# Functional Programming with Scheme

Keep reading: Scott, Chapter 11.1-11.3, 11.5-11.6, Scott, 3.6

# Lecture Outline

- Scheme
  - Exercises with map, foldl and foldr
  - Binding with let, let*, and letrec
  - Scoping in Scheme
  - Closures
  - Scoping, revisited

# Exercises

(foldr op lis id)

$($ $e_1$ … $e_{n-1}$ $e_n$ $)$ id

$($ $e_1$ … $e_{n-1}$ $)$ $res_1$

…

$($ $e_1$ $)$ $res_{n-1}$

$\underline{res_n}$

Write rev, which reverses a list, using a single call to foldr

(define (rev lis) (foldr …) )

# Exercises

(foldl op lis id)

$$id \quad ( \quad e_1 \quad e_2 \quad e_3 \quad \ldots \quad e_n \quad )$$

$$id_1 \quad ( \quad e_2 \quad e_3 \quad \ldots \quad e_n \quad )$$

$$id_2 \quad ( \quad e_3 \quad \ldots \quad e_n \quad )$$

$$\ldots$$

$$id_{n-1} \quad ( \quad e_n \quad )$$

$$\underline{id_n}$$

Write len, which computes length of list, using a single call to foldl

(define (len lis) (foldl …) )

# Exercises

```
(define (foldl op lis id)
  (if (null? lis) id
      (foldl op (cdr lis) (op id (car lis)))) )
```

- Write flatten3 using map and foldl/foldr

```
(define (flatten3
```

- Write flatten4 this time using foldl but not map.

# Exercises

- Write a function that counts the appearances of symbols a, b and c in a list of flat lists
  - (count-sym ‘((a b) (c a) (a b d)) yields

    ((a 3) (b 2) (c 1))
  - Natural idea: use map and fold
- map and fold (or map and reduce), are the foundation of Google’s MapReduce model
  - Canonical MapReduce example [Dean and Ghemawat OSDI’04] is WordCount

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# Let Expressions

Let-expr ::= ( let ( Binding-list ) S-expr1 )

Let*-expr ::= ( let* ( Binding-list ) S-expr1 )

Binding-list ::= ( Var S-expr ) { ( Var S-expr ) }

---

- let and let* expressions define a binding between each Var and the S-expr value, which holds during execution of S-expr1
- let evaluates the S-exprs in current environment “in parallel”; Vars are bound to fresh locations holding the results
- let* evaluates the S-exprs from left to right

- Associate values with variables for the local computation

# Questions

(let ((x 2)) (* x x)) **yields** 4

(let ((x 2)) (let ((y 1)) (+ x y)) ) **yields** what?

(let ((x 10) (y (* 2 x)))  (* x y)) **yields** what?

(let* ((x 10) (y (* 2 x))) (* x y)) **yields** what?

# Let Expressions

Letrec-expr ::= ( letrec ( Binding-list ) S-expr1 )

Binding-list ::= ( Var **S-expr** ) { ( Var **S-expr** ) }

---

- letrec Vars are bound to fresh locations holding undefined values; **S-exprs** are evaluated “in parallel” in current environment
- letrec allows for definition of mutually recursive functions

```
(letrec (( even? (lambda (n) (if (zero? n) #t (odd? (- n 1)))) )
         ( odd?   (lambda (n) (if (zero? n) #f (even? (- n 1)))) )
         )
   (even? 88)
)
```

# Regions (Scopes) in Scheme

- let, let* and letrec give rise to block structure
- They have the same syntax but define different regions (scopes)
- let
  - Region where binding is active: body of let

# Regions (Scopes) in Scheme

- let, let* and letrec give rise to block structure
- They have the same syntax but define different regions (scopes)
- let*
  - Region: all bindings to the right plus body of let*

# Regions (Scopes) in Scheme

- let, let* and letrec give rise to block structure
- They have the same syntax but define different regions (scopes)
- letrec
  - Region: entire letrec expression

# Let Introduces Nested Scopes

```
(let ((x 10))                                ;causes x to be bound to 10
     (let ((f (lambda (a) (+ a x)))          ;causes f to be bound to
                                              a lambda expression
          (let ((x 2)) (f 5) ) ))
```

Assuming that Scheme uses static scoping, what would this expression yield?

# Question

```
(define (f  z)
   (let* ( (x 5) (f (lambda (z) (* x  z))) )
        (map f z) ) )
```

What does this function do?

Answer: takes a list of numbers, z, and maps it to the x*5 list. E.g., (f ‘(1 2 3)) yields (5 10 15).

# Scoping in Scheme: Two Choices

**a** is a "bound" variable

```
(let ((x 10))
    (let ((f (lambda (a) (+ a x))))
        (let ((x 2))
            (* x (f 3) ) ) )
```

**x** is a "free" variable; must be found in "outer" scope

With static scoping it evaluates to

(* x ((lambda (a)(+ a x)) 3)) -->

(* 2 ((lambda (a)(+ a 10)) 3) ) --> ???

With dynamic scoping it evaluates to

(* x ((lambda (a)(+ a x)) 3)) -->

(* 2 ((lambda (a)(+ a 2)) 3) ) --> ???

# Scheme Chose Static Scoping

```
(let  ((x 10))
     (let   ((f (lambda (a) (+ a  x))))
          (let ((x  2))
               (*  x  (f  3) ) ) )
```

**f** is a closure:
The function value: **(lambda (a) (+ a  x))**
The environment: **{ x → 10 }**

Scheme chose static scoping:

(*  x  (lambda (a)(+ a x) 3))  -->
(*  2   ((lambda (a)(+ a 10) 3)  ) -->
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# Closures

- A closure is a function value plus the environment in which it is to be evaluated
  - Function value: e.g., (lambda (x) (+ x y))
  - Environment consists of bindings for variables not local to the function so the closure can eventually be evaluated: e.g., { y $\rightarrow$ 2 }
- A closure can be used as a function
  - Applied to arguments
  - Passed as an argument
  - Returned as a value

# Closures

- Normally, when let expression exits, its bindings disappear
- Closure bindings (i.e., bindings part of a closure) are special
  - When let exits, bindings become inactive, but they do not disappear
  - When closure is called, bindings become active
  - Closure bindings are "immortal"

```
(let ((x 5))
     (let  (( f  (let ((x 10))  (lambda ()  x ) ) ))
          (list x (f) x (f)) )  )
```

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  - Scoping, revisited

# Scoping, revisited (Scott, Ch. 3.6)

- We discussed the two choices for mapping non-local variables to locations
  - Static scoping (early binding)

  and
  - Dynamic scoping (late binding)

- Most languages choose static scoping

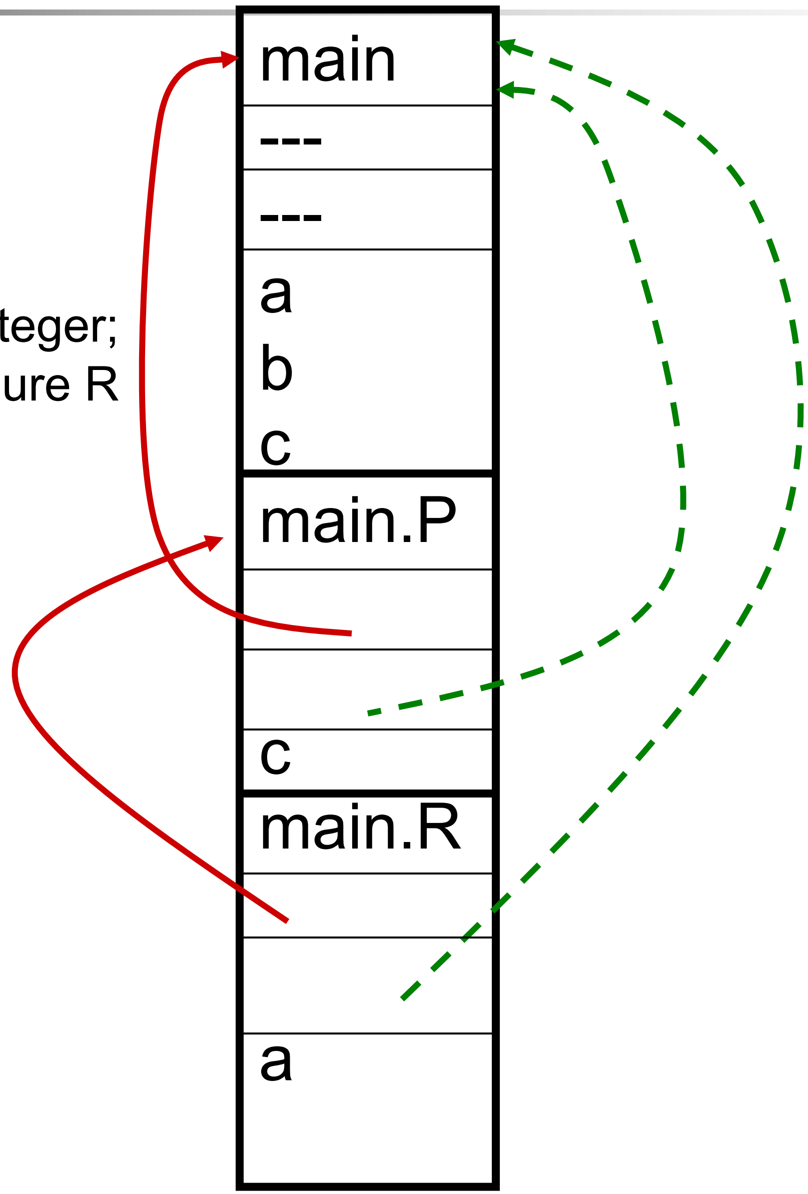
# Scoping, revisited

- When we discussed scoping earlier, we assumed that functions were third-class values (i.e., functions cannot be passed as arguments or returned from other functions)

- Functions as third-class values…
  - When functions are third-class values, the function’s static reference environment (i.e., closure bindings) is available on the stack. Function cannot outlive its referencing environment!

# Functions as Third-Class Values and Static Scoping

```
program
    a, b, c: integer;
    procedure P
        c: integer;
        procedure S
            c, d: integer;
            procedure R
            …
            end R;
            R();
        end S;
        R();
        S();
    end P;
    procedure R
        a: integer;
        = a, b, c;
    end R;
    …; P(); …
end program
```




Static Scoping:
- a bound to R.a,
- b to main.b,
- c to main.c

# Scoping, revisited

- Functions as first-class values
  - Static scoping is more involved. Function value may outlive static referencing environment!
  - Therefore, need “immortal” closure bindings
  - In languages that choose static scoping, local variables must have “unlimited extent” (i.e., when stack frame is popped, local variables do not disappear!)

# Scoping, revisited

- In functional languages local variables typically have unlimited extent
- In imperative languages local variables typically have limited extent (i.e., when stack frame is popped, local variables disappear)
  - Imperative languages (Fortran, Pascal, C) disallow truly first-class function values
  - More and more languages do allow first-class functions, e.g., Java 8, C++11

# More on Dynamic Scoping

- Shallow binding vs. deep binding

- Dynamic scoping with shallow binding
  - Reference environment for function/routine is not created until the function is called
    - I.e., all non-local references are resolved using the most-recent-frame-on-stack rule
  - Shallow binding is usually the default in languages with dynamic scoping
  - All examples of dynamic scoping we saw so far used shallow binding

# More on Dynamic Scoping

- Dynamic scoping with deep binding
  - When a function/routine is passed as an argument, the code that passes the function/routine has a particular reference environment (the current one!) in mind. It passes this reference environment along with the function value (it passes a closure).

# Example

```
v : integer := 10
people : database

print_routine (p : person)
  if p.age > v
    write_person(p)

other_routine (db : database, P : procedure)
    v : integer := 5
    foreach record r in db
        P(r)

other_routine(people, print_routine) /* call in main */
```

# Exercise

```
(define A
  (lambda ()
    (let* ((x 2)
           (C (lambda (P) (let ((x 4)) (P) )))
           (D (lambda () x))
           (B (lambda () (let ((x 3)) (C D)))))
      (B))))
```

When we call **> (A)** in the interpreter, what gets printed? What would get printed if Scheme used dynamic scoping with shallow binding? Dynamic scoping and deep binding?

# Evaluation Order

```
(define (square x) (* x x))
```

- Applicative-order (also referred to as eager) evaluation
  - Evaluates arguments before function value

```
(square (+ 3 4)) =>
(square 7) =>
(* 7 7) =>
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```

# Evaluation Order

```
(define (square x) (* x x))
```

- Normal-order (also referred to as lazy) evaluation
  - Evaluates function value before arguments

```
(square (+ 3 4)) =>
(* (+ 3 4) (+ 3 4)) =>
(* 7 (+ 3 4)) =>
(* 7 7)
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```

- Scheme uses applicative-order evaluation

# So Far

- Essential functional programming concepts
  - Reduction semantics
  - Lists and recursion
  - Higher-order functions
    - Map and fold (also known as reduce)
  - Evaluation order
- Scheme

# Coming Up

- Lambda calculus: theoretical foundation of functional programming

- Haskell
  - Algebraic data types and pattern matching
  - Lazy evaluation
  - Type inference
  - Monads

# The End