The Scheme Programming Language

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Scheme philosophy

"Programming languages should be designed not by piling feature on top of feature, but by removing the weaknesses and restrictions that make additional features appear necessary."

Scheme

- R5RS = Revised^5 Report on Scheme
  (R4RS is the older standard that Dr. Scheme and Guile use)
  - Only 50 pages describe the whole language
- Descends from Lisp and Algol
- Strong theoretical foundations
- Becoming a favourite introductory language

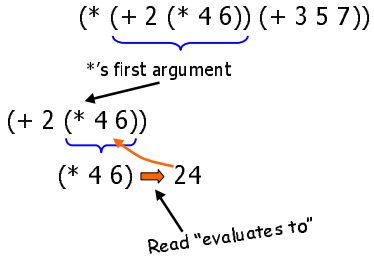
C vs. Scheme expressions

C	Scheme
`factorial(9)`	`(factorial 9)`
`1 + 2`	`(+ 1 2)`
`1 + 3 + 5`	`(+ 1 3 5)`
`(low < x)&&(x < high)`	`(< low x high)`
`f(g(2,-1), 7)`	`(f (g 2 -1) 7)`
`(6+3)*4`	`(* (+ 6 3) 4)`

Prefix vs. infix

- Infix: 2 * (1 + 2)
  - Group explicitly to override precedence
  - Operator must be repeated when applied to more than 2 arguments
- Prefix: (* 2 (+ 1 2))
  - Lots of parentheses **required**
  - (+ 1 2 3 4 5) ⇒ 15
- **Same execution order!**

Nested expressions 1



Nested expressions 2

(* (+ 2 (* 4 6)) (+ 3 5 7))

*'s first argument

(+ 2 (* 4 6)) ⇒ 26

24

Nested expressions 3

(* (+ 2 (* 4 6)) (+ 3 5 7))

26

*'s 2nd argument

(+ 3 5 7)) ⇒ 15

Nested expressions 4

(* (+ 2 (* 4 6)) (+ 3 5 7))

26 15

Finally, do outer multiplication:

(* 26 15) ⇒ 390

Nested expressions 5

(* (+ 2 (* 4 6)) (+ 3 5 7))

390

Moral: Compute expressions "inside-out"

Evaluating arguments

- (+ 1 2)
  - 1 ⇒ 1
  - 2 ⇒ 2

So whole expression: (+ 1 2) ⇒ 3

- 1 and 2 are literal numbers that evaluate to themselves!

Types

- Numbers: 1 3.1415 9/5 -2
- Strings: "Hello world"
- Characters: #\A #\space #\newline
- Booleans: #t #f
  (represent TRUE and FALSE)

More types

- Symbols: + a-list x lambda
- Procedures: #<primitive:+>
  #<procedure:factorial>
- Lists: (1 "str" #\g factorial +)
- Vectors: #(1 "str" #\g factorial +)
- Ports for I/O #<input-port>

What's in a symbol?

- Operators are just procedures, so identifiers must allow them
- Valid characters include
  – + * / < > ^ ~ _ % ! ? $: =
- Digits not allowed at start of symbol

Some "literals" evaluate to themselves

- Numbers: 2 ⇒ 2
- Strings: "Hello world" ⇒ "Hello world"
- Characters: #\g ⇒ #\g
- Booleans: #t ⇒ #t
- Vectors: #(a 2 5/2) ⇒ #(a 2 5/2)

Symbols evaluate by variable lookup

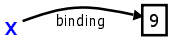
Symbols:
  x ⇒ 9
  a-list ⇒ ("ally" "georgia" "elaine")
  factorial ⇒ #<procedure:factorial>
  + ⇒ #<primitive:+>

➡So how do we give variables a value?

define special form

(define x 9)

- define is not a procedure
  it is a "special form" which does not necessarily evaluate all of its arguments
- Allocates space, and binds the symbol x to that space after initializing it to the value:



Lists evaluate by procedure application*

*Except special forms!

Lists:
  (factorial 4) ⇒ 24
  (+ 1 2) ⇒ 3

  ("ally" "georgia" "elaine") ⇒
  Error: procedure application:
  expected procedure, given: "ally";
  arguments were: "georgia" "elaine"

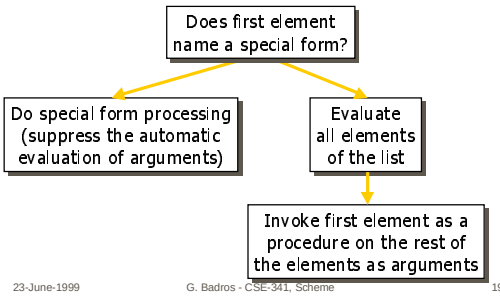
Special forms

Must memorize them!

define	lambda	let, let*, letrec
quote	quasiquote	set!
if	case	cond
begin	do	and, or
let-syntax	letrec-syntax	delay

+ any macros (also must be learned)

List evaluation



Creating symbol value

- Symbols evaluate by variable lookup:
  factorial ⇒ #<procedure:factorial>
- How do we enter a symbol as a value?
  e.g., suppose we want:
  x ⇒ foobar
  What do we write?
  (define x [ ])

Suppressing evaluation

(define x foobar)

Error: reference to undefined identifier: foobar

- foobar is evaluated
  Since symbols are evaluated by variable lookup we get the error
- But we want the symbol foobar
- Solution: must *suppress the evaluation* of the symbol foobar

quote special form

(define x (quote foobar))

Gets evaluated to initialize space x is bound to

(quote foobar) ⇒ foobar

Because quote is a special form, foobar does not get evaluated when evaluating the list (quote foobar).

quote just returns its argument un-evaluated!

Quoting

(quote foobar) ⇒ foobar

- ' is shorthand because quote is so useful
  'foobar ⇒ foobar
- Suppose we want a value that is a list?
  (1 2 3) ⇒ ERROR (1 is not a procedure)
  '(1 2 3) ⇒ (1 2 3)

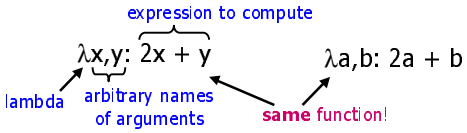
Forcing evaluation with eval

(+ 1 2 3) ⇒ 6
'(+ 1 2 3) ⇒ (+ 1 2 3)
(eval '(+ 1 2 3)) ⇒ 6

- eval evaluates its single argument
- eval is implicitly called to evaluate each expression you enter into the repl (read eval print loop)

The Lambda Calculus

- Typical function in mathematics: f(x,y) = 2x + y
- Alonzo Church's lambda calculus lets us talk about un-named (anonymous) functions:



Creating procedures with the lambda special form

(lambda (x y)
  (+ (* 2 x) y)) ⇒ #<procedure>

(4 5) ⇒ 13
i.e.,
((lambda (x y) (+ (* 2 x) y)) 4 5) ⇒ 13

A moment for syntax

((lambda (x y) (+ (* 2 x) y)) 4 5)
([lambda (x y) (+ (* 2 x) y)] 4 5)
;;; can use [and] as grouping constructs
;;; in some versions of Scheme
;;; (including Dr. Scheme)

Naming a procedure

- No new rule!
  (define f [lambda (x y) (+ (* 2 x) y)])
  (f 4 5) ⇒ 13

- Remember list evaluation rule: we evaluate f by doing variable lookup!

Shorthand for procedure definition

(define f [lambda (x y) (+ (* 2 x) y)])

(define (f x y)
  (+ (* 2 x) y))

Procedures vs. variables

- (define f 3)
  f ⇒ 3
  (f) ⇒ ERROR
- (define (f) 3)
  f ⇒ #<procedure:f>
  (f) ⇒ 3

Parentheses around name make this the same as:
(define f (lambda () 3))
which is a procedure that, when called, returns 3.

Conditionals: if special form

(if *TEST TRUE-EXPR FALSE-EXPR*)

- if is an expression—evaluates to either TRUE-EXPR or FALSE-EXPR depending on the value of TEST
- (if #t 3 4) ⇒ 3
- (if (> 5 6) 3 4) ⇒ 4

C vs. Scheme

C

```
if (operator == PLUS)
  return add(x,y);
else
  return subtract(x,y);
```

Scheme

```
(if (eq? operator 'PLUS)
    (add x y)
    (subtract x y))
```


C vs. Scheme

C

```
if (operator == PLUS)
  return add(x,y);
else
  return subtract(x,y);
```

Repeated arguments

Scheme

```
([if (eq? operator 'PLUS)
    add
    subtract]
  x y)
```

Evaluates to either #<procedure:subtract> or #<procedure:add>

eq? procedure tests for identity equality

- (eq? 'foo 'foo) ⇒ #t
- (eq? 'foo 'bar) ⇒ #f

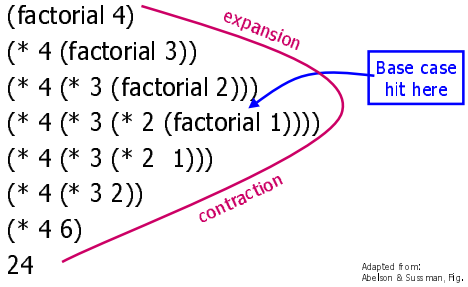
- Procedures ending in ? are predicates—they return a boolean value, #t or #f
- Symbols are only useful as identifiers and for eq? comparison testing

Recursion

```
(define (factorial n)
  (if (<= n 1)
      1                                  ; base case
      [* n (factorial (- n 1))]))        ; inductive step
```

Procedure is calling itself

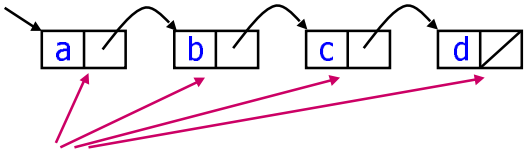
Linear recursive process



Lists are made of *cons* cells

- Lists are a recursive data structure!

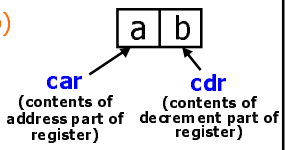
(a b c d) is shorthand for:



"cons" cells—each holds a pair of values

cons cells and the cons procedure

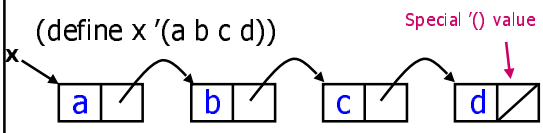
- (cons 'a 'b) ⇒ (a . b)



Axioms:
(car (cons α β)) ⇒ α
(cdr (cons α β)) ⇒ β

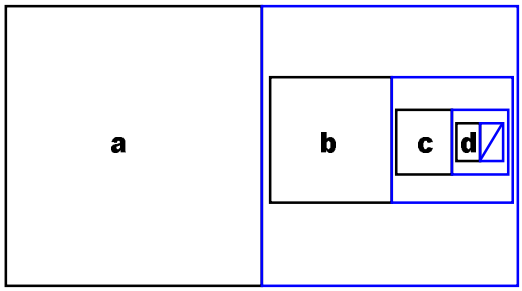
List syntax shorthand

(define x '(a b c d))



(cons a (cons b (cons c (cons d '()))))
(car x) ⇒ a
(cdr x) ⇒ (b c d) ; another list!

Beware the arrow: Another look at lists



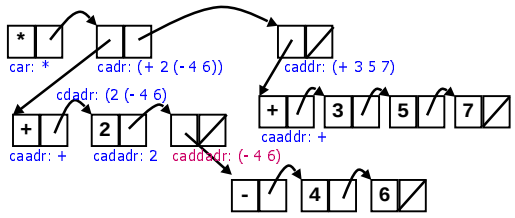
car, cdr, and friends

(define x '(a b c d))
(car (cdr x)) ⇒ b (cadr x) ⇒ b
(car (cdr (cdr x))) ⇒ c (caddr x) ⇒ c

All combinations of up to four a/d characters are standard; e.g.:
caaaar, cddddr, cdadar, cdar, cadadr, etc.

Nested lists

(*(+ 2 (- 4 6)) (+ 3 5 7))



Do not try this at home

```
(define (caddadr a-list)
  (car (cddadr a-list)))
```

- Rely instead on recursive processing of the data structure

our-list-ref procedure

```
(define (our-list-ref items n)
  "Return element N of list ITEMS."
  (if (= n 0)
      (car items)
      (our-list-ref (cdr items) (- n 1))))
```


our-list-ref trace
Linear iterative process

```
(our-list-ref '(a b c d) 3)
(our-list-ref '(b c d) 2)
(our-list-ref '(c d) 1)
(our-list-ref '(d) 0)
d
```

base case n=0, so return (car '(d))

- No expansion and contraction!

Contrast the inductive steps

(* n [factorial (– n 1)])

[our-list-ref (cdr items) (- n 1)]

- factorial recurses and the result is used in further computation:
  (* n □)

Tail-recursion

our-list-ref is "tail-recursive"

- Recursive call's return value is the final result
- Thus, the recursion can be replaced with iteration (i.e., a "goto" the top of the procedure with variables re-bound)
- Standard Scheme implementations are **required** to eliminate tail recursions!

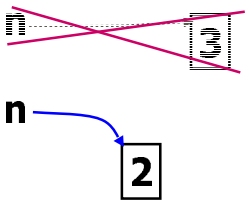
our-list-ref tail recursion

```
(define (our-list-ref items n)
  (if (= n
      (car
      (our-list-ref (cdr items) (- n 1))))
```

Bind items to (cdr items),

Bind n to (- n 1)

Re-binding is NOT assignment



Iterative version of factorial

```
(define (factorial n)
  (fact-iter 1 1 n))

(define (fact-iter product counter max-count)
  (if (> counter max-count)
      product
      [fact-iter  (* counter product)
                  (+ counter 1)
                  max-count]))
```

Helper procedure

Iterative factorial trace

(factorial 4) ;;	product	counter	max
(fact-iter	1	1	4)
(fact-iter	1	2	4)
(fact-iter	2	3	4)
(fact-iter	6	4	4)
(fact-iter	24	5	4)

counter > max, so terminate

Nested procedure defines

```
(define (factorial n)
  [define (iter product counter)
    (if (> counter n)
        product
        [iter (* counter product)
              (+ counter 1)])]
  (iter 1 1))
```

iter is bound only within this block

Factoring out common sub-expressions

$f(x,y) = x(1+xy)^2 + y(1-y) + (1+xy)(1-y)$

$a = 1+xy$

$b = 1-y$

$f(x,y) = xa^2 + yb + ab$

let special form

a = 1+xy
b = 1-y
f(x,y) = xa² + yb + ab

```
(define (f x y)
  (let ([a (+ 1 (* x y))]
        [b (- 1 y)])
    (+ [* x (square a)] [* y b] [* a b])))
```

list of bindings

expression to evaluate and return

Scope is visibility

```
(define (f x y)
  (let ([a (+ 1 (* x y))]
        [b (- 1 y)])
    (+ [* x (square a)] [* y b] [* a b])))
```

Scope of a and b only in this block

a ⇒ ERROR (a not visible at "top level")

let bindings happen in parallel

(define x 'a)
(define y 'b)
(list x y) ⇒ (a b)
(let ([x y] [y x]) (list x y)) ⇒ (b a)

- Remember, it is still **not** assignment—only re-binding

Bad let bindings

```
(let ([x 1] [y (+ x 1)]) (list x y))
```

Reference to undefined identifier

- So what if we do want y to be computed in terms of x?

let* special form

(let* ([x 1] [y (+ x 1)]) (list x y)) ⇒ (1 2)

Syntactic sugar for nested lets

```
(let ([x 1])
  (let ([y (+ x 1)]) (list x y)))
```


More about conditionals: cond special form

(if *TEST EXPR-TRUE EXPR-FALSE*)

- cond evalutates to EXPR-K, where K is the lowest of the TEST-Ks that evaluates to #t

```
(cond [TEST-1 EXPR-1]
      [TEST-2 EXPR-2]

      [TEST-N EXPR-N]
      [else ELSE-EXPR])  ; or [#t ELSE-EXPR]
```

cond example

```
(define (sign number)
  (cond [(> number 0) 'positive]
        [(< number 0) 'negative]
        [else 'zero]))
```

(sign -1) ⇒ negative
(sign 0) ⇒ zero
(sign 'a) ⇒ ERROR!

Short-circuiting and, or special forms

(and (> 1 0) (> 2 3) (/ 5 0)) ⇒ #f
#f, so never evaluates this

(or (> 0 1) (> 2 1) (/ 5 0)) ⇒ #t
#t, so never evaluates this

Boolean values & and, or

- All values except #f are treated as #t in conditionals
- and evaluates to the last value in sequence if it succeeds (not necessarily #t)
  (and (+ 2 3) (- 3 1)) ⇒ 2
- or evaluates to the first true value in sequence if it succeeds (not necessarily #t)
  (or (> 4 5) 'a (/ 5 0)) ⇒ a

Procedures are first-class values

- lambda special form returns a procedure
- Procedures can take procedures as arguments
- Procedures can return procedures
- Procedures are treated no differently from other kinds of values
  (e.g., numbers, lists, strings, symbols, etc.)

map, a higher-order function

(define (negation x) (- x))
the list of return values
(map negation '(1 2 -5 7)) ⇒ (-1 -2 5 -7)
(map + '(1 2 3) '(4 5 6)) ⇒ (5 7 9)
two lists, so give two arguments to each + call
(map [lambda (x) (+ x 2)]
  '(-2 0 2)) ⇒ 0 2 4

- A higher-order function is one that operates on other functions

Filter procedure

(filter number? '(a 4 "testing" +)) ⇒ (4)

(filter [lambda (x) (>= x 0)]
  '(-2 3 -1 1 4)) ⇒ (3 1 4)

(filter [lambda (x) (>= x 2)]
  '(-2 3 -1 1 4)) ⇒ (3 4)

Typechecking predicates

(number? 4) ⇒ #t
(string? "foo") ⇒ #t
(symbol? 'foo) ⇒ #t
(pair? (cons 'a 'b)) ⇒ #t
(pair? '(a b c d e f)) ⇒ #t
(pair? '(1)) ⇒ #t
(pair? '()) ⇒ #f (pair? 6) ⇒ #f
(null? '()) ⇒ #t (null? 0) ⇒ #f

All names end in ?

Procedure factories

```
(filter [lambda (x) (>= x 0)]
  '(-2 3 -1 1 4)) ⇒ (3 1 4)
(filter [lambda (x) (>= x 2)]
  '(-2 3 -1 1 4)) ⇒ (3 4)

(define (greater-than-n?? n)
  (lambda (x) (>= x n)))
```


Building procedures

```
(define (greater-than-n?? n)
  (lambda (x) (>= x n)))
greater-than-n?? ⇒ #<procedure>
(greater-than-n?? 2) ⇒ #<procedure>
((greater-than-n?? 2) 3) ⇒ #t
(define greater-than-2 (greater-than-n?? 2))
(greater-than-2 3) ⇒ #t
```

A factory procedure

predicate

Dr. Scheme Graphics

```
(define v (open-viewport ...))
(define red (make-rgb 1 0 0))
((draw-pixel v) (make-posn 100 120) red)
```

Returns a procedure that is specialized for drawing a pixel on the viewport v

```
(define draw-on-v (draw-pixel v))
(draw-on-v (make-posn 100 120) red)
```


lambdas and closures

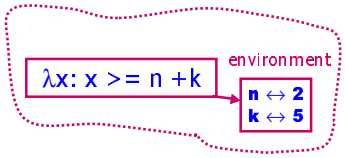
```
(define (greater-than-n?? n)
  (lambda (x) (>= x n)))

(lambda (x) (>= x n))
```

- which n? Looks like an undefined reference!
- lambda "remembers" the value n had when the procedure was created—it "closes" over its environment and gives a "closure"

lambdas and their environments

```
(define (greater-than-n-by-k?? n k)
  (lambda (x) (>= x (+ n k))))
(greater-than-n-by-k?? 2 5) ⇒
```



Free variables and Lexical Scoping

```
(define (greater-than-n-by-k?? n k)
  (lambda (x) (>= x (+ n k))))
(define pred (greater-than-n-by-k?? 2 5))

(let ([n 0] [k 0])
  (pred 1)) ⇒ #f
```

These bindings are unused

Dynamic Scoping

```
(define (greater-than-n-by-k?? n k)
  (lambda (x) (>= x (+ n k))))
(define pred (greater-than-n-by-k?? 2 5))

(let ([n 0] [k 0])
  (pred 1)) ⇒ #t
```

These args are unused

Lexical vs. Dynamic Scope

- Lexical
  - Fewer surprises
  - Easier to compile—all mentions of a variable refer to the same variable
- Dynamic
  - Historical LISPs—considered an implementation bug by McCarthy
  - Can result in confusing "name capture"
    (Sometimes (but rarely) this is what you want)

Lexical scope and variable hiding

```
(define x 4)
(display x)          ; writes 4
(let ([x "hello"])
  (display x)        ; writes "hello"
  (let ([x '(1 2)])
    (display x))     ; writes (1 2)
  (display x))       ; writes "hello" again
```


When the arguments don't fit

- Suppose we have args ⇒ (1 2 3) and we want to compute the sum:
  (+ args) ⇒ Error; expects args of type number
- We need a list with + as first element, then the elements of args: (+ 1 2 3)
- Create the list and evaluate it:
  (cons + args) ⇒ (+ 1 2 3)
  (eval (cons + args)) ⇒ 6

A more direct approach: the apply procedure

```
(apply + args)
```

Procedure — Arguments to use

```
(apply [lambda (x y) (+ x y)] '(1 2))
```

Procedure arity

- (define (proc0) 'foo)
  (arity proc0) ⇒ 0
- (define (proc1 arg) 'foo)
  (arity proc1) ⇒ 1
- (define (procn . args) 'foo))
  (arity procn) ⇒ #(struct arity-at-least 0)
- (define (proc reqd1 reqd2 . rest) 'foo))
  (arity proc) ⇒ #(struct arity-at-least 2)

Rest arguments

(define (skip-first ignore . rest) rest)
(skip-first 1 2 3) ⇒ (2 3)
(define (skip-first . args) (cdr args))

(define skip-first (lambda (. args) (cdr args))
  Error! Can't put "." as first element in list

(define skip-first (lambda args (cdr args)))

Controlling evaluation inside of lists

Evaluated
Unevaluated

(define a "Hello")
'(1 a (+ 2 3)) ⇒ (1 a (+ 2 3))
(list 1 a (+ 2 3)) ⇒ (1 "Hello" 5)
(list 1 'a (+ 2 3)) ⇒ (1 a 5)
`(1 a (+ 2 3)) ⇒ (1 a (+ 2 3))
`(1 a ,(+ 2 3)) ⇒ (1 a 5)
`(1 ,a ,(+ 2 3)) ⇒ (1 "Hello" 5)

quasiquote and unquote

- (quasiquote (α)) ⇔ `(α)
  Only evaluate parts of α that are unquoted
- (unquote β) ⇔ ,β

(quasiquote (1 a (unquote (+ 2 3)))
  ⇒ (1 a 5)

Forcing and suppressing evaluation are fundamental

- Not Scheme's fault—
  it just gives you finer control!
- C/C++ lack such complexity in the general case because they are more restricted languages
- Analogous to dereferencing or taking address of variables when dealing with pointers

Comparisons

- C/C++:
  (4 == x) && ('\n' == ch)
- Scheme:
  (and (= 4 x) (char=? ch #\newline))
- Other comparison procedures:
  string=?
  eq? eqv? equal?

eq?, eqv?, equal?

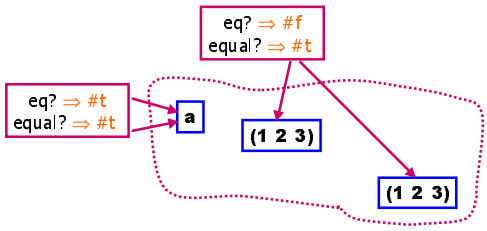
(eq? 'a 'a) ⇒ #t (eq? 'a 'b) ⇒ #f
(eq? 9 9) ⇒ #t (eq? 1234567890 1234567890) ⇒ #f
(eqv? 9 9) ⇒ #t (eqv? 1234567890 1234567890) ⇒ #t
(eq? "foo" "foo") ⇒ #f
(eqv? "foo" "foo") ⇒ #f
(equal? "foo" "foo") ⇒ #t
(eq? (list 1 2 3) (list 1 2 3)) ⇒ #f
(equal? (list 1 2 3) (list 1 2 3)) ⇒ #t

More eq?, eqv?, equal?

(define a "foo")
(eq? a "foo") ⇒ #f
(eq? a a) ⇒ #t
(equal? a "foo") ⇒ #t

- Values can look the same, but be different objects
- eq? tests for object-identity equality
  - returns #t only when they are same object
  - symbols are "intern"ed to make them the same

Objects/values in the Scheme Heap



Do not use eq? for numbers

- Some numbers compare eq? to themselves, others do not
- Answer depends on how Scheme stores numbers (implementation-dependent):

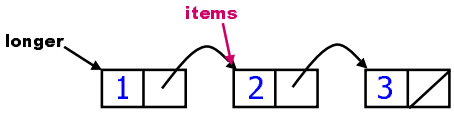
Making new lists

(define items '(2 3))

- Already saw how to get a list with a new first element:
  (cons 1 items) ⇒ (1 2 3)
  items ⇒ (2 3) ; items is unchanged
- How can we get (2 3 4)?
  (cons items 4) ⇒ ((2 3) . 4) ; wrong!
  (append items 4) ⇒ (2 3 . 4) ; closer...
  (append items '(4)) ⇒ (2 3 4) ; Yes!

Sharing of list structure

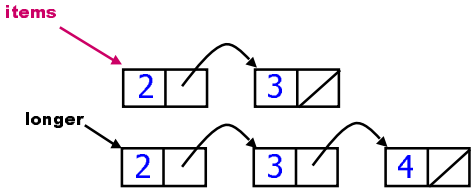
(define items '(2 3))
(define longer (cons 1 items))



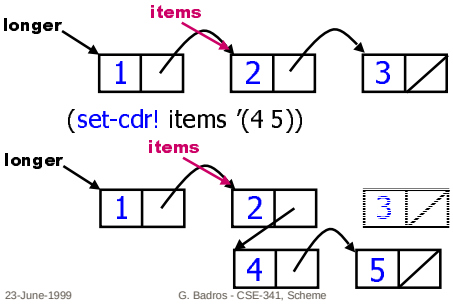
longer ⇒ (1 2 3)
items ⇒ (2 3)
(eq? items (cdr longer)) ⇒ #t

append must duplicate the list

(define items '(2 3))
(define longer (append items '(4)))



List surgery



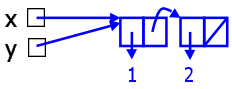
(set-cdr! items '(4 5))

set-cdr! and set-car!

- Change what a cons cell contains
- They side-effect the values passed in!
- Exclamation point (!) tells you that an argument is being altered
- Non-functional feature—useful mostly for efficiency

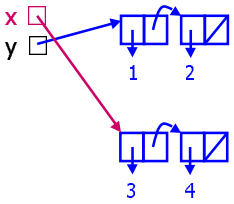
Assignment

(define x '(1 2))
(define y x)
(eq? x y) ⇒ #t
(set! x '(3 4))



set! procedure

(define x '(1 2))
(define y x)
(eq? x y) ⇒ #t
(set! x '(3 4))
x ⇒ (3 4)
y ⇒ (1 2)



Other side-effects

- display procedure input/output in general (display 1) ⇒ #unspecified
- (define x #\A) ⇒ #unspecified
- (/ 5 0) ⇒ Run-time error
- (iconify-window (get-window)) ⇒ #unspecified

Sequencing and the begin special form

```
(define hw (lambda ()
                (display "hello ")
                (display "world")))
(hw) ⇒ #unspecified ; prints "hello world"
(begin
  (display "hello ") 2 "foo" (display "world")
  "last"))) ⇒ "last" ; prints "hello world"
```