Continuations

CS242

Lecture 8

Today's Variant of Lambda Calculus …

$e \rightarrow x \mid \lambda x.e \mid e\ e \mid i \mid e + e$

Start Simple

- How do we evaluate e + e' ?

- First evaluate e to a value x
- Second evaluate e' to a value y
- Third compute x + y

- Note that this description fixes an order of evaluation
  - Could evaluate e' and then e instead

Explicit Order of Evaluation

We can rewrite the expression to make the order of evaluation explicit:

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

Going one step further:

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

Explicit Order of Evaluation

We can rewrite $e + e'$ to make the order of evaluation explicit:

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

Going one step further:

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

And one more step:

$(\lambda x.((\lambda y.\ (\lambda z.z)\ (x + y))\ e'))\ \ e$

A More Readable Version

Recall

(λx.e) e' = let x = e' in e

Then (λx.((λy. (λz.z) (x + y)) e')) e

Can be rewritten as

```
let x = e in
   let y = e' in
      let z = x + y in
         z
```

Comments

```
let x = e in
  let y = e' in
    let z = x + y in
      z
```

Can be read as a sequential program

```
x = e
y = e'
z = x + y
```

Comments

```
let x = e in
  let y = e' in
    let z = x + y in
      z
```

Note:

- The order of evaluation is explicit
- Every intermediate result has a name

Back to the First Step

Recall the first step of the transformation:

(λx.x + e’) e

Which is equivalent to

let x = e in x + e’

Continuations

let $x = e_1$ in e_2

We can view this as splitting the program into two sequentially ordered parts:

- The computation of $x = e_1$
- The *continuation* e_2 which represents the computation of the rest of the program

What is a Continuation?

Recall $\text{let } x = e_1 \text{ in } e_2 \;\Leftrightarrow\; (\lambda x.e_2)\; e_1$

A continuation is a function that takes a value as an argument and evaluates the “rest of the program”.

Continuation Passing Style

- Rewrite the program using continuations

- Each continuation
  - Performs just one primitive step of the computation
  - And then passes the result to another continuation

Back to the Example

Recall we translated $e + e'$ to

$(\lambda x.((\lambda y.\ (\lambda z.z)\ (x + y))\ e'))\ \ e$

$k_0 = \ \lambda w.\ k_1\ e$

$k_1 = \lambda x.\ k_2\ e'$

$k_2\ = \lambda y.\ k_3\ (x + y)$

$k_3\ = \lambda z.z$

Back to the Example

Recall we translated $e + e'$ to

$(\lambda x.((\lambda y.\ (\lambda z.z)\ (x + y))\ e'))\ \ e$

$k_0 = \lambda w.\ k_1\ e$

$k_1 = \lambda x.\ k_2\ e'$

$k_2 = \lambda y.\ k_3\ (x + y)$

$k_3 = \lambda z.z$

k_0: let x = e in

k_1: let y = e' in

k_2: let z = x + y in

k_3: z

Continuations

- Continuations are like statement labels in C
  - Syntactically, names a point in the program
  - Semantically, names the computation that executes by jumping to that point

- By systematically using continuations, we
  - Make the order of evaluation explicit
  - Give a name to every intermediate value
  - *Name every step (continuation) of the computation*

Continuation Passing Style Transformation

Define C(e,k) to be the translation of e with continuation k into continuation passing style

So semantically, C(e,k) = k e

i.e., evaluate e and pass the value to k to run the rest of the program.
But of course we want to convert e into CPS style, too …

CPS Transformation: Constants and Variables

Easy cases first!

C(i,k) = k i

C(x,k) = k x

For an integer or variable there is no further translation to do, just pass the value directly to the continuation.

CPS Transformation: Addition

$C(e + e', k) = C(e, \lambda v.C(e', \lambda v'.k\ (v + v')))$

Note: The variables v and v' must be fresh.

CPS Transformation: Abstraction

$C(\lambda x.e, k) = ?$

Here k is the continuation of the function definition.

We also want to translate the body e of the function. What is the continuation of the function body?

Problem: The function is called at a different time than it is defined, so the continuation for the body is different from the continuation for the function itself.

CPS Transformation: Abstraction

$C(\lambda x.e, k) = k\ (\lambda k'.\lambda x.\ C(e,k'))$

Idea: Simply define the translation of the function to first take a continuation k' and then take the function argument.

The continuation when the function is applied is k', which we use in the translation of the function body.

Notice how the two continuations k and k' capture the two relevant points in a function's life: When it is defined and when it is applied.

CPS Transformation: Application

C(e e',k) = C(e, λf.C(e', λv.f k v))

The translation is fully determined by two things:

We evaluate e and then e'. Note the structural similarity to addition, the other construct with two subexpressions.

The expression e evaluates to a CPS-transformed function f, requiring a continuation k and a value v as arguments.

Continuation Passing Style Transformation

$C(x,k) = k\ x$

$C(\lambda x.e,\ k) = k\ (\lambda k'.\lambda x.\ C(e,k'))$

$C(e\ e',k) = C(e,\ \lambda f.C(e',\ \lambda v.f\ k\ v))$

$C(i,k) = k\ i$

$C(e + e',k) = C(e,\ \lambda v.C(e',\ \lambda v'.k\ (v + v'))$

Reminder

When reading lambda expressions, the scope of an abstraction $\lambda x.e$ extends as far to the right as possible

- All the way to the end of the expression
- Or until blocked by a right parenthesis

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

is very different from

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

AnExample

$C((\lambda x.x + 1)\ 2,\ k_0) =$

$C(\lambda x.x + 1,\ \lambda f.C(2,\ \lambda v_0.f\ k_0\ v_0)) =$

$C(\lambda x.x + 1,\ \lambda f.((\lambda v_0.f\ k_0\ v_0)\ 2)) =$

$(\lambda f.((\lambda v_0.f\ k_0\ v_0)\ 2))\ \lambda k_1.\lambda x.C(x + 1, k_1) =$

$(\lambda f.((\lambda v_0.f\ k_0\ v_0)\ 2))\ \lambda k_1.\lambda x.C(x,\ \lambda v_1.C(1,\ \lambda v_2.\ k_1\ (v_1+v_2))) =$

$(\lambda f.((\lambda v_0.f\ k_0\ v_0)\ 2))\ \lambda k_1.\lambda x.C(x,\ \lambda v_1.(\lambda v_2.\ k_1\ (v_1+v_2))\ 1) =$

$(\lambda f.((\lambda v_0.f\ k_0\ v_0)\ 2))\ \lambda k_1.\lambda x.(\lambda v_1.(\lambda v_2.\ k_1\ (v_1+v_2))\ 1)\ x$

Evaluation

$(\lambda f.((\lambda v_0.f\ k_0\ v_0)\ 2))\ \lambda k_1.\lambda x.(\lambda v_1.(\lambda v_2.\ k_1\ (v_1+v_2))\ 1)\ x \rightarrow$

$(\lambda v_0.\ (\lambda k_1.\lambda x.(\lambda v_1.(\lambda v_2.\ k_1\ (v_1+v_2))\ 1)\ x)\ k_0\ v_0)\ 2 \rightarrow$

$(\lambda k_1.\lambda x.(\lambda v_1.(\lambda v_2.\ k_1\ (v_1+v_2))\ 1)\ x)\ k_0\ 2 \rightarrow$

$(\lambda x.(\lambda v_1.(\lambda v_2.\ k_0\ (v_1+v_2))\ 1)\ x)\ 2 \rightarrow$

$(\lambda v_1.(\lambda v_2.\ k_0\ (v_1+v_2))\ 1)\ 2$

$(\lambda v_2.\ k_0\ (2+v_2))\ 1$

$k_0\ (2+1)$

$k_0\ 3$

Complete Programs

For a full program P, the initial continuation is the identify function I.

So the CPS transformation of P is

C(P,I)

Discussion

- The CPS transformation is important in language implementations
  - Very convenient to have a program representation where every intermediate result is named.

- But we can go a step further and make it useful to the programmer
  - By making continuations available as program values

Call/CC

$e \rightarrow x \mid \lambda x.e \mid e\ e \mid i \mid e + e \mid \text{call/cc}\ \lambda k.e \mid \text{resume}\ k\ e$

Call/cc calls its function argument with the current continuation.

Resume passes the value of its expression argument to its continuation argument.

Call/CC

$C(x,k) = k\ x$

$C(\lambda x.e,\ k) = k\ (\lambda k'.\lambda x.\ C(e,k'))$

$C(e\ e',k) = C(e,\ \lambda f.C(e',\ \lambda v.f\ k\ v))$

$C(i,k) = k\ i$

$C(e + e',k) = C(e,\ \lambda v.C(e',\ \lambda v'.k\ (v + v'))$

$C(\text{call/cc}\ \lambda x.e,\ k) = (\lambda x.C(e,k))\ k$

$C(\text{resume}\ k\ e,\ k') = C(e,k)$

Example

call/cc λk.1 + (resume k 0)

What is the result of this program?

Translation and Evaluation

$C(\text{call/cc } \lambda k.1 + (\text{resume } k\ 0), I) =$

$(\lambda k.C(1 + (\text{resume } k\ 0), I))\ I =$

$(\lambda k.C(1, \lambda m.C(\text{resume } k\ 0, \lambda n.I\ (m + n))))\ I =$

$(\lambda k.C(1, \lambda m.C(0,k)))\ I =$

$(\lambda k.C(1, \lambda m.k\ 0))\ I =$

$(\lambda k.(\lambda m.k\ 0)\ 1)\ I \rightarrow$

$(\lambda m.\ I\ 0)\ 1 \rightarrow$

$I\ 0 \rightarrow$

0

A Variation

$C(\text{call/cc } \lambda k.\ (\text{resume } k\ 0) + 1, I) =$

$(\lambda k.C((\text{resume } k\ 0) + 1, I))\ I =$

$(\lambda k.C(\text{resume } k\ 0, \lambda m.C(1, \lambda n.I\ (m + n))))\ I =$

$(\lambda k.C(0,k))\ I =$

$(\lambda k.\ k\ 0)\ I \rightarrow$

$I\ 0 \rightarrow$

0

Discussion

This program simulates an “abort” or “exit” statement

- Capture the continuation at the start of the program
- Invoking that continuation at any point will terminate the computation

Discussion

- In general continuations can be used to resume execution from an arbitrary point in the program

- Can implement many non-local control operations
  - Exceptions
  - Backtracking
  - Setjmp/longjmp
  - Co-routines
  - …

Discussion

- A few languages expose call/cc or something similar
  - Scheme, Racket
- But programmers can also code continuation-passing style directly
  - Often used as a software architecture device
  - E.g., event-driven systems
- Pluses and minuses
  - Makes program control into first-class values, which is necessary for programs that need to programmatically manipulate the flow of control
  - Turns programs “inside out”
  - Contagious: Affects the structure of the entire program