Combining Proofs and Programs

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The TRELLYS project

The Trellys project

Penn
University of Pennsylvania

The University of Iowa

Portland State University

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Vilhelm Sjöberg	Peng (Frank) Fu	Nathan Collins
	Garrin Kimmell	

A collaborative project to design a statically-typed functional programming language based on dependent type theory.

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A collaborative project to design a statically-typed functional programming language based on dependent type theory.

Work-in-progress

Why Dependent Types?

- *Lightweight verification*: Dependent types express application-specific program invariants that are beyond the scope of existing type systems.
- *Expressiveness*: Dependent types enable flexible interfaces, allowing more programs to be statically checked.
- *Uniformity*: Full-spectrum dependent types provide the same syntax and semantics for program computations, type-level computations, and proofs.

A programming language, not a logic

Start with a general purpose, call-by-value, functional programming language and strengthen its type system.

- Draw programmers from Haskell and ML
- Existing code should work with minor modification
- Ease of programming more important than completeness of verification
- Incremental verification... only provide the strongest guarantees about the most critical code

On the shoulders of giants

Not the first to propose programming with dependent types

- Agda, Epigram, Coq, Lego, Nuprl

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- GHC, Ur, Sage, ATS, Ωmega, DML

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Not the first functional language to incorporate ideas from Type Theory

- GHC, Ur, Sage, ATS, Ωmega, DML

Not the first to propose a full-spectrum functional programming language based on dependent types

- Guru, Cayenne, Cardelli "A Polymorphic λ-calculus with Type:Type"

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- Have to choose something. Want to include nontermination so the order of evaluation makes a difference

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- Have to choose something. Want to include nontermination so the order of evaluation makes a difference
- Good cost model. Programmers can better predict the running time and space usage of their programs
- Distinction between values and computations built into the language. Variables stand for values, not computations

A programming language, not a logic

Can't use Curry-Howard Isomorphism to interpret this language as a logic.

A seeming contradiction

How can we have a full-spectrum, dependently-typed language based on an inconsistent logic?

Syntactic type soundness

Theorem (Syntactic type soundness)

If $\vdash a : A$ *then either* a *diverges or* $a \rightsquigarrow^{*}_{\mathsf{cbv}} v$ *and* $\vdash v : A$.

Proven by an *elementary syntactic* argument and extends in a straightforward manner to many language features (such as references, concurrency, exceptions, continuations, etc.)

Theorem gives us a form of *partial correctness*

Partial correctness

Can give a logical interpretation for *values*

$$\vdash a : \Sigma x \!:\! \mathsf{Nat}. \mathit{even}\ x = \mathit{true}$$

If a terminates, then it *must* produce a pair of a natural number and a *proof* that the result is even.

Partial correctness

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But, not all proofs are informative:

$$\vdash a : \Sigma x\!:\!\mathsf{Nat}.(\mathit{even}\ x = \mathit{true}) \to (x = 3)$$

Total correctness

Partial correctness is not enough

- Can't compile this language efficiently (have to run proofs)
- Users are willing to work harder for stronger guarantees

From partial correctness to total correctness

Plan for the rest of the talk:

- Part I: present a full-spectrum CBV language that satisfies type soundness only
- Part II: identify a "logical" sublanguage and discuss the interactions between the two parts

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- Part I: present a full-spectrum CBV language that satisfies type soundness only
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Not covered by this talk:

- How to make type checking decidable by adding annotations to the syntax
- How to make program development feasible by inferring annotations

Part I : A call-by-value programming language with dependent types

Uniform language

Types, terms, kinds defined using the same syntax

Syntax

$$
\begin{array}{llcl}
\textit{terms} & a, b, A, B & ::= & \star \mid \mathsf{Nat} \mid (x\!:\!A) \to B \\
 & & \mid & 0 \mid \mathsf{S}\ a \mid \mathsf{case}\ a\ \mathsf{of}\ \{0 \Rightarrow a_1 ; \mathsf{S}\ x \Rightarrow a_2\} \\
 & & \mid & x \mid \mathsf{rec}\, f\ x.a \mid a\ b \\
 & & & \\
\textit{values} & v, u & ::= & \star \mid \mathsf{Nat} \mid (x\!:\!A) \to B \\
 & & \mid & 0 \mid \mathsf{S}\ v \\
 & & \mid & x \mid \mathsf{rec}\, f\ x.a
\end{array}
$$

Use standard abbreviations:

- $\lambda x.a$ for $\mathsf{rec}\, f\ x.a$ when f is not free in a
- $A \to B$ for $(x\!:\!A) \to B$ when x is not free in B

Call-by-value operational semantics

$\boxed{a \rightsquigarrow_{\mathsf{cbv}} b}$

$$\frac{}{(\mathsf{rec}\, f\ x.a)\ v \rightsquigarrow_{\mathsf{cbv}} [v/x][\mathsf{rec}\, f\ x.a/f]a}$$

$$\frac{}{\mathsf{case}\ 0\ \mathsf{of}\ \{0 \Rightarrow a_1; \mathsf{S}\ x \Rightarrow a_2\} \rightsquigarrow_{\mathsf{cbv}} a_1}$$

$$\frac{}{\mathsf{case}\ (\mathsf{S}\ v)\ \mathsf{of}\ \{0 \Rightarrow a_1; \mathsf{S}\ x \Rightarrow a_2\} \rightsquigarrow_{\mathsf{cbv}} [v/x]a_2}$$

Example

Polymorphic application

$$app : (x : \star) \to (f : x \to x) \to (z : x) \to x$$
$$app = \lambda x.\lambda f.\lambda z.f\ z$$

$$app\ \mathsf{Nat}\ (\lambda x.x)\ 0 \equiv 0$$

Expressive example

$$
\begin{aligned}
zeroApp &= \lambda g.\lambda z.g \\
oneApp &= \lambda g.\lambda z.g\ z \\
twoApp &= \lambda g.\lambda z.g\ z\ z
\end{aligned}
$$

$$
\begin{aligned}
nApp = \mathsf{rec}\ f\ n.\ \mathsf{case}\ n\ \mathsf{of}\ & \\
\{\ 0 \quad &\Rightarrow\ \lambda g.\lambda z.g\ ; \\
\mathsf{S}\ m \quad &\Rightarrow\ \lambda g.\lambda z.f\ m\ (g\ z)\ z\}
\end{aligned}
$$

Expressive example

$$
\begin{array}{lcl}
zeroApp & : & \mathsf{Nat} \to \mathsf{Nat} \to \mathsf{Nat} \\
zeroApp & = & \lambda g.\lambda z.g \\
oneApp & : & (\mathsf{Nat} \to \mathsf{Nat}) \to \mathsf{Nat} \to \mathsf{Nat} \\
oneApp & = & \lambda g.\lambda z.g\ z \\
twoApp & : & (\mathsf{Nat} \to \mathsf{Nat} \to \mathsf{Nat}) \to \mathsf{Nat} \to \mathsf{Nat} \\
twoApp & = & \lambda g.\lambda z.g\ z\ z
\end{array}
$$

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twoApp & = & \lambda g.\lambda z.g\ z\ z
\end{array}
$$

$$
\begin{array}{l}
nApp\ :\ (n{:}\mathsf{Nat}) \to (N\ n) \to \mathsf{Nat} \to \mathsf{Nat} \\
nApp = \mathsf{rec}\ f\ n.\ \mathsf{case}\ n\ \mathsf{of} \\
\qquad\qquad \begin{array}{lcl}
\{\ 0 & \Rightarrow & \lambda g.\lambda z.g\ ; \\
\ \ \mathsf{S}\ m & \Rightarrow & \lambda g.\lambda z.f\ m\ (g\ z)\ z\}
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\end{array}
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\end{array}
$$

$$
\begin{array}{lcl}
N & : & \mathsf{Nat} \to * \\
N & = & \mathsf{rec}\ f\ n.\ \mathsf{case}\ n\ \mathsf{of} \\
 & & \quad \{\ 0 \quad \Rightarrow \quad \mathsf{Nat}\ ; \\
 & & \quad\ \ \mathsf{S}\ m \quad \Rightarrow \quad \mathsf{Nat} \to f\ m \} \\
nApp & : & (n{:}\mathsf{Nat}) \to (N\ n) \to \mathsf{Nat} \to \mathsf{Nat} \\
nApp & = & \mathsf{rec}\ f\ n.\ \mathsf{case}\ n\ \mathsf{of} \\
 & & \quad \{\ 0 \quad \Rightarrow \quad \lambda g.\lambda z.g\ ; \\
 & & \quad\ \ \mathsf{S}\ m \quad \Rightarrow \quad \lambda g.\lambda z.f\ m\ (g\ z)\ z \}
\end{array}
$$

Typing relation

$\boxed{\Gamma \vdash a : A}$

General recursion

$$\frac{\Gamma, y : A, f : (y\!:\!A) \to B \vdash a : B}{\Gamma \vdash \mathsf{rec}\, f\ y.a : (y\!:\!A) \to B}$$

Type is a type

$$\frac{}{\vdash \star : \star}$$

Conversion

Because types depend on programs, we want to identify types that contain equivalent programs.

$$\mathsf{Vec\ Nat}\ (1+2) \equiv \mathsf{Vec\ Nat}\ 3$$

Expressions can be assigned any equivalent type

Conversion

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But what does it mean for types to be equal?

Definitional Equality

- Based on operational semantics (hence undecidable)
- Ideally: identify all terms that are contextually equivalent to each other
- For now: close step relation under reflexivity, symmetry, transitivity and substitutivity
- Strictly computational, properties shown via rewriting

$\boxed{a \equiv b}$

$$\frac{a_1 \leadsto_{\mathsf{cbv}} a_2}{a_1 \equiv a_2} \qquad \frac{}{a \equiv a} \qquad \frac{a_1 \equiv a_2}{a_2 \equiv a_1}$$

$$\frac{a_1 \equiv a_2 \quad a_2 \equiv a_3}{a_1 \equiv a_3} \qquad \frac{a_1 \equiv a_2}{[a_1/x]A \equiv [a_2/x]A}$$

Internalizing equality

Internalize definitional equality as a proposition, with a trivial proof

$$a, b, A, B ::= \dots \mid a = b \mid \mathsf{join}$$

$$\frac{a \;\equiv\; b \quad \Gamma \vdash a = b : \star}{\Gamma \vdash \mathsf{join} : a = b}$$

$$\frac{\Gamma \vdash a : A \quad \Gamma \vdash b : B}{\Gamma \vdash a = b : \star}$$

Conversion and propositional equality

Extend conversion rule to propositional equality

$$\frac{\Gamma \vdash a : A \quad \Gamma \vdash v : A = B}{\Gamma \vdash a : B}$$

- Subsumes previous conversion rule (using join as the value)
- Conversion is implicit. Terms that differ only in convertible types are trivially equal
- Proof must be a *value*
- Don't care which value it is

Why can we do this?

Type soundness follows from the following property (which can be proven *syntactically*):

Lemma (Soundness of propositional equality)

If $\vdash v : A_1 = A_2$ *then* $A_1 \equiv A_2$.

The cost of CBV

Call-by-value semantics adds extra hypothesis to application:

$$\frac{\Gamma \vdash a : (x : A) \to B \quad \Gamma \vdash b : A \quad \Gamma \vdash [b/x]B : \star}{\Gamma \vdash a\ b : [b/x]B}$$

The cost of CBV

Call-by-value semantics adds extra hypothesis to application:

$$\frac{\Gamma \vdash a : (x\!:\!A) \to\ B \quad \Gamma \vdash b : A \quad \color{red}{\Gamma \vdash [b/x]B : \star}}{\Gamma \vdash a\ b : [b/x]B}$$

If b is a non-value, the rule must make sure that x was never treated as a value in B.

Implicit arguments

Some values have no runtime effect.
Useful for:

- Parametric polymorphism $(x : \star) \to\ x \to x$
- Preconditions $(x : \mathsf{Nat}) \to\ \neg(x = 0) \to \mathsf{Nat}$

Want to elide them from the syntax of terms

$$\mathit{app}\ (\lambda x.x)\ 0 \quad \text{instead of} \quad \mathit{app}\ \mathsf{Nat}\ (\lambda x.x)\ 0$$

cf. Implicit Calculus of Constructions (ICC)

Implicit arguments

Add implicit abstraction type

$$a, b, A, B ::= \ldots \mid [x : A] \to B$$

but... can only generalize over values

$$\frac{\Gamma, x : A \vdash v : B \quad x \notin \mathrm{FV}\, v}{\Gamma \vdash v : [x : A] \to B}$$

...can only instantiate with values

$$\frac{\Gamma \vdash a : [x : A] \to B \quad \Gamma \vdash v : A}{\Gamma \vdash a : [v/x]B}$$

Value restrictions are annoying

Suppose we write a program that "proves" the following fact about natural numbers:

$$f : (x : \mathsf{Nat}) \to (y : \mathsf{Nat}) \to (x = \mathsf{S}\ y) \to \neg(x = 0)$$

However, a use of this lemma "$f\ x\ y\ z$" is not a value and cannot be erased.

Must first use an explicit argument to evaluate it to a value, even though the value is irrelevant.

Taking stock

- Make type checking decidable by adding annotations to the syntax
- Make program development feasible by inferring annotations

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- Make program development feasible by inferring annotations
- ...but, irrelevant computations remain at runtime
- ...slowing execution
- ...weakening equivalence
- ...and weakening static guarantees

Part II : A logical sublanguage

A logical language

- There is a logically-consistent sublanguage hiding in here.

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- Annotate typing judgement to specify the *logical* language or the *programmatic* language.

A logical language

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- Annotate typing judgement to specify the *logical* language or the *programmatic* language.

New typing judgement form:

$$\Gamma \vdash^{\theta} a : A \quad \textit{where} \quad \theta ::= \mathsf{L} \mid \mathsf{P}$$

Subsumption

Logical language is a *sublanguage* of the programmatic language.

$$\frac{\Gamma \vdash^{\mathsf{L}} a : A}{\Gamma \vdash^{\mathsf{P}} a : A}$$

It guarantees stronger properties about its expressions.

Theorem (Syntactic type soundness)

If $\vdash^{\mathsf{P}} a : A$ *then either* a *diverges or* $a \leadsto^{*}_{\mathsf{cbv}} v$ *and* $\vdash^{\mathsf{P}} v : A$*.*

Theorem (Semantic consistency)

If $\vdash^{\mathsf{L}} a : A$ *then* $a \leadsto^{*}_{\mathsf{cbv}} v$ *and* $\vdash^{\mathsf{L}} v : A$

Some features must be programmatic

Some capabilities only available for the programmatic language

Type-In-Type

$$\frac{}{\vdash^{\mathsf{P}} \star : \star}$$

General recursion

$$\frac{\Gamma \vdash^{\mathsf{P}} (x :^{\theta} A) \to B : \star \qquad \Gamma, x :^{\theta} A, f :^{\mathsf{P}} (x :^{\theta} A) \to B \vdash^{\mathsf{P}} b : B}{\Gamma \vdash^{\mathsf{P}} \mathsf{rec}\, f\ x.b : (x :^{\theta} A) \to B}$$

What does the logical language look like?

Logical functions should not be recursive...

$$\frac{\Gamma \vdash^{\mathsf{L}} (x :^{\theta} A) \to B : \star \quad \Gamma, x :^{\theta} A \vdash^{\mathsf{L}} b : B}{\Gamma \vdash^{\mathsf{L}} \mathsf{rec}\, f\ x.b : (x :^{\theta} A) \to B}$$

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...except for primitive recursion over natural numbers

$$\frac{\begin{array}{l}\Gamma, x :^{\mathsf{L}} \mathsf{Nat} \vdash^{\mathsf{L}} B : \star \\ \Gamma, x :^{\mathsf{L}} \mathsf{Nat}, f :^{\mathsf{L}} (y :^{\mathsf{L}} \mathsf{Nat}) \to [z :^{\mathsf{L}} (\mathsf{S}\ y) = x] \to [y/x]B \vdash^{\mathsf{L}} b : B\end{array}}{\Gamma \vdash^{\mathsf{L}} \mathsf{rec}\, f\ x.b : (x :^{\mathsf{L}} \mathsf{Nat}) \to\ B}$$

Mixing the sublanguages

Programmatic functions can have logical parameters:

$$\frac{\begin{array}{c}\Gamma \vdash^{\mathsf{P}} (x :^{\mathsf{L}} A) \to B : \star \\ \Gamma, x :^{\mathsf{L}} A, f :^{\mathsf{P}} (x :^{\mathsf{L}} A) \to B \vdash^{\mathsf{P}} b : B\end{array}}{\Gamma \vdash^{\mathsf{P}} \mathsf{rec}\, f\ x.b : (x :^{\mathsf{L}} A) \to B}$$

Such arguments are logical “proofs” that the preconditions of the function are satisfied.

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Such arguments are logical "proofs" that the preconditions of the function are satisfied.
These arguments can be implicit, even if they are not values.

Freedom of Speech

Logical functions can have programmatic parameters:

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Application restricted to terminating arguments.

$$\frac{\begin{array}{l}\Gamma \vdash^{\mathsf{L}} a : (x :^{\mathsf{P}} A) \to B \\ \Gamma \vdash_{\downarrow} b : A \quad \Gamma \vdash^{\mathsf{L}} [b/x]B : \star\end{array}}{\Gamma \vdash^{\mathsf{L}} a\ b : [b/x]B}$$

Total arguments are either logical or values.

$$\frac{\Gamma \vdash^{\mathsf{L}} a : A}{\Gamma \vdash_{\downarrow} a : A} \qquad \frac{\Gamma \vdash^{\mathsf{P}} v : A}{\Gamma \vdash_{\downarrow} v : A}$$

Conversion

- Conversion available for both languages
- Equality proof must be total

$$\frac{\Gamma \vdash^{\theta} a : A \quad \Gamma \vdash_{\downarrow} b : A = B}{\Gamma \vdash^{\theta} a : B}$$

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For example, all natural numbers are values in the logical language as well as in the programmatic language.

$$\frac{}{\vdash^{\mathsf{L}} \mathsf{Nat} : \star} \qquad \frac{}{\vdash^{\mathsf{L}} 0 : \mathsf{Nat}} \qquad \frac{\Gamma \vdash^{\theta} n : \mathsf{Nat}}{\Gamma \vdash^{\theta} \mathsf{S}\ n : \mathsf{Nat}}$$

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This means that it is sound to treat a variable of type Nat as logical, no matter what it is assumed to be in the context.

$$\frac{\Gamma \vdash^{\mathsf{P}} x : \mathsf{Nat}}{\Gamma \vdash^{\mathsf{L}} x : \mathsf{Nat}}$$

Uniform equality

Equality proofs are also shared.
All equality proofs and propositions are logical, no matter what sort of terms they equate.

$$\frac{\Gamma \vdash^{\mathsf{P}} a : A \qquad \Gamma \vdash^{\mathsf{P}} b : B}{\Gamma \vdash^{\mathsf{L}} a = b : \star} \qquad \frac{\Gamma \vdash^{\mathsf{L}} a = b : \star \qquad a \equiv b}{\Gamma \vdash^{\mathsf{L}} \mathsf{join} : a = b}$$

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We can treat a programmatic variable as a logical equality proof.

$$\frac{\Gamma \vdash^{\mathsf{P}} x : A = B}{\Gamma \vdash^{\mathsf{L}} x : A = B}$$

This supports incremental verification. We can have a partial function return an equality proof and then use that to satisfy the preconditions of any part of the code.

Conclusion

Related work

- Bar types in Nuprl
- Partiality Monad
- Monadic “possible worlds” semantics

Future work

- What logical system should we use? Predicative? Impredicative? Large Eliminations? Induction-Recursion?

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- Strengthen definitional and propositional equality

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- What logical system should we use? Predicative? Impredicative? Large Eliminations? Induction-Recursion?
- Interaction with classical reasoning: allow proofs to branch on whether a program halts or diverges
- Strengthen definitional and propositional equality
- Elaboration to an annotated language

Summary

- Can have full-spectrum dependently-typed language with nontermination, effects, etc.
- Call-by-value semantics permits "partial correctness"
- Logical and programmatic languages can interact
  - All proofs are programs
  - Logic can talk about programs
  - Shared values can be passed from programs to the logic