

# A Case Study in Dependent Type Theory: Extracting a Certified Program from the Formal Proof of its Specification

Andreas Salhus Bakseter

Department of Informatics  
University of Bergen

June 9, 2023

# Overview

1. Background
2. The Case
3. Approach & Design Choices
4. Implementation
5. Examples & Results
6. Evaluation
7. Related & Future Work
8. Conclusion

# Proofs

- ▶ proofs are an important part of mathematics

# Proofs

- ▶ proofs are an important part of mathematics
- ▶ two kinds of proofs:

# Proofs

- ▶ proofs are an important part of mathematics
- ▶ two kinds of proofs:
  - ▶ **informal proofs**, natural language, by humans for humans

# Proofs

- ▶ proofs are an important part of mathematics
- ▶ two kinds of proofs:
  - ▶ **informal proofs**, natural language, by humans for humans
  - ▶ **formal proofs**, formal language, hard for humans easy for computers

# Proofs

- ▶ proofs are an important part of mathematics
- ▶ two kinds of proofs:
  - ▶ **informal proofs**, natural language, by humans for humans
  - ▶ **formal proofs**, formal language, hard for humans easy for computers
- ▶ we can transform informal proofs into formal proofs (formalization)

# Proofs

- ▶ proofs are an important part of mathematics
- ▶ two kinds of proofs:
  - ▶ **informal proofs**, natural language, by humans for humans
  - ▶ **formal proofs**, formal language, hard for humans easy for computers
- ▶ we can transform informal proofs into formal proofs (formalization)
- ▶ using computers & proof assistants we can check formal proofs (verification)



# Proofs

- ▶ proofs are an important part of mathematics
- ▶ two kinds of proofs:
  - ▶ **informal proofs**, natural language, by humans for humans
  - ▶ **formal proofs**, formal language, hard for humans easy for computers
- ▶ we can transform informal proofs into formal proofs (formalization)
- ▶ using computers & proof assistants we can check formal proofs (verification)
- ▶ we can also extract programs from formal proofs

# (Dependent) Type Theory & Propositions as Types

- foundation of mathematics

# (Dependent) Type Theory & Propositions as Types

- ▶ foundation of mathematics
- ▶ every object has a type,  $a : A$ , must know its construction

# (Dependent) Type Theory & Propositions as Types

- ▶ foundation of mathematics
- ▶ every object has a type,  $a : A$ , must know its construction

# (Dependent) Type Theory & Propositions as Types

- ▶ foundation of mathematics
- ▶ every object has a type,  $a : A$ , must know its construction
- ▶ provides us with rules of inference for manipulating types & objects

# (Dependent) Type Theory & Propositions as Types

- ▶ foundation of mathematics
- ▶ every object has a type,  $a : A$ , must know its construction
- ▶ provides us with rules of inference for manipulating types & objects
- ▶ **propositions as types:**

## (Dependent) Type Theory & Propositions as Types

- ▶ foundation of mathematics
- ▶ every object has a type,  $a : A$ , must know its construction
- ▶ provides us with rules of inference for manipulating types & objects
- ▶ **propositions as types:**
  - ▶ propositions are types

# (Dependent) Type Theory & Propositions as Types

- ▶ foundation of mathematics
- ▶ every object has a type,  $a : A$ , must know its construction
- ▶ provides us with rules of inference for manipulating types & objects
- ▶ **propositions as types:**
  - ▶ propositions are types
  - ▶ proofs are objects



## (Dependent) Type Theory & Propositions as Types

- ▶ foundation of mathematics
- ▶ every object has a type,  $a : A$ , must know its construction
- ▶ provides us with rules of inference for manipulating types & objects
- ▶ **propositions as types:**
  - ▶ propositions are types
  - ▶ proofs are objects
  - ▶ proof of a proposition is an object of that type

## (Dependent) Type Theory & Propositions as Types

- ▶ foundation of mathematics
- ▶ every object has a type,  $a : A$ , must know its construction
- ▶ provides us with rules of inference for manipulating types & objects
- ▶ **propositions as types:**
  - ▶ propositions are types
  - ▶ proofs are objects
  - ▶ proof of a proposition is an object of that type
- ▶ **dependent types:**

# (Dependent) Type Theory & Propositions as Types

- ▶ foundation of mathematics
- ▶ every object has a type,  $a : A$ , must know its construction
- ▶ provides us with rules of inference for manipulating types & objects
- ▶ **propositions as types:**
  - ▶ propositions are types
  - ▶ proofs are objects
  - ▶ proof of a proposition is an object of that type
- ▶ **dependent types:**
  - ▶ gives us more expressive types

## (Dependent) Type Theory & Propositions as Types

- ▶ foundation of mathematics
- ▶ every object has a type,  $a : A$ , must know its construction
- ▶ provides us with rules of inference for manipulating types & objects
- ▶ **propositions as types:**
  - ▶ propositions are types
  - ▶ proofs are objects
  - ▶ proof of a proposition is an object of that type
- ▶ **dependent types:**
  - ▶ gives us more expressive types
  - ▶  $\Sigma$ -types to model existential quantification

# (Dependent) Type Theory & Propositions as Types

- ▶ foundation of mathematics
- ▶ every object has a type,  $a : A$ , must know its construction
- ▶ provides us with rules of inference for manipulating types & objects
- ▶ **propositions as types:**
  - ▶ propositions are types
  - ▶ proofs are objects
  - ▶ proof of a proposition is an object of that type
- ▶ **dependent types:**
  - ▶ gives us more expressive types
  - ▶  $\Sigma$ -types to model existential quantification
  - ▶  $\Pi$ -types to model universal quantification

# Proof Assistants

- ▶ software tools for constructing & verifying formal proofs

## Proof Assistants

- ▶ software tools for constructing & verifying formal proofs
- ▶ based on type theory, propositions as types

# Proof Assistants

- ▶ software tools for constructing & verifying formal proofs
- ▶ based on type theory, propositions as types
- ▶ **Coq**:



## Proof Assistants

- ▶ software tools for constructing & verifying formal proofs
- ▶ based on type theory, propositions as types
- ▶ **Coq:**
  - ▶ based on the type theory *Calculus of Inductive Constructions*

## Proof Assistants

- ▶ software tools for constructing & verifying formal proofs
- ▶ based on type theory, propositions as types
- ▶ **Coq:**
  - ▶ based on the type theory *Calculus of Inductive Constructions*
  - ▶ uses *Gallina* as its specification language

## Proof Assistants

- ▶ software tools for constructing & verifying formal proofs
- ▶ based on type theory, propositions as types
- ▶ **Coq:**
  - ▶ based on the type theory *Calculus of Inductive Constructions*
  - ▶ uses *Gallina* as its specification language
  - ▶ uses *Ltac* as its tactic language, for ease of use
  - ▶ supports extraction of programs

## Overview of case

- ▶ two problems in lattice theory solved by Bezem & Coquand

## Overview of case

- ▶ two problems in lattice theory solved by Bezem & Coquand
- ▶ we want to answer these questions:

## Overview of case

- ▶ two problems in lattice theory solved by Bezem & Coquand
- ▶ we want to answer these questions:
  - ▶ are the results from Bezem & Coquand correct?

## Overview of case

- ▶ two problems in lattice theory solved by Bezem & Coquand
- ▶ we want to answer these questions:
  - ▶ are the results from Bezem & Coquand correct?
  - ▶ is it feasible to formalize complex proofs, such as these?

## Overview of case

- ▶ two problems in lattice theory solved by Bezem & Coquand
- ▶ we want to answer these questions:
  - ▶ are the results from Bezem & Coquand correct?
  - ▶ is it feasible to formalize complex proofs, such as these?
  - ▶ is the formalization process worth the effort?



## Relevant parts of the paper

- ▶ join-semilattices: partially ordered set where any two elements have a least upper bound, called their join, denoted  $\vee$

## Relevant parts of the paper

- ▶ join-semilattices: partially ordered set where any two elements have a least upper bound, called their join, denoted  $\vee$

