CIS 624: Structure of Programming Languages
Lecture 7 — Lambda Calculus

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Data + Code
Higher-order functions work well for scope and data structures
- Scope: not all memory available to all code
  let x = 1
  let add3 y =
  let z = 2 in
  x + y + z
  let seven = add3 4
- Data: Function closures store data. Example: Association "list"
  let empty = (fun k -> raise Empty)
  let cons k v lst = (fun k' ->
    if k'=k then v else lst k')
  let lookup k lst = lst k
(Later: Objects do both too)

Adding data structures
Extending IMP with data structures is not too hard:
- Data structures:
  e ::= c|x|e+ e|e*e|(e,e) |e.1 |e.2
  v ::= ...
- Functions:
  e ::= ... | fun x -> s
  v ::= ... | fun x -> ...
- Relations:
  H ::= · | H; x ⇒ v

What about functions
But adding functions (or objects) does not work well:
- Functions:
  e ::= ... | fun x -> s
  v ::= ... | fun x -> s
  s ::= ... | e(e)

H; e ⇓ v
H; s ⇒ H'; s'

Additions:

H; e1 ⇓ fun x -> s
H; e2 ⇓ v
H; fun x -> s ⇓ fun x -> s
H; e1(e2) ⇒ H; x := v; s

Does this match "the semantics we want" for function calls?

Where we are
- Done: Syntax, semantics, and equivalence
- For a language with little more than loops and global variables
- Now: Didn’t IMP leave some things out?
  - In particular: scope, functions, and data structures
  - (Not to mention threads, I/O, exceptions, strings, …)

Time for a new model…

Notice:
- We allow pairs of values, not just pairs of integers
- We now have stuck programs (e.g., c.1)
  - Division also causes stuckness

What about functions
But adding functions (or objects) does not work well:
- Functions:
  e ::= ... | fun x -> s
  v ::= ... | fun x -> s
  s ::= ... | e(e)

H; e1 ⇓ fun x -> s
H; e2 ⇓ v
H; fun x -> s ⇓ fun x -> s
H; e1(e2) ⇒ H; x := v; s

NO: Consider x := 1; (fun x -> y := x)(2); ans := x.

Scope matters; variable name does not. That is:
- Local variables should "be local"
- Choice of local-variable names should have only local ramifications
Another try

\[
\begin{align*}
H; e_1 & \downarrow \text{fun } x \to s & H; e_2 & \downarrow v & y \text{ “fresh”} \\
\quad & H; e_1(e_2) & \rightarrow & H; y := x; x := v; s; x := y
\end{align*}
\]

- “fresh” is not very IMP-like but okay (think malloc)
- not a good match to how functions are implemented
- yuck: the way we want to think about something as fundamental as a call?
- NO: wrong model for most functional and OO languages
  - (Even wrong for C if \( s \) calls another function that accesses the global variable \( x \))

Punch line

Cannot properly model local scope via a global heap of integers.
- Functions are not syntactic sugar for assignments to globals
  - So let’s build a new model that focuses on this essential concept
    - (can add back IMP features later)
  - Or just borrow a model from Alonzo Church
  - And drop mutation, conditionals, integers (!), and loops (!)

Why Lambda Calculus?

The benefit of lambda calculus is that it’s an extremely simple model of computation that is equivalent to a Turing machine. But while a Turing machine is more like assembly language, lambda calculus is more a like a high-level language. And if you learn Church encodings that will help you learn the programming technique called continuation-passing style, which is quite useful for implementing backtracking search and other neat tricks.

The main use of lambda calculus in practice is that it is a great laboratory tool for studying new programming-language ideas. If you have an idea for a new language feature, you can add the new feature to the lambda calculus and you get something that is expressive enough to program while being simple enough to study very thoroughly. This use is really more for language designers and theoreticians than for programmers.

Lambda calculus is also just very cool in its own right: just like knowing assembly language, it will deepen your understanding of computation. It’s especially fun to program a universal living machine in the lambda calculus. But this is foundational mathematics, not practical programming.

Why Lambda Calculus?

The wrong model

\[
\begin{align*}
H; e_1 & \downarrow \text{fun } x \to s & H; e_2 & \downarrow v & y \text{ “fresh”} \\
\quad & H; e_1(e_2) & \rightarrow & H; y := x; x := v; s; x := y
\end{align*}
\]

\[
\begin{align*}
& f_1 := (\text{fun } x \to f_2 := (\text{fun } z \to \text{ans := } x + z)); \\
& f_1(2); \\
& x := 3; \\
& f_2(4)
\end{align*}
\]

“Should” set \( \text{ans} \) to 6:
- \( f_1(2) \) should assign to \( f_2 \) a function that adds 2 to its argument and stores result in \( \text{ans} \)

“Actually” sets \( \text{ans} \) to 7:
- \( f_2(2) \) assigns to \( f_2 \) a function that adds the current value of \( x \) to its argument

The Lambda Calculus

The Lambda Calculus:

\[
\begin{align*}
e & ::= \lambda x. e \mid x \mid ee \\
v & ::= \lambda x. e
\end{align*}
\]

You apply a function by substituting the argument for the bound variable
- (There is an equivalent environment definition not unlike heap-copying; see future homework)

Example Substitutions

\[
\begin{align*}
e & ::= \lambda x. e \mid x \mid ee \\
v & ::= \lambda x. e
\end{align*}
\]

Substitution is the key operation we were missing:

\[
\begin{align*}
(\lambda x. x)(\lambda y. y) & \to (\lambda y. y) \\
(\lambda x. \lambda y. y x)(\lambda z. z) & \to (\lambda y. y \lambda z. z) \\
(\lambda x. x x)(\lambda x. x x) & \to (\lambda x. x x)(\lambda x. x x)
\end{align*}
\]

After substitution, the bound variable is gone, so its “name” was irrelevant. (Good!)
A Programming Language

Given substitution \( (e_1[e_2/x] = e_3) \), we can give a semantics:

\[
\begin{align*}
\text{e} & \rightarrow \text{e}' \\
\text{e}[v/x] & = \text{e}' \\
(\lambda x. \text{e}) v & \rightarrow \text{e}'
\end{align*}
\]

A small-step, call-by-value (CBV), left-to-right semantics

- Terminates when the “whole program” is some \( \lambda x. \text{e} \)

But (also) gets stuck when there’s a free variable “at top-level”

- Won’t “cheat” like we did with \( H(x) \) in IMP because scope is what we are interested in

This is the “heart” of functional languages like OCaml

- But “real” implementations do not substitute; they do something equivalent

Roadmap

- Motivation for a new model (done)
- CBV lambda calculus using substitution (done)
- Notes on concrete syntax
- Simple Lambda encodings (it is Turing complete!)
- Other reduction strategies
- Defining substitution

Concrete-Syntax Notes

We (and OCaml) resolve concrete-syntax ambiguities as follows:

1. \( \lambda x. \text{e}_1 \text{e}_2 \) is \((\lambda x. \text{e}_1) \text{e}_2\), not \((\lambda x. \text{e}_1) \text{e}_2\)
2. \( \text{e}_1 \text{e}_2 \text{e}_3 \) is \((\text{e}_1 \text{e}_2) \text{e}_3\), not \(\text{e}_1 (\text{e}_2 \text{e}_3)\)

- Convince yourself application is not associative

More generally:

1. Function bodies extend to an unmatched right parenthesis
   Example: \((\lambda x. y)(\lambda z. z)vq\)
2. Application associates to the left
   Example: \(\text{e}_1 \text{e}_2 \text{e}_3 \text{e}_4\) is \(((\text{e}_1 \text{e}_2) \text{e}_3) \text{e}_4\)

- Like in IMP, assume we really have ASTs (with non-leaves labeled \( \lambda \) or “application”)
- Rules may seem strange at first, but it is the most convenient concrete syntax
  - Based on 70 years experience

Lambda Encodings

Fairly crazy: we left out constants, conditionals, primitives, and data structures

In fact, we are Turing complete and can encode whatever we need (just like assembly language can)

Motivation for encodings:

- Fun and mind-expanding
- Shows we are not oversimplifying the model (“numbers are syntactic sugar”)
- Can show languages are too expressive (e.g., unlimited C++ template instantiation)

Encodings are also just “(re)definition via translation”

Encoding booleans

The “Boolean ADT”

- There are two booleans and one conditional expression.
  - The conditional takes 3 arguments (e.g., via currying). If the first is one boolean it evaluates to the second. If it is the other boolean it evaluates to the third.

Any set of three expressions meeting this specification is a proper encoding of booleans

Here is one of an infinite number of encodings:

- “true” \( \lambda x. \lambda y. x \)
- “false” \( \lambda x. \lambda y. y \)
- “if” \( \lambda b. \lambda t. \lambda f. b \ t \ f \)

Example: “if” “true” \( v_1 \) \( v_2 \rightarrow^* v_1 \)

Evaluation Order Matters

Careful: With CBV we need to “thunk”…

\[
\text{“if” “true” } (\lambda x. x) ((\lambda x. x)(\lambda x. x)) \rightarrow \text{an infinite loop}
\]
diverges, but

\[
\text{“if” “true” } (\lambda x. x) ((\lambda x. x)((\lambda x. x)(\lambda x. x)) z) \rightarrow \text{a value that when called diverges}
\]
does not
Encoding Pairs

The "pair ADT":
- There is 1 constructor (taking 2 arguments) and 2 selectors
- 1st selector returns the 1st arg passed to the constructor
- 2nd selector returns the 2nd arg passed to the constructor

"mkpair" $\lambda z. \lambda y. \lambda z. z \times y$
"fst" $\lambda p. p(\lambda x. \lambda y. x)$
"snd" $\lambda p. p(\lambda x. \lambda y. y)$

Example:
"snd" ("fst" ("mkpair" ("mkpair" v1 v2) v3)) $\rightarrow^* v2$

Reusing Lambdas

Is it weird that the encodings of Booleans and pairs both used $\lambda x. \lambda y. x$ and $\lambda x. \lambda y. y$ for different purposes?

Is it weird that the same bit-pattern in binary code can represent an int, a float, an instruction, or a pointer?

Von Neumann: Bits can represent (all) code and data

Church (?): Lambdas can represent (all) code and data

Beware the "Turing tarpit"

Encoding Lists

Rather than start from scratch, notice that booleans and pairs are enough to encode lists.
- "emptylst" = "mkpair" "false" "false" (each node represented by a pair whose first element is head of the list, and second element is the tail; "false" as the first element of a pair designates the empty list)
- "nonemptylst" = $\lambda h. \lambda t. \text{"mkpair" } \text{"true" } \text{("mkpair" } h \ t)$
- "isempty" = "fst" = $\lambda p. p(\lambda x. \lambda y. x)$
- "head" = $\lambda z. \text{"fst" } (\text{"snd" } z) =$ $\lambda z. \lambda p. p(\lambda x. \lambda y. y)(\lambda p. p(\lambda x. \lambda y. y)z)$
- "tail" = $\lambda z. \text{"snd" } (\text{"snd" } z) =$ $\lambda z. \lambda p. p(\lambda x. \lambda y. y)(\lambda p. p(\lambda x. \lambda y. y)z)$

Note:
- Not too far from how lists are implemented
- Taking "tail" ("tail" "empty") will produce some lambda
- Just like, without page-protection hardware, null->tail->tail would produce some bit-pattern

The Y-combinator

\[
\lambda f. (\lambda x. (f (x x))) (\lambda x. f (x x))
\]

Y-combinator
"fix" $\lambda f. (\lambda x. f (\lambda y. x x y)) (\lambda x. f (\lambda y. x x y))$

A bit more on combinators

- Recall definition of combinator: a function or definition with no free variables
- A combinator is a function which builds program fragments from program fragments.
- You have written and used combinators: e.g., map, fold...
- Can be defined/used in many languages:
  http://rosettacode.org/wiki/Y_combinator

Example: Apply the Y-combinator
$\lambda f. (\lambda x. f (\lambda y. x x y)) (\lambda x. f (\lambda y. x x y))$ to a function $g$

\[
Y g = \lambda f. (\lambda x. f (\lambda y. x x y)) (\lambda x. f (\lambda y. x x y)) g = (\lambda x. g (\lambda y. x x y)) (\lambda x. g (\lambda y. x x y)) = g ((\lambda x. g (\lambda y. x x y)) (\lambda x. g (\lambda y. x x y))) = g (Y g)
\]
Encoding Arithmetic Over Natural Numbers

How about arithmetic?
- Focus on non-negative numbers, addition, is-zero, etc.

How I would do it based on what we have so far:
- Lists of booleans for binary numbers
  - Zero can be the empty list
  - Use fix to implement adders, etc.
  - Like in hardware except fixed-width avoids recursion
  - Or just use list length for a unary encoding

But instead everybody always teaches Church numerals. Why?
- Tradition? Some sense of professional obligation?
- Better reason: You do not need fix: Basic arithmetic is often encodable in languages where all programs terminate
In any case, we will show some basics “just for fun”

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Church Numerals

“0” \( \lambda s. \lambda z. z \)
“1” \( \lambda s. \lambda z. s z \)
“2” \( \lambda s. \lambda z. s (s z) \)
“3” \( \lambda s. \lambda z. s (s (s z)) \)

“successor” \( \lambda n. \lambda s. \lambda z. s (n s z) \)
“plus” \( \lambda n. \lambda m. \lambda s. \lambda z. n s (m s z) \)
“times” \( \lambda n. \lambda m. \lambda s. \lambda z. n (m z) \)

Times: take two “numbers” \( m \) and \( n \) and pass to \( m \) a function that adds \( n \) to its argument (so this will happen \( m \) times) and “zero” (where to start the \( m \) iterations of addition)

“successor” \( \lambda n. \lambda s. \lambda z. s (n s z) \)
“plus” \( \lambda n. \lambda m. \lambda s. \lambda z. n s (m s z) \)
“times” \( \lambda n. \lambda m. \lambda s. \lambda z. n (m s z) \)
“isZero” \( \lambda n. (\lambda x. \text{false}) (\lambda x. \text{true}) \)

IsZero: an easy one, see how the two arguments will lead to the correct answer
**Church Numerals**

"0"  \( \lambda s. \lambda z. z \)

"1"  \( \lambda s. \lambda z. sz \)

"2"  \( \lambda s. \lambda z. s(sz) \)

"3"  \( \lambda s. \lambda z. s(s(sz)) \)

"successor"  \( \lambda n. \lambda s. \lambda z. s(ns z) \)

"plus"  \( \lambda n. \lambda m. \lambda s. \lambda z. ns (ms z) \)

"times"  \( \lambda n. \lambda m. m("plus" n) "zero" \)

"isZero"  \( \lambda n. n (\lambda x. "false") "true" \)

"predecessor"  (with 0 sticky) the hard one; see Wikipedia

"isEqual"  similar to times with pred instead of plus

"subtract and test for zero"

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**Roadmap**

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Then start type systems

- Later take a break from types to consider first-class continuations and related topics

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**Can you compute 2 + 2?**

Did you think you would be asked this in graduate school?

From

http://www.reddit.com/r/math/comments/2k29z9/just_for_fun_whats_the_most_complicated_way_to/

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```
plus 2 2 = \n. \m. \n. \m. \n. \m. \n. \m. \n (\plus n) "zero"
```

---

```
= 4.
```