CMPT325: Issues in Functional Progamming

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Variables and Efficiency

- Variables are symbolic labels used to refer to data values
  - provided by the programmer, or
  - calculated from functions of data
- Variables allow us to refer to the same data multiple times
- Variables can improve efficiency - consider:

```
Y := F(x) × F(x)        vs.      Z := F(x)
                                  Y := Z × Z
```

- First example computes `F(x)` twice; Second example only once
- Optimizing compilers can often detect simple redundancies, but it is important to be aware of the general principle

Examples in LISP

- How would we optimize the following code in Lisp:

```
(APPEND (foo x) (foo x))
```

- Solution 1:

```
( (LAMBDA (z)
      (APPEND z z)
  ) (foo x) )
```

- Alternatively, equivalently and more transparently

```
(LET ((z (foo x)))
   (APPEND z z))
```


Using Functions Efficiently

- Consider the append predicate (see last lecture)

```
(DEFUN append (list1 list2)
   (COND ((NULL list1) list2 )
         ( T (CONS (CAR list1)
                   (append (CDR list1) list2)))) )
```

Analysis of Append

- What is $\mathrm{runTime}(\mathit{append})$?
  (Hint: examine reduction operator)

(length L1)	(length L2)	#Calls
0	5	1
1	5	2
6	5	7
10	5	11
10	100	11
10	1000	11

- Running time of append is LINEAR in length of 1st arg
  $runTime(Append) = O(length(L1))$
- Implication: always call with short list in first position

Efficiency Tricks

- First analysis of recursive structure may not yield an efficient solution
- Additional examination of the recursion can lead to significant improvements

Naive reverse implementation

```
(reverse '()) → ()
(reverse '(A)) → (A)              ;; (APPEND '() '(A))
(reverse '(B A)) → (A B)          ;; (APPEND '(A) '(B))
(reverse '(C B A)) → (A B C)  ;; (APPEND '(A B) '(C))
```

- Analysis
  - Base case? '()→()
  - Reduction? (CDR *l1*)
  - Composition? (APPEND reduced-problem (LIST (CAR *l1*)))
- Solution based on this analysis (DO NOT IMPLEMENT!):

```
(DEFUN reverse-1 (l1)
   (COND ((NULL list) nil)
         (   t     (APPEND (reverse-1 (CDR l1))
                           (LIST (CAR l1))    ) )))
```


Trace of Naive reverse-1 I

- The `reverse-1` method starts by successively reducing the problem to the base case

```
(reverse-1 '(a b c d))
Enter reverse-1 (a b c d)
  Enter reverse-1 (b c d)
    Enter reverse-1 (c d)
      Enter reverse-1 (d)
        Enter reverse-1 nil
```

- As recursion unwinds, append is called at each step

```
        Exit reverse-1 ()
        Enter append () (d)
```

Trace of Naive reverse-1 II

```
        Exit append (d)
      Exit my-reverse-1 (d)
      Enter append (d) (c)
      Exit append (d c)
    Exit my-reverse-1 (d c)
    Enter append (d c) (b)
    Exit append (d c b)
  Exit my-reverse-1 (d c b)
  Enter append (d c b) (a)
  Exit append (d c b a)
Exit my-reverse-1 (d c b a)
```


Complexity of Naive reverse-1

```
(DEFUN reverse-1 (l1)
   (COND ((NULL l1) nil)
         (   t     (APPEND (reverse-1 (CDR l1))
                           (LIST (CAR l1))    ) )))
```

- Each time reverse-1 completes, APPEND is called
- APPEND traverses the entire singly-linked list
  runtime(append) = $O(n)$
- $\text{runtime}(\texttt{reverse} - 1) = n + (n-1) + \cdots + 1 = \frac{n(n+1)}{2} = O(n^2)$

LIST as STACK and Accumulators II

- Note: CONS operator is like a stack push and CAR is like stack pop

```
(SETF STK nil)
STK → ()
(SETF STK (CONS 'A STK))
STK → (A)
(SETF STK (CONS 'B STK))
STK → (B A)
(SETF STK (CONS 'C STK))
STK → (C B A)
```


LIST as STACK and Accumulators II

items	*stk*
A B C	nil
B C	A
C	B A
nil	C B A

- We push items into a lambda parameter named stk

```
(DEFUN load-stack (items stk)
   (COND ((NULL items) stk)
         ( t    (load-stack
                   (CDR items)(CONS (CAR items) stk)))))
```

- **Don't return composed result, pass it forward**
- Stk is an *accumulator* variable returned on last call

Collector Variables or Accumulators

- Collector variable = extra argument in function that represents calculation so far
- When function is done
  (typically by exhausting another argument)
  it simply returns collector variable as value of function.
- Here: composition operator is *identity* function
  (it simply returns the result)

Using load-stack for my-reverse

- Using "helper function" load-stack to implement my-reverse

```
(DEFUN my-reverse (l1)
   (load-stack l1 nil))
```

- Internal defintition of "helper function"

```
(DEFUN my-reverse (l1)
  (LABELS (
    (load-stack (items stk)
     (IF (NULL items)
       stk
       (load-stack (CDR items)
                   (CONS (CAR items) stk)))))
   (load-stack l1 nil)))
```

- This version is $O(n)$!

Trace of efficient my-reverse

```
1 Enter my-reverse (a b c d)
1 Enter load-stack (a b c d) nil
  2 Enter load-stack (b c d) (a)
    3 Enter load-stack (c d) (b a)
      4 Enter load-stack (d) (c b a)
        5 Enter load-stack nil (d c b a)
        5 Exit load-stack (d c b a)
      4 Exit load-stack (d c b a)
    3 Exit load-stack (d c b a)
  2 Exit load-stack (d c b a)
1 Exit load-stack (d c b a)
1 Exit my-reverse (d c b a)
```

- Note: this implementation is tail-recursive

Efficiency in General

- Q: Is $\langle fn_1 \rangle$ *more efficient* than $\langle fn_2 \rangle$?
  wrt expected *Run Time Cost*
  for LARGE problems

- Defined in terms of
  # of Function Applications
  as a function of "Size" of Argument(s)

- "Size"
  Usually Assymptotic
  "... for sufficiently large lists..."
  wrt LISP: Usually "length of list"

Efficiency Classes I

- "Constant Order" $O(1)$
  # of Function Applications
  is INDEPENDENT of args
  ...No recursion
  [Eg, `(LAMBDA (x) (CAR (CDR x)))`]
- "Linear Order" $O(n)$
  (n is size of argument)
  Recursive calls ∝ length of list but CONSTANT work on each call
  - (e.g., `APPEND ...(CONS (CAR x) (APPEND (CDR x) y))... )`

Efficiency Classes II

- "Polynomial Order" $O(n^2)$, $O(n^5)$, ...
  Recursion on length of list, with Linear (poly) work at each level
  - (e.g. naive `reverse-1` does an append after each call, so $O(n^2)$)
- "Exponential Order" $O(2^n)$, $O(n^n)$, ...
  More than 1 recursive call for each call
  - (e.g. naive fibonacci calls self TWICE at each step – stay tuned!)

Linear-time Power Function Analysis

```
(power n 0) →1
(power n 1) →n
(power n 2) →n²=n*n
(power n 3) →n³=n*n*n
(power n 4) →n⁴=n*n*n*n
⋮
```

- Analysis
  1. Base case? (power n 0) →1
  2. Reduction? `(- e 1)`
  3. Composition? `(* n (power (- e 1))`

Linear-time Power Function Analysis

```
(DEFUN my-power-2 (n e)
   (IF (= e 0)
       1
       (* n (my-power-2 n (- e 1)))))
```

- `my-power-2` will be called e times, so it is linear in e: $O(e)$

Logarithmic-time Power Function Analysis

(power n 0) $\rightarrow$1
(power n 1) $\rightarrow$n
(power n 2) $\rightarrow n^2$= n*n = n*n
(power n 3) $\rightarrow n^3$= n*n*n = $n^2 n$
(power n 4) $\rightarrow n^4$= n*n*n*n = n^{2^2}
(power n 5) $\rightarrow n^5$= n*n*n*n*n = $n^{2^2} n$
⋮

- Analysis
  1. Base case? (power n 0) $\rightarrow$1
  2. Reduction? If e odd: (- e 1)
     If e even: (/ e 2)
  3. Composition?
     If e odd: (* n (power (- e 1))
     If e even: (* (p n e/2) (p n e/2))

Logarithmic-time Power Function Code

- Analysis
  1. Base case? (power n 0) $\rightarrow$1
  2. Reduction? Odd e:(- e 1); Even e: e/2
  3. Composition? [see below]

```
(DEFUN my-power (n e)
   (COND
     ((= e 0) 1)
     ((EVENP e) (LET ((result (my-power n (/ e 2 ) )))
                     (* result result)))
     (   t       (* n (my-power n (- e 1) ))) ))
```

- Note: two distinct cases for recursive calls

Fibonacci Function Case Study

```
fib(1)→ 1
fib(2)→ 1
fib(3)→ 2
fib(4)→ 3
fib(5)→ 5
fib(6)→ 8
fib(7)→ 13    ; 13 = 5+8
```

- Analysis
  1. Base case? `fib(1) →1, fib(2)→1`
  2. Reduction? `(- n 1) (- n 2)`
  3. Composition?
     `(+ (fib (- n 1)) (fib (- n 2)) )`

Naive Fibonacci

- Analysis
  1. Base case? `fib(1) →1, fib(2)→1`
  2. Reduction? `(- n 1) (- n 2)`
  3. Composition? `(+ (fib (- n 1)) (fib (- n 2)) )`
- A naive implementation (DO NOT IMPLEMENT)

```
(DEFUN fib1 (n)
   (COND ((< n 3) 1)
         (   t    (+ (fib1 (- n 1))
                     (fib1 (- n 2)) ))))
```

Partial Trace of Naive Fibonacci

```
ENTER fib1 6      ;; Each call → 2 subcalls
   ENTER fib1 5    ;; runtime(fib − 1) = O(2^n)
      ENTER fib1 4
         ENTER fib1 3
            ENTER fib1 2 →1
            ENTER fib1 1→1
         ENTER fib1 2
      ENTER fib1 3
         ENTER fib1 2→1
         ENTER fib1 1→1
   ENTER fib1 4
     ENTER fib1 3
        ENTER fib1 2→1
        ENTER fib1 1→1
     ENTER fib1 2→1
```


Linear Fibonacci

- Naive `fib-1` generates 2 branches at (essentially) each call
- Build up answer from bottom forwards, using accumulators and stop when we have computed n terms
- `n` is #desired terms, `I` is a counter, `fibI` is i^{th}fibonacci term, `fibPrev` is $i - 1^{st}$ fibonacci term

```
(DEFUN fib2 (n)
   (LABELS ( (fibHelp (n I fibI fibPrev)
         (IF (EQ n I)
            FibI
            (fibHelp  n (+ I 1)  (+ fibI fibPrev) fibI))
      (fibHelp n 1 1 0)))
```

Trace of Linear Fibonacci

```
ENTER: (FIB2 6)
  ENTER: (FIBHELP 6 1 1 0)
    ENTER: (FIBHELP 6 2 1 1)
      ENTER: (FIBHELP 6 3 2 1)
        ENTER: (FIBHELP 6 4 3 2)
          ENTER: (FIBHELP 6 5 5 3)
            ENTER: (FIBHELP 6 6 8 5)
            ENTER: FIBHELP ==> 8
          ENTER: FIBHELP ==> 8
          ⋮
  ENTER: FIBHELP ==> 8
ENTER: FIB2 ==> 8
```

- tail-recursive structure permits compiler optimization to linear loop

Sublinear Fibonacci I

- Define **fib**(n) to return vector $\begin{pmatrix} f_n \\ f_{n-1} \end{pmatrix}$
- Base case: **fib**$(2) = \begin{pmatrix} f_2 \\ f_1 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$
- Recursion:

$$\mathbf{fib}(n) = \begin{pmatrix} f_n \\ f_{n-1} \end{pmatrix} = \begin{pmatrix} f_{n-1} + f_{n-2} \\ f_{n-1} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} f_{n-1} \\ f_{n-2} \end{pmatrix}$$

- Still *linear* recursion

Sublinear Fibonacci II

- Sequence of recursive calls has its own shared substructure

$$\mathbf{fib}(n) = \begin{pmatrix} f_n \\ f_{n-1} \end{pmatrix} = \begin{pmatrix} f_{n-1} + f_{n-2} \\ f_{n-1} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} f_{n-1} \\ f_{n-2} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} f_{n-2} \\ f_{n-3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}^2 \begin{pmatrix} f_{n-2} \\ f_{n-3} \end{pmatrix}$$

Sublinear Fibonacci III

- On repeated substitution all the way down to the base case:

$$\begin{pmatrix} f_n \\ f_{n-1} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}^{n-2} \begin{pmatrix} f_2 \\ f_1 \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}^{n-2} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

- Examples:
  - $\begin{pmatrix} f_2 \\ f_1 \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}^0 \begin{pmatrix} 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix},$
  - $\begin{pmatrix} f_3 \\ f_1 \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}^1 \begin{pmatrix} 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 2 \\ 1 \end{pmatrix}$

Sublinear Fibonacci IV

- Showed (power n e) has time *logarithmic* in exponent
- Substituting matrix multiplication for '*' implements matrix power
- Showed Fibonacci can be reduced to matrix exponentiation
- Fibonacci can therefore be computed in *logarithmic* time

Scope of Variables

- Consider function bindings of variables in ⟨form⟩ given:

```
(LAMBDA (y z) ⟨form⟩)
```

  - y refers to 1^{st} arg
  - z refers to 2^{nd} arg
- Consider *nested* functions

```
(LAMBDA (y z)
   ( (LAMBDA (x v) ⟨form⟩)
         (CDR y) 'A)))
```

Variables usable within ⟨form⟩:

  - x is bound to CDR of 1^{st} arg
  - v is bound to value A
  - y is bound to 1^{st} arg
  - z is bound to 2^{nd} arg

Variables

```
(LAMBDA (y z)
   ( (LAMBDA (x y) (LIST x y z)) 'A (CDR y) ))
```

- is a function that takes 2 args, and evaluates to 3 element list: (A (CDR of 1^{st} arg) (2^{nd} arg))
- Notation: In inner λ-expr
  - Variable x and y are BOUND
  - Variable z is FREE
  - y's value is "shadowed" by (CDR y)

Dealing with Free Variables

- Def'n: *Formal* variables of a function are **bound** within the function definition.
- All other variables are **free**.
- Consider function

```
(DEFUN foo (z x) (LIST z x y) )
```

- When (foo 5 t) is called
  - z→ 5, bound
  - x→ t, bound
  - y will be FREE
- Is (foo ⟨f1⟩ ⟨f2⟩) always defined? No

Evaluating foo

- Case 1: ((LAMBDA (x y) (foo 'A (CDR x))) '(5) t)

```
Eval: "(foo 'A (CDR x))" with x ← (5), y ← t
    Eval: "(LIST z x y)" with z ← A, x ← (), y ← t
    Returns: (A () t)
```

- Case 2: ((LAMBDA (x) (foo 'A (CDR x))) '(5))

```
  Eval: (foo 'A (CDR x)) with x ← (5)
    Eval: (LIST z x y) with z←A, x←(), y undefined
    Undefined!!
```


Scope: Dynamic vs Static

- Dynamic Scoping:
  Value of variable depends on RUN-time situation!
  EG: *Lisp*
- Static Scoping:
  Value of variable determined by COMPILE-time declaration.
  EG: *Pascal*, *Turing*, . . .
- Examples . . .

Example of Static Scoping

Foo

x ← 5

Bar

⋯ **x** ⋯

put x; {*value is “5”*}

Glob

x ← 7

⋯ **Bar()** ⋯ {*prints 5*}

put x; {*prints 7*}

Example of Dynamic Scoping

```
(SETQ x 20) →   20
(SETQ y 10)→   10
(DEFUN plusy (x) (+ x y)) →
plusy   ;;; y is free
(plusy 5)→   15
(+ x y)→   30
(SETQ y 20)→   20
(plusy 5)→   25
```

Contexts

- Identify each variable with a (LIFO) STACK of values.
- Variable's current "value" is top of stack
- Initializing/Updating Variable's Stack
  - Initally, each variable's stack is [`undefined`]
  - If `(SETQ a v)`,
    reset top of `a`'s stack to (value of) `v`.
  - When entering function `fn`
    with args $a_1, \ldots, a_n$
    bound to values $v_1, \ldots, v_n$
    PUSH the value of v_i onto a_i's stack
    for each i
  - When exiting function,
    POP stack of each of function's variables

Maintaining Contexts

Evaluate:

```
( (LAMBDA (x y)
     ( (LAMBDA (z x) (LIST z x y))
       'a (CDR x) ) )
  '(A B C) '(D E F) )    with  x←[], y←[], z←[]
ENTER λ1(x y) with  x←[(A B C)], y←[(D E F)], z←[]
  ENTER λ2(z x)  with x←[(B C)(A B C)], y←[(D E F)], z
  EXIT λ2 with (A (B C) (D E F))
EXIT λ1 (A (B C) (D E F))
```

Examples of Tracing

```
(DEFUN foo (x y) (APPEND x (bar y)))
(DEFUN bar (p) (IF (NULL p) x (foo y (CDR p))))
Evaluate (FOO '(A) '(B C))
  enter FOO { X←(A), Y←(B C) }
    enter BAR { P←(B C) }
      enter FOO { X←(B C), Y←(C) }
        enter BAR { P←(C) }
          enter FOO { X←(C), Y←() }
            enter BAR { P ←() }
            return (C)
          return (C C)
        return (C C)
      return (B C C C)
    return (B C C C)
  return (A B C C C)
```


Functional Arguments – Revisited

- Can take a function as argument
  treat it as an s-expr
  "apply" it
- Dynamic vs Static Scoping
  QUOTE vs FUNCTION

Successor Function

- '1+' generates the numeric successor of its argument

```
(1+ 0) →1
(1+ 1)→ 2
(1+ 1.5)→2.5
(1+ (sqrt 2))→ 2.41421374
(1+ (/ 3 9))→ 4/3
```


Mapping Function: plus1

- Applies a function to each element of list.
- Eg 1: Add 1 to each element:

```
(DEFUN plus1 (list)
   (IF (NULL list)
       nil
       (CONS (1+ (CAR list))
             (plus1 (CDR list))) ))
(plus1 (list 3 -10 (sqrt 2) (/ 4 7)))
→ (4 -9 2.4142137 11/7)
```

Mapping Function: carAll

- Eg 2: Take CAR of each element:

```
(DEFUN carAll (list)
   (IF (NULL list)
      nil
      (CONS (CAR (CAR list))
            (carAll (CDR list))) ))
(CarAll '((A B) (C D E) (t) (5 A)))
→(A C t 5)
```


Mapping Function – MAPCAR

- Each mapping function has
  - a recursive loop over list elements
  - applying some specific function to each element
- Use higher-order function to define common parts!
- Pass in `list` and `function` to apply

```
(DEFUN MAPCAR (list fn)
   (IF (NULL list)
      nil
      (CONS (funcall fn (CAR list))
            (MAPCAR (CDR list) fn)) )))
```

- MAPCAR is built into Common Lisp

MAPCAR Examples

```
(MAPCAR '(3 5 0) '1+) → (4 6 1)
(MAPCAR '( (4) (t Q) ) 'CAR) → (4 t)
(MAPCAR '( (4) (t Q) ) 'CDR) → ( () (Q))
(MAPCAR '( (4) (t) )   'LISTP) → (T T)
(MAPCAR '( A B (C D))  'ATOM → (T T nil)
(MAPCAR '() 'ATOM) → ()
(MAPCAR '(A B C) '(LAMBDA (x) (CONS x '(t) ))) →
     ( (A t) (B t) (C t) )
```


Mapping Function – AnyOf

- True if any element of list x satisfies the predicate function fn (*Note carefully: list argument is named x*)

```
(DEFUN AnyOf (fn x)
   (COND ((NULL x)     nil)
         ((funcall fn (CAR x)) t)
         (     t           (AnyOf fn (CDR x))) ))
```

- An alternative definition emphasizing readability (might lose tail-recursion)

```
(DEFUN AnyOf-2 (fn list)
   (AND (NOT (NULL list))
        (OR (funcall fn (FIRST list))
            (AnyOf-2 fn (REST list)))))
```

AnyOf Examples

```
(AnyOf 'ATOM '(A B (C D)) )→  t
(AnyOf 'ATOM '((4) (t Q)) )→ nil
(AnyOf 'LISTP '((4) (t Q)) )→ t
(AnyOf 'CAR '((4) (t)) )→ t
(AnyOf 'CDR '((4) (t)) )→ nil
(AnyOf 'ATOM () )→ nil
(AnyOf '(LAMBDA (y) (EQ y 'A)) '(B A C))→ t
```


Mapping Functions

- Apply function to each [element | sublist] of list, returning list of values.
  - MapCar applies function to each element of list, returning list of values.
  - MapList — like `MAPCAR`, but uses successive SUBLISTS (not elements)
  - MapCan, MapCon ... destructive (Not PURE lisp)
- Apply function to each [element | sublist] of list, returning `nil`. (used for side effect – eg printing values. Not PURE lisp)
  - MapC — like `MapCar`, but returns nil
  - MapL — like `MapList`, but returns nil
- "Boolean" Functions (not in Common Lisp)
  - ANYOF determines if *any* element satisfies predicate.
  - ALLOF determines if *all* elements satisfy predicate.

Function Argument Problem

- Using functions with free variables can cause problems
- We might expect `memq` to return `t` if `at` is in `list`

```
(DEFUN memq (at list)
   (AnyOf '(LAMBDA (i) (EQ i at)) list ))
```

- Not necessarily true:
- Note: `at` is inside a quoted expression
  → it is not scoped in the context of `defun memq`
- Therefore `at` is a *Free Variable* within inner λ-expr.

MEMQ with DYNAMIC Scoping

- In a Lisp with dynamic scoping
  (e.g. Franz lisp but not Common Lisp),
  variables are resolved by checking bindings upwards along the stack

```
(DEFUN memq (at l)
   (AnyOf '(LAMBDA (i) (EQ i at)) l ))
```

- The `at` in the λ is unbound within the λ
- But, `memq` calls `AnyOf` which calls λ

```
(DEFUN AnyOf (fn x)
   (COND ((NULL x)      nil)
         ((funcall fn (CAR x)) t)
         (      t           (AnyOf fn (CDR x))) ))
```

- The `at` binding created by `memq` will resolve `at` in λ

Tracing MEMQ with DYNAMIC Scoping I

```
(memq 'a '(b a c))
Enter memq {at←a, l←(b a c)}
   Enter AnyOf  {fn←(LAMBDA (i) (EQ i at))
                 x←(b a c) }
      Enter λ(fn) {i← b}
         EVAL (EQ i at)  {i←b, at←a} ⇝nil
         ⋮
```

- Here, at is resolved against the binding made further up the stack ... so computation continues normally

MEMQ with DYNAMIC Scoping II

- Now *rename* at to x, but the x in λ is still free

```
(DEFUN memq (x i)
   (AnyOf '(LAMBDA(i) (EQ i x)) i))
```

- Recall AnyOf uses parameter x as well

```
(DEFUN AnyOf (fn x)
   (COND ((NULL x)     nil)
         ((funcall fn (CAR x)) t)
         (     t           (AnyOf fn (CDR x))) ))
```

- Again: memq calls AnyOf which calls λ
- Here, AnyOf has left closest binding to λ of x on the stack

Tracing memq with Dynamic Scoping II

```
(memq 'a '(b a c))
   Enter memq {x←a, l←(b a c)}
      Enter AnyOf {fn←(LAMBDA (i) (EQ i x)),
                    x←(b a c) }
         Enter  λ { i←b }
            EVAL (EQ i x ) {i←b,x←(b a c)}
               ⇝ERROR, as x is (b a c)
```

- The λ retrieves closest `x` on the stack, which is bound by `AnyOf`
- The λ requires `x` to be a executable expression: error!

FunArg Problem

- If Dynamic Scoping,

  ```
  (LAMBDA (at L) (AnyOf L '(LAMBDA (i) (EQ i at)) )
  (LAMBDA (x  L) (AnyOf L '(LAMBDA (i) (EQ i x )) )
  ```

  can have completely different results,
  as `x` and `at` are free within λ
- Want `x` evaluated *STATICALLY* (based on program definition)
  Not *DYNAMICALLY* (based on run-time environ.)
- Older *Lisp*'s usually evaluates free variables DYNAMICALLY.
- To get STATIC evaluation use new special form: `FUNCTION`

MEMQ *without* DYNAMIC Scoping

- Dynamic scoping can introduce subtle and hard-to-find errors
- In Lisp's without dynamic scoping (e.g., Modern Common Lisp), the x in quoted λ is still unbound

```
(DEFUN memq (x l)
   (AnyOf '(LAMBDA(i) (EQ i x)) l))
```

- Without dynamic scoping, x cannot be resolved on the stack

Tracing memq without Dynamic Scoping

```
(memq 'a '(b a c))
   Enter memq {x←a, l←(b a c)}
      Enter AnyOf {fn←(LAMBDA (i) (EQ i x)),
                        x←(b a c) }
         Enter  λ { i←b }
            EVAL (EQ i x ) {i←b,x←(b a c)}
               ⇝ERROR, as x undefined!
```

- x cannot be resolved

QUOTE is for Dynamic Scoping

- Dynamic Scoping: free variables isolated by quote

```
(DEFUN memq1 (x l)
   (AnyOf (QUOTE (LAMBDA (i) (EQ i x)))
      l))
```

- In Lisps that support dynamic scoping, free variables are evaluated DYNAMICALLY
- Hence: value of `x` in `memq1`'s is value of `AnyOf`'s 2^{nd} arg.

```
(QUOTE (LAMBDA (i) (EQ i x)))
```

- FunArg problem!

FUNCTION Specifies Static Scoping

- Static Scoping

```
(DEFUN memq2 (x l)
   (AnyOf (FUNCTION (LAMBDA (i) (EQ i x)))
      l))
```

- Free variables are evaluated STATICALLY
  - bindings are taken from the environment where λ was defined
- As it "sees" the `x` in `memq2`, that is the value it will take

Function Special Form

- FUNCTION behaves exactly like QUOTE except wrt evaluation of free variables:
- FUNCTION ≈ STATIC EVALUATION [based on (compile-time) function definition]
- QUOTE ≈ DYNAMIC EVALUATION [based on current (run-time) context]
- *Lisp*'s Compiler can compile `(function (LAMBDA (...)  ...))`

MEMQ with STATIC scoping

- In both Lisps with dynamic scoping and those without, the FUNCTION form introduces static scoping

```
(DEFUN memq (x l)
   (AnyOf (FUNCTION (LAMBDA (i) (EQ i x))) l ))
```

- The x in the λ is resolved in the scope of memq so it is bound to the first paramter of memq
- Again, memq calls AnyOf which calls the λ

```
(DEFUN AnyOf (fn x)
   (COND ((NULL x)     nil)
         ((funcall fn (CAR x)) t)
         (     t           (AnyOf fn (CDR x))) ))
```

- But, the x in AnyOf cannot interfere with the x in λ

Factory Method Example I

- In the absense of some global definition or binding higher up on the stack

```
(defun dynamic-funs (x)
   (list (quote (lambda () x))
         (quote (lambda (y) (setq x y)))))
(setq funs (dynamic-funs 6))
(funcall (first funs)) → variable x unbound
```


Factory Method Example II

- If a global definition exists, it can be used

```
(defun dynamic-funs (x)
   (list (quote (lambda () x))
         (quote (lambda (y) (setq x y)))))
(setf x nil)
(setq funs (dynamic-funs 6))
(funcall (first funs)) → nil
(funcall (second funs) 5)  → 5
(funcall (first funs)) →5
```

Factory Method Example III

- Even in Lisp's with static binding, function is necessary to tell the compiler that static scoping is desired for an expression

```
(defun static-funs (x)
   (list (function (lambda () x))
         (function (lambda (y) (setq x y)))))
(setq funs (static-funs 6))
(funcall (first funs)) → 6
(funcall (second funs) 43) →43
(funcall (first funs)) → 43
```

- Note: it is possible to create "objects" this way that have local data protected by accessor methods