First-Order Logic

(Based on [Gallier 1986], [Goubault-Larrecq and Mackie 1997], and [Huth and Ryan 2004])

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Introduction

- Logic concerns mainly two concepts: truth and provability (of truth from assumed truth).
- *Formal (symbolic) logic* approaches logic by rules for manipulating symbols:
  - Syntax rules: for writing statements (or formulae).
  - Semantic rules: for giving meanings (truth values) to statements.
  - Inference rules: for obtaining true statements from other true statements.
- We shall introduce two main branches of formal logic: *propositional logic* and *first-order logic*.
- The following slides cover first-order logic.

Predicates

- A *predicate* is a "parameterized" statement that, when supplied with actual arguments, is either *true* or *false* such as the following:
  - Leslie is a teacher.
  - Chris is a teacher.
  - Leslie is a pop singer.
  - Chris is a pop singer.
- Like propositions, simplest (atomic) predicates may be combined to form compound predicates.

Inferences

- We are given the following assumptions:
  - *For any* person, *either* the person is not a teacher *or* the person is not rich.
  - *For any* person, *if* the person is a pop singer, *then* the person is rich.
- We wish to conclude the following:
  - *For any* person, *if* the person is a teacher, *then* the person is not a pop singer.

Symbolic Predicates

- Like propositions, predicates are represented by *symbols*.
  - $p(x)$: x is a teacher.
  - $q(x)$: x is rich.
  - $r(y)$: y is a pop singer.
- Compound predicates can be expressed:
  - For all x, $r(x) \to q(x)$: *For any* person, *if* the person is a pop singer, *then* the person is rich.
  - For all y, $p(y) \to \neg r(y)$: *For any* person, *if* the person is a teacher, *then* the person is *not* a pop singer.

Symbolic Inferences

- We are given the following assumptions:
  - For all $x, \neg p(x) \vee \neg q(x)$.
  - For all $x, r(x) \rightarrow q(x)$.
- We wish to conclude the following:
  - For all $x, p(x) \rightarrow \neg r(x)$.
- To check the correctness of the inference above, we ask:
  Is $(($for all $x, \neg p(x) \vee \neg q(x)) \wedge ($for all $x, r(x) \rightarrow q(x))) \rightarrow$ $($for all $x, p(x) \rightarrow \neg r(x))$ valid?

First-Order Logic: Syntax

- Logical symbols:
  - A countable set V of *variables*: $x, y, z, \ldots$;
  - *Logical connectives* (operators): $\neg$, $\wedge$, $\vee$, $\rightarrow$, $\leftrightarrow$, $\perp$, $\forall$ (for all), $\exists$ (there exists);
  - Auxiliary symbols: "(", ")".
- Non-logical symbols:
  - A countable set of *function symbols* with associated ranks (arities);
  - A countable set of *constants*;
  - A countable set of *predicate symbols* with associated ranks (arities);
- We refer to a first-order language as *Language* L, where L is the set of non-logical symbols (e.g., $\{+, 0, 1, <\}$).

First-Order Logic: Syntax (cont.)

- Terms:
  - Every *constant* and every *variable* is a term.
  - If $t_1, t_2, \cdots, t_k$ are terms and f is a k-ary function symbol ($k > 0$), then $f(t_1, t_2, \cdots, t_k)$ is a term.
- Atomic formulae:
  - Every *predicate symbol* of 0-arity is an atomic formula and so is $\perp$.
  - If $t_1, t_2, \cdots, t_k$ are terms and p is a k-ary predicate symbol ($k > 0$), then $p(t_1, t_2, \cdots, t_k)$ is an atomic formula.
- For example, consider Language $\{+, 0, 1, <\}$.
  - 0, x, $x + 1$, $x + (x + 1)$, etc. are terms.
  - $0 < 1$, $x < (x + 1)$, etc. are atomic formulae.

First-Order Logic: Syntax (cont.)

- Formulae:
  - Every atomic formula is a formula.
  - If A and B are formulae, then so are $\neg A$, $(A \wedge B)$, $(A \vee B)$, $(A \rightarrow B)$, and $(A \leftrightarrow B)$.
  - If x is a variable and A is a formula, then so are $\forall x A$ and $\exists x A$.
- First-order logic *with equality* includes equality ($=$) as an additional logical symbol, which behaves like a predicate symbol.
- Example formulae in Language $\{+, 0, 1, <\}$:
  - $(0 < x) \vee (x < 1)$
  - $\forall x (\exists y (x + y = 0))$

First-Order Logic: Syntax (cont.)

- We may give the logical connectives different binding powers, or precedences, to avoid excessive parentheses, usually in this order:

  $$\neg, \{\forall, \exists\}, \{\wedge, \vee\}, \rightarrow, \leftrightarrow\ .$$

  For example, $(A \wedge B) \rightarrow C$ becomes $A \wedge B \rightarrow C$.
- Common Abbreviations:
  - $x = y = z$ means $x = y \wedge y = z$.
  - $p \rightarrow q \rightarrow r$ means $p \rightarrow (q \rightarrow r)$. Implication associates to the right, so do other logical symbols.
  - $\forall x, y, zA$ means $\forall x(\forall y(\forall zA))$.

Free and Bound Variables

- In a formula $\forall x A$ (or $\exists x A$), the variable x is *bound* by the quantifier $\forall$ (or $\exists$).
- A *free* variable is one that is not bound.
- The same variable may have both a free and a bound occurrence.
- For example, consider $(\forall x(R(x, \underline{y}) \rightarrow P(x)) \wedge \forall y(\neg R(\underline{x}, y) \wedge \forall x P(x)))$. The underlined occurrences of x and y are free, while others are bound.
- A formula is *closed*, also called a *sentence*, if it does not contain a free variable.

Free Variables Formally Defined

For a term t, the set $FV(t)$ of free variables of t is defined inductively as follows:

- $FV(x) = \{x\}$, for a variable x;
- $FV(c) = \emptyset$, for a contant c;
- $FV(f(t_1, t_2, \cdots, t_n)) = FV(t_1) \cup FV(t_2) \cup \cdots \cup FV(t_n)$, for an n-ary function f applied to n terms $t_1, t_2, \cdots, t_n$.

Free Variables Formally Defined (cont.)

For a formula A, the set $FV(A)$ of free variables of A is defined inductively as follows:

- $FV(P(t_1, t_2, \cdots, t_n)) = FV(t_1) \cup FV(t_2) \cup \cdots \cup FV(t_n)$, for an n-ary predicate P applied to n terms $t_1, t_2, \cdots, t_n$;
- $FV(t_1 = t_2) = FV(t_1) \cup FV(t_2)$;
- $FV(\neg B) = FV(B)$;
- $FV(B * C) = FV(B) \cup FV(C)$, where $* \in \{\wedge, \vee, \rightarrow, \leftrightarrow\}$;
- $FV(\bot) = \emptyset$;
- $FV(\forall x B) = FV(B) - \{x\}$;
- $FV(\exists x B) = FV(B) - \{x\}$.

Bound Variables Formally Defined

For a formula A, the set $BV(A)$ of bound variables in A is defined inductively as follows:

- $BV(P(t_1, t_2, \cdots, t_n)) = \emptyset$, for an n-ary predicate P applied to n terms $t_1, t_2, \cdots, t_n$;
- $BV(t_1 = t_2) = \emptyset$;
- $BV(\neg B) = BV(B)$;
- $BV(B * C) = BV(B) \cup BV(C)$, where $* \in \{\wedge, \vee, \rightarrow, \leftrightarrow\}$;
- $BV(\perp) = \emptyset$;
- $BV(\forall x B) = BV(B) \cup \{x\}$;
- $BV(\exists x B) = BV(B) \cup \{x\}$.

Substitutions

- Let t be a term and A a formula.
- The result of substituting t for a free variable x in A is denoted by $A[t/x]$.
- Consider $A = \forall x(P(x) \to Q(x, f(y)))$.
  - When $t = g(y)$, $A[t/y] = \forall x(P(x) \to Q(x, f(g(y))))$.
  - For any t, $A[t/x] = \forall x(P(x) \to Q(x, f(y))) = A$, since there is no free occurrence of x in A.
- A substitution is *admissible* if no free variable of t would become bound after the substitution.
- For example, when $t = g(x, y)$, $A[t/y]$ is not admissible, as the free variable x of t would become bound.

Substitutions Formally Defined

Let s and t be terms. The result of substituting t in s for a variable x, denoted $s[t/x]$, is defined inductively as follows:

- $x[t/x] = t$;
- $y[t/x] = y$, for a variable y that is not x;
- $c[t/x] = c$, for a contant c;
- $f(t_1, t_2, \cdots, t_n)[t/x] = f(t_1[t/x], t_2[t/x], \cdots, t_n[t/x])$, for an n-ary function f applied to n terms $t_1, t_2, \cdots, t_n$.

Substitutions Formally Defined (cont.)

For a formula A, $A[t/x]$ is defined inductively as follows:

- $P(t_1, t_2, \cdots, t_n)[t/x] = P(t_1[t/x], t_2[t/x], \cdots, t_n[t/x])$, for an n-ary predicate P applied to n terms $t_1, t_2, \cdots, t_n$;
- $(t_1 = t_2)[t/x] = (t_1[t/x] = t_2[t/x])$;
- $(\neg B)[t/x] = \neg B[t/x]$;
- $(B * C)[t/x] = (B[t/x] * C[t/x])$, where $* \in \{\wedge, \vee, \rightarrow, \leftrightarrow\}$;
- $\perp[t/x] = \perp$;
- $(\forall x B)[t/x] = (\forall x B)$;
- $(\forall y B)[t/x] = (\forall y B[t/x])$, if variable y is not x;
- $(\exists x B)[t/x] = (\exists x B)$;
- $(\exists y B)[t/x] = (\exists y B[t/x])$, if variable y is not x;

First-Order Structures

- A first-order structure $\mathcal{M}$ is a pair (M, I), where
  - M (a non-empty set) is the *domain* of the structure, and
  - I is the *interpretation function*, that assigns functions and predicates over M to the function and predicate symbols.
- An interpretation may be represented by simply listing the functions and predicates.
- For instance, $(Z, \{+_Z, 0_Z\})$ is a structure for the language $\{+, 0\}$. The subscripts are omitted, as $(Z, \{+, 0\})$, when no confusion may arise.

Semantics of First-Order Logic

- Since a formula may contain free variables, its truth value depends on the specific values that are assigned to these variables.
- Given a first-order language and a structure $\mathcal{M} = (M, I)$, an *assignment* is a function from the set of variables to M.
- The structure $\mathcal{M}$ along with an assignment s determines the truth value of a formula A, denoted as $A_{\mathcal{M}}[s]$.
- For example, $(x + 0 = x)_{(Z,\{+,0\})}[x := 1]$ evaluates to T.

Semantics of First-Order Logic (cont.)

- We say $\mathcal{M}, s \models A$ when $A_{\mathcal{M}}[s]$ is T (true) and $\mathcal{M}, s \not\models A$ otherwise.
- Alternatively, $\models$ may be defined as follows (propositional part is as in propositional logic):

  $$\mathcal{M}, s \models \forall x A \iff \mathcal{M}, s[x := m] \models A \text{ for all } m \in M.$$

  $$\mathcal{M}, s \models \exists x A \iff \mathcal{M}, s[x := m] \models A \text{ for some } m \in M.$$

  where $s[x := m]$ denotes an updated assignment s' from s such that $s'(y) = s(y)$ for $y \neq x$ and $s'(x) = m$.
- For example, $(Z, \{+, 0\}), s \models \forall x(x + 0 = x)$ holds, since $(Z, \{+, 0\}), s[x := m] \models x + 0 = x$ for all $m \in Z$.

Satisfiability and Validity

- A formula A is *satisfiable in $\mathcal{M}$* if there is an assignment s such that $\mathcal{M}, s \models A$.
- A formula A is *valid in $\mathcal{M}$*, denoted $\mathcal{M} \models A$, if $\mathcal{M}, s \models A$ for every assignment s.
- For instance, $\forall x(x + 0 = x)$ is valid in $(Z, \{+, 0\})$.
- $\mathcal{M}$ is called a *model* of A if A is valid in $\mathcal{M}$.
- A formula A is *valid* if it is valid in every structure, denoted $\models A$.

Relating the Quantifiers

Lemma.

$$\models \neg\forall x A \leftrightarrow \exists x \neg A$$

$$\models \neg\exists x A \leftrightarrow \forall x \neg A$$

$$\models \forall x A \leftrightarrow \neg\exists x \neg A$$

$$\models \exists x A \leftrightarrow \neg\forall x \neg A$$

Note: These equivalences show that, with the help of negation, either quantifier can be expressed by the other.

The Sequent Calculus: Quantifier Rules

$$\frac{\Gamma, A[t/x] \vdash \Delta}{\Gamma, \forall x A \vdash \Delta} (\forall L) \qquad \frac{\Gamma \vdash A[y/x], \Delta}{\Gamma \vdash \forall x A, \Delta} (\forall R)$$

$$\frac{\Gamma, A[y/x] \vdash \Delta}{\Gamma, \exists x A \vdash \Delta} (\exists L) \qquad \frac{\Gamma \vdash A[t/x], \Delta}{\Gamma \vdash \exists x A, \Delta} (\exists R)$$

In the rules above, we assume that all substitutions are admissible, y is not free in A, and y does not occur free in the lower sequent.

Soundness and Completeness

The quantifier rules, together with the structural rules, logical rules, and axioms introduced in Part I (Propositional Logic), constitute Gentzen's System LK.

Theorem.
System LK is *sound*, i.e., if a sequent $\Gamma \vdash \Delta$ is provable in LK, then $\Gamma \vdash \Delta$ is valid.

Theorem.
System LK is *complete*, i.e., if a sequent $\Gamma \vdash \Delta$ is valid, then $\Gamma \vdash \Delta$ is provable in LK.

Note: assume no equality in the logic language.

Compactness

Theorem.
For any (possibly infinite) set Γ of formulae, if every finite non-empty subset of Γ is satisfiable then Γ is satisfiable.

Consistency

Recall that a set Γ of formulae is *consistent* if there exists some formula B such that the sequent $\Gamma \vdash B$ is not provable. Otherwise, Γ is *inconsistent*.

Lemma.
For System LK, a set Γ of formulae is inconsistent *if and only if* there is some formula A such that both $\Gamma \vdash A$ and $\Gamma \vdash \neg A$ are provable.

Theorem.
For System LK, a set Γ of formulae is satisfiable *if and only if* Γ is *consistent*.

The Sequent Calculus: Axioms for Equality

Let $t, s_1, \cdots, s_n, t_1, \cdots, t_n$ be arbitrary terms.

$$\frac{}{\vdash t = t}$$

For every n-ary function f,

$$\frac{}{s_1 = t_1, \cdots, s_n = t_n \vdash f(s_1, \cdots, s_n) = f(t_1, \cdots, t_n)}$$

For every n-ary predicate P (including $=$),

$$\frac{}{s_1 = t_1, \cdots, s_n = t_n, P(s_1, \cdots, s_n) \vdash P(t_1, \cdots, t_n)}$$

Note: The $=$ sign is part of the object language, not a meta symbol.

Theory

Assume a fixed first-order language.

- A set S of sentences is closed under provability if

$$S = \{A \mid A \text{ is a sentence and } S \vdash A \text{ is provable}\}.$$

- A set of sentences is called a *theory* if it is closed under provability.
- A theory is typically represented by a smaller set of sentences, called its *axioms*.

Group as a First-Order Theory

- The set of non-logical symbols is $\{\cdot, e\}$, where $\cdot$ is a binary function (operation) and e is a constant (the identity).
- Axioms:
  - $\forall a, b, c(a \cdot (b \cdot c) = (a \cdot b) \cdot c)$ (Associativity)
  - $\forall a(a \cdot e = e \cdot a = a)$ (Identity)
  - $\forall a(\exists b(a \cdot b = b \cdot a = e))$ (Inverse)
- $(Z, \{+, 0\})$ and $(Q \setminus \{0\}, \{\times, 1\})$ are models of the theory.
- Additional axiom for Abelian groups:
  - $\forall a, b(a \cdot b = b \cdot a)$ (Commutativity)

Quantifier Rules of Natural Deduction

$$\frac{\Gamma \vdash A[y/x]}{\Gamma \vdash \forall x A} (\forall I) \qquad \frac{\Gamma \vdash \forall x A}{\Gamma \vdash A[t/x]} (\forall E)$$

$$\frac{\Gamma \vdash A[t/x]}{\Gamma \vdash \exists x A} (\exists I) \qquad \frac{\Gamma \vdash \exists x A \qquad \Gamma, A[y/x] \vdash B}{\Gamma \vdash B} (\exists E)$$

In the rules above, we assume that all substitutions are admissible and y does not occur free in Γ or A.

Equality Rules of Natural Deduction

Let t, t_1, t_2 be arbitrary terms; again, assume all substitutions are admissible.

$$\frac{}{\Gamma \vdash t = t}\,(=I) \qquad\qquad \frac{\Gamma \vdash t_1 = t_2 \qquad \Gamma \vdash A[t_1/x]}{\Gamma \vdash A[t_2/x]}\,(=E)$$

Note: The $=$ sign is part of the object language, not a meta symbol.