A proof library shared by different proof systems

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Sharing data

A C program can be executed on any computer

A jpg, png... photo can be seen on any telephone, computer...

A webpage can be displayed in any browser
Sharing proofs across systems

A PVS proof of $x + y = y + x$

A HOL Light proof of $x + y = y + x$

A CoQ proof of $x + y = y + x$

...
Although

We all would like to have a proof of

- Hales’ theorem
- the correctness of ACCoRD
- the Four color theorem
- Heule’s theorem

in PVS, CoQ, HOL Light...
Why don’t we have it?

Lack of standard

But also different logics
I. Building a shared library in five steps
Step 1: A logical framework
Different logics: nothing new

\[ \text{ZF} \vdash \text{Every vector has a unique decomposition in a base} \]

\[ \text{ZF} \nvdash \text{Every vector space has a base} \]
\[ \text{ZFC} \vdash \text{Every vector space has a base} \]
But... ZF and ZFC are expressed in the same logical framework (Predicate logic)

Only the axioms differ

Easy to analyse if a proof uses the axiom of choice or not
Logical frameworks

- Predicate logic
- $\lambda\Pi$-calculus (Harper, Honsell, Plotkin, 1993): proof-terms, binders
- Deduction modulo theory (D, Hardin, Kircher, 2003): computations, cut elimination
- $\lambda\Pi$-calculus modulo theory (Cousineau, D, 2007) implemented in Dedukti (Boespflug, Saillard, et al.)
- Many others: LFSC, ProofCert...
Step 2: Expressing logics in {\texttt{DEDUKTI}}
Simple type theory as a theory in the \( \lambda \Pi \)-calculus modulo theory

\[
\begin{align*}
type & : Type \\
\eta & : type \to Type \\
o & : type \\
nat & : type \\
arrow & : type \to type \to type \\
\varepsilon & : (\eta o) \to Type \\
\Rightarrow & : (\eta o) \to (\eta o) \to (\eta o) \\
\forall & : \Pi a : type (((\eta a) \to (\eta o)) \to (\eta o))
\end{align*}
\]

\[
\begin{align*}
(\eta (arrow x y)) & \to (\eta x) \to (\eta y) \\
(\varepsilon (\Rightarrow x y)) & \to (\varepsilon x) \to (\varepsilon y) \\
(\varepsilon (\forall x y)) & \to \Pi z : (\eta x) (\varepsilon (y z))
\end{align*}
\]
Examples

Types: $nat \rightarrow nat$ expressed as $(\text{arrow } nat \; nat)$ of type $type$
Then as $(\eta \; (\text{arrow } nat \; nat))$ of type $Type$ that reduces to
$(\eta \; nat) \rightarrow (\eta \; nat)$

Terms: $\lambda x : nat \; x$ expressed as $\lambda x : (\eta \; nat) \; x$ of type
$(\eta \; nat) \rightarrow (\eta \; nat)$

Propositions: $\forall X : o \; (X \Rightarrow X)$ expressed as
$\forall \; o \; \lambda X : (\eta \; o) \; (\Rightarrow \; X \; X)$ of type $(\eta \; o)$
Then as $(\varepsilon \; (\forall \; o \; \lambda X : (\eta \; o) \; (\Rightarrow \; X \; X)))$ of type $Type$ that reduces
to $\Pi X : (\eta \; o) \; ((\varepsilon \; X) \rightarrow (\varepsilon \; X))$.

Proofs: well-know expressed as $\lambda X : (\eta \; o) \; \lambda \alpha : (\varepsilon \; X) \; \alpha$ of type
$\Pi X : (\eta \; o) \; ((\varepsilon \; X) \rightarrow (\varepsilon \; X))$
The Calculus of constructions as a theory in the $\lambda\Pi$-calculus modulo theory

\[
\begin{align*}
type & : \text{Type} \\
\eta & : type \rightarrow Type \\
o & : type \\
nat & : type \\
arrow & : \prod x : type (((\eta \ x) \rightarrow type) \rightarrow type) \\
\varepsilon & : (\eta \ o) \rightarrow Type \\
\Rightarrow & : \prod x : (\eta \ o) (((\varepsilon \ x) \rightarrow (\eta \ o)) \rightarrow (\eta \ o)) \\
\forall & : \prod x : type (((\eta \ x) \rightarrow (\eta \ o)) \rightarrow (\eta \ o)) \\
\pi & : \prod x : (\eta \ o) (((\varepsilon \ x) \rightarrow type) \rightarrow type) \\
\end{align*}
\]

\[
\begin{align*}
(\eta \ (arrow \ x \ y)) & \rightarrow \prod z : (\eta \ x) \ (\eta \ (y \ z)) \\
(\varepsilon \ (\Rightarrow \ x \ y)) & \rightarrow \prod z : (\varepsilon \ x) \ (\varepsilon \ (y \ z)) \\
(\varepsilon \ (\forall \ x \ y)) & \rightarrow \prod z : (\eta \ x) \ (\varepsilon \ (y \ z)) \\
(\eta \ (\pi \ x \ y)) & \rightarrow \prod z : (\varepsilon \ x) \ (\eta \ (y \ z))
\end{align*}
\]
Coq and Matita

The Calculus of constructions + inductive types, universes...

Calculus of constructions with inductive types, universes... in Dedukti (Boespflug, Burel, Assaf, 2015)
Step 3: Translating proofs to Dedukti
HOL Light proofs: Assaf (2015)
Matita proofs: Assaf (2015)
FoCaLiZe proofs: Cauderlier, Dubois (2016)

Zenon modulo proofs: Halmagrand (2016)
i-prover modulo proofs: Burel (2014)

On going: Coq proofs, SAT proofs, SMT proofs...
Step 4: Reverse mathematics
Simple type theory as a theory in the $\lambda\Pi$-calculus modulo theory

type : Type

$\eta$ : type $\rightarrow$ Type

$o$ : type

$\text{nat}$ : type

$\text{arrow}$ : type $\rightarrow$ type $\rightarrow$ type

$\varepsilon$ : (\$\eta\ o\$) $\rightarrow$ Type

$\Rightarrow$ : (\$\eta\ o\$) $\rightarrow$ (\$\eta\ o\$) $\rightarrow$ (\$\eta\ o\$)

$\forall$ : $\Pi a$ : type (((\$\eta\ a\$) $\rightarrow$ (\$\eta\ o\$)) $\rightarrow$ (\$\eta\ o\$))

\[
(\eta\ (\text{arrow}\ x\ y)) \quad \rightarrow \quad (\eta\ x) \rightarrow (\eta\ y)
\]

\[
(\varepsilon\ (\Rightarrow\ x\ y)) \quad \rightarrow \quad (\varepsilon\ x) \rightarrow (\varepsilon\ y)
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\[
(\varepsilon\ (\forall\ x\ y)) \quad \rightarrow \quad \Pi z : (\eta\ x)\ (\varepsilon\ (y\ z))
\]
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\begin{align*}
\text{type} &: \quad \text{Type} \\
\eta &: \quad \text{type} \to \text{Type} \\
o &: \quad \text{type} \\
nat &: \quad \text{type} \\
ar\ellow &: \quad \Pi x : \text{type} (((\eta \, x) \to \text{type}) \to \text{type}) \\
\varepsilon &: \quad (\eta \, o) \to \text{Type} \\
\Rightarrow &: \quad \Pi x : (\eta \, o) (((\varepsilon \, x) \to (\eta \, o)) \to (\eta \, o)) \\
\forall &: \quad \Pi x : \text{type} (((\eta \, x) \to (\eta \, o)) \to (\eta \, o)) \\
\pi &: \quad \Pi x : (\eta \, o) (((\varepsilon \, x) \to \text{type}) \to \text{type}) \\
\end{align*}
\]

\[
\begin{align*}
(\eta \, (\text{arrow} \, x \, y)) & \to \Pi z : (\eta \, x) \, (\eta \, (y \, z)) \\
(\varepsilon \, (\Rightarrow \, x \, y)) & \to \Pi z : (\varepsilon \, x) \, (\varepsilon \, (y \, z)) \\
(\varepsilon \, (\forall \, x \, y)) & \to \Pi z : (\eta \, x) \, (\varepsilon \, (y \, z)) \\
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\end{align*}
\]
Analyzing proofs expressed in the Calculus of constructions

A subset of the proofs expressed in the Calculus of constructions

- do not use the dependency of \( \text{arrow} \)
- do not use the dependency of the symbol \( \Rightarrow \),
- do not use the symbol \( \pi \)

Can be translated to Simple type theory:
just replace \((\text{arrow} \ A \ \lambda x : (\eta \ A) \ B)\) with \((\text{arrow} \ A \ B)\)
(similar for \( \Rightarrow \))
Otherwise

The proof genuinely uses a feature of the Calculus of constructions that does not exist in Simple type theory

Should be tagged as such

Same as in ZFC: genuinely uses the axiom of choice: not in ZF
The arithmetic library of Matita in Dedukti, including a proof of Fermat’s little theorem

Dependency of arrow and $\Rightarrow$, $\pi$, and universes can be eliminated from this library (Thiré, 2018)

Inductive types: replaced by a induction on natural numbers

Actual proofs are much simpler than what is allowed by the logic
Fermat’s little theorem

A proof in constructive Simple type theory

Novelty: a formal proof in a theory weaker than Matita
Also weaker than HOL Light (excluded middle, extensionality, choice...)
(Genuine) reverse mathematics

Friedman, Simpson...
An important source of inspiration

But some differences:

- analyze proofs not theorems
- focus on formal proofs expressed and checked in computerized proof systems
- less ambitious: the Calculus of constructions, Simple type theory... rather than fragments of Second-order arithmetic
Step 5: Exporting from Dedukti
Exporting this library

From Dedukti

To HOL Light, Isabelle/HOL, HOL4 (using OpenTheory)
To Coq and (of course) to Matita

1.5 Mo, 340 lemmas
II. Abstracting enough
Both in Matita and HOL Light
Proving propositions by induction / defining functions by induction

But justified in different ways
Inductive type vs. impredicative definition of finite cardinals

Ignored by the library
Left to the host (the proof must land on a comfortable enough pillow)

Any system containing a notion of natural number and an induction principle
Connectives and quantifiers

Same as natural numbers
Inductive types / $Q_0$
Should be ignored by the library

Making formal the saying: Cauchy sequences or Dedekind cuts immaterial (isomorphic and only structural statements)
III. What about PVS?
Using the library

PVS contains Simple type theory

The full arithmetic library can be translated to PVS (or has it been translated already?)
Contributing to the library

Express PVS in Dedukti

What is the logic of PVS already? (Gilbert, 2018)

Can it be expressed in Dedukti?
Future work

Arithmetic library: the beginning of a shared library

A formal proof of Fermat’s little theorem in constructive Simple type theory: weaker theories (predicative, PA...)