DATA 61

COMP4161: Advanced Topics in Software Verification

$\lambda^{\rightarrow}$

Gerwin Klein, June Andronick, Christine Rizkallah, Miki Tanaka
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data61.csiro.au

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Last time...

- ➜ λ calculus syntax
- ➜ free variables, substitution
- ➜ β reduction
- ➜ α and η conversion
- ➜ β reduction is confluent
- ➜ λ calculus is expressive (Turing complete)
- ➜ λ calculus is inconsistent (as a logic)

Content

- ➜ Intro & motivation, getting started [1]
- ➜ Foundations & Principles
  - Lambda Calculus, natural deduction [1,2]
  - Higher Order Logic [3[a]]
  - Term rewriting [4]
- ➜ Proof & Specification Techniques
  - Inductively defined sets, rule induction [5]
  - Datatypes, recursion, induction [6, 7]
  - Hoare logic, proofs about programs, invariants [8[b],9]
  - (mid-semester break)
  - C verification [10]
  - CakeML, Isar [11[c]]
  - Concurrency [12]

[a] a1 due; [b] a2 due; [c] a3 due

λ calculus is inconsistent

Can find term R such that $R\ R =_\beta \texttt{not}(R\ R)$

There are more terms that do not make sense:

$$1\ 2, \quad \texttt{true false}, \quad \text{etc.}$$

Solution: rule out ill-formed terms by using types.
(Church 1940)

Introducing types

Idea: assign a type to each "sensible" λ term.

Examples:

- for *term t has type α* write $t :: \alpha$
- if x has type α then $\lambda x.\ x$ is a function from α to α
  Write: $(\lambda x.\ x) :: \alpha \Rightarrow \alpha$
- for $s\ t$ to be sensible:
  s must be a function
  t must be right type for parameter

  If $s :: \alpha \Rightarrow \beta$ and $t :: \alpha$ then $(s\ t) :: \beta$

That's about it

Now formally again

Syntax for $\lambda^{\rightarrow}$

Terms: $t ::= v \mid c \mid (t\ t) \mid (\lambda x.\ t)$
$v, x \in V, \quad c \in C, \quad V, C$ sets of names

Types: $\tau ::= \mathtt{b} \mid \nu \mid \tau \Rightarrow \tau$
$\mathtt{b} \in \{\mathtt{bool}, \mathtt{int}, \ldots\}$ base types
$\nu \in \{\alpha, \beta, \ldots\}$ type variables

$$\alpha \Rightarrow \beta \Rightarrow \gamma \quad = \quad \alpha \Rightarrow (\beta \Rightarrow \gamma)$$

Context Γ:
Γ: function from variable and constant names to types.

Term t has type τ in context Γ: $\quad \Gamma \vdash t :: \tau$

Examples

$$\Gamma \vdash (\lambda x.\ x) :: \alpha \Rightarrow \alpha$$

$$[y \leftarrow \texttt{int}] \vdash y :: \texttt{int}$$

$$[z \leftarrow \texttt{bool}] \vdash (\lambda y.\ y)\ z :: \texttt{bool}$$

$$[] \vdash \lambda f\ x.\ f\ x :: (\alpha \Rightarrow \beta) \Rightarrow \alpha \Rightarrow \beta$$

A term t is **well typed** or **type correct**
if there are Γ and τ such that $\Gamma \vdash t :: \tau$

Type Checking Rules

Variables: $$\frac{}{\Gamma \vdash x :: \Gamma(x)}$$

Application: $$\frac{\Gamma \vdash t_1 :: \tau_2 \Rightarrow \tau \quad \Gamma \vdash t_2 :: \tau_2}{\Gamma \vdash (t_1\ t_2) :: \tau}$$

Abstraction: $$\frac{\Gamma[x \leftarrow \tau_x] \vdash t :: \tau}{\Gamma \vdash (\lambda x.\ t) :: \tau_x \Rightarrow \tau}$$

Example Type Derivation:

$$\cfrac{\cfrac{\overline{[x \leftarrow \alpha, y \leftarrow \beta] \vdash x :: \alpha}}{[x \leftarrow \alpha] \vdash \lambda y.\ x :: \beta \Rightarrow \alpha}}{[] \vdash \lambda x\ y.\ x :: \alpha \Rightarrow \beta \Rightarrow \alpha}$$

More complex Example

$$\dfrac{\dfrac{\dfrac{\dfrac{\overline{\Gamma \vdash f :: \alpha \Rightarrow (\alpha \Rightarrow \beta)} \quad \overline{\Gamma \vdash x :: \alpha}}{\Gamma \vdash f\ x :: \alpha \Rightarrow \beta} \qquad \overline{\Gamma \vdash x :: \alpha}}{\Gamma \vdash f\ x\ x :: \beta}}{[f \leftarrow \alpha \Rightarrow \alpha \Rightarrow \beta] \vdash \lambda x.\ f\ x\ x :: \alpha \Rightarrow \beta}}{[] \vdash \lambda f\ x.\ f\ x\ x :: (\alpha \Rightarrow \alpha \Rightarrow \beta) \Rightarrow \alpha \Rightarrow \beta}$$

$$\Gamma = [f \leftarrow \alpha \Rightarrow \alpha \Rightarrow \beta, x \leftarrow \alpha]$$

More general Types

A term can have more than one type.

Example: $[] \vdash \lambda x.\ x :: \texttt{bool} \Rightarrow \texttt{bool}$
$[] \vdash \lambda x.\ x :: \alpha \Rightarrow \alpha$

Some types are more general than others:

$\tau \lesssim \sigma$ if there is a substitution S such that $\tau = S(\sigma)$

Examples:

$$\texttt{int} \Rightarrow \texttt{bool} \quad \lesssim \quad \alpha \Rightarrow \beta \quad \lesssim \quad \beta \Rightarrow \alpha \quad \not\lesssim \quad \alpha \Rightarrow \alpha$$

Most general Types

Fact: each type correct term has a most general type

Formally:

$$\Gamma \vdash t :: \tau \quad \Longrightarrow \quad \exists \sigma.\ \Gamma \vdash t :: \sigma \wedge (\forall \sigma'.\ \Gamma \vdash t :: \sigma' \Longrightarrow \sigma' \lesssim \sigma)$$

It can be found by executing the typing rules backwards.

- ➜ **type checking:** checking if $\Gamma \vdash t :: \tau$ for given Γ and τ
- ➜ **type inference:** computing Γ and τ such that $\Gamma \vdash t :: \tau$

Type checking and type inference on $\lambda^{\rightarrow}$ are decidable.

What about β reduction?

Definition of β reduction stays the same.

Fact: Well typed terms stay well typed during β reduction

Formally: $\Gamma \vdash s :: \tau \ \wedge \ s \longrightarrow_\beta t \Longrightarrow \Gamma \vdash t :: \tau$

This property is called **subject reduction**

What about termination?

β reduction in $\lambda^{\rightarrow}$ always terminates.

(Alan Turing, 1942)

- **$=_\beta$ is decidable**
  To decide if $s =_\beta t$, reduce s and t to normal form (always exists, because $\longrightarrow_\beta$ terminates), and compare result.
- **$=_{\alpha\beta\eta}$ is decidable**
  This is why Isabelle can automatically reduce each term to $\beta\eta$ normal form.

What does this mean for Expressiveness?

Not all computable functions can be expressed in $\lambda^{\rightarrow}$!

How can typed functional languages then be turing complete?

Fact:
Each computable function can be encoded as closed, type correct $\lambda^{\rightarrow}$ term using $Y :: (\tau \Rightarrow \tau) \Rightarrow \tau$ with $Y\ t \longrightarrow_\beta t\ (Y\ t)$ as only constant.

- Y is called fix point operator
- used for recursion
- lose decidability (what does $Y\ (\lambda x.\ x)$ reduce to?)
- (Isabelle/HOL doesn't have Y; it supports more restricted forms of recursion)

Types and Terms in Isabelle

Types: $\tau \quad ::= \quad \mathtt{b} \mid {}'\nu \mid {}'\nu :: C \mid \tau \Rightarrow \tau \mid (\tau, \ldots, \tau)\ K$

$\mathtt{b} \in \{\mathtt{bool}, \mathtt{int}, \ldots\}$ base types

$\nu \in \{\alpha, \beta, \ldots\}$ type variables

$K \in \{\mathtt{set}, \mathtt{list}, \ldots\}$ type constructors

$C \in \{\mathtt{order}, \mathtt{linord}, \ldots\}$ type classes

Terms: $t \quad ::= \quad v \mid c \mid ?v \mid (t\ t) \mid (\lambda x.\ t)$

$v, x \in V, \quad c \in C, \quad V, C$ sets of names

- ➜ **type constructors**: construct a new type out of a parameter type.
  Example: `int list`
- ➜ **type classes**: restrict type variables to a class defined by axioms.
  Example: $\alpha :: \mathit{order}$
- ➜ **schematic variables**: variables that can be instantiated.

Type Classes

- similar to Haskell's type classes, but with semantic properties

  class order =

  assumes order_refl: "$x \le x$"

  assumes order_trans: "$[\![x \le y; y \le z]\!] \Longrightarrow x \le z$"

  ...

- theorems can be proved in the abstract

  lemma order_less_trans:

  "$\bigwedge x :: 'a :: order.\ [\![x < y; y < z]\!] \Longrightarrow x < z$"

- can be used for subtyping

  class linorder = order +

  assumes linorder_linear: "$x \le y \vee y \le x$"

- can be instantiated

  instance nat :: "{order, linorder}" **by** ...

Schematic Variables

$$\frac{X \quad Y}{X \wedge Y}$$

- ➜ X and Y must be **instantiated** to apply the rule

But: **lemma** "$x + 0 = 0 + x$"

- ➜ x is free
- ➜ convention: lemma must be true for all x
- ➜ **during the proof**, x must **not** be instantiated

Solution:
Isabelle has **free** (x), **bound** (x), and **schematic** (?X) variables.

Only schematic variables can be instantiated.

Free converted into schematic after proof is finished.

Higher Order Unification

Unification:
Find substitution σ on variables for terms s, t such that
$\sigma(s) = \sigma(t)$

In Isabelle:
Find substitution σ on schematic variables such that
$\sigma(s) =_{\alpha\beta\eta} \sigma(t)$

Examples:

$$\begin{array}{llll} ?X \wedge ?Y & =_{\alpha\beta\eta} & x \wedge x & [?X \leftarrow x, ?Y \leftarrow x] \\ ?P\ x & =_{\alpha\beta\eta} & x \wedge x & [?P \leftarrow \lambda x.\ x \wedge x] \\ P\ (?f\ x) & =_{\alpha\beta\eta} & ?Y\ x & [?f \leftarrow \lambda x.\ x, ?Y \leftarrow P] \end{array}$$

Higher Order: schematic variables can be functions.

Higher Order Unification

- Unification modulo $\alpha\beta$ (Higher Order Unification) is semi-decidable
- Unification modulo $\alpha\beta\eta$ is undecidable
- Higher Order Unification has possibly infinitely many solutions

But:

- Most cases are well-behaved
- Important fragments (like Higher Order Patterns) are decidable

Higher Order Pattern:

- is a term in β normal form where
- each occurrence of a schematic variable is of the form $?f\ t_1\ \ldots\ t_n$
- and the $t_1\ \ldots\ t_n$ are η-convertible into n distinct bound variables

We have learned so far...

- Simply typed lambda calculus: $\lambda^{\rightarrow}$
- Typing rules for $\lambda^{\rightarrow}$, type variables, type contexts
- β-reduction in $\lambda^{\rightarrow}$ satisfies subject reduction
- β-reduction in $\lambda^{\rightarrow}$ always terminates
- Types and terms in Isabelle