COMP 4161
NICTA Advanced Course

Advanced Topics in Software Verification

Gerwin Klein, June Andronick, Toby Murray

$$\lambda^{\rightarrow}$$

Slide 1

Exercises from last time

- ➜ Reduce $(\lambda x.\ y\ (\lambda v.\ x\ v))\ (\lambda y.\ v\ y)$ to $\beta\eta$ normal form.
- ➜ Find an encoding for function fs, sn, and $pair$ such that $fs\ (pair\ a\ b)\ =_\beta\ a$ and $sn\ (pair\ a\ b)\ =_\beta\ b$.
- ➜ (harder) Find an encoding of list objects, i.e. for the function $cons$ and nil. Then find an encoding for map (that is, map $f\ [x_1, \ldots, x_n] = [f\ x_1, \ldots, f\ x_n]$), and for $foldl$ (that is, foldl $f\ i\ [x_1, \ldots, x_n] = f\ x_1\ (f\ x_2\ (f\ x_3\ (\ldots (f\ x_n\ i))) \ldots))$

Slide 2

Content

	Rough timeline
➜ Intro & motivation, getting started	[1]
➜ Foundations & Principles	
• Lambda Calculus, natural deduction	[2,3,4[a]]
• Higher Order Logic	[5,6[b],7]
• Term rewriting	[8,9,10[c]]
➜ Proof & Specification Techniques	
• Isar	[11,12[d]]
• Inductively defined sets, rule induction	[13[e],15]
• Datatypes, recursion, induction	[16,17[f],18,19]
• Calculational reasoning, mathematics style proofs	[20]
• Hoare logic, proofs about programs	[21[g],22,23]

[a] a1 out; [b] a1 due; [c] a2 out; [d] a2 due; [e] session break; [f] a3 out; [g] a3 due

Slide 3

λ calculus is inconsistent

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

There are more terms that do not make sense:
$1\ 2$, `true false`, etc.

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

Slide 4

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: $(\lambda x.\ x) :: \alpha \Rightarrow a$
- for $s\ t$ to be sensible:
  s must be function
  t must be right type for parameter

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

Slide 5

THAT'S ABOUT IT

Slide 6

NOW FORMALLY AGAIN

Slide 7

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: $\tau\ ::=\ \mathsf{b} \mid \nu \mid \tau \Rightarrow \tau$
$\mathsf{b} \in \{\texttt{bool}, \texttt{int}, \ldots\}$ 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: $\Gamma \vdash t :: \tau$

Slide 8

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 $\Gamma \vdash t :: \tau$

Slide 9

Type Checking Rules

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

Application: $$\frac{\Gamma \vdash t_1 :: \tau_2 \Rightarrow \tau_1 \quad \Gamma \vdash t_2 :: \tau_2}{\Gamma \vdash (t_1\ t_2) :: \tau_1}$$

Abstraction: $$\frac{\Gamma[x \leftarrow \tau_1] \vdash t :: \tau_2}{\Gamma \vdash (\lambda x.\ t) :: \tau_1 \Rightarrow \tau_2}$$

Slide 10

Example Type Derivation:

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

Slide 11

More complex Example

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

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

Slide 12

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:

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

Slide 13

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.

Slide 14

What about β reduction?

Definition of β reduction stays the same.

Fact: Well typed terms stay well typed during β reduction

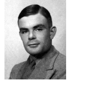
Formally: $\Gamma \vdash s :: \tau \ \wedge\ s \longrightarrow_\beta t \Longrightarrow \Gamma \vdash t :: \tau$

This property is called **subject reduction**

Slide 15

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.

Slide 16

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?)

Slide 17

Types and Terms in Isabelle

Types: $\tau\ ::=\ \mathsf{b}\ \mid\ '\nu\ \mid\ '\nu :: C\ \mid\ \tau \Rightarrow \tau\ \mid\ (\tau, \ldots, \tau)\ K$
$\mathsf{b} \in \{\texttt{bool}, \texttt{int}, \ldots\}$ base types
$\nu \in \{\alpha, \beta, \ldots\}$ type variables
$K \in \{\texttt{set}, \texttt{list}, \ldots\}$ type constructors
$C \in \{\texttt{order}, \texttt{linord}, \ldots\}$ type classes

Terms: $t\ ::=\ v\ \mid\ c\ \mid\ ?v\ \mid\ (t\ t)\ \mid\ (\lambda x.\ t)$
$v, x \in V, \quad c \in C, \quad V, C$ 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: $\alpha :: order$
- ➜ **schematic variables**: variables that can be instantiated.

Slide 18

Type Classes

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

  axclass order < ord
  order_refl: "$x \le x$"
  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

  axclass linorder < order
  linorder_linear: "$x \le y \vee y \le x$"
- ➜ can be instantiated

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

Slide 19

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.

Slide 20

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.

Slide 21

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 from $?f\ t_1\ \ldots\ t_n$
- ➜ and the $t_1\ \ldots\ t_n$ are η-convertible into n distinct bound variables

Slide 22

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

Slide 23

Exercises

- ➜ Construct a type derivation tree for the term $\lambda x\ y\ z.\ z\ x\ (y\ x)$
- ➜ Find a unifier (substitution) such that $\lambda x\ y\ z.\ ?F\ y\ z = \lambda x\ y\ z.\ z\ (?G\ x\ y)$

Slide 24