6.001 SICP
Variations on a Scheme

- Scheme Evaluator – a Grand Tour
  - Make the environment model concrete
  - Defining eval defines the language
    - – Provide a mechanism for unwinding abstractions
- Techniques for language design:
  - Interpretation: eval/apply
  - Semantics vs. syntax
  - Syntactic transformations
- Beyond Scheme – designing language variants
  - Today: Lexical scoping vs. Dynamic scoping
  - Next time: Eager evaluation vs. Lazy evaluation

Last Lecture

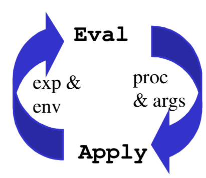
- Last time, we built up an interpreter for a new language, **`scheme*`**
  - Conditionals (**`if*`**)
  - Names (**`define*`**)
  - Applications
  - Primitive procedures
  - Compound procedures (**`lambda*`**)
- *Everything still works if you delete the stars from the names.*
  - So we actually wrote (most of) a Scheme interpreter in Scheme.
  - Seriously nerdly, eh?

Today's Lecture: the Metacircular Evaluator

- Today we'll look at a complete Scheme interpreter written in Scheme
- Why?
  - An interpreter makes things explicit
    - – e.g., procedures and procedure application in the environment model
  - Provides a precise definition for what the Scheme language means
  - Describing a process in a computer language forces precision and completeness
  - Sets the foundation for exploring variants of Scheme
    - – Today: lexical vs. dynamic scoping
    - – Next time: eager vs. lazy evaluation

The Core Evaluator

1. eval/apply core




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

(square 4)

x = 4
(* x x)
```

- Core evaluator
  - eval: evaluate expression by dispatching on type
  - apply: apply procedure to argument values by evaluating procedure body

Metacircular evaluator
(Scheme implemented in Scheme)

primitives

special forms

application

```
(define (m-eval exp env)
  (cond ((self-evaluating? exp) exp)
        ((variable? exp) (lookup-variable-value exp env))
        ((quoted? exp) (text-of-quotation exp))
        ((assignment? exp) (eval-assignment exp env))
        ((definition? exp) (eval-definition exp env))
        ((if? exp) (eval-if exp env))
        ((lambda? exp)
         (make-procedure (lambda-parameters exp)
                         (lambda-body exp)
                         env))
        ((begin? exp) (eval-sequence (begin-actions exp) env))
        ((cond? exp) (m-eval (cond->if exp) env))
        ((application? exp)
         (m-apply (m-eval (operator exp) env)
               (list-of-values (operands exp) env)))
        (else (error "Unknown expression type -- EVAL" exp))))
```


Pieces of Eval&Apply

```
(define (m-eval exp env)
  (cond ((self-evaluating? exp) exp)
        ((variable? exp) (lookup-variable-value exp env))
        ((quoted? exp) (text-of-quotation exp))
        ((assignment? exp) (eval-assignment exp env))
        ((definition? exp) (eval-definition exp env))
        ((if? exp) (eval-if exp env))
        ((lambda? exp)
         (make-procedure (lambda-parameters exp)
                         (lambda-body exp)
                         env))
        ((begin? exp) (eval-sequence (begin-actions exp) env))
        ((cond? exp) (eval (cond->if exp) env))
        ((application? exp)
         (m-apply (m-eval (operator exp) env)
                (list-of-values (operands exp) env)))
        (else (error "Unknown expression type -- EVAL" exp))))
```

Pieces of Eval&Apply

```
(define (list-of-values exps env)
 (cond ((no-operands? exps) '())
       (else
        (cons (m-eval (first-operand exps) env)
             (list-of-values (rest-operands exps) env)))))
```


m-apply

```
(define (m-apply procedure arguments)
  (cond ((primitive-procedure? procedure)
         (apply-primitive-procedure procedure arguments))
        ((compound-procedure? procedure)
         (eval-sequence
          (procedure-body procedure)
          (extend-environment (procedure-parameters procedure)
                              arguments
                              (procedure-environment procedure))))
        (else (error "Unknown procedure type -- APPLY" procedure))))
```


Side comment – procedure body

- The procedure body is a *sequence* of one or more expressions:

```
(define (foo x)
  (do-something (+ x 1))
  (* x 5))
```

- In `m-apply`, we `eval-sequence` the procedure body.

Pieces of Eval&Apply

```
(define (eval-sequence exps env)
   (cond ((last-exp? exps) (m-eval (first-exp exps) env))
         (else (m-eval (first-exp exps) env)
               (eval-sequence (rest-exps exps) env))))
```


Pieces of Eval&Apply

```
(define (m-eval exp env)
  (cond ((self-evaluating? exp) exp)
        ((variable? exp) (lookup-variable-value exp env))
        ((quoted? exp) (text-of-quotation exp))
        ((assignment? exp) (eval-assignment exp env))
        ((definition? exp) (eval-definition exp env))
        ((if? exp) (eval-if exp env))
        ((lambda? exp)
         (make-procedure (lambda-parameters exp)
                         (lambda-body exp)
                         env))
        ((begin? exp) (eval-sequence (begin-actions exp) env))
        ((cond? exp) (eval (cond->if exp) env))
        ((application? exp)
         (m-apply (m-eval (operator exp) env)
              (list-of-values (operands exp) env)))
        (else (error "Unknown expression type -- EVAL" exp))))
```


Pieces of Eval&Apply

```
(define (eval-assignment exp env)
  (set-variable-value! (assignment-variable exp)
                       (m-eval (assignment-value exp) exp)
                       env))

(define (eval-definition exp env)
  (define-variable! (definition-variable exp)
                    (m-eval (definition-value exp) env)
                    env))
```

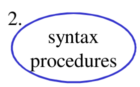
Pieces of Eval&Apply

```
(define (m-eval exp env)
 (cond ((self-evaluating? exp) exp)
       ((variable? exp) (lookup-variable-value exp env))
       ((quoted? exp) (text-of-quotation exp))
       ((assignment? exp) (eval-assignment exp env))
       ((definition? exp) (eval-definition exp env))
       ((if? exp) (eval-if exp env))
       ((lambda? exp)
        (make-procedure (lambda-parameters exp)
                        (lambda-body exp)
                        env))
       ((begin? exp) (eval-sequence (begin-actions exp) env))
       ((cond? exp) (eval (cond->if exp) env))
       ((application? exp)
        (m-apply (m-eval (operator exp) env)
              (list-of-values (operands exp) env)))
       (else (error "Unknown expression type -- EVAL" exp))))
```

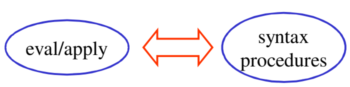

Pieces of Eval&Apply

```
(define (eval-if exp env)
   (if (m-eval (if-predicate exp) env)
       (m-eval (if-consequent exp) env)
       (m-eval (if-alternative exp) env)))
```


Syntactic Abstraction



- Semantics
  - What the language ***means***
  - Model of computation
- Syntax
  - Particulars of writing expressions
  - E.g. how to signal different expressions
- Separation of syntax and semantics: allows one to easily alter syntax



Basic Syntax

```
(define (tagged-list? exp tag)
  (and (pair? exp) (eq? (car exp) tag)))
```

- Routines to detect expressions

```
(define (if? exp) (tagged-list? exp 'if))
(define (lambda? exp) (tagged-list? exp 'lambda))
(define (application? exp)  (pair? exp))
```

- Routines to get information out of expressions

```
(define (operator app) (car app))
(define (operands app) (cdr app))
```

- Routines to manipulate expressions

```
(define (no-operands? args) (null? args))
(define (first-operand args) (car args))
(define (rest-operands args) (cdr args))
```


Example – Changing Syntax

- Suppose you wanted a "verbose" application syntax, i.e., instead of

```
(<proc> <arg1> <arg2> . . .)
```

use

```
(CALL <proc> ARGS <arg1> <arg2> ...)
```

- Changes – only in the syntax routines!

```
(define (application? exp) (tagged-list? exp 'CALL))
(define (operator app) (cadr app))
(define (operands app) (cdddr app))
```


Implementing "Syntactic Sugar"

- Idea:
  - Easy way to add alternative/convenient syntax
  - Allows us to implement a simpler "core" in the evaluator, and support the alternative syntax by translating it into core syntax
- "let" as sugared procedure application:

```
(let ((<name1> <val1>)
      (<name2> <val2>))
   <body>)
```

```
((lambda (<name1> <name2>)   <body>)
  <val1> <val2>)
```

Detect and Transform the Alternative Syntax

```
(define (m-eval exp env)
  (cond ((self-evaluating? exp) exp)
        ((variable? exp)
         (lookup-variable-value exp env))
        ((quoted? exp)
         (text-of-quotation exp))
        ...
        ((let? exp)
         (m-eval (let->combination exp) env))
        ((application? exp)
         (m-apply (m-eval (operator exp) env)
                  (list-of-values
                      (operands exp) env)))
        (else (error "Unknown expression" exp))))
```


Let Syntax Transformation

FROM

```
(let ((x 23)
      (y 15))
   (dosomething x y))
```

TO

```
( (lambda (x y) (dosomething x y))
  23 15 )
```

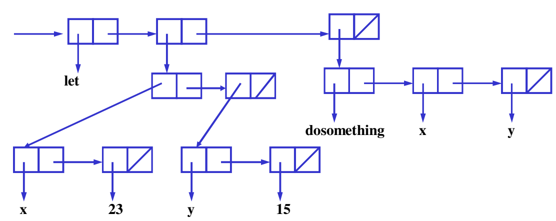

Let Syntax Transformation

```
(define (let? exp) (tagged-list? exp 'let))

(define (let-bound-variables let-exp)
  (map car (cadr let-exp)))

(define (let-values let-exp)
  (map cadr (cadr let-exp)))

(define (let-body let-exp)
  (cddr let-exp))

(define (let->combination let-exp)
  (let ((names (let-bound-variables let-exp))
        (values (let-values let-exp))
        (body (let-body let-exp)))
    (cons (make-lambda names body)
          values)))
```

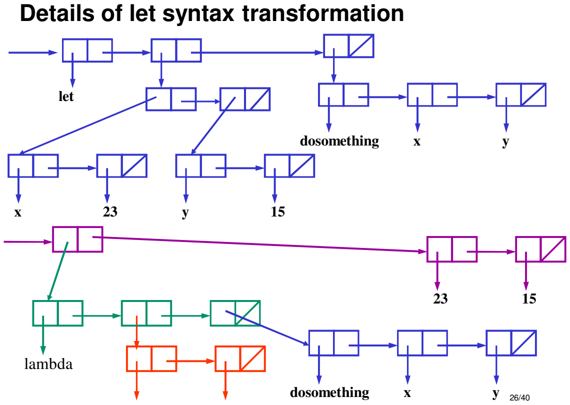
NOTE: only manipulates list structure, returning new list structure that acts as an expression

Details of let syntax transformation

```
(let ((x 23)
      (y 15))
   (dosomething x y))
```



Details of let syntax transformation



Defining Procedures

```
(define foo (lambda (x) <body>))
(define (foo x) <body>)
```

- Semantic implementation – just another define:

```
(define (eval-definition exp env)
  (define-variable! (definition-variable exp)
                    (m-eval (definition-value exp) env)
                    env))
```

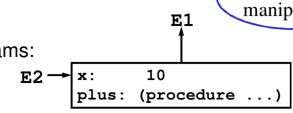
- Syntactic transformation:

```
(define (definition-value exp)
  (if (symbol? (cadr exp))
      (caddr exp)
      (make-lambda (cdadr exp)    ;formal params
                   (cddr exp))))  ;body
```

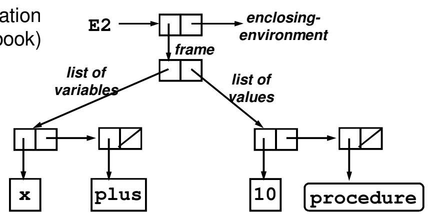
How the Environment Works

3. environment manipulation

- *Abstractly* – in our environment diagrams:



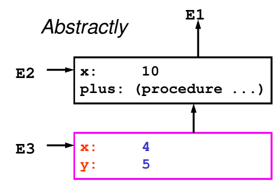
- *Concretely* – our implementation (as in textbook)



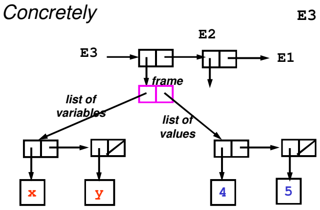
Extending the Environment

- `(extend-environment '(x y) '(4 5) E2)`

Abstractly



Concretely



"Scanning" the environment

- Look for a variable in the environment...
  - Look for a variable in a frame...
    - loop through the list of vars and list of vals in parallel
    - detect if the variable is found in the frame
  - If not found in frame (i.e. we reached end of list of vars), look in enclosing environment

Scanning the environment (details)

```
(define (lookup-variable-value var env)
  (define (env-loop env)
    (define (scan vars vals)
      (cond ((null? vars) (env-loop (enclosing-environment env)))
            ((eq? var (car vars)) (car vals))
            (else (scan (cdr vars) (cdr vals)))))
    (if (eq? env the-empty-environment)
        (error "Unbound variable -- LOOKUP" var)
        (let ((frame (first-frame env)))
          (scan (frame-variables frame) (frame-values frame)))))
  (env-loop env))
```


The Initial (Global) Environment

4. primitives and initial env.

- setup-environment

```
(define (setup-environment)
  (let ((initial-env (extend-environment
                       (primitive-procedure-names)
                       (primitive-procedure-objects)
                       the-empty-environment)))
    (define-variable! 'true #T initial-env)
    (define-variable! 'false #F initial-env)
    initial-env))
```

- define initial variables we always want
- bind explicit set of "primitive procedures"
  - here: use underlying Scheme procedures
  - in other interpreters: assembly code, hardware, ...

Read-Eval-Print Loop

5. read-eval-print loop

```
(define (driver-loop)
  (prompt-for-input input-prompt)
  (let ((input (read)))
    (let ((output (m-eval input the-global-env)))
      (announce-output output-prompt)
      (display output)))
  (driver-loop))
```

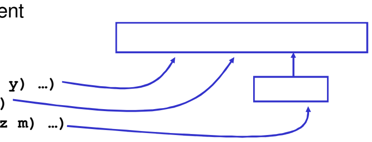
Variations on a Scheme

- More (not-so) stupid syntactic tricks
  - Let with sequencing
    ```
    (let* ((x 4)
           (y (+ x 1))) . . . )
    ```
  - Infix notation
    `((4 * 3) + 7)` instead of `(+ (* 4 3) 7)`
- Semantic variations
  - *Lexical* vs *dynamic* scoping
    - Lexical: defined by the program text
    - Dynamic: defined by the runtime behavior

Diving in Deeper: Lexical Scope

- Scoping is about how **free variables** are looked up (as opposed to bound parameters)
  `(lambda (x) (* x x))`
  ***** is free   **x** is bound
- How does our evaluator achieve lexical scoping?
  - environment chaining
  - procedures capture their enclosing **lexical** environment

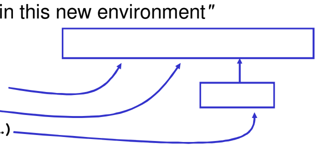
```
(define (foo x y) …)
(define (bar l)
  (define (baz m) …)
  …)
```



Diving in Deeper: Lexical Scope

- Why is our language lexically scoped? Because of the semantic rules we use for procedure application:
  - "Drop a new frame"
  - "Bind parameters to actual args in the new frame"
  - "Link frame to the **environment in which the procedure was defined**" (i.e., the environment surrounding the procedure in the program text)
  - "Evaluate body in this new environment"

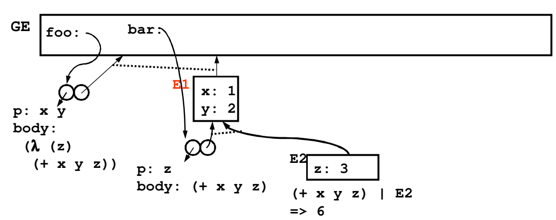
```
(define (foo x y) …)
(define (bar l)
  (define (baz m) …)
  …)
```



Lexical Scope & Environment Diagram

```
(define (foo x y)
  (lambda (z) (+ x y z)))

(define bar (foo 1 2))

(bar 3)
```

Will always evaluate `(+ x y z)` in a new environment inside the surrounding lexical environment.

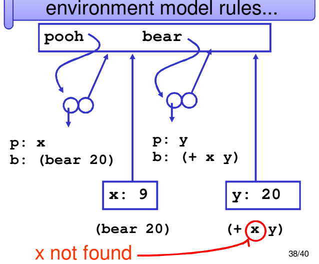


Alternative Model: Dynamic Scoping

- Dynamic scope:
  - Look up free variables in the caller's environment rather than the surrounding lexical environment
- Example:

Suppose we use our usual environment model rules...

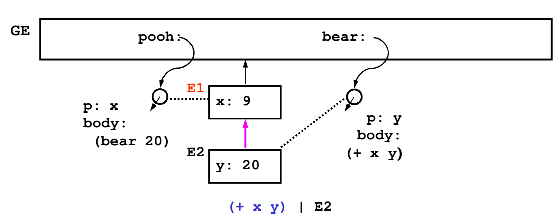
```
(define (pooh x)
  (bear 20))
(define (bear y)
  (+ x y))
(pooh 9)
```



Dynamic Scope & Environment Diagram

```
(define (pooh x)
  (bear 20))

(define (bear y)
  (+ x y))

(pooh 9)
```

Will evaluate `(+ x y)` in an environment that extends the caller's environment.



A "Dynamic" Scheme

```
(define (m-eval exp env)
 (cond
   ((self-evaluating? exp) exp)
   ((variable? exp) (lookup-variable-value exp env))
   ...
   ((lambda? exp)
    (make-procedure (lambda-parameters exp)
                    (lambda-body exp)
                    '*no-environment*))  ;CHANGE: no env
   ...
   ((application? exp)
    (d-apply (m-eval (operator exp) env)
                     (list-of-values (operands exp) env)
                     env)) ;CHANGE: add env
   (else (error "Unknown expression -- M-EVAL" exp))))
```


A "Dynamic" Scheme – d-apply

```
(define (d-apply procedure arguments calling-env)
  (cond ((primitive-procedure? procedure)
         (apply-primitive-procedure procedure
                                    arguments))
        ((compound-procedure? procedure)
         (eval-sequence
          (procedure-body procedure)
          (extend-environment
             (procedure-parameters procedure)
             arguments
             calling-env))) ;CHANGE: use calling env
       (else (error "Unknown procedure" procedure))))
```


Summary

- Scheme Evaluator – Know it Inside & Out
- Techniques for language design:
  - Interpretation: eval/apply
  - Semantics vs. syntax
  - Syntactic transformations
- Able to design new language variants!
  - Lexical scoping vs. Dynamic scoping