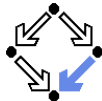


The Language of Logic

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The Language of Logic

Two kinds of syntactic phrases.

- **Term** T denoting an object.
 - Variable x
 - Object constant c
 - Function application $f(T_1, \dots, T_n)$
 n -ary function constant f (may be infix)
- **Formula** F denoting a truth value.
 - Atomic formula $p(T_1, \dots, T_n)$ (may be infix)
 n -ary predicate constant p .
 - Negation $\neg F$ ("not F ")
 - Conjunction $F_1 \wedge F_2$ (" F_1 and F_2 ")
 - Disjunction $F_1 \vee F_2$ (" F_1 or F_2 ")
 - Implication $F_1 \Rightarrow F_2$ (" F_1 implies F_2 ")
 - Equivalence $F_1 \Leftrightarrow F_2$ (" F_1 is equivalent to F_2 ")
 - Universal quantification $\forall x : F$ ("for all x , F ")
 - Existential quantification $\exists x : F$ ("for some x , F ")



Syntactic Shortcuts

- $\forall x_1, \dots, x_n : F$
 - $\forall x_1 : \dots : \forall x_n : F$
- $\exists x_1, \dots, x_n : F$
 - $\exists x_1 : \dots : \exists x_n : F$
- $\forall x \in S : F$
 - $\forall x : x \in S \Rightarrow F$
- $\exists x \in S : F$
 - $\exists x : x \in S \wedge F$
- **let** $x = T$ **in** F
 - $F[T/x]$

Help to make formulas more readable.



Example

Terms and formulas may appear in various syntactic forms.

- **Terms:**

$$\exp(x)$$

$$a \cdot b + 1$$

$$a[i] \cdot b$$

$$\sqrt{\frac{x^2+2x+1}{(y+1)^2}}$$

- **Formulas:**

$$a^2 + b^2 = c^2$$

$$n \mid 2n$$

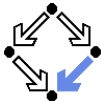
$$\forall x \in \mathbb{N} : x \geq 0$$

$$\forall x \in \mathbb{N} : 2 \mid x \vee 2 \mid (x + 1)$$

$$\forall x \in \mathbb{N}, y \in \mathbb{N} : x < y \Rightarrow$$

$$\exists z \in \mathbb{N} : x + z = y$$

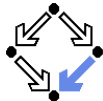
Terms and formulas may be nested arbitrarily deeply.



The Meaning of Formulas

- Atomic formula $p(T_1, \dots, T_n)$
 - True if the predicate denoted by p holds for the values of T_1, \dots, T_n .
- Negation $\neg F$
 - True if and only if F is false.
- Conjunction $F_1 \wedge F_2$ (" F_1 and F_2 ")
 - True if and only if F_1 and F_2 are both true.
- Disjunction $F_1 \vee F_2$ (" F_1 or F_2 ")
 - True if and only if at least one of F_1 or F_2 is true.
- Implication $F_1 \Rightarrow F_2$ (" F_1 implies F_2 ")
 - False if and only if F_1 is true and F_2 is false.
- Equivalence $F_1 \Leftrightarrow F_2$ (" F_1 is equivalent to F_2 ")
 - True if and only if F_1 and F_2 are both true or both false.
- Universal quantification $\forall x : F$ (" $\text{for all } x, F$ ")
 - True if and only if F is true for every possible value assignment of x .
- Existential quantification $\exists x : F$ (" $\text{for some } x, F$ ")
 - True if and only if F is true for at least one value assignment of x .

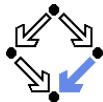
Example



We assume the domain of natural numbers and the “classical” interpretation of constants $1, 2, +, =, <$.

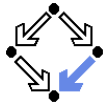
- $1 + 1 = 2$
 - True.
- $1 + 1 = 2 \vee 2 + 2 = 2$
 - True.
- $1 + 1 = 2 \wedge 2 + 2 = 2$
 - False.
- $1 + 1 = 2 \Rightarrow 2 = 1 + 1$
 - True.
- $1 + 1 = 1 \Rightarrow 2 + 2 = 2$
 - True.
- $1 + 1 = 2 \Rightarrow 2 + 2 = 2$
 - False.
- $1 + 1 = 1 \Leftrightarrow 2 + 2 = 2$
 - True.

Example



- $x + 1 = 1 + x$
 - True, for every assignment of a number a to variable x .
- $\forall x : x + 1 = 1 + x$
 - True (because for every assignment a to x , $x + 1 = 1 + x$ is true).
- $x + 1 = 2$
 - If x is assigned “one”, the formula is true.
 - If x is assigned “two”, the formula is false.
- $\exists x : x + 1 = 2$
 - True (because $x + 1 = 2$ is true for assignment “one” to x).
- $\forall x : x + 1 = 2$
 - False (because $x + 1 = 2$ is false for assignment “two” to x).
- $\forall x : \exists y : x < y$
 - True (because for every assignment a to x , there exists the assignment $a + 1$ to y which makes $x < y$ true).
- $\exists y : \forall x : x < y$
 - False (because for every assignment a to y , there is the assignment $a + 1$ to x which makes $x < y$ false).

The Usage of Formulas



Precise formulation of statements describing object relationships.

- **Statement:**

If x and y are natural numbers and y is not zero, then q is the truncated quotient of x divided by y .

- **Formula:**

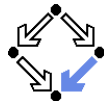
$$x \in \mathbb{N} \wedge y \in \mathbb{N} \wedge y \neq 0 \Rightarrow \\ q \in \mathbb{N} \wedge \exists r \in \mathbb{N} : r < y \wedge x = y \cdot q + r$$

- **Problem specification:**

Given natural numbers x and y such that y is not zero, compute the truncated quotient q of x divided by y .

- Inputs: x, y
- Input condition: $x \in \mathbb{N} \wedge y \in \mathbb{N} \wedge y \neq 0$
- Output: q
- Output condition: $q \in \mathbb{N} \wedge \exists r \in \mathbb{N} : r < y \wedge x = y \cdot q + r$

Problem Specifications



- **Specification** of a computation problem:
 - Input: variables $X_1 \in S_1, \dots, X_n \in S_n$
 - Input condition: formula I in which only X_1, \dots, X_n may be free.
 - Output: variables $Y_1 \in T_1, \dots, Y_m \in T_n$
 - Output condition: formula O in which only $X_1, \dots, X_n, Y_1, \dots, Y_m$ may be free.

A variable is **free** in a formula, if it occurs in the formula outside the scope of a quantifier (such as \forall or \exists).

- **Implementation** of the specification:
 - A function (program) $f : S_1 \times \dots \times S_n \rightarrow T_1 \times \dots \times T_m$ such that
$$\forall X_1 \in S_1, \dots, X_n \in S_n : I(X_1, \dots, X_n) \Rightarrow$$
$$\text{let } (Y_1, \dots, Y_m) = f(X_1, \dots, X_n) \text{ in}$$
$$O(X_1, \dots, X_n, Y_1, \dots, Y_m)$$
 - For all arguments that satisfy the input condition, f must compute results that satisfy the output condition.

Basis of all specification formalisms.



Example

Given an array a , a position p , and a length l , compute the array b derived from a by removing $a[p], \dots, a[p + l]$.

■ Input: $a \in \text{Arr}, p \in \mathbb{N}, l \in \mathbb{N}$

■ Input condition:

$$p + l \leq \text{length}(a)$$

■ Output: $b \in \text{Arr}$

■ Output condition:

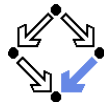
let $n = \text{length}(a)$ **in**

$$\text{length}(b) = n - l \wedge$$

$$(\forall i \in \mathbb{N} : i < p \Rightarrow b[i] = a[i]) \wedge$$

$$(\forall i \in \mathbb{N} : p \leq i < n - l \Rightarrow b[i] = a[i + l])$$

Proving Formulas



- **Proof:** a structured argument that a formula is true.
 - Can be depicted as a tree whose nodes represent proof situations.
 - Each proof situation consists of knowledge (formulas assumed to be true) and a goal (a formula to be proved relative to that knowledge).
 - The root goal is the overall formula to be proved.
- **Proof rules:** describe how a proof situation can be reduced to zero or more “subsituations”.
 - Zero subsituations: the current goal has been proved.
 - One or more subsituations: the current goal has been proved, if all subgoals have been proved.
 - **Top-down rules:** focus on goal formula.
 - Goal formula is decomposed into simpler formulas.
 - **Bottom-up rules:** focus on some formula in knowledge.
 - Additional formulas are added to the knowledge.

In each proof situation, we aim at showing that the goal is “apparently” true with respect to the given knowledge.

Conjunction



Formula $F_1 \wedge F_2$.

- Formula as goal.

- Create two subsituations with goals F_1 and F_2 .

We have to show $F_1 \wedge F_2$.

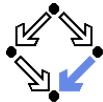
- *We show F_1 : ... (proof continues with goal F_1)*
- *We show F_2 : ... (proof continues with goal F_2)*

- Formula in knowledge.

- Create one subsituation with F_1 and F_2 in knowledge.

*We know $F_1 \wedge F_2$. We thus know F_1 and also F_2 .
(proof continues with current goal and additional
knowledge F_1 and F_2)*

Disjunction



Formula $F_1 \vee F_2$.

- Formula as goal.
 - Create one subsituation where F_2 is proved under the assumption that F_1 does not hold (or vice versa):

*We have to show $F_1 \vee F_2$. We assume $\neg F_1$ and show F_2 .
(proof continues with goal F_2 and additional knowledge $\neg F_1$)*

- Formula in knowledge.
 - Create two subsituations, one with F_1 and one with F_2 in knowledge.
We know $F_1 \vee F_2$. We thus proceed by case distinction:
 - *Case F_1 : ... (proof continues with current goal and additional knowledge F_1).*
 - *Case F_2 : ... (proof continues with current goal and additional knowledge F_2).*

Implication



Formula $F_1 \Rightarrow F_2$.

- Formula as goal.

- Create one subsituation where F_2 is proved under the assumption that F_1 holds:

*We have to show $F_1 \Rightarrow F_2$. We assume F_1 and show F_2 .
(proof continues with goal F_2 and additional knowledge F_1)*

- Formula in knowledge.

- Create two subsituations, one with goal F_1 and one with knowledge F_2 .

We know $F_1 \Rightarrow F_2$.

- *We show F_1 : ... (proof continues with goal F_1)*
- *We know F_2 : ... (proof continues with current goal and additional knowledge F_2).*

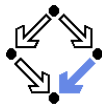
Equivalence



Formula $F_1 \Leftrightarrow F_2$.

- Formula as goal.
 - Create two subsituations with implications in both directions as goals:
We have to show $F_1 \Leftrightarrow F_2$.
 - *We show $F_1 \Rightarrow F_2$: ... (proof continues with goal $F_1 \Rightarrow F_2$)*
 - *We show $F_2 \Rightarrow F_1$: ... (proof continues with goal $F_2 \Rightarrow F_1$)*
- Formula in knowledge.
 - Create two subsituations, one with goal F_1 and one with knowledge F_2 .
We know $F_1 \Leftrightarrow F_2$.
 - *We show $F_1 (\neg F_1)$: ... (proof continues with goal F_1)*
 - *We know $F_2 (\neg F_2)$: ... (proof continues with current goal and additional knowledge F_2)*

Universal Quantification



Formula $\forall x : F$

- Formula as goal.

- Introduce new (arbitrarily named) constant x_0 and create one subsituation with goal $F[x_0/x]$.

We have to show $\forall x : F$. Take arbitrary x_0 .

We show $F[x_0/x]$. (proof continues with goal $F[x_0/x]$)

- Formula in knowledge.

- Choose term T to create one subsituation with formula $F[T/x]$ added to the knowledge.

We know $\forall x : F$ and thus also $F[T/x]$.

(proof continues with current goal and additional knowledge $F[T/x]$)

Existential Quantification



Formula $\exists x : F$

- Formula as goal.

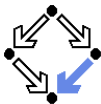
- Choose term T to create one subsituation with goal $F[T/x]$.

*We have to show $\exists x : F$. It suffices to show $F[T/x]$.
(proof continues with goal $F[T/x]$)*

- Formula in knowledge

- Introduce new (arbitrarily named constant) x_0 and create one subsituation with additional knowledge $F[x_0/x]$.

*We know $\exists x : F$. Let x_0 be such that $F[x_0/x]$.
(proof continues with current goal and additional
knowledge $F[x_0/x]$)*



Formula Equivalences

Formulas in knowledge and goals may be replaced by equivalent formulas.

- $\neg\neg F_1 \iff F_1$
- $\neg(F_1 \wedge F_2) \iff \neg F_1 \vee \neg F_2$
- $\neg(F_1 \vee F_2) \iff \neg F_1 \wedge \neg F_2$
- $\neg(F_1 \Rightarrow F_2) \iff F_1 \wedge \neg F_2$
- $\neg\forall x : F \iff \exists x : \neg F$
- $\neg\exists x : F \iff \forall x : \neg F$
- $F_1 \Rightarrow F_2 \iff \neg F_2 \Rightarrow \neg F_1$
- $F_1 \Rightarrow F_2 \iff \neg F_1 \vee F_2$
- $F_1 \Leftrightarrow F_2 \iff \neg F_1 \Leftrightarrow \neg F_2$
- ...

Transformation sometimes offers new view on a proof situation.

Indirect Proofs



Proof situation with goal formula G .

- Add $\neg G$ to the knowledge and show a contradiction.
 - Prove that “false” is true.
 - Prove that a formula F is true and also prove that it is false.
 - Prove that a formula F in the knowledge is false, i.e. that $\neg F$ is true.
 - Switches goal G and some knowledge F (negating both).

Sometimes simpler than a direct proof.



Example

We show

$$(a) (\exists x : p(x)) \wedge (\forall x : p(x) \Rightarrow \exists y : q(x, y)) \Rightarrow (\exists x, y : q(x, y))$$

We assume

$$(1) (\exists x : p(x)) \wedge (\forall x : p(x) \Rightarrow \exists y : q(x, y))$$

and show

$$(b) \exists x, y : q(x, y)$$

From (1), we know

$$(2) \exists x : p(x)$$

$$(3) \forall x : p(x) \Rightarrow \exists y : q(x, y)$$

From (2) we know for some x_0

$$(4) p(x_0)$$

...



Example (Contd)

...

From (3), we know

$$(5) p(x_0) \Rightarrow \exists y : q(x_0, y)$$

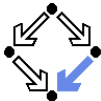
From (4) and (5), we know

$$(6) \exists y : q(x_0, y)$$

From (6), we know for some y_0

$$(7) q(x_0, y_0)$$

From (7), we know (b). QED.



Example

We show

$$(a) (\exists x : \forall y : P(x, y)) \Rightarrow (\forall y : \exists x : P(x, y))$$

We assume

$$(1) \exists x : \forall y : P(x, y)$$

and show

$$(b) \forall y : \exists x : P(x, y)$$

Take arbitrary y_0 . We show

$$(c) \exists x : P(x, y_0)$$

From (1) we know for some x_0

$$(2) \forall y : P(x_0, y)$$

From (2) we know

$$(3) P(x_0, y_0)$$

From (3), we know (c). QED.



Example (Indirect Proof)

We show

$$(a) (\exists x : \forall y : P(x, y)) \Rightarrow (\forall y : \exists x : P(x, y))$$

We assume

$$(1) \exists x : \forall y : P(x, y)$$

and show

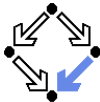
$$(b) \forall y : \exists x : P(x, y)$$

We assume

$$(2) \neg \forall y : \exists x : P(x, y)$$

and show a contradiction.

...



Example (Indirect Proof Contd)

...

From (2), we know

$$(3) \exists y : \forall x : \neg P(x, y)$$

Let y_0 be such that

$$(4) \forall x : \neg P(x, y_0)$$

From (1) we know for some x_0

$$(5) \forall y : P(x_0, y)$$

From (5) we know

$$(6) P(x_0, y_0)$$

From (4), we know

$$(7) \neg P(x_0, y_0)$$

From (6) and (7), we have a contradiction. QED.