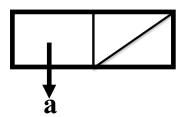
Lists in Lisp and Scheme



Lists in Lisp and Scheme

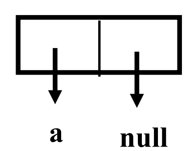
- Lists are Lisp's fundamental data structures, but there are others
  - Arrays, characters, strings, etc.
  - Common Lisp has moved on from being merely a **LIS**t **P**rocessor
- However, to understand Lisp and Scheme you must understand lists
  - common functions on them
  - how to build other useful data structures with them

Lisp Lists

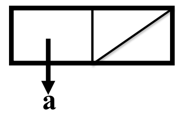
- Lists in Lisp and its descendants are very simple linked lists
  - Represented as a linear chain of nodes
- Each node has a (pointer to) a value (car of list) and a pointer to the next node (cdr of list)
  - Last node's cdr pointer is to null
- Lists are immutable in Scheme
- Typical access pattern is to traverse the list from its head processing each node

In the beginning was the cons (or pair)

- What cons really does is combines two objects into a two-part object called a *cons* in Lisp and a *pair* in Scheme
- Conceptually, a cons is a pair of pointers -- the first is the car, and the second is the cdr
- Conses provide a convenient representation for pairs of any type
- The two halves of a cons can point to any kind of object, including conses
- This is the mechanism for building lists
- (pair? '(1 2)) => #t



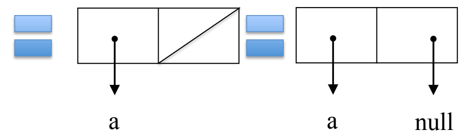
Pairs



- Lists in Lisp and Scheme are defined as [pairs]
- Any non empty list can be considered as a pair of the first element and the rest of the list
- We use one half of a cons cell to point to the 1st element of the list, and the other to point to the rest of the list (either another cons or null)

Box and pointer notation

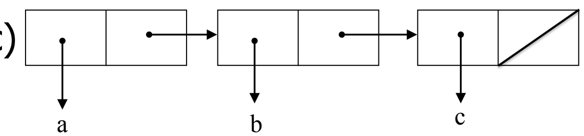
(a)



Common notation: use diagonal line in cdr part of a cons cell for a pointer to null

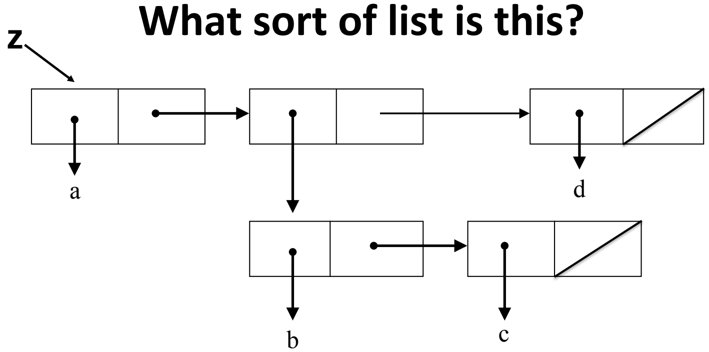
A one element list (a)

(a b c)



A list of three elements (a b c)

What sort of list is this?



Z is a list with three elements: (i) the atom a, (ii) a list of two elements, b & c and (iii) the atom d.

```
> (define  Z  (list  ‘a  (list  ‘b ‘c)  ‘d))
> Z
(a  (b c)  d)
> (car (cdr z))
??
```

Pair?

- The function pair? returns true if its argument is a cons cell
- The equivalent function in CL is *consp*
- So list? could be defined:

  (define (list? x) (or (null? x) (pair? x)))
- Since everything that is not a pair is an atom, the predicate *atom* could be defined:

  (define (atom? x) (not (pair? x)))

Equality

- Each time you call cons, Scheme allocates a new cons cell from memory with room for two pointers
- If we call cons twice with the same args, we get two values that look the same, but are distinct objects

```
➢(define  L1 (cons 'a null))
➢L1
(A)
➢(define L2 (cons 'a null)))
➢L2
➢(A)
➢(eq? L1 L2)
➢#f
➢(equal? L1 L2)
➢#t
➢(and (eq? (car L1)(car L2))
        (eq? (cdr L1)(cdr L2)))
➢#t
```

Equal?

- Do two lists have the same elements?
- Scheme provides a predicate *equal?* that is like Java's equal method
- Eq? returns true iff its arguments are the same object, and
- Equal?, more or less, returns true if its arguments would print the same.

```
> (equal? L1 L2)
#t
```

- Note: (eq? x y) implies (equal? x y)

Equal?

```
(define (myequal? x y)
  ; this is ~ how equal? could be defined
  (cond ((number? x) (= x y))
        ((not (pair? x)) (eq? x y))
        ((not (pair? y)) #f)
        ((myequal (car x) (car y))
         (myequal? (cdr x) (cdr y)))
        (else #f)))
```

Use trace to see how it works

```
> (require racket/trace)
> (trace myequal?)
> (myequal? '(a b c) '(a b c))
>(myequal? (a b c) (a b c))
> (myequal? a a)
< #t
>(myequal? (b c) (b c))
> (myequal? b b)
< #t
```

```
>(myequal? (c) (c))
> (myequal? c c)
< #t
>(myequal? () ())
<#t
#t
```

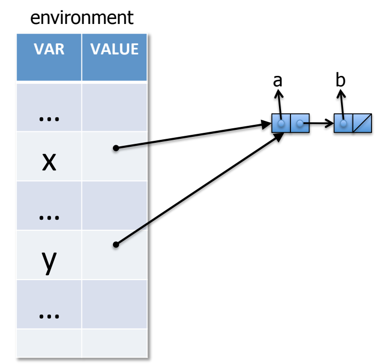
- Trace is a debugging package showing what args a user-defined function is called with and what it returns
- The require function loads the package if needed

Does Lisp have pointers?

- A secret to understanding Lisp is to realize that variables have values in the same way that lists have elements
- As pairs have pointers to their elements, variables have pointers to their values
- Scheme maintains a data structure representing the mapping of variables to their current values.

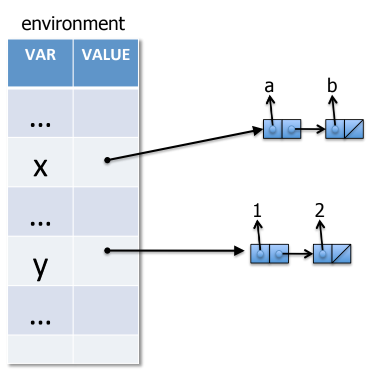
Variables point to their values

```
> (define  x  '(a b))
> x
(a b)
> (define  y  x)
y
(a b)
```



Variables point to their values

```
> (define  x  '(a b))
> x
(a b)
> (define  y  x)
y
(a b)
> (set! y '(1 2)
> y
(1 2)
```



Does Scheme have pointers?

- The location in memory associated with the variable x does not contain the list itself, but a pointer to it.
- When we assign the same value to y, Scheme copies the pointer, not the list.
- Therefore, what would be the value of
  - ➢ (eq? x y)

  #t or #f?

Length is a simple function on Lists

- The built-in function length takes a list and returns the number of its top-level elements
- Here's how we could implement it

```
(define (length L)
   (if (null? L) 0 (+ 1 (length (cdr L)))))
```

- As typical in dynamically typed languages (e.g., Python), we do minimal type checking
  - The underlying interpreter does it for us
  - Get run-time error if we apply length to a non-list

Building Lists

- *list-copy* takes a list and returns a copy of it
- The new list has the same elements, but contained in new pairs

```
> (set!  x  '(a  b  c))
(a b c)
> (set! y  (list-copy  x))
(a b c)
```

- Spend a few minutes to draw a box diagram of x and y to show where the pointers point

Copy-list

- List-copy is a Lisp built-in (as copy-list) that could be defined in Scheme as:

```
(define (list-copy s)
  (if (pair? s)
    (cons (list-copy (car s))
          (list-copy (cdr s)))
    s))
```

- Given a non-atomic s-expression, it makes and returns a complete copy (e.g., not just the top-level spine)

Append

- *append* returns the concatenation of any number of lists
- *Append* copies its arguments except the last
  - If not, it would have to *modify* the lists
  - Such *side effects* are undesirable in functional languages

```
>(append '(a b) '(c d))
(a b c d)
> (append '((a)(b)) '(((c))))
((a) (b) ((c)))
> (append  '(a  b)  '(c  d)  '(e))
(a b c d e)
>(append '(a b) '())
(a b)
>(append '(a b))
(a b)
>(append)
()
```

Append

- The two argument version of append could be defined like this

```
(define (append2 s1 s2)
  (if (null? s1)
      s2
      (cons (car s1)
            (append2 (cdr s1) s2))))
```

- Notice how it ends up *copying* the top level list structure of its first argument

Visualizing Append

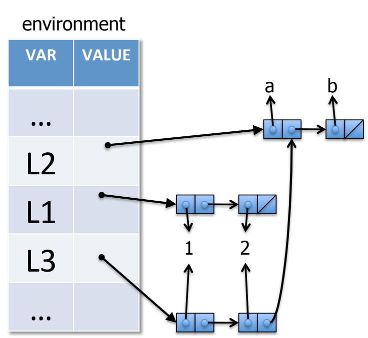
```
> (load "append2.ss")
> (define L1 '(1 2))
> (define L2 '(a b))
> (define L3 (append2 L1 L2))
> L3
(1 2 a b)
> L1
(1 2)
> L2
(a b)
```

```
> (require racket/trace)
> (trace append2)
> (append2 L1 L2)
>(append2 (1 2) (a b))
> (append2 (2) (a b))
> >(append2 () (a b))
< <(a b)
< (2 a b)
<(1 2 a b)
(1 2 a b)
```

Append does not modify its arguments. It makes copies of all of the lists save the last.

Visualizing Append

```
> (load "append2.ss")
> (define L1 '(1 2))
> (define L2 '(a b))
> (define L3
   (append2 L1 L2))
> L3
(1 2 a b)
> L1
(1 2)
> L2
(a b)
> (eq? (cdr (cdr L3) L2)
#f
```



Append2 copies the *top level* of its first list argument, L1

List access functions

- To find the element at a given position in a list use the function list-ref (*nth in CL)*
  - \> (list-ref ‘(a b c) 0)
  - a
- To find the *n*th cdr, use list-tail (*nthcdr in CL)*
  - \> (list-tail ‘(a b c) 2)
  - (c)
- Both functions are zero indexed

List-ref and list-tail

```
> (define L '(a b c d))
> (list-ref L 2)
c
> (list-ref L 0)
a
> (list-ref L -1)
list-ref: expects type <non-negative exact integer> as 2nd arg, given: -1; other arguments were: (a b c d)
> (list-ref L 4)
list-ref: index 4 too large for list: (a b c d)
```

```
> (list-tail L 0)
(a b c d)
> (list-tail L 2)
(c d)
> (list-tail L 4)
()
> (list-tail L 5)
list-tail: index 5 too large for list: (a b c d)
```

Defining Scheme's list-ref & list-tail

```
(define (mylist-ref l n)
  (cond ((< n 0)  (error...))
        ((not (pair? l))  (error...))
        ((= n 0)  (car l))
        (else  (mylist-ref (cdr l) (- n 1)))))

(define (mylist-tail l n)
  (cond ((< n 0) (error...))
        ((not (pair? l)) (error...))
        ((= n 0)  (cdr l))
        (else  (mylist-ref (cdr l) (- n 1)))))
```

Accessing lists

- Scheme's *last* returns the last element in a list

```
> (define (last l)
    (if (null? (cdr l))
        (car l)
        (last (cdr l))))
> (last  '(a  b  c))
c
```

- Note: in CL, last returns last cons cell (aka pair)
- We also have: *first*, *second, third*, and *CxR*, where *x* is a string of up to four **a**s or **d**s.
  – E.g., cadr, caddr, cddr, cdadr, …

Member

- *Member* returns true, but instead of simply returning *t*, its returns the part of the list beginning with the object it was looking for.

```
> (member  'b  '(a  b  c))
(b c)
```

- *member* compares objects using *equal?*
- *There are versions that use eq? and eqv? And that take an arbitrary function*

Defining member

```
(define (member X L)
  (cond ((null? L) #f)
        ((equal? X (car L)) L)
        (else (member X (cdr L)))))
```

Memf

- If we want to find an element satisfying an arbitrary predicate we use the function *memf*:

  > (memf odd? ‘(2 3 4))

  (3 4)

- Which could be defined like:

```
(define (memf f l)
  (cond ((null? l) #f)
        ((f (car l)) l)
        (else (memf f (cdr l)))))
```

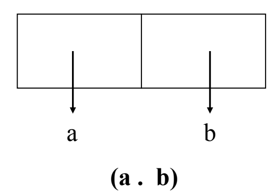
Dotted pairs and lists

- Lists built by calling *list* are known as *proper lists;* they always end with a pointer to null
  - A proper list is either *the empty list*, or a *pair* whose *cdr* is a proper list
- Pairs aren’t just for building lists, if you need a structure with two fields, you can use a pair
- Use *car* to get the 1st field and *cdr* for the 2nd
  - ➢ (define the_pair (cons ‘a ‘b))
    (a . b)

➢ Pair isn’t a proper list, so it’s displayed in *dot notation*

In dot notation the car and cdr of each pair are shown separated by a period

Dotted pairs and lists



- A pair that isn’t a proper list is called a dotted pair
  - Remember that a dotted pair isn’t really a list at all, It’s a just a two part data structure
- Doted pairs and lists that end with a dotted pair are not used very often
- If you produce one for 331 code, you’ve probably made an error

Conclusion

- Simple linked lists were the only data structure in early Lisps
  - From them you can build most other data structures though efficiency may be low
- Its still the most used data atructure in Lisp and Scheme
  - Simple, elegant, less is more
- Recursion is the natural way to process lists