CSC324 Principles of Programming Languages

Lecture 3

September 25, 2019

Exercise 2 Debrief

Do not modify the starter code line beginning with `(provide ...)`

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Do not modify the starter code line beginning with `(provide ...)`

Common issue (for both tasks 1 and 2): missing recursive call

```
<expr> = NUM
       | (<op> <expr> <expr>)
       | (if (<comp> <expr> <expr>) <expr> <expr>)
```

In task 2, every time you see `<expr>`, there should be a recursive call!

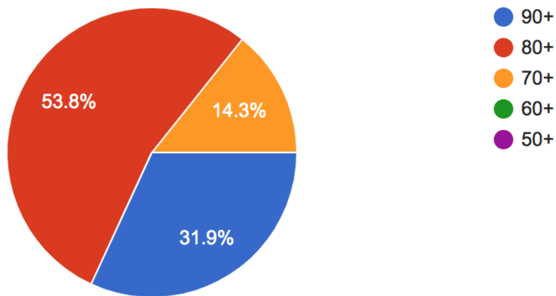
Exercise 2 value pattern matching

Possible helper function:

```
(define/match (op x)
  [('+) +]
  [('-) -]
  ...)
```

What grade are you aiming for in this course?

91 responses



Last class. . .

Functions of various kinds:

- Pattern matching
- Tail recursion
- Higher-order functions
- Currying

These are tool we use to build interesting programs in a functional language.

Today

Today is about **semantics**, evaluating code, and building an **interpreter**.

These are some of the choices we make about the semantics of a language:

- Strict and non-strict evaluation
- Closures & Environments
- Lexical & Dynamic Scoping

To be more specific, let's review the **lambda-calculus** before we begin.

Recall the lambda-calculus

1. Identifier; e.g. x
2. Function expression; e.g. $\lambda x \mapsto x$ (identity function)
3. Function application; e.g. $f\ expr$ (applies f to the expression $expr$)

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Lambda Calculus in Racket:

```
<expr> = ID
       | (lambda (ID) <expr>)
       | (<expr> <expr>)
```

Semantics of the lambda-calculus

- Identifiers and function expressions are already fully-evaluated
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       | (lambda (ID) <expr>)
       | (<expr> <expr>)
```

Strict and non-strict evaluation

Order of Operations

Consider `((lambda (x) (* x 2)) (+ 3 1))`

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- `((lambda (x) (* x 2)) 4)`
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Q. Do we always get the same answer?

Church-Rosser Theorem (Informal)

For any valid program in the lambda calculus, every possible order of function application must result in the same final value.

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Sidenote: we **can** have infinite loops in the lambda calculus!

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Q. Should `(f #t (/ 1 0))` always fail for all `f`?

Left-to-right Eager Evaluation

When evaluating a function call

1. Evaluate function subexpression being called
2. Evaluate each argument subexpression, left-to-right
3. "Call" the function by substituting the *value* of each argument subexpression into the body of the function.

This is how Racket evaluates function calls.

Q. Which evaluation order is “eager”?

Choice A:

- `((lambda (x) (* x 2)) (+ 3 1))`
- `((lambda (x) (* x 2)) 4)`
- `(* 4 2)`
- `8`

Choice B:

- `((lambda (x) (* x 2)) (+ 3 1))`
- `(* (+ 3 1) 2)`
- `(* 4 2)`
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Choice B:

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- `(* (+ 3 1) 2)`
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Strict denotational semantics

If an argument expression is undefined (e.g. contains an error), the call expression is undefined.

Example: Try this in Racket!

```
(define (f x y) x)
(f 4 (/ 1 0))
```

Racket has strict denotational semantics (eager evaluation)

Examples of non-eager (non-strict) evaluation

Try entering this in a Racket shell:

```
(or #t (/ 1 0))
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Why do we not see an error?

The identifier `or` does not refer to a function, but rather a *syntactic form* that implements **short-circuiting**.

We'll talk more about syntactic forms in the next 2 weeks.

What about Haskell?

Haskell uses *non-strict semantics* for function calls and name bindings.

When evaluating a function call

1. Evaluate function subexpression being called
2. ~~Evaluate each argument subexpression, left-to-right~~
3. “Call” the function by substituting the *unevaluated* argument subexpressions into the body of the function.

This strategy is called **lazy evaluation**.

Non-strict semantic

Try this in Haskell:

```
f x y = x
f 4 (1/0)
```

Lazy Evaluation in Haskell

Lazy evaluation lets us do cool things in Haskell, like define an infinite list!

List elements are not evaluated until they are needed.

```
> x = [1..10]
> take 5 x
[1,2,3,4,5]
> length x
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```

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[1,2,3,4,5]
> length x
10
```

```
> y = [1..]
> take 20 y
[1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20]
> length y
```

The trouble with lazy evaluation

Recall the discussion on tail recursion, and the function `foldl`.

Here is how `foldl` is defined in Haskell

```
foldl _ acc [] = acc
foldl f acc (x:xs) =
  let acc' = f acc x
  in
      foldl f acc' xs
```

Why is this a problem?

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foldl _ acc [] = acc
foldl f acc (x:xs) =
  let acc' = f acc x
  in
      foldl f acc' xs
```

Why is this a problem?

The problem is that `acc'` is not evaluated *before* the recursive call on `f`.

`foldl f acc' xs` reduces to

- `foldl f (f acc x) xs`

Delaying evaluation in Racket

Q. What does this expression evaluate to?

```
(define x (length (range 3000)))
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Q. What about this?

```
(define (g) (length (range 3000)))
```

Evaluation of Functions

Function bodies are not evaluated until the function is called!

```
(define (g) (length (range 3000)))
```

This function `g` is called a **thunk**: a nullary function that delays evaluation.

Closures and Environments

Interpreter 101

An **interpreter** executes instructions written in a programming language.

Your calculator application from exercises 1 and 2...

- took an expression as an argument
- returned a value

But what about variables?

Interpreter

More generally, an interpreter should take two arguments:

- the expression to be evaluated
- an **environment**

An **environment** is a collection of name-value bindings.

Example (from Exercise 3)

If we want to evaluate this expression:

```
(let* ((a 3))
   (+ a 1))
```

We'll need to store the environment `{a: 3}` and use it to evaluate `(+ a 1)`.

Example (from Exercise 4)

If we want to evaluate this expression:

```
((lambda (a) (+ a 1)) 3)
```

We also need to store the environment `{a: 3}` and use it to evaluate `(+ a 1)`.

Functions Saving Information

Recall that functions can return functions

```
(define (add-prefix lst1)
  (lambda (lst2) (append lst1 lst2)))

> (add-prefix '(1 2))
```

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```

```
#<procedure>
```

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```

```
> (add-prefix '(1 2))
```

```
#<procedure>
```

```
> ((add-prefix '(1 2)) '(3 4 5))
'(1 2 3 4 5)
```

What if we called add-prefix many times?

```
(define (add-prefix lst1)
  (lambda (lst2) (append lst1 lst2)))

(define prepend-1 (add-prefix '(1))
(define prepend-2 (add-prefix '(2))
(define prepend-3 (add-prefix '(3))

> (prepend-1 '(4 5 6))
'(1 4 5 6)
> (prepend-3 '(4 5 6))
'(3 4 5 6)
```

We need to store the value of `lst1` for each of `prepend-1` and `prepend-3`. (They need to be evaluated using different environments!)

Closures (Evaluating Function Expressions)

Function expressions should evaluate to **closures**.

A **closure** is a data structure that contains information about:

- the function body
- the environment at the time the function expression is evaluated (i.e. when the function was defined)

Closures (Evaluating Function Expressions)

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Example: the closure `prepend-1` contains

- its definition (including its body): `(lambda (lst2) (append lst1 lst2))`
- its environment: `{lst1: '(1), ...}`

Evaluating Function Calls

When evaluating a function call `(<expr> <expr> ...)`

- Make sure that the function expression evaluates to a *closure*
- Evaluate its arguments (assuming a strict semantic, with left-to-right eager evaluation)
- Evaluate the function body with... *what environment?*

Evaluating Function Calls

When evaluating a function call `(<expr> <expr> ...)`

- Make sure that the function expression evaluates to a *closure*
- Evaluate its arguments (assuming a strict semantic, with left-to-right eager evaluation)
- Evaluate the function body with... *what environment?*

Choices:

- Environment at the time the function is defined (stored in the closure)
- Environment at the time the function is called

The different choices lead to different types of scoping.

Scoping

What should this evaluate to?

```
(define n 100)
(define (f a) n)
(define (g n) n)
(define (h n) (f 0))

> (f 10)
100
> (g 10)
10
> (h 10)
???
```

Scoping...

- **Lexical Scoping**: environment used is the one in scope *where the function is defined*.
- **Dynamic Scoping**: environment used is the one in scope *where the function is called* (during program execution)

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Scoping...

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Q: Is Racket lexically scoped or dynamically scoped?

A: Lexically scoped.

Haskell Scoping

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n = 100
f a = n
g n = n
h n = f 0

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100
> g 10
10
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```

Haskell Scoping

Q: Is Haskell lexically scoped or dynamically scoped?

```
n = 100
f a = n
g n = n
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> f 10
100
> g 10
10
> h 10
???
```

A: Lexically scoped.

Python Scoping

Q: Is Python lexically scoped or dynamically scoped?

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Q: Is Python lexically scoped or dynamically scoped?

A: Lexically scoped.

Bash Scoping

```
X="batman"

function printX {
  echo $X
}

function localX {
  local X="superman"
  printX
}

printX
localX
```

Python Scoping Bug

You will run into this bug at some point in your career:

```
adders = []
for i in [1, 2, 3]:
    add_i = lambda x: x + i
    adders.append(add_i)

add1 = adders[0]
print(add1(5))
```

What happened?

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add1 = adders[0]
print(add1(5))
```

What happened?

Mutation! The value of `i` has changed. We don't have referential transparency here.

Summary

- Order of evaluation in a function application
  - Strict and non-strict evaluation
- Identifier binding / name lookups
  - Closures & Environments
  - Lexical & Dynamic Scoping

When you build interpreters, remember the left-to-right eager evaluation order, and use lexical scoping!