Logic of Proof Assistants

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Contents

1 Introduction

The topics of this class are:

(i) First-order Logic/ Set Theory

(ii) Lambda Calculus

(iii) Simple Type Theory (Higher-Order Logic)

(iv) Dependent Type Theory/ Homotopy Type Theory

Example 1.1. Here are examples of proof assistants for these different types of logics:

(i) First-order Logic/ Set Theory: Mizar, Metamath

(ii) Simple Type Theory: Isabelle/HoL, HoL Light

(iii) Dependent Type Theory: Lean, Rocq (formally Coq), Agda

(iv) Homotopy Type Theory: cubicaltt, rezk

Remark 1.2. You might want to have the following criteria for a logic:

(i) Appropriate (You can encode mathematical arguments.)

(ii) Simple (It is relatively easy to understand.)

(iii) Expressive (Mathematical arguments are convenient to express.)

Theorem 1.3. *Let* π *be the prime counting function, i.e.* $\pi \colon \mathbb{R} \to \mathbb{N}$, $x \mapsto |\{p \leq x \mid p \text{ prime}\}|$. *Then* $\lim_{x\to\infty} \frac{\pi(x)}{x/\log(x)} = 1$.

Remark 1.4. When formalizing/stating this theorem in a formal logic there are a few things that you need to think about:

(i) What do you do about division by zero?

(ii) What does division even mean? (Do you define division for $\mathbb{R}$ explicitly? Do you define it generally for a field? Or even for a group? How do you ensure that the "correct" field structure on $\mathbb{R}$ gets used?)

(iii) How do you define a limit? (Do you define a limit for $\mathbb{R}$ explicitly? Or for every topological space? How do you ensure the "correct" topology on $\mathbb{R}$ gets used? How do you deal with potentially non-unique limits (for example in non-Hausdorff spaces)?)

Remark 1.5. You can make the following design choices for "a logic":

(i) Is the logic typed or untyped?

(ii) Is the logic constructive or classical?

(iii) Does the logic support computation?

Remark 1.6. In logic there is the **object language** and we reason about it in a **meta-language** ("ordinary mathematical reasoning").

1.1 Inductive Definitions

Example 1.7. The natural numbers are inductively defined by $0 \in \mathbb{N}$ and $S\colon \mathbb{N} \to \mathbb{N}$, $n \mapsto n+1$.

Definition 1.8. Let U be a set and $\mathcal{C} \subseteq \bigcup_{n\in\mathbb{N}}(U^n \to U)$ a set of **constructors**. $c\colon U^n \to U$ is called an **n-ary function**.

(i) $A \subseteq U$ is **closed under $\mathcal{C}$** if for any n-ary $c \in \mathcal{C}$ and for all $x_1, \dots, x_n \in A$ we have that $c(x_1, \dots, x_n) \in A$.

(ii) $A \subseteq U$ is **generated by $\mathcal{C}$** or **inductively defined by $\mathcal{C}$** if A is the smallest set that is closed under $\mathcal{C}$, i.e. $A = \bigcap\{B \subseteq U \mid B \text{ is closed under } \mathcal{C}\}$.

(iii) $A \subset U$ is **freely generated by $\mathcal{C}$** if

   (a) each constructor is injective on A and

   (b) the images of different constructors are disjoint.

Remark 1.9. $\varnothing$ is closed under $\mathcal{C}$ iff $\mathcal{C}$ has no nullary constructors.

Exercise 1.10. $\bigcap\{B \subseteq U \mid B \text{ is closed under } \mathcal{C}\}$ *is closed under* $\mathcal{C}$.

Example 1.11.

(i) The free group.

(ii) The σ-algebra generated by a collection of subsets. (This is not freely generated.)

(iii) The topology generated by a collection of subsets. (This is not freely generated.)

Theorem 1.12 (Structural Induction)**.** *If $A \subset U$ is generated by $\mathcal{C}$ and P is a predicate on A, to prove $\forall a \in A, P(a)$ it suffices to show: for any n-ary $c \in \mathcal{C}$ and any $x_1, \dots, x_n \in A$ if $P(x_1), \dots, P(x_n)$ then $P(c(x_1, \dots, x_n))$.*

Proof. Exercise. □

Remark 1.13. The base case of the induction is given by nullary constructors.

Theorem 1.14 (Structural Recursion)**.** *If $A \subset U$ is freely generated by $\mathcal{C}$, B is a set and for any n-ary $c \in \mathcal{C}$ we have a $g_c\colon B^n \to B$ then there is a unique function $f\colon A \to B$ such that $f(c(a_1, \dots, a_n)) = g_c(f(a_1), \dots, f(a_n))$ for every $c \in \mathcal{C}$ and $a_1, \dots a_n \in A$.*

Proof. Exercise. □

Example 1.15. For $A = \mathbb{N}$ this reduces to $f(0) \coloneqq g_0$ and $f(S(n)) \coloneqq g_s(f(n))$.

2 First-Order Logic

Definition 2.1. A (first-order) **language** $\mathcal{L}$ is a triple $(\mathcal{F}, \mathcal{R}, a)$ where $\mathcal{F}$ is a set of function symbols, $\mathcal{R}$ is a set of relation symbols, $\mathcal{F}$ and $\mathcal{R}$ are disjoint and $a\colon \mathcal{F} \cup \mathcal{R} \to \mathbb{N}$ is the arity function.

Example 2.2. A language for groups $\mathcal{L}_{\text{Group}}$ has $\mathcal{F} \coloneqq \{\cdot, ^{-1}, 1\}$, $\mathcal{R} \coloneqq \varnothing$, $a(\cdot) = 2$, $a(^{-1}) = 1$ and $a(1) = 0$.

Definition 2.3. We fix an infinite set of **variables** $\mathcal{V} \coloneqq \{x_0, x_1, \dots\}$.

Remark 2.4. We use x for variables, f and g for functions and R and S for relations.

Definition 2.5. We can define the **terms** $T_{\mathcal{L}}$ in the language $\mathcal{L}$ using the **Backus–Naur form (BNF)** :

$$s, t ::= x \mid f(t_1, \dots, t_n)$$

where f is an n-ary function symbol.

Definition 2.6. Formally, we define the **terms** $T_{\mathcal{L}}$ in the language $\mathcal{L}$ in the following way. We define the set of **symbols** $S \coloneqq \mathcal{F} \,\dot\cup\, \mathcal{V} \,\dot\cup \{\text{"("}, \text{")"}, \text{","}\}$ and the set of finite sequences of symbols S^*. Let $\mathcal{C}$ be defined as:

(i) for each variable $x \in \mathcal{V}$ there is a nullary constructor $c_x \coloneqq x$

(ii) for each n-ary function symbol f there is an n-ary constructor $c_f\colon (S^*)^n \to S^*$, $c_f(t_1, \dots, t_n) \coloneqq f\text{"("}t_1\text{","}\dots\text{","}t_n\text{")"}$

Then $T_{\mathcal{L}} \subseteq S^*$ is the set generated by $\mathcal{C}$.

Example 2.7.

(i) $\text{"(""))"","}f$ is in S^* but not in $T_{\mathcal{L}}$.

(ii) If f is binary then $f\text{"("}x_0\text{","}x_1\text{")"}$ is in $T_{\mathcal{L}}$.

Remark 2.8. Technically, the brackets and commas are not necessary. They are however necessary when you use infix notation. (For example the meaning of $a \cdot b + c$ is unclear.)

Definition 2.9. First-order **formulas** $\Phi_{\mathcal{L}}$ are specified by

$$\varphi, \psi ::= \bot \mid s = t \mid R(t_1, \dots t_n) \mid (\varphi \wedge \psi) \mid (\varphi \vee \psi) \mid (\varphi \to \psi) \mid (\forall x.\varphi) \mid (\exists x.\varphi)$$

where $\mathcal{R}$ is an n-ary relation symbol and $t_1, \dots, t_n \in T_{\mathcal{L}}$.

Remark 2.10. In classical logic one could omit the rules $(\varphi \wedge \psi)$ and $(\varphi \vee \psi)$ (as they can be defined using the other rules). They are however necessary for constructive logic.

Remark 2.11. We can define other connectives:

(i) $\neg\varphi \coloneqq (\varphi \to \bot)$

(ii) $\varphi \leftrightarrow \psi \coloneqq ((\varphi \to \psi) \wedge (\psi \to \varphi))$

Remark 2.12. When writing formulas we omit some parentheses:

(i) $\varphi \to \psi \to \theta$ means $\varphi \to (\psi \to \theta)$

(ii) $\forall x.\varphi \to \psi$ means $\forall x.(\varphi \to \psi)$

Remark 2.13. We want $\forall x.x = x$ and $\forall y.y = y$ to mean the same thing. Options to achieve this are:

(i) Define $(\forall x.x = x) \equiv_\alpha (\forall y.y = y)$ to be **α-equivalent**. And then define the set of formulas to be $\Phi_{\mathcal{L}}/\equiv_\alpha$.

(ii) We could not use variable names for bound variables and use **de Bruijn indices** instead.