Variables, Environments and Closures

Overview

- Touch on the notions of variable extent and scope
- Introduce the notions of lexical scope and dynamic scope for variables
- Provide a simple model for variable environments in Scheme
- Show examples of closures in Scheme

Variables, free and bound

- In this function, to what does the variable *GOOGOL* refer?

```
(define (big-number? x)
   ;; returns true if x is a really big number
  (> x GOOGOL))
```

- The **scope** of the variable X is just the body of the function for which it's a parameter.

Here, GOOGOL is a global variable

```
> (define GOOGOL (expt 10 100))
> GOOGOL
10000000000000000000000000000000000000
  0000000000000000000000000000000000000
  00000000000000000000000000
> (define (big-number? x) (> x GOOGOL))
> (big-number? (add1 (expt 10 100)))
#t
```

Which X is accessed at the end?

```
> (define GOOGOL (expt 10 100))
> GOOGOL
10000000000000000000000000000000000000000000
  000000000000000000000000000000000000000000
  000000000000000
> (define x -1)
> (define (big-number? x) (> x GOOGOL))
> (big-number? (add1 (expt 10 100)))
#t
```

Variables, free and bound

- In the body of this function, we say that the variable (or symbol) X is **bound** and GOOGOL is **free**

```
(define (big-number? x)
  ; returns true if X is a really big number
  (> X GOOGOL))
```

- If it has a value, it has to be bound somewhere else

The let form creates local variables

```
> (let [ (pi 3.1415)
         (e 2.7168) ]
    (big-number? (expt pi e)))
#f
```

Note: square brackets are like parens, but only match other square brackets. They can to help you cope with paren fatigue.

- The general form is (let <varlist> . <body>)
- It creates a local environment, binding the variables to their initial values, and evaluates the expressions in <body>

Let creates a block of expressions

```
(if (> a b)
  (let ( )
     (printf "a is bigger than b.~n")
     (printf "b is smaller than a.~n")
     #t)
  #f)
```

Let is just syntactic sugar for lambda

```
(let [(pi 3.1415) (e 2.7168)]
  (big-number? (expt pi e)))

((lambda (pi e) (big-number? (expt pi e)))
 3.1415
 2.7168)
```

and this is how we did it back before ~1973

Let is just syntactic sugar for lambda

What happens here:

```
(define x 2)
(let [ (x 10) (xx (* x 2)) ]
  (printf "x is ~s and xx is ~s.~n" x xx))
```

x is 10 and xx is 4.

Let is just syntactic sugar for lambda

What happens here:

```
(define x 2)
( (lambda (x xx) (printf "x is ~s and xx is ~s.~n" x xx))
 10
 (* 2 x))
```

x is 10 and xx is 4.

Let is just syntactic sugar for lambda

What happens here:

```
(define x 2)
(define (f000034 x xx)
  (printf "x is ~s and xx is ~s.~n" x xx))
(f000034 10 (* 2 x))
```

x is 10 and xx is 4.

let and let*

- The let special form evaluates all initial value expressions, and then creates a new environment with local variables bound to them, "in parallel"
- The let* form does sequentially
- let* expands to a series of nested lets

```
(let* [(x 100)(xx (* 2 x))] (foo x xx) )
(let [(x 100)]
   (let [(xx (* 2 x))]
     (foo x xx) ) )
```

What happens here?

```
> (define X 10)
> (let [(X (* X X))]
     (printf "X is ~s.~n" X)
     (set! X 1000)
     (printf "X is ~s.~n" X)
     -1 )
???
> X
???
```

What happens here?

```
> (define X 10)
> (let [(X (* X X))]
     (printf "X is ~s\n" X)
     (set! X 1000)
     (printf "X is ~s\n" X)
     -1 )
X is 100
X is 1000
-1
> X
10
```

What happens here?

```
> (define GOOGOL (expt 10 100))
> (define (big-number? x) (> x GOOGOL))
> (let [(GOOGOL (expt 10 101))]
    (big-number? (add1 (expt 10 100))))
???
```

What happens here?

```
> (define GOOGOL (expt 10 100))
> (define (big-number? x) (> x GOOGOL))
> (let [(GOOGOL (expt 10 101))]
    (big-number? (add1 (expt 10 100))))
#t
```

- The free variable GOOGOL is looked up in the environment in which the big-number? function was defined!
- Not in the environment in which it was called

functions

- Note that a simple notion of a function can give us the machinery for
  - Creating a block of code with a sequence of expressions to be evaluated in order
  - Creating a block of code with one or more local variables
- Functional programming language is to use functions to provide other familiar constructs (e.g., objects)
- And also constructs that are unfamiliar

Dynamic vs. Static Scoping

- Programming languages either use dynamic or static (aka lexical) scoping
- In a statically scoped language, free variables in functions are looked up in the environment in which the function is *defined*
- In a dynamically scoped language, free variables are looked up in the environment in which the function is *called*

History

- Lisp started out as a dynamically scoped language and moved to static scoping with Common Lisp in ~1980
- Today, fewer languages use only dynnamic scoping, Logo and Emacs Lisp among them
- Perl and Common Lisp let you define some variables as dynamically scoped

Dynamic scoping

Here's a model for dynamic binding:

- Variables have a global stack of bindings
- Creating a new variable X in a block pushes a binding onto the global X stack
- Exiting the block pops X's binding stack
- Accessing X always produces the top binding

Special variables in Lisp

- Common Lisp's dynamically scoped variables are called special variables
- Declare a variable special using defvar

```
> (set 'reg 5)
5
> (defun check-reg () reg)
CHECK-REG
> (check-reg)
5
> (let ((reg 6)) (check-reg))
5
```

```
> (defvar *spe* 5)
*SPE*
> (defun check-spe () *spe*)
CHECK-SPE
> (check-spe)
5
> (let ((*spe* 6)) (check-spe))
6
```

Advantages and disadvantages

- + Easy to implement
- + Easy to modify a function's behavior by dynamically rebinding free variables
  (let ((IO stderr)) (printf "warning…"))
- - Can unintentionally shadow a global variable
- - A compiler can never know what a free variable will refer to, making type checking impossible

Closures

- Lisp is a **lexically scoped** language
- Free variables referenced in a function are looked up in the environment in which the function is defined

  Recall: free variables are those a function (or block) doesn't create scope for
- A closure is a function that remembers the environment in which it was created
- An **environment** is just a collection of variable names and their values, plus a parent environment

Why closures, where closures

- Closures turn out to be very useful in languages that support functional programming
- Most modern dynamic PLs do: Python, Javascript, Php, Ruby, etc.
- They are interesting when you can (1) define a function in an environment, (2) return a reference to it outside the environment and (3) call the function later

Example: make-counter

- make-counter creates an environment using let with a local variable *C* initially 0
- It defines and returns a new function, using lambda, that can access & modify *C*

```
> (define (make-counter)
   (let ((C 0))
     (lambda ()
       (set! C (+ 1 C))
        C)))
> (define c1 (make-counter))
> (define c2 (make-counter))
```

```
> (c1)
1
> (c1)
2
> (c1)
3
> (c2)
???
```

What is a function?

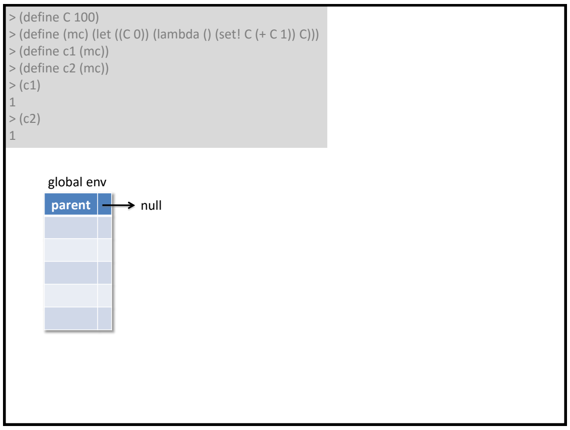
- (define (add1 x) (+ x 1))
- This binds the variable add1 to a new function
- In Scheme, a function is just a data structure with three components:
  - A parameter list (e.g., (x))
  - An expression to evaluate (e.g., (+ x 1))
  - A pointer to the variable environment it was created in

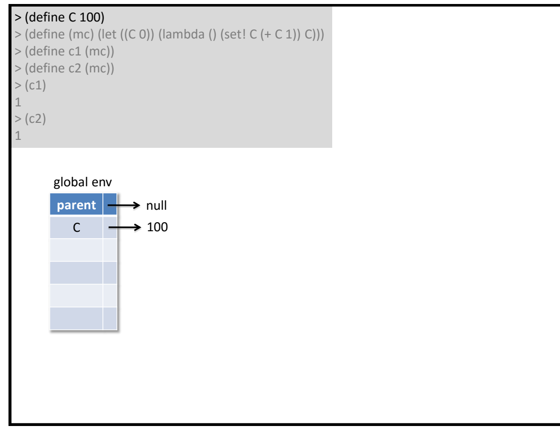
What's an environment?

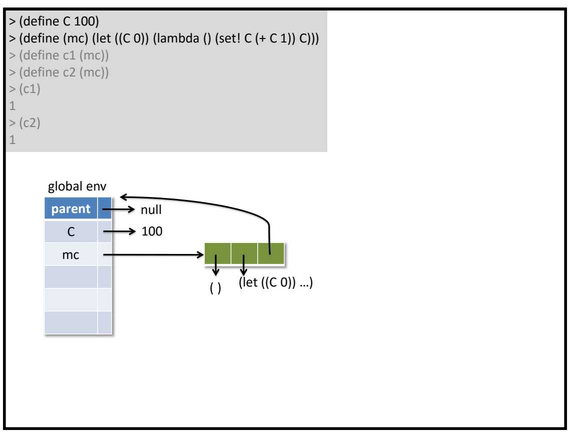
- An environment is a data structure with two parts:
  1. A pointer to its parent environment (which might be null if this environment is the top-level global one)
  2. A data structure to hold pairs of variable names and their current values (e.g., a dictionary, hashtable or even a simple list)
- Operations on an environment include define, set! and lookup

Environment Operations

- Define: add a new variable in an environment and give it an initial value
- Lookup: find a variable in an enviroment or one of its ancestors and return its value
- Set!: find a variable in an environment or one of its ancestors and change its value


> (define C 100)
> (define (mc) (let ((C 0)) (lambda () (set! C (+ C 1)) C)))
> (define c1 (mc))
> (define c2 (mc))
> (c1)
1
> (c2)
1
global env
parent
null


> (define C 100)
> (define (mc) (let ((C 0)) (lambda () (set! C (+ C 1)) C)))
> (define c1 (mc))
> (define c2 (mc))
> (c1)
1
> (c2)
1
global env
parent
null
C
100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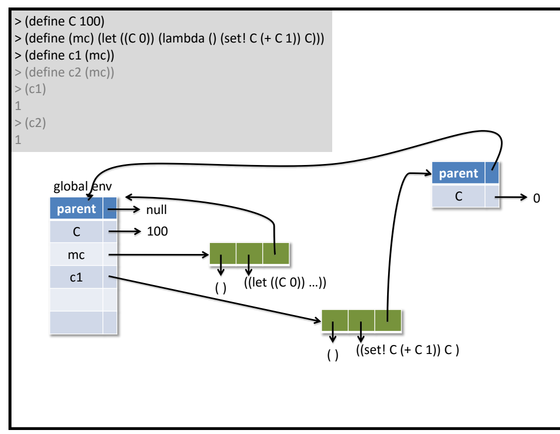
> (define (mc) (let ((C 0)) (lambda () (set! C (+ C 1)) C)))
> (define c1 (mc))
> (define c2 (mc))
> (c1)
1
> (c2)
1
global env
parent
null
C
100
mc
( )
(let ((C 0)) ...)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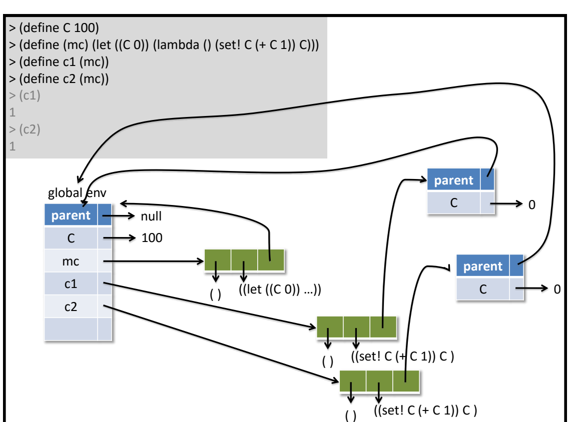
> (define (mc) (let ((C 0)) (lambda () (set! C (+ C 1)) C)))
> (define c1 (mc))
> (define c2 (mc))
> (c1)
1
> (c2)
1
global env
parent
null
C
100
mc
c1
( )
((let ((C 0)) ...))
parent
C
0
( )
((set! C (+ C 1)) C)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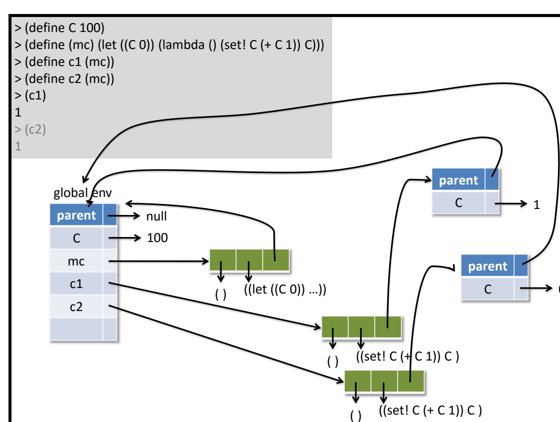
> (define (mc) (let ((C 0)) (lambda () (set! C (+ C 1)) C)))
> (define c1 (mc))
> (define c2 (mc))
> (c1)
1
> (c2)
1
global env
parent
null
C
100
mc
c1
c2
( )
((let ((C 0)) ...))
parent
C
0
parent
C
0
( )
((set! C (+ C 1)) C)
( )
((set! C (+ C 1)) C)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> (define (mc) (let ((C 0)) (lambda () (set! C (+ C 1)) C)))
> (define c1 (mc))
> (define c2 (mc))
> (c1)
1
> (c2)
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global env
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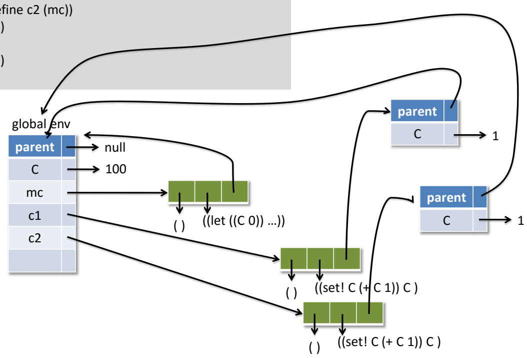
mc
c1
c2
( )
((let ((C 0)) ...))
parent
C
1
parent
C
0
( )
((set! C (+ C 1)) C)
( )
((set! C (+ C 1)) C)

```
> (define C 100)
> (define (mc) (let ((C 0)) (lambda () (set! C (+ C 1)) C)))
> (define c1 (mc))
> (define c2 (mc))
> (c1)
1
> (c2)
1
```



A fancier make-counter

Write a fancier make-counter function that takes an optional argument that specifies the increment

```
> (define by1-counter (make-counter))
> (define by2-counter (make-counter 2))
> (define decrementing-counter (make-counter -1))
> (by2-counter)
2
(by2-counter)
4
```

Optional arguments in Scheme

```
> (define (f (x 10) (y 20))
      (printf "x=~a and y=~a\n" x y))
> (f)
x=10 and y=20
> (f -1)
x=-1 and y=20
> (f -1 -2)
x=-1 and y=-2
```

Fancier make-counter

```
(define (make-counter (inc 1))
 (let ((C 0))
    (lambda ( ) (set! C (+ C inc)))))
```

Keyword arguments in Scheme

- Scheme, like Lisp, also has a way to define functions that take *keyword arguments*
  - (make-counter)
  - (make-counter :initial 100)
  - (make-counter :increment -1)
  - (make-counter :initial 10 :increment -2)
- Scheme dialects have introduced different ways to mix positional arguments, optional arguments, default values, keyword argument, etc.

Closure tricks

We can write several functions that are closed in the same environment, which can then provide a private communication channel

```
(define foo #f)
(define bar #f)

(let ((secret-msg "none"))
  (set! foo
    (lambda (msg)
      (set! secret-msg msg)))
  (set! bar
     (lambda () secret-msg)))

(display (bar)) ; prints "none"
(newline)
(foo "attack at dawn")
(display (bar)) ; prints ”attack at dawn"
```

Closures are powerful

- Closures let do many interesting and useful things, including
  - Delay a computation and execute it later
  - Implement streams
  - Curry functions
  - Etc.
- We'll look at some of these next

Summary

- Scheme, like most modern languages, is lexically scoped
- Common Lisp is by default, but still allows some variables to be declared to be dynamically scoped
- A few languages still use dynamic scoping
- Lexical scoping supports functional programming & powerful mechanisms (e.g., closures)
- More complex to implement, though