

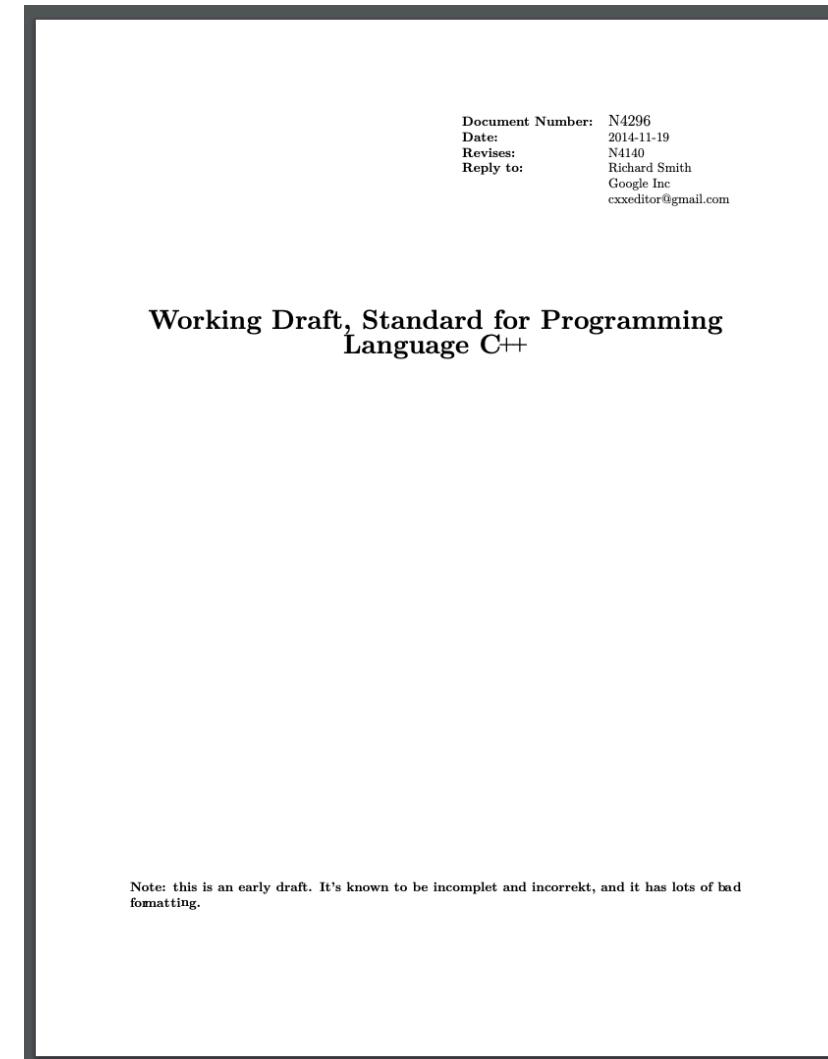
CS 162 Programming languages

Lecture 5: λ -calculus

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Your favorite language?

- Assignment
- Booleans, integers, characters, strings, ...
- Conditionals
- Loops
- Functions
- Recursion
- References / pointers
- Objects and classes
- Inheritance



1368 pages in 2014!

The smallest universal language



Alan Turing



Alonzo Church

The Calculi of Lambda-Conversion, 1936
ENIAC, 1943

The next 700 languages



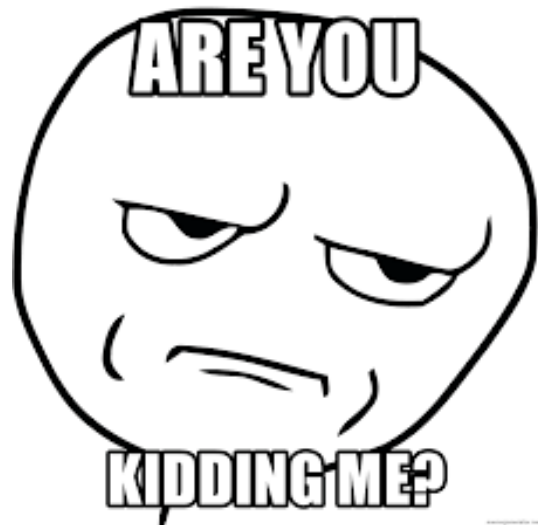
“Whatever the next 700 languages turn out to be, they will surely be variants of lambda calculus.”

Peter Landin 1966

The λ -Calculus

Has one and ONLY one feature

- Functions



- ~~Assignment~~
- ~~Booleans, integers, characters, strings, ...~~
- ~~Conditionals~~
- ~~Loops~~
- Functions
- ~~Recursion~~
- ~~References / pointers~~
- ~~Objects and classes~~
- ~~Inheritance~~

The λ -Calculus

More precisely, the only things you can do are:

Define a function

Call a function



“Free your mind”

Design a programming language

- Syntax: what do programs look like?
 - Grammar: what programs are we allowed to write?
- Semantics: what do programs mean?
 - Operational semantics: how do programs execute step-by-step?

Syntax: what programs look like

$$e ::= x$$
$$| \lambda x. e$$
$$| e_1 e_2$$

$\backslash x \rightarrow e$ (Haskell)

fun $x \rightarrow e$ (OCaml)

lambda $x. e$ ($\lambda+$)

- Programs are expressions e (also called λ -terms) of one of three kinds:
 - Variable x, y, z
 - Abstraction (i.e. nameless function definition)
 - $\lambda x. e$
 - x is the formal parameter, e is the function body
 - Application (i.e. function call)
 - $e_1 e_2$
 - e_1 is the function, e_2 is the argument

Running examples

$\lambda x. x$

The identity function

$\lambda x. (\lambda y. y)$

A function that returns the identity function

$\lambda f. f (\lambda x. x)$

A function that applies its argument to the identity

Semantics: what programs mean

- How do I execute a λ -term?
- “Execute”: rewrite step-by-step following simple rules, until no more rules apply

$e ::= x$
| $\lambda x. e$
| $e_1 e_2$

Similar to simplifying $(x+1) * (2x-2)$
using middle-school algebra

What are the rewrite rules for λ -calculus?

Operational semantics

$$(\lambda x . t_1) t_2 \rightarrow [x \mapsto t_2]t_1$$

β -reduction
(function call)

$[x \mapsto t_2]t_1$ means “ t_1 with all **free occurrences** of x replaced with t_2 ”

```
incl(int x) {  
    return x+1  
}
```

$$(\lambda x . x + 1) 2 \rightarrow [x \mapsto 2]x + 1 = 3$$

```
incl(2);
```

$$[x \mapsto y]\lambda x . x = \lambda x . y \quad \times$$

What does free occurrences mean?

Semantics: variable scope

The part of a program where a variable is visible

In the expression $\lambda x. e$

- x is the newly introduced variable
- e is the scope of x
- any occurrence of x in $\lambda x. e$ is bound (by the binder λx)

$\lambda x. x$

$\lambda x. (\lambda y. x)$

x is bounded

$x y$

$\lambda y. x y$

$(\lambda x. \lambda y. y) x$

x is free

An occurrence of x in e is **free** if it's *not bound* by an enclosing abstraction

Semantics: free variables

An variable x is free in e if there exists a free occurrence of x in e

We use “FV” to represent the set of all free variables in a term:

$$FV(x) = x$$

$$FV(\lambda x. e) = FV(e) \setminus x$$

$$FV(e_1 e_2) = FV(e_1) \cup FV(e_2)$$

$$FV(x y) = \{x, y\}$$

$$FV(\lambda y. x y) = \{x\}$$

$$FV((\lambda x. \lambda y. y) x) = \{x\}$$

If e has no free variables it is said to be closed, or combinators

Semantics: β -reduction

$$(\lambda x . t_1) t_2 \rightarrow [x \mapsto t_2]t_1$$

β -reduction
(function call)

$[x \mapsto t_2]t_1$ means “ t_1 with all **free occurrences** of x replaced with t_2 ”

$$[x \mapsto s]x = s$$

$$[x \mapsto s]y = y (x \neq y)$$

$$[x \mapsto s]\lambda y . t_1 = \lambda y . [x \mapsto s]t_1 (y \neq x \wedge y \notin FV(s))$$

$$[x \mapsto s]t_1 t_2 = [x \mapsto s]t_1 [x \mapsto s]t_2$$

Semantics: α -renaming

$$\lambda x . e =_{\alpha} \lambda y . [x \mapsto y]e$$

- Rename a formal parameter and replace all its occurrences in the body

$$\lambda x . x =_{\alpha} \lambda y . y =_{\alpha} \lambda z . z$$

$$[x \mapsto y]\lambda x . x = \lambda x . y \quad \text{✗}$$

$$[x \mapsto y]\lambda x . x =_{\alpha} [x \mapsto y]\lambda z . z = \lambda z . z \quad \text{✓}$$

Currying: multiple arguments

$$\lambda(x, y) . e = \lambda x . \lambda y . e$$

$$(\lambda(x, y) . x + y) \ 2 \ 3 =$$

$$(\lambda x . \lambda y . x + y) \ 2 \ 3 = (\lambda y . 2 + y) \ 3 = [y \mapsto 3]2 + y = 5$$

Transformation of multi-arguments functions to higher-order functions is called currying (in the honor of Haskell Curry)



TODOs by next lecture

- Join Slack for CS162!
- Install OCaml/ λ^+ on your laptop
- Finish Quiz 1 by the end of this Friday