CSC 533: Organization of Programming Languages

Spring 2007

Functional programming

- LISP & Scheme
- S-expressions: atoms, lists
- functional expressions, evaluation, define
- primitive functions: arithmetic, predicate, symbolic, equality, higher-order
- special forms: if, cond
- recursion: tail vs. full

Functional programming

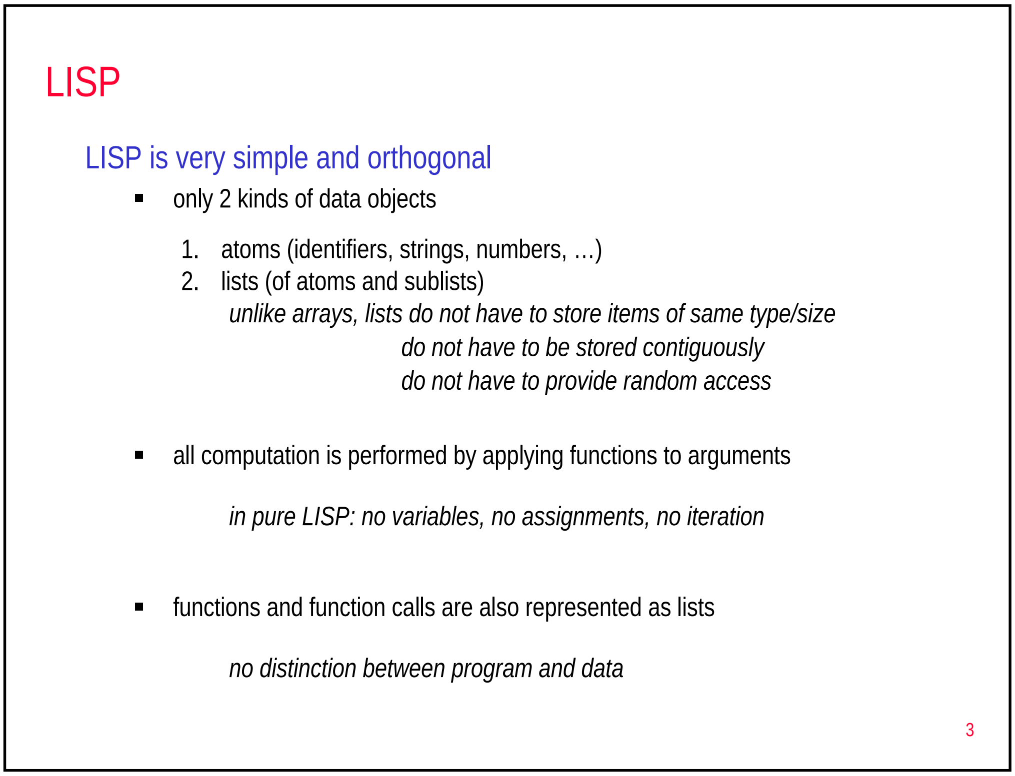
imperative languages are modeled on the von Neumann architecture

in mid 50's, AI researchers (Newell, Shaw & Simon) noted that could define a language closer to human reasoning

- symbolic
- (dynamic) list-oriented
- transparent memory management

in late 50's, McCarthy developed LISP (List Processing Language)

- instantly popular as the language for AI
- separation from the underlying architecture tended to make it less efficient (and usually interpreted)



LISP

LISP is very simple and orthogonal

- only 2 kinds of data objects
  1. atoms (identifiers, strings, numbers, …)
  2. lists (of atoms and sublists)

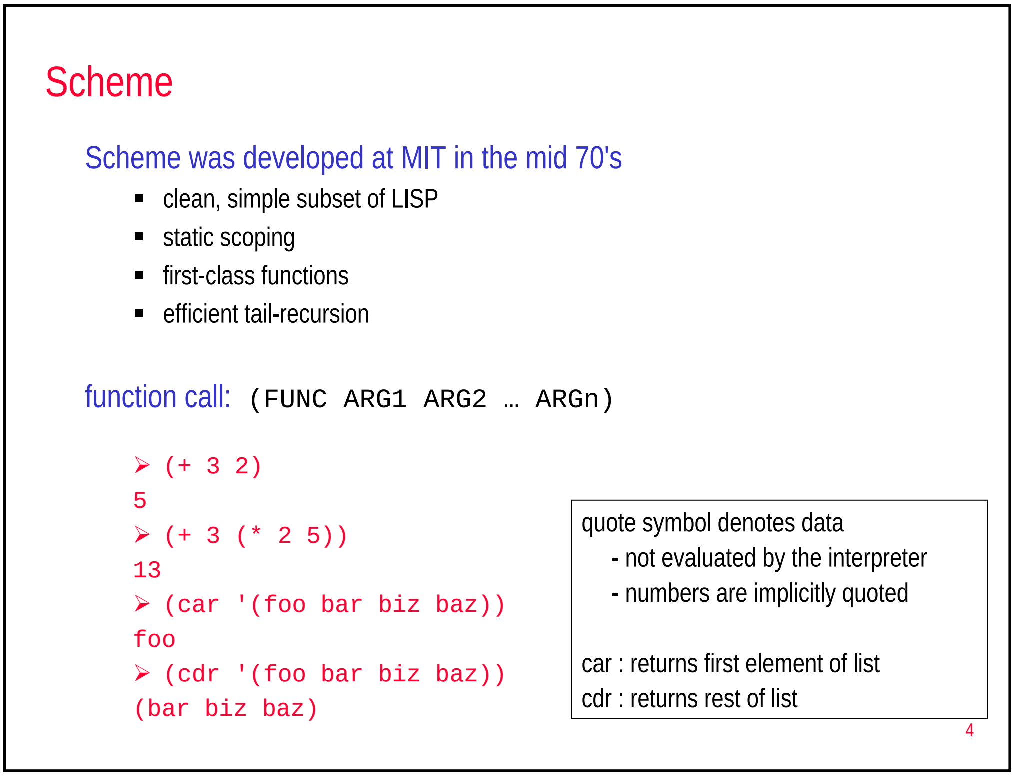
unlike arrays, lists do not have to store items of same type/size
do not have to be stored contiguously
do not have to provide random access

- all computation is performed by applying functions to arguments

in pure LISP: no variables, no assignments, no iteration

- functions and function calls are also represented as lists

no distinction between program and data



Scheme

Scheme was developed at MIT in the mid 70's

- clean, simple subset of LISP
- static scoping
- first-class functions
- efficient tail-recursion

function call: `(FUNC ARG1 ARG2 … ARGn)`

```
➢ (+ 3 2)
5
➢ (+ 3 (* 2 5))
13
➢ (car '(foo bar biz baz))
foo
➢ (cdr '(foo bar biz baz))
(bar biz baz)
```

quote symbol denotes data
- not evaluated by the interpreter
- numbers are implicitly quoted

car : returns first element of list
cdr : returns rest of list

Scheme functions

to define a new function:

```
(define (FUNC ARG1 ARG2 . . . ARGn)
    RETURN_EXPRESSION)
```

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


➢ (square 3)
9
➢ (square 1.5)
2.25
```

```
(define (last arblist)
  (car (reverse arblist)))


➢ (last '(a b c))
c
➢ (last '(foo))
foo
```

Obtaining a Scheme interpreter

many free Scheme interpreters/environments exist

- Dr. Scheme is an development environment developed at Rice University
- contains an integrated editor, syntax checker, debugger, interpreter
- Windows, Mac, and UNIX versions exist

- can download a personal copy from

  `http://download.plt-scheme.org/drscheme/`

  be sure to set Language to "Textual (MzScheme, includes R5RS)"

S-expressions

in LISP/Scheme, data & programs are all of the same form:
S-expressions (Symbolic-expressions)

- an S-expression is either an atom or a list

atoms

numbers	`4`	`3.14`	`1/2`	`#xA2`	`#b1001`
characters	`#\a`	`#\Q`	`#\space`	`#\tab`	
strings	`"foo"`	`"Dave Reed"`		`"@%!?#"`	
Booleans	`#t`	`#f`			
symbols	`Dave`	`num123`	`miles->km`	`!_^_!`	

symbols are sequences of letters, digits, and "extended alphabetic characters"
`+ - . * / < > = ! ? : $ % + & ~ ^`
can't start with a digit, case insensitive

S-expressions (cont.)

lists

`()`	is a list
`(L1 L2 . . . Ln)`	is a list, where each `Li` is either an atom or a list

for example:

`()`	`(a)`
`(a b c d)`	`((a b) c (d e))`
`(((((a)))))`	

note the recursive definition of a list – GET USED TO IT!
also, get used to parentheses (LISP = Lots of Inane, Silly Parentheses)

Functional expressions

computation in a functional language is via function calls

```
(FUNC ARG1 ARG2 . . . ARGn)
```

note: functional expressions are S-expressions

```
(car '(a b c))          (+ 3 (* 4 2))
```

evaluating a functional expression:

- function/operator name & arguments are evaluated in unspecified order
  note: if argument is a functional expression, evaluate recursively

- the resulting function is applied to the resulting values

```
(car '(a b c))
```

evaluates to list (a b c) : ' terminates recursive evaluation

evaluates to primitive function

so, primitive car function is called with argument (a b c)

Arithmetic primitives

predefined functions:

```
+   -   *   /
quotient   remainder   modulo
max   min   abs   gcd   lcm
floor   ceiling   truncate   round
=   <   >   <=   >=
```

- many of these take a variable number of inputs

```
(+ 3 6 8 4)                →  21
(max 3 6 8 4)              →  8
(= 1 (-3 2) (* 1 1))       →  #t
(< 1 2 3 4)                →  #t
```

- functions that return a true/false value are called *predicate functions*

```
zero?   positive?   negative?   odd?   even?

(odd? 5)                   →  #t
(positive? (- 4 5))        →  #f
```

Data types in LISP/Scheme

similar to JavaScript, LISP/Scheme is dynamically typed

- types are associated with values rather than variables, bound dynamically

numbers can be described as a hierarchy of types

number
complex
real
rational
integer

↑ MORE GENERAL

integers and rationals are *exact* values, others can be *inexact*

- arithmetic operators preserve exactness, can explicitly convert

```
(+ 3 1/2)              →  7/2
(+ 3 0.5)              →  3.5

(inexact->exact 4.5)   →  9/2
(exact->inexact 9/2)   →  4.5
```

Symbolic primitives

predefined functions: `car` `cdr` `cons`
`list` `list-ref` `length` `member`
`reverse` `append`

```
(list 'a 'b 'c)           →  (a b c)

(list-ref '(a b c) 1)     →  b

(member 'b '(a b c))      →  (b c)
(member 'd '(a b c))      →  #f
```

- `car` and `cdr` can be combined for brevity

```
(cadr '(a b c))  ≡  (car (cdr '(a b c))) → b
```

`cadr` returns 2nd item in list
`caddr` returns 3rd item in list
`cadddr` returns 4th item in list (can only go 4 levels deep)

Equality primitives

`equal?` compares 2 inputs, returns `#t` if equivalent, else `#f`

```
(equal? 'a 'a)                          →  #t
(equal? '(a b) '(a b))                  →  #t
(equal? (cons 'a '(b)) '(a b))          →  #t
```

other (more restrictive) equivalence functions exist

`eq?`	compares 2 symbols (efficient, simply compares pointers)
`eqv?`	compares 2 atomics (symbols, numbers, chars, strings, bools) -- less efficient, strings & numbers can't be compared in constant time

```
(eq? 'a 'a)  →  #t                (eqv? 'a 'a)  →  #t
(eq? '(a b) '(a b))  →  #f        (eqv? '(a b) '(a b))  →  #f
(eq? 2 2)  →  unspecified         (eqv? 2 2)  →  #t
```

equal? uses eqv?, applied recursively to lists

Defining functions

can define a new function using `define`

- a function is a mapping from some number of inputs to a single output

(define (NAME IN1 IN2 … INn)
  OUTPUT_VALUE)

```
(define (square x)          (define (next-to-last arblist)
  (* x x))                    (cadr (reverse arblist)))
```

basically, parameter passing is by-value since each argument is evaluated before calling the function – but no copying (instead, structure sharing)

Conditional evaluation

can select alternative expressions to evaluate

```
(if TEST TRUE_EXPRESSION FALSE_EXPRESSION)
```

```
(define (my-abs num)
  (if (negative? num)
      (- 0 num)
      num))


(define (singleton? arblist)
  (if (and (list? arblist) (= (length arblist) 1))
      #t
      #f))
```

`and`, `or`, `not` are standard boolean connectives
evaluated from left-to-right, short-circuit evaluation

Conditional evaluation (cont.)

predicates exist for selecting various types

```
symbol?     char?      boolean?    string?    list?     null?
number?     complex?   real?       rational?  integer?
exact?      inexact?
```

note: an if-expression is a *special form*

- is *not* considered a functional expression, doesn't follow standard evaluation rules

```
(if (list? x)
    (car x)
    (list x))
```

test expression is evaluated
- if value is anything but #f, first expression is evaluated & returned
- if value is #f, second expression is evaluated & returned

- anything but #f is considered "true"

```
(if (member 'foo '(biz foo foo bar)) 'yes 'no)
```

Multi-way conditional

when there are more than two alternatives, can

- nest if-expressions (i.e., cascading if's)
- use the `cond` special form (i.e., a switch)

```
(cond (TEST1 EXPRESSION1)
      (TEST2 EXPRESSION2)
         . . .
      (else EXPRESSIONn))
```

evaluate tests in order

- when reach one that evaluates to "true", evaluate corresponding expression & return

```
(define (compare num1 num2)
  (cond ((= num1 num2) 'equal)
        ((> num1 num2) 'greater)
        (else 'less)))
```

```
(define (my-member item lst)
  (cond ((null? lst) #f)
        ((equal? item (car lst)) lst)
        (else (my-member item (cdr lst)))))
```

Repetition via recursion

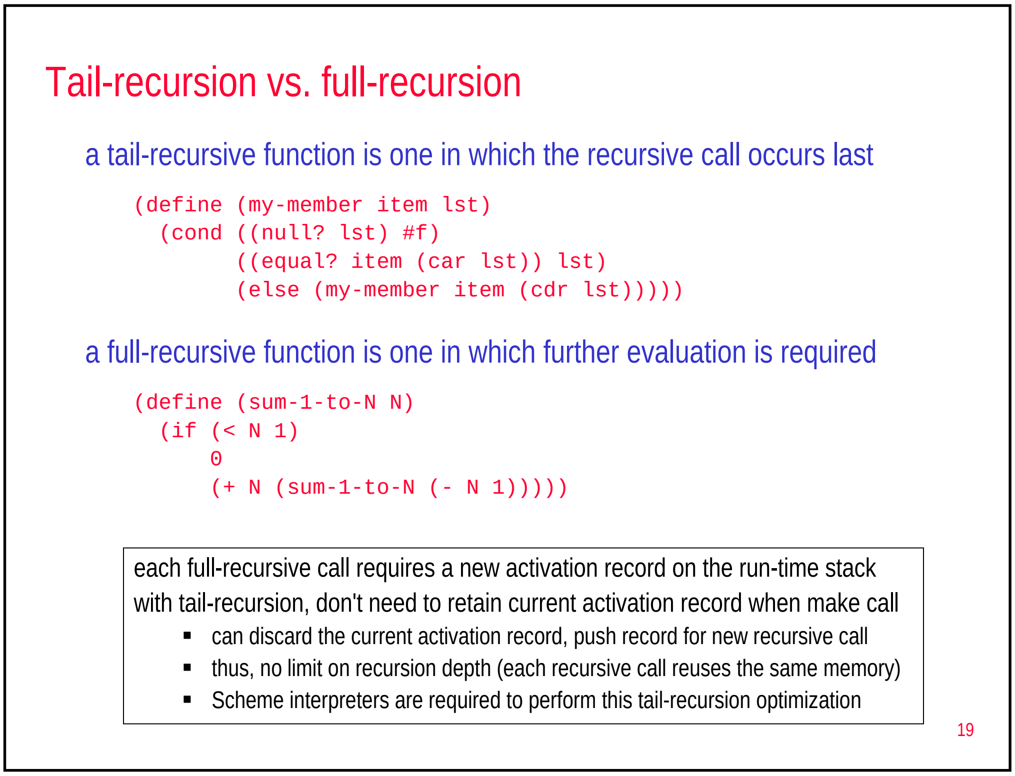
pure LISP/Scheme does not have loops

- repetition is performed via recursive functions

```
(define (sum-1-to-N N)
  (if (< N 1)
      0
      (+ N (sum-1-to-N (- N 1)))))
```

```
(define (my-member item lst)
  (cond ((null? lst) #f)
        ((equal? item (car lst)) lst)
        (else (my-member item (cdr lst)))))
```

```
(define (my-length lst)
  IN-CLASS EXERCISE
  )
```



Tail-recursion vs. full-recursion

a tail-recursive function is one in which the recursive call occurs last

```
(define (my-member item lst)
  (cond ((null? lst) #f)
        ((equal? item (car lst)) lst)
        (else (my-member item (cdr lst)))))
```

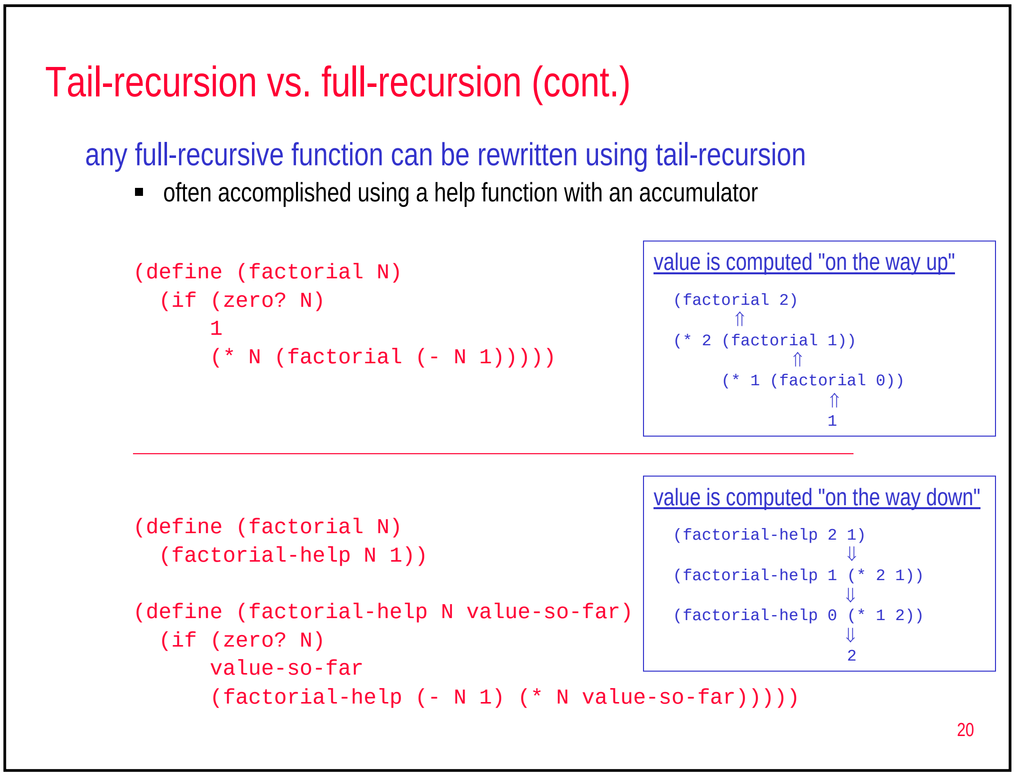
a full-recursive function is one in which further evaluation is required

```
(define (sum-1-to-N N)
  (if (< N 1)
      0
      (+ N (sum-1-to-N (- N 1)))))
```

each full-recursive call requires a new activation record on the run-time stack

with tail-recursion, don't need to retain current activation record when make call

- can discard the current activation record, push record for new recursive call
- thus, no limit on recursion depth (each recursive call reuses the same memory)
- Scheme interpreters are required to perform this tail-recursion optimization



Tail-recursion vs. full-recursion (cont.)

any full-recursive function can be rewritten using tail-recursion

- often accomplished using a help function with an accumulator

```
(define (factorial N)
  (if (zero? N)
      1
      (* N (factorial (- N 1)))))
```

value is computed "on the way up"

```
(factorial 2)
     ⇑
(* 2 (factorial 1))
          ⇑
    (* 1 (factorial 0))
               ⇑
               1
```

```
(define (factorial N)
  (factorial-help N 1))

(define (factorial-help N value-so-far)
  (if (zero? N)
      value-so-far
      (factorial-help (- N 1) (* N value-so-far))))
```

value is computed "on the way down"

```
(factorial-help 2 1)
                 ⇓
(factorial-help 1 (* 2 1))
                 ⇓
(factorial-help 0 (* 1 2))
                 ⇓
                 2
```

Scoping in Scheme

unlike early LISPs, Scheme is statically scoped

- can nest functions and hide details

```
(define (factorial N)

  (define (factorial-help N value-so-far)
    (if (zero? N)
        value-so-far
        (factorial-help (- N 1) (* N value-so-far))))

  (factorial-help N 1))
```

- since factorial-help is defined inside of factorial, hidden to outside

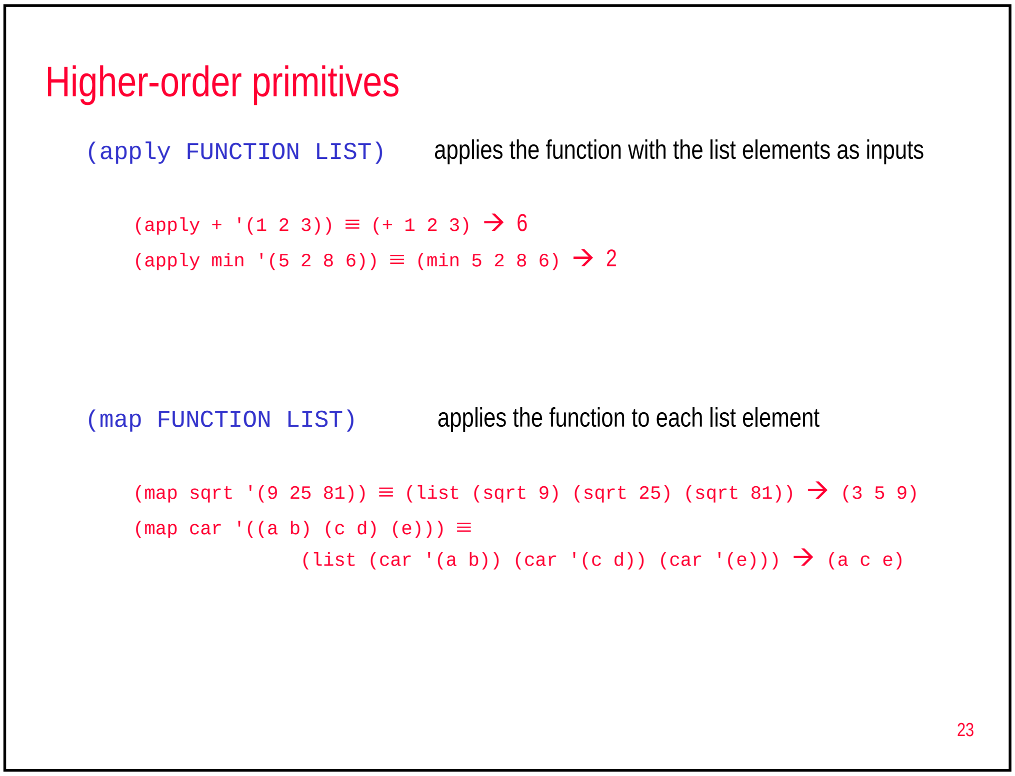
- since statically scoped, arguments in enclosing function are visible to enclosed functions (i.e., non-local variables)

When tail-recursion?

```
(define (sum-1-to-N N)

  (define (sum-help N sum-so-far)
    (if (< N 1)
        sum-so-far
        (sum-help (- N 1) (+ N sum-so-far))))

    (sum-help N 0))



(define (my-length lst)

  IN-CLASS EXERCISE

  (length-help lst 0))
```

usually, a full-recursive solution is simpler, more natural

- for a small number of repetitions, full-recursion is sufficient
- for a potentially large number of repetitions, need tail-recursion



Higher-order primitives

`(apply FUNCTION LIST)` applies the function with the list elements as inputs

```
(apply + '(1 2 3)) ≡ (+ 1 2 3) → 6
(apply min '(5 2 8 6)) ≡ (min 5 2 8 6) → 2
```

`(map FUNCTION LIST)` applies the function to each list element

```
(map sqrt '(9 25 81)) ≡ (list (sqrt 9) (sqrt 25) (sqrt 81)) → (3 5 9)
(map car '((a b) (c d) (e))) ≡
               (list (car '(a b)) (car '(c d)) (car '(e))) → (a c e)
```