ is known as the resolvent

Resolution — Example 1

$\vdash \exists x(P(x) \rightarrow \forall x P(x))$

CNF$(\neg\exists x(P(x) \rightarrow \forall x P(x)))$

$\forall x \neg(\neg P(x) \vee \forall x\, P(x))$ [Drive $\neg$ inwards]

$\forall x(\neg\neg P(x) \wedge \neg\forall x\, P(x))$ [Drive $\neg$ inwards]

$\forall x(P(x) \wedge \exists x\, \neg P(x))$ [Drive $\neg$ inwards]

$\forall x(P(x) \wedge \exists z\, \neg P(z))$ [Standardise Variables]

$\forall x(P(x) \wedge \neg P(f(x)))$ [Skolemise]

$P(x) \wedge \neg P(f(x))$ [Drop $\forall$]

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1. $P(x)$ [$\neg$ Conclusion]
2. $\neg P(f(y))$ [$\neg$ Conclusion]
3. $P(f(y))$ [1. $\{x/f(y)\}$]
4. $\square$ [2, 3. Resolution]

Resolution — Example 2

1. $P(f(x)) \vee Q(g(x))$ [¬ Conclusion]
2. $\neg P(y)$ [¬ Conclusion]
3. $\neg Q(z)$ [¬ Conclusion]
4. $P(f(a)) \vee Q(g(a))$ [1. $\{x/a\}$]
5. $\neg P(f(a))$ [2. $\{y/f(a)\}$]
6. $\neg Q(g(a))$ [3. $\{z/g(a)\}$]
7. $Q(g(a))$ [4, 5. Resolution]
8. $\square$ [6, 7. Resolution]

Resolution — Example 3

1. $man(Marcus)$ [Premise]
2. $Pompeian(Marcus)$ [Premise]
3. $\neg Pompeian(x) \vee Roman(x)$ [Premise]
4. $ruler(Caesar)$ [Premise]
5. $\neg Roman(y) \vee loyaltyto(y, Caesar) \vee hate(y, Caesar)$ [Premise]
6. $loyaltyto(z, f(z))$ [Premise]
7. $\neg man(w) \vee \neg ruler(u) \vee \neg tryassassinate(w, u) \vee \neg loyaltyto(w, u)$ [Premise]
8. $tryassassinate(Marcus, Caesar)$ [Premise]
9. $\neg hate(Marcus, Caesar)$ [$\neg$ Conclusion]
10. $\neg Roman(Marcus) \vee loyaltyto(Marcus, Caesar) \vee hate(Marcus, Caesar)$ [5. $\{y/Marcus\}$]
11. $\neg Roman(Marcus) \vee loyaltyto(Marcus, Caesar)$ [9, 10. Resolution]

Resolution — Example 3

12. $\neg Pompeian(Marcus) \vee Roman(Marcus)$ [3. $\{x/Marcus\}$]

13. $loyaltyto(Marcus,\ Caesar) \vee \neg Pompeian(Marcus)$ [11, 12. Resolution]

14. $loyaltyto(Marcus, Caesar)$ [2, 13. Resolution]

15. $\neg man(Marcus) \vee\ \neg ruler(Caesar) \vee\ \neg tryassassinate(Marcus, Caesar) \vee\ \neg loyaltyto(Marcus, Caesar)$ [7. $\{w/Marcus,\ u/Caesar\}$]

16. $\neg man(Marcus) \vee \neg ruler(Caesar) \vee \neg tryassassinate(Marcus, Caesar)$ [14, 15. Resolution]

17. $\neg ruler(Caesar) \vee \neg tryassassinate(Marcus,\ Caesar)$ [1, 16. Resolution]

18. $\neg tryassassinate(Marcus, Caesar)$ [4, 17. Resolution]

19. $\Box$ [8, 18. Resolution]

Soundness and Completeness

- Resolution is
  - sound (if $\lambda \vdash \rho$, then $\lambda \models \rho$)
  - complete (if $\lambda \models \rho$, then $\lambda \vdash \rho$)

Decidability

- First-order logic is not decidable
- How would you prove this?

Conclusion

- First-order logic allows us to speak about objects, properties of objects and relationships between objects
- It also allows quantification over variables
- First-order logic is quite an expressive knowledge representation language; much more so than propositional logic
- However, we do need to add things like equality if we wish to be able to do things like counting
- We have also traded expressiveness for decidability
- How much of a problems is this?
- If we add (Peano) axioms for mathematics, then we encounter Gödel's famous incompleteness theorem (which is beyond the scope of this course)