CMSC 631 – Program Analysis and Understanding

Lambda Calculus

Motivation

- Commonly-used programming languages are large are complex
  - ANSI C99 standard: 538 pages
  - ANSI C++ standard: 714 pages
  - Java language specification 2.0: 505 pages

- Not good vehicles for understanding language features or explaining program analysis

Goal

- Develop a "core language" that has
  - The essential features
  - No overlapping constructs
  - And none of the cruft
    - Extra features of full language can be defined in terms of the core language ("syntactic sugar")
- Lambda calculus
  - Standard core language for single-threaded procedural programming
  - Often with added features (e.g., state); we'll see that later

Lambda Calculus is Practical!

- An 8-bit microcontroller (Zilog Z8 encore board w/4KB SRAM) computing 1 + 1 using Church numerals in the Lambda calculus

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Origins of Lambda Calculus

- Invented in 1936 by Alonzo Church (1903-1995)
  - Princeton Mathematician
  - Lectures of lambda calculus published in 1941
  - Also know for
    - Church's Thesis
      - All effective computation is expressed by recursive (decidable) functions, i.e., in the lambda calculus
    - Church's Theorem
      - First order logic is undecidable

Lambda Calculus

- Syntax:

e ::= x	variable
| λx.e	function abstraction
| e e	function application

- Only constructs in pure lambda calculus
  - Functions take functions as arguments and return functions as results
  - I.e., the lambda calculus supports *higher-order functions*

Semantics

- To evaluate (λx.e1) e2
  - Bind x to e2
  - Evaluate e1
  - Return the result of the evaluation

- This is called "beta-reduction"
  - $(\lambda x.e1)\ e2 \rightarrow_{\beta} e1[e2\backslash x]$
  - (λx.e1) e2 is called a *redex*
  - We'll usually omit the beta

Three Conveniences

- Syntactic sugar for local declarations
  - let x = e1 in e2 is short for (λx.e2) e1
- Scope of λ extends as far to the right as possible
  - λx.λy.x y is λx.(λy.(x y))
- Function application is left-associative
  - x y z is (x y) z

Scoping and Parameter Passing

- Beta-reduction is not yet precise
  - (λx.e1) e2 → e1[e2\x]
  - what if there are multiple x's?
- Example:
  - let x = a in
  -   let y = λz.x in
  -   let x = b in y x
  - which x's are bound to a, and which to b?

Static (Lexical) Scope

- Just like most languages, a variable refers to the closest definition

- Make this precise using variable renaming
  - The term
    - let x = a in let y = λz.x in let x = b in y x
  - is "the same" as
    - let x = a in let y = λz.x in let w = b in y w
  - Variable names don't matter

Free Variables and Alpha Conversion

- The set of *free variables* of a term is

  $FV(x) = \{x\}$
  $FV(\lambda x.e) = FV(e) - \{x\}$
  $FV(e1\ e2) = FV(e1) \cup FV(e2)$

- A term e is *closed* if $FV(e) = \emptyset$

- A variable that is not free is *bound*

Alpha Conversion

- Terms are equivalent up to renaming of bound variables
  - $\lambda x.e = \lambda y.(e[y\backslash x])$ if $y \notin FV(e)$

- This is often called *alpha conversion*, and we will use it implicitly whenever we need to avoid capturing variables when we perform substitution

Substitution

- Formal definition:
  - $x[e\backslash x] = e$
  - $z[e\backslash x] = z$ if $z \neq x$
  - $(e1\ e2)[e\backslash x] = (e1[e\backslash x]\ e2[e\backslash x])$
  - $(\lambda z.e1)[e\backslash x] = \lambda z.(e1[e\backslash x])$ if $z \neq x$ and $z \notin FV(e)$

- Example:
  - $(\lambda x.y\ x)\ x =_{\alpha} (\lambda w.y\ w)\ x \rightarrow_{\beta} y\ x$
  - (We won't write alpha conversion down in the future)

A Note on Substitutions

- People write substitution many different ways
  - e1[e2\x]
  - e1[x↦e2]
  - [x/e2]e1
  - and more...

- But they all mean the same thing

Multi-Argument Functions

- We can't (yet) write multi-argument functions
  - E.g., a function of two arguments $\lambda(x, y).e$
- Trick: Take arguments one at a time
  - $\lambda x.\lambda y.e$
  - This is a function that, given argument x, returns a function that, given argument y, returns e
  - $(\lambda x.\lambda y.e)\ a\ b \rightarrow (\lambda y.e[a\backslash x])\ b \rightarrow e[a\backslash x][b\backslash y]$
- This is often called *Currying* and can be used to represent functions with any # of arguments

Booleans

- true = $\lambda x.\lambda y.x$
- false = $\lambda x.\lambda y.y$
- if a then b else c = a b c

- Example:
  - if true then b else c $\rightarrow$ $(\lambda x.\lambda y.x)$ b c $\rightarrow$ $(\lambda y.b)$ c $\rightarrow$ b
  - if false then b else c $\rightarrow$ $(\lambda x.\lambda y.y)$ b c $\rightarrow$ $(\lambda y.y)$ c $\rightarrow$ c

Combinators

- Any closed term is also called a *combinator*
  - So true and false are both combinators

- Other popular combinators
  - $I = \lambda x.x$
  - $S = \lambda x.\lambda y.x$
  - $K = \lambda x.\lambda y.\lambda z.x\ z\ (y\ z)$
  - Can also define calculi in terms of combinators
    - E.g., the SKI calculus
    - Turns out the SKI calculus is also Turing complete

Pairs

- $(a, b) = \lambda x.\text{if } x \text{ then } a \text{ else } b$
- $\text{fst} = \lambda p.p \text{ true}$
- $\text{snd} = \lambda p.p \text{ false}$

- Then
  - $\text{fst } (a, b) \to^* a$
  - $\text{snd } (a, b) \to^* b$

Natural Numbers (Church)

- 0 = λx.λy.y
- 1 = λx.λy.x y
- 2 = λx.λy.x(x y)
- i.e., n = λx.λy.<apply x n times to y>

- succ = λz.λx.λy.x(z x y)
- iszero = λz.z (λy.false) true

Natural Numbers (Scott)

- $0 = \lambda x.\lambda y.x$
- $1 = \lambda x.\lambda y.y\ 0$
- $2 = \lambda x.\lambda y.y\ 1$
- I.e., $n = \lambda x.\lambda y.y\ (n\text{-}1)$

- $\text{succ} = \lambda z.\lambda x.\lambda y.y\ z$
- $\text{pred} = \lambda z.z\ 0\ (\lambda x.x)$
- $\text{iszero} = \lambda z.z\ \text{true}\ (\lambda x.\text{false})$

A Nonderministic Semantics

$$\frac{}{(\lambda x.e1)\ e2 \rightarrow e1[e2\backslash x]}$$

$$\frac{e \rightarrow e'}{(\lambda x.e) \rightarrow (\lambda x.e')}$$

$$\frac{e1 \rightarrow e1'}{e1\ e2 \rightarrow e1'\ e2}$$

$$\frac{e2 \rightarrow e2'}{e1\ e2 \rightarrow e1\ e2'}$$

- Why are these semantics non-deterministic?

Example

- We can apply reduction anywhere in a term
  - (λx.(λy.y) x ((λz.w) x) → λx.(x ((λz.w) x) → λx.x w
  - (λx.(λy.y) x ((λz.w) x) → λx.(λy.y x (w)) → λx.x w

- Does the order of evaluation matter?

The Church-Rosser Theorem

- If a $\rightarrow^*$ b and a $\rightarrow^*$ c, there there exists d such that b $\rightarrow^*$ d and c $\rightarrow^*$ d
  - Proof: http://www.mscs.dal.ca/~selinger/papers/lambdanotes.pdf

- Church-Rosser is also called confluence

Normal Form

- A term is in *normal form* if it cannot be reduced
  - Examples: λx.x, λx.λy.z
- By Church-Rosser Theorem, every term reduces to at most one normal form
  - Warning: All of this applies only to the pure lambda calculus with non-deterministic evaluation
- Notice that for our application rule, the argument need not be in normal form

Beta-Equivalence

- Let $=_\beta$ be the reflexive, *symmetric*, and transitive closure of $\rightarrow$
  - E.g., $(\lambda x.x)\ y \rightarrow y \leftarrow (\lambda z.\lambda w.z)\ y\ y$, so all three are beta equivalent

- If $a =_\beta b$, then there exists c such that $a \rightarrow^* c$ and $b \rightarrow^* c$
  - Proof: Consequence of Church-Rosser Theorem

- In particular, if $a =_\beta b$ and both are normal forms, then they are equal

Not Every Term Has a Normal Form

- Consider
  - $\Delta = \lambda x.x\ x$
  - Then $\Delta\ \Delta \to \Delta\ \Delta \to \cdots$

- In general, *self application* leads to loops
  - ...which is good if we want recursion

A Fixpoint Combinator

- Also called a paradoxical combinator
  - $Y = \lambda f.(\lambda x.f\ (x\ x))\ (\lambda x.f\ (x\ x))$
  - Note: There are many versions of this combinator

- Then $Y\ F =_\beta F\ (Y\ F)$
  - $Y\ F = (\lambda f.(\lambda x.f\ (x\ x))\ (\lambda x.f\ (x\ x)))\ F$
  - $\rightarrow (\lambda x.F\ (x\ x))\ (\lambda x.F\ (x\ x))$
  - $\rightarrow F\ ((\lambda x.F\ (x\ x))\ (\lambda x.F\ (x\ x)))$
  - $\leftarrow F\ (Y\ F)$

Example

- Fact n = if n = 0 then 1 else n * fact(n-1)
- Let G = λf.<body of factorial>
  - I.e., G = λf. λn.if n = 0 then 1 else n*f(n-1)
- Y G 1 $=_\beta$ G (YG) 1
  - $=_\beta$ (λf.λn.if n = 0 then 1 else n*f(n-1)) (Y G) 1
  - $=_\beta$ if 1 = 0 then 1 else 1*((Y G) 0)
  - $=_\beta$ if 1 = 0 then 1 else 1*(G (Y G) 0)
  - $=_\beta$ if 1 = 0 then 1 else 1*(λf.λn.if n = 0 then 1 else n*f(n-1) (Y G) 0)
  - $=_\beta$ if 1 = 0 then 1 else 1*(if 0 = 0 then 1 else 0*((Y G) 0)
  - $=_\beta$ 1*1 = 1

In Other Words

- The Y combinator "unrolls" or "unfolds" its argument an infinite number of times
  - Y G = G (Y G) = G (G (Y G) = G (G (G (Y G))) = ...
  - G needs to have a "base case" to ensure termination

- But, only works because we're call-by-name
  - Different combinator(s) for call-by-value
    - $Z = \lambda f.(\lambda x.f\ (\lambda y.\ x\ x\ y))\ (\lambda x.f\ (\lambda y.\ x\ x\ y))$
    - Why is this a fixed-point combinator? How does its difference from Y make it work for call-by-value?

Encodings

- Encodings are fun
- They show language expressiveness

- In practice, we usually add constructs as primitives
  - Much more efficient
  - Much easier to perform program analysis on and avoid silly mistakes with
    - E.g., our encodings of true and 0 are exactly the same, but we may want to forbid mixing booleans and integers

Lazy vs. Eager Evaluation

- Our non-deterministic reduction rule is fine for theory, but awkward to implement

- Two deterministic strategies:
  - *Lazy:* Given (λx.e1) e2, do not evaluate e2 if x does not "need" e1
    - Also called left-most, call-by-name, call-by-need, applicative, normal-order (with slightly different meanings)
  - *Eager:* Given (λx.e1) e2, always evaluate e2 fully before applying the function
    - Also called call-by-value

Lazy Operational Semantics

$$\frac{}{(\lambda x.e1) \rightarrow^{l} (\lambda x.e1)}$$

$$\frac{e1 \rightarrow^{l} \lambda x.e \quad e[e2\backslash x] \rightarrow^{l} e'}{e1\ e2 \rightarrow^{l} e'}$$

- The rules are deterministic and *big-step*
  - The right-hand side is reduced "all the way"
- The rules do not reduce under λ
- The rules are normalizing:
  - If a is closed and there is a normal form b such that $a \rightarrow^{*} b$, then $a \rightarrow^{l} b$

Eager (Big-Step) Op. Semantics

$$\frac{}{(\lambda x.e1) \rightarrow^{e} (\lambda x.e1)}$$

$$\frac{e1 \rightarrow^{e} \lambda x.e \quad e2 \rightarrow^{e} e' \quad e[e'\backslash x] \rightarrow^{e} e''}{e1\ e2 \rightarrow^{e} e''}$$

- This big-step semantics is also deterministic and and does not reduce under λ
- But it is not normalizing
  - Example: let x = Δ Δ in (λy.y)

Lazy vs. Eager in Practice

- Lazy evaluation (call by name, call by need)
  - Has some nice theoretical properties
  - Terminates more often
  - Lets you play some tricks with “infinite” objects
  - Main example: Haskell

- Eager evaluation (call by value)
  - Is generally easier to implement efficiently
  - Blends more easily with side effects
  - Main examples: Most languages (C, Java, ML, etc.)

Functional Programming

- The λ calculus is a prototypical functional programming language:
  - Lots of higher-order functions
  - No side-effects

- In practice, many functional programming languages are "impure" and permit side-effects
  - But you're supposed to avoid using them

Functional Programming Today

- Two main camps:
  - Haskell – Pure, lazy functional language; no side effects
  - ML (SML/NJ, OCaml) – Call-by-value, with side effects

- Still around: LISP, Scheme
  - Disadvantage/advantage: No static type systems
  - (RIP John McCarthy, died 24 Oct 2011, inventor of LISP.)

Influence of Functional Programming

- Functional ideas in many other languages
  - Garbage collection was first designed with Lisp; most languages often rely on a GC today
  - Generics in Java/C++ came from polymorphism in ML and from type classes in Haskell
  - Higher-order functions and closures (used widely in Ruby; proposed extension to Java) are pervasive in all functional languages
  - Many data abstraction principles of OO came from ML's module system
  - …

Call-by-Name Example

OCaml

```
let cond p x y = if p then x else y
let rec loop () = loop ()
let z = cond true 42 (loop ())
```

infinite loop at call

Haskell

```
cond p x y = if p then x else y
loop () = loop ()
z = cond True 42 (loop ())
```

3rd argument never used by cond, so never invoked

Two Cool Things to Do with CBN

- Build control structures with functions

```
cond p x y = if p then x else y
```

- “Infinite” data structures

```
integers n = n:(integers (n+1))
take 10 (integers 0)  (* infinite loop in cbv *)
```