
Polymorphic and Monomorphic Functions

- *Polymorphic* functions can be applied to arguments of many forms
- The function `length` is polymorphic: it works on lists of numbers, lists of symbols, lists of lists, lists of anything
- The function `square` is monomorphic: it only works on numbers

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Higher-Order Procedures

Procedures as **input values**:

```
(define (all-num lst)
  (or (null? lst)
      (and (number? (car lst))
           (all-num (cdr lst)))))

(define (all-num-f f lst)
  (cond ((all-num lst) (f lst))
        (else 'error)))

1 ]=> (all-num-f abs-list '(1 -2 3))
;Value 1: (1 2 3)

1 ]=> (all-num-f abs-list '(1 a))
;Value: error
```

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Higher-Order Procedures

Procedures as **returned values**:

```
(define (plus-list x)
  (cond (number? x)
        (lambda (y) (+ (sum-n x) y)))
        (list? x)
        (lambda (y) (+ (sum-list x) y)))
        (else (lambda (x) x))))

1 ]=> ((plus-list 3) 4)
;Value: 10

1 ]=> ((plus-list '(1 3 5)) 5)
;Value: 14
```

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Built-In Higher-Order Procedures: map

There is a built-in procedure `map`. Let's define our own restricted version first....

```
(define (mymap f l)
  (cond ((null? l) '())
        (else (cons (f (car l))
                      (mymap f (cdr l))))))
```

- `mymap` takes two arguments: a function and a list
- `mymap` builds a new list whose elements are the result of applying the function to each element of the (old) list

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Higher-order Procedures: map

- Example:

```
(mymap abs '(-1 2 -3 4)) =>
(1 2 3 4)

(mymap (lambda (x) (+ 1 x)) '(-1 2 -3)) =>
(0 3 -2)
```
- The built-in `map` will produce the same results, but note that the built-in `map` can take more than two arguments:

```
(map cons '(a b c) '((1) (2) (3))) =>
((a 1) (b 2) (c 3))
```

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What's Wrong Here??

```
1 ]=>
(define (atomcount s)
  (cond ((null? s) 0)
        ((atom? s) 1)
        (else (+ (map atomcount s))))
  )
;Value: atomcount
1 ]=> (atomcount '(a b))

;The object (1 1), passed as an argument
;to +, is not the correct type.
..
2 error>
```

Why doesn't this work?

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Using eval to Correct the Problem

```
(define (atomcount s)
  (cond ((null? s) 0)
        ((atom? s) 1)
        (else
         (eval
          (cons '+ (map atomcount s)) '()))))
  )
;Value: 2

1 ]=> (atomcount '(a b))

;Value: 2

1 ]=> (atomcount '((1) (2 3 4) (((5))))))
;Value: 5
```

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Limitations of Using eval

BUT: `eval` only works in the current definition of `atomcount` because numbers evaluate to themselves.

```
1 ]=> (+ 1 2 3)
;Value: 6

1 ]=> (cons '+ '(1 2 3))
;Value 12: (+ 1 2 3)

1 ]=> (eval (cons '+ '(1 2 3)) '())
;Value: 6
```

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Using eval to Evaluate Expressions

```
1 ]=> (append '(a) '(b))
;Value 13: (a b)
1 ]=> (cons 'append '((a) (b)))
;Value 14: (append (a) (b))

1 ]=> (eval (cons 'append '((a) (b))) '())
;Unbound variable: b
...
1 ]=> (cons 'append '( '(a) '(b) ))
;Value 15: (append (quote (a)) (quote (b)))

1 ]=> (eval
      (cons 'append '( '(a) '(b))) '())
;Value 16: (a b)
```

Too complicated!!

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Applying Procedures with apply

```
1 ]=> (apply + '(1 2 3))
;Value: 6
1 ]=> (apply append '((a) (b)))
;Value 5: (a b)

1 ]=>
(define (atomcount s)
  (cond ((null? s) 0)
        ((atom? s) 1)
        (else
         (apply + (map atomcount s)))))
;Value: atomcount
1 ]=> (atomcount '(a (b) c))
;Value: 3
```

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Higher-order Procedures: my-reduce

```
(define (my-reduce op l id)
  (if (null? l)
      id
      (op (car l)
           (my-reduce op (cdr l) id))))
```

A binary \mapsto n-ary procedure.

The my-reduce procedure takes a binary operation and applies it right-associatively to a list of an arbitrary number of arguments.

NOTE: my-reduce is not equivalent to apply.

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Higher-order Procedures: my-reduce

```
(my-reduce + '(1 2 3) 0)  $\Rightarrow$  6:
(my-reduce + '(1 2 3) 0)
(+ 1 (my-reduce + '(2 3) 0))
(+ 1 (+ 2 (my-reduce + '(3) 0)))
(+ 1 (+ 2 (+ 3 (my-reduce + '() 0))))
(+ 1 (+ 2 (+ 3 0)))
6
Note: (+ 1 2 3)  $\Rightarrow$  6
```

```
(my-reduce / '(24 6 2) 1)  $\Rightarrow$  8:
(my-reduce / '(24 6 2) 1)
(/ 24 (my-reduce / '(6 2) 1))
(/ 24 (/ 6 (my-reduce / '(2) 1)))
(/ 24 (/ 6 (/ 2 (my-reduce / '() 1))))
(/ 24 (/ 6 (/ 2 1)))
8
Note: (/ 24 6 2)  $\Rightarrow$  2
```

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Higher-order Procedures: my-reduce

Given union, which takes two lists representing sets and returns their union:

```
1 ]=> (apply union '((1 3)(2 3 4)))
;Value 21: (1 2 3 4)

1 ]=> (apply union '((1 3)(2 3)(4 5)))
;The procedure #[compound-procedure union]
;has been called with 3 arguments;
;it requires exactly 2 arguments.

1 ]=> (reduce union '((1 3)(2 3)(4 5)) '())
;Value 22: (1 2 3 4 5)
```

Question: How would you have to change my-reduce to be able to take intersection as its function argument?

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Important

Note that Scheme has a built-in higher-order procedure reduce that is different from my-reduce. You may use my-reduce in assignments and tests. In assignments, you would of course have to define it by copying the code provided here. In tests, you may use it without defining it.

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Example Practice Procedures

- cdrLists: given a list of lists, form new list giving all elements of the cdr's of the sublists.
 $((1\ 2)\ (3\ 4\ 5)\ (6)) \Rightarrow (2\ 4\ 5)$
- swapFirstTwo: given a list, swap the first two elements of the list.
 $(1\ 2\ 3\ 4) \Rightarrow (2\ 1\ 3\ 4)$
- swapTwoInLists: given a list of lists, form new list of all elements in all lists, with first two of each swapped.
 $((1\ 2\ 3)(4)(5\ 6)) \Rightarrow (2\ 1\ 3\ 4\ 6\ 5)$
- addSums: given a list of numbers, sum the total of all sums from 0 to each number.
 $(1\ 3\ 5) \Rightarrow 22$

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More Practice Procedures

- addToEnd: add an element to the end of a list.
 $(\text{addToEnd 'a '(a b c)}) \Rightarrow (a\ b\ c\ a)$
- revLists: given a list of lists, form new list consisting of all elements of the sublists in reverse order.
 $((1\ 2)\ (3\ 4\ 5)\ (6)) \Rightarrow (6\ 5\ 4\ 3\ 2\ 1)$
- revListsAll: given a list of lists, form new list from reversal of elements of each list.
 $((1\ 2)\ (3\ 4\ 5)\ (6)) \Rightarrow (2\ 1\ 5\ 4\ 3\ 6)$

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Passing procedures: prune

Suppose we want a procedure that will test every element of a list and return a list containing only those that pass the test.

We want it to be very general: it should be able to use any test we might give it. How will we tell it what test to apply?

What should a procedure call look like?

Example: Prune out the elements of `myList` that are not atoms.

Now let's write the procedure.

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```
; Return a new list containing only the elements of list
; that pass the test.
; Precondition:
```

```
(define prune
  (lambda (test lst)
    (cond ((null? lst) '())
          ((test (car lst))
           (cons (car lst)
                 (prune test (cdr lst))))
          (else (prune test (cdr lst))))))
```

Sample run

```
1 ]=> (define (atom? x) (not (pair? x)))
;Value: atom?
```

```
1 ]=> (prune atom? '((3 1) 4 (x y z) (x) y ()))
;Value 12: (4 y ())
```

```
1 ]=> (prune null? '(() (a b c) (1 2) () (()) (x (y w) z)))
;Value 13: (() ())
```

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Write calls to `prune` that will prune `myList` in these ways:

- Prune out elements that are null.
- (Assume `myList` contains lists of integers.) Prune out elements whose minimum is not at least 50.
Hint: there is a built-in `min` procedure.
- (Assume `myList` contains lists.) Prune out elements that themselves have more than 2 elements.

This is becoming tedious. We need to declare a procedure for each possible test we might dream up.

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Passing Anonymous Procs

```
1 ]=> (define myList
      '(() (a b c) (1 2) () (()) (x (y w) z)))
;Value: myList
```

```
1 ]=> (prune (lambda (x) (not (null? x))) myList)
;Value 4: ((a b c) (1 2) (()) (x (y w) z))
```

```
1 ]=> (define myList '((59 72 40) (85 70 88 56)))
;Value: myList
```

```
1 ]=> (prune (lambda (x) (> (apply min x) 50)) myList)
;Value 5: ((85 70 88 56))
```

```
1 ]=> (define myList '((23 34) (10 1 3 4) () (2 3 4)))
;Value: myList
```

```
1 ]=> (prune (lambda (x) (<= (length x) 2)) myList)
;Value 6: ((23 34) ())
```

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set!

Global Assignment (Generally EVIL!)

When an assignment statement is applied to variables (i.e., memory locations) that are:

- maintained AFTER the procedure call is completed.
- are used for their values in this or other procedures.

it **violates referential transparency** and destroys the ability to statically analyze source code (formally and intuitively).

E.g.,

```
(define g 10) ; define global variable g
```

```
(define (func a)
  (set! g (* g g)) ; globally assign g=g*g
  (+ a g))
)
```

```
] => (func 7)
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```

```
] => (func 7)
10007 ; BAD!
```

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set! (cont.)

```
(set! <var> <expr>)
```

alters the value of an existing binding for `var`. Evaluates `expr` then assigns `var` to `expr`.

Useful for implementing counters, state change or for caching values.

References: Dybvig

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set! (cont.)

```
(define cons-count 0)
(define cons
  (let ((old-cons cons))
    (lambda (x y)
      (set! cons-count (+ cons-count 1))
      (old-cons x y))
    )
  )
)
```

```
(cons 'a '(b c)) => (a b c)
cons-count => 1
(cons 'a (cons 'b (cons 'c '()))) => (a b c)
cons-count => 4
```

What's the problem?

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set! (cont)

```
(define count
  (let ((next 0))
    (lambda ()
      (let (v next)
        (set! next (+ next 1))
        v))))
```

```
count => 0
```

```
count => 1
```

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More on Efficiency

We previously saw that helper procedures and local variables (`let`, `let*`) can improve the efficiency of a Scheme program. A third way of improving efficiency (sometimes) is through the use of an accumulator.

Trace the following two procedures. What is their complexity?

```
(define (rev1 lst)
  (cond ((null? lst) '())
        (else (append
                (rev1 (cdr lst))
                (list (car lst))))))
)
```

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More on Efficiency

Using an **accumulator** `new`.

```
(define (rev2 lst new)
  (cond ((null? lst) new)
        (else (rev2 (cdr lst)
                    (cons (car lst) new))))))
)
```

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A Lesson in (In)efficiency: Fibonacci

Problem: Compute the n^{th} Fibonacci number.

Recall, the *Fibonacci numbers* are an infinite sequence of integers 0, 1, 1, 2, 3, 5, 8, etc., in which each number is the sum of the two preceding numbers in the sequence. $F(0) = 0, F(1) = 1$, etc.

Let's define a simple fibonacci procedure:

```
(define fib
  ; (fib n) returns the nth Fibonacci number
  ; Pre: n is a non-negative integer
  ; Pre: n is a non-negative integer
  (lambda (n)
```

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Simple Fibonacci

```
(define fib
  ; (fib n) returns the nth Fibonacci number
  ; Pre: n is a non-negative integer
  ; We added some display statements so we could see what was happening
  ; Of course trace also works!
  (lambda (n)
    (display "entering fib")
    (display n)
    (newline)
    (cond ((= n 0) 0)
          ((= n 1) 1)
          (else (+ (fib (- n 1)) (fib (- n 2))))))
  )
)
```

Problem: Procedure is doubly recursive. Complexity is exponential!

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Let's Run Simple Fibonacci

```
1 ]=> (fib 6)
entering fib6
entering fib4
entering fib2
entering fib0
entering fib1
entering fib3
entering fib1
entering fib2
entering fib0
entering fib1
entering fib6
entering fib3
entering fib1
entering fib2
entering fib0
entering fib1
entering fib4
entering fib2
entering fib0
entering fib1
entering fib3
entering fib1
entering fib2
entering fib0
entering fib1
entering fib3
entering fib1
entering fib2
entering fib0
entering fib1
;Value: 8
```

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Trace of Simple Fibonacci

```
1 ]=> (fib 3)
entering fib3
entering fib1
entering fib2
entering fib0
entering fib1
;Value: 2
1 ]=> (trace fib)
;Unspecified return value
1 ]=> (fib 3)
[Entering #[compound-procedure 1 fib]
  Args: 3]
entering fib3
[Entering #[compound-procedure 1 fib]
  Args: 1]
entering fib1
[1 <=> #[compound-procedure 1 fib]
  Args: 1]
[Entering #[compound-procedure 1 fib]
  Args: 2]
entering fib2
[Entering #[compound-procedure 1 fib]
  Args: 0]
entering fib0
[0 <=> #[compound-procedure 1 fib]
```

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```
  Args: 0]
[Entering #[compound-procedure 1 fib]
  Args: 1]
entering fib1
[1 <=> #[compound-procedure 1 fib]
  Args: 1]
[1 <=> #[compound-procedure 1 fib]
  Args: 2]
[2 <=> #[compound-procedure 1 fib]
  Args: 3]
;Value: 2
```

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Faster Fibonacci

Hint: Use an **accumulator** (or two!) to store intermediate values.

```
; (fast-fib p1 p2 i n) returns the nth Fibonacci number
;;;;
;Pre: n>=0 is an integer, 0<=i<=n is an integer
; p1 is the ith Fibonacci number
; p2 is the i+1th Fibonacci number
;
(define fast-fib
  (lambda (p1 p2 i n)
```

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Faster Fibonacci (cont.)

```
; (fast-fib p1 p2 i n) returns the nth Fibonacci number
;Pre: n>=0 is an integer, 0<=i<=n is an integer
; p1 is the ith Fibonacci number
; p2 is the i+1th Fibonacci number
;
(define fast-fib
  (lambda (p1 p2 i n)
    (display "entering fast-fib ")
    (display i)
    (newline)
    (if (= i n)
        p1
        (fast-fib p2 (+ p1 p2) (+ i 1) n)))
  )

; (fib n) returns the nth Fibonacci number
; Pre: n is a non-negative integer
(define fib
  (lambda (n)
    (fast-fib 0 1 0 n)))
```

Time complexity of this fib procedure is linear!

Lesson: Accumulators are useful for writing efficient code. (e.g., factorial, reverse, etc.)

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Let's Run Faster Fibonacci

```
1 ]=> (fib 6)
entering fast-fib 0
entering fast-fib 1
entering fast-fib 2
entering fast-fib 3
entering fast-fib 4
entering fast-fib 5
entering fast-fib 6
;Value: 8

1 ]=> (fib 3)
entering fast-fib 0
entering fast-fib 1
entering fast-fib 2
entering fast-fib 3
;Value: 2
```

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Trace of Faster Fibonacci

```
1 ]=> (trace fast-fib)
;Unspecified return value

1 ]=> (fib 3)
[Entering #[compound-procedure 1 fast-fib]
  Args: 0
        1
        0
        3]
entering fast-fib 0
[Entering #[compound-procedure 1 fast-fib]
  Args: 1
        1
        1
        3]
entering fast-fib 1
[Entering #[compound-procedure 1 fast-fib]
  Args: 2
        2
        2
        3]
entering fast-fib 2
[Entering #[compound-procedure 1 fast-fib]
  Args: 3
        3
        3
        3]
entering fast-fib 3
[2
```

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```
<== #[compound-procedure 1 fast-fib]
Args: 2
      3
      3]
[2
  <== #[compound-procedure 1 fast-fib]
  Args: 1
        2
        3]
[2
  <== #[compound-procedure 1 fast-fib]
  Args: 1
        1
        1
        3]
[2
  <== #[compound-procedure 1 fast-fib]
  Args: 0
        1
        0
        3]
;Value: 2
```

Other Useful Scheme: Strings

Sequences of characters.
Written within double quotes, e.g., "hi mom"

Useful string predicate procedures:

```
(string=? <string1> <string2> ...)
(string<? <string1> <string2> ...)
(string<=? ...
etc.
```

Case-insensitive versions:

```
(string-ci=? <string1> <string2> ...)
(string-ci<? <string1> <string2> ...)
(string-ci<=? ...
```

Other string procedures:

```
(string-length <string>)
(string->symbol <string>)
(symbol->string <symbol>)
(string->list <string>)
(list->string <list>)
```

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Other Useful Scheme Procedures

Input and Output

```
(read ...) ; reads and returns an expression
(read-char ...) ; reads & returns a character
(peek-char ...) ; returns next avail char w/o updating
(char-ready? ...) ; returns #t if char has been entered
(write-char ...) ; outputs a single character
(write <object> ...) ; outputs the object
(display <object> ...) ; outputs the object (pretty)
(newline) ; outputs end-of-line

;; Display a number of objects, with a space between each.
(define display-all
  (lambda (lst)
    (cond ((null? lst) ())
          ((null? (cdr lst)) (display (car lst)) ())
          (else (display (car lst)) (display " ")
                (apply display-all (cdr lst)))))
  )
```

```
(define lst '(a b c d))
(display-all "List: " lst "\n") ; List (a b c d) <cr>
(apply display-all lst) ; a b c d
```

Reading/writing files

```
(open-input-file)
(open-output-file)
```

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Syntactic Forms

if, begin, or, and are useful **syntactic forms**.

They have *lazy evaluation*, i.e., their subexpressions are not evaluated until required.

Let's look at lazy evaluation and how to exploit it.

```
(if (= n 0)
    (display "oops")
    (/ 1 n))
```

if is evaluated left to right. The "else part" is only evaluated as necessary, so (/ 1 n) is only evaluated if the conditional expression is false.

Imagine if if were implemented as a procedure. We'd be in trouble! It's a syntactic form so its evaluation is different.

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Syntactic Forms (cont.)

(begin *expr1 expr2* ...)

begin evaluates its subexpressions from left to right and returns the value of the last subexpression. begin can be used to sequence assignment statements, inputs/outputs, or other operations that cause side effects. E.g.,

```
(begin
  (display "this is line 1 of the message")
  (display "this is line 2 of the message")
  #f
)
```

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Syntactic Forms (cont.)

```
(or) => #f  
(or (= 0 1) (= 0 2) (= 0 0)) => #t  
(or #f) => #f  
(or #f #t) => #t  
(or #f 'a #f) => a (treated as #t in a conditional)
```

or evaluates its subexpressions from left to right until either (a) one expression is true, or (b) no more expressions are left. In case (a), the value is true, in (b) the value is false.

Important subtlety: Every Scheme object is considered to be either true or false by conditional expressions and by the procedure not. Only #f (i.e., ()) is considered false; **all other objects are considered true.**

```
(and) => #t  
(and (= 0 0) (= 0 1) (= 0 2)) => #f  
(and #f) => #f  
(and #t #t) => #t  
(and #t #f) => #f  
(and 'a 'b 'c) => c (treated as #t in a conditional)
```

and evaluates its subexpressions from left to right until (a) one expression is false, or (b) no more expressions are left. In case (a), the value is false, in (b) the value is true.