Scheme

A Lisp dialect:

- dynamically, strongly typed
- expression-oriented, largely side-effect-free
- functional
- list-oriented, garbage-collected heap-based
- **highly regular and expressive**

Lisp designed by McCarthy in late 50's

Scheme dialect introduced by Steele and Sussman in mid 70's, embodying an executable version of the lambda calculus

Typically used with interactive read-eval-print loop, with interpreted implementation

- rapid development of small programs
- good debugging support

Good compilers exist, too

Syntax

```
Program ::= { Definition | Expr }

Definition ::=
          (define id Expr)
        | (define (id_fn id_formal1 ... id_formalN)
             Expr)

Expr  ::= id
        | Literal
        | SpecialForm
        | (Expr_fn Expr_arg1 ... Expr_argN)

Literal ::= int | float | string
          | symbol | ...

SpecialForm ::=
          (if Expr_test Expr_then Expr_else)
        | ...
```


Examples

Identifiers:

```
x  x1_2  is-string?  make-string!  <=
```

Literals (self-evaluating expressions):

```
3  -4  0.34 -5.6e-7  "hi there"  ""  #t  #f
```

Definitions, expressions, and evaluation results:

```
(+ 3 4)           → 7
(define seven (+ 3 4))
seven             → 7
(+ seven 8)       → 15
(define (square n) (* n n))
(square seven)    → 49
(define (fact n)
  (if (<= n 0)
      1
      (* n (fact (- n 1)))))
(fact 20)         → 2432902008176640000
```

Everything is an expression, including "control structures"

Prefix operators & function calls is regular, but not "traditional"

Special forms

Regular call expressions evaluation all arguments then invoke procedure ("call by value")

- user-defined procedures work this way

Special forms are special "functions" where arguments aren't all treated as expressions to be evaluated first

- can define new special forms using special macros

Example:

```
(define x 0)
(define y 5)
(if (= x 0) 0 (/ y x))        → 0
(define (my-if test then else)
  (if test then else))
(my-if (= x 0) 0 (/ y x))     → error!
```

Other special forms

`cond`: like `if-elseif-...-else` chain:

```
(cond ((> x 0) 1)
      ((= x 0) 0)
      (else -1))
```

Short-circuiting `and` and `or`:

```
(or (= x 0) (> (/ y x) 5) ...)
```

`let`: local variable bindings:

```
(define x 1) (define y 2) (define z 3)
(let ((x 5)
      (y (+ 3 4))
      (z (+ x y z)))
  (+ x y z))            → 5+7+(1+2+3)=18
```

`let*`: sequentially defined local variable bindings:

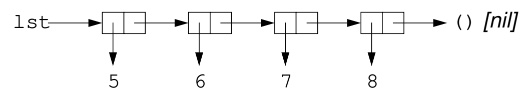
```
(let* ((x 5)
       (y (+ 3 4))
       (z (+ x y z)))
  (+ x y z))            → 5+7+(5+7+3)=27
```


Lists

Standard aggregate data structure is the list
(arrays are available, but less often used except for numerical computations)

A list is a singly-linked chain of cons-cells (a.k.a. pairs):

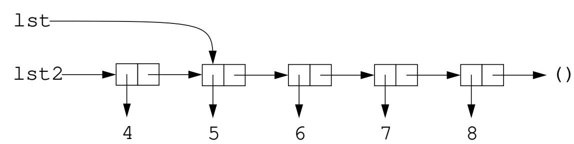
```
(define lst (list 5 6 7 8))
```




```
lst     → (5 6 7 8)
```

`cons` adds a new element to the front of a list, non-destructively:

```
(define lst2 (cons 4 lst))
```




```
lst     → (5 6 7 8)
lst2    → (4 5 6 7 8)
```

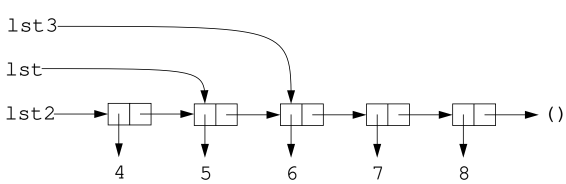

List accessors

`car` extracts the first element of the list:

```
(+ (car lst) (car lst2))    → 9
```

`cdr` extracts the rest of the list after the first, non-destructively:

```
(define lst3 (cdr lst))
```




```
lst     → (5 6 7 8)
lst2    → (4 5 6 7 8)
lst3    → (6 7 8)
```


List properties

`()` is the empty list literal, which is the result of `(list)`

- `#f` and `()` are the same in our implementation (yuck!)

Lists can be heterogenous, due to dynamic typing:

```
(list 3 4.5 () "hi" (list 3 5))
        → (3 4.5 () "hi" (3 5))
```

Lists can be nested within lists

E.g. an association list of key-value pairs:

```
(define Zips (list (list "Seattle" 98195)
                   (list "Boston" 02115)
                   (list "Reston" 22091)))
        → (("Seattle" 98195)
           ("Boston" 02115)
           ("Reston" 22091))
```

Very simple, regular, flexible structure

Quoting

List literals via `quote` or `'` special form:

```
(list 3 (list 4 5) 6)    → (3 (4 5) 6)
(quote (3 (4 5) 6))      → (3 (4 5) 6)
'(3 (4 5) 6)             → (3 (4 5) 6)
```

Quoted identifiers are symbol constants:

```
'positive                → positive
(car '(if (> a b) 3 4))  → if
```

Programs and data share same regular syntax

Equality

`eqv?`, `equal?`:
test whether two things are the same or isomorphic

`eqv?` ⇒ `equal?`

```
(eqv? 3 3)                        → #t

(eqv? (list 3 4) (list 3 4))      → #f
(let ((lst (list 3 4)))
  (eqv? lst lst))                 → #t
(equal? (list 3 4) (list 3 4))    → #t

(eqv? "hi" "hi")                  → #f
(equal? "hi" "hi")                → #t

(eqv? 'hi 'hi)                    → #t

(eqv? () ())                      → #t
```

`eq?`: low-level and more precise than `eqv?`
(are two pointers equal?)
probably should be avoided

Other predicates

Numeric comparisons like =, <, >=

- no not-equal

Type-testing predicates, because of dynamic typing:

```
null?
pair?
symbol?
boolean?
number?  integer?  ...
string?
...
```

Note `?` naming convention

A note about binding and parameter passing

All variables *refer* to data values

`let` binding & parameter passing do not copy r.h.s. value
but introduce new name that refers & shares r.h.s. value

("call-by-value with pointer semantics")

```
(define x(list 3 4 5))

(define (test s)
  (eqv? s x))

(test x) => #t
```

Simple, regular model

Garbage collection

All data structures implicitly allocated in the global heap

- gives data structures unlimited lifetime (**indefinite extent**)
- allows all data to be passed around and returned from functions and stored in other data structures

System automatically reclaims memory for unused data structures

- programmer doesn't have to worry about freeing unused memory
- avoids freeing too early (dangling pointer bugs) and freeing too late (storage leak bugs)
- system can sometimes be *more* efficient than programmer

Indefinite extent is simple, expressive

Automatic storage reclamation is much less error-prone

Some small efficiency concerns

Recursion over lists

Lists are a recursive data type:

A **list** is `()` (base case)

or a pair of a value and another **list** (inductive case)

Well-suited for manipulation by recursive functions with same structure as the recursive data type definition:

```
(define (f lst ...)
  (if (null? lst) ...base-case...
      ... (car lst) ... (f (cdr lst) ...) ...
```

Examples:

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

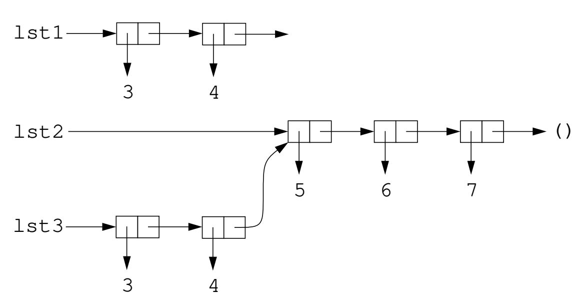
```
(define (sum lst)
  (if (null? lst) 0
      (+ (car lst) (sum (cdr lst)))))
```


Another example

```
;; find value associated with given key in alist
;; alist is a list of key-value pairs
(define (assoc key alist)
  (if (null? lst) #f
    (let* ((pair (car alist))
           (k (car pair))
           (v (cdr pair)))
      (if (equal? key k) v
        (assoc key (cdr alist))))))
(assoc "Boston" Zips)    → 02115
(assoc "Tacoma" Zips)    → #f
```


Another example

```
;; append two lists, non-destructively
(define (append lst1 lst2)
  (if (null? lst1) lst2
    (cons (car lst1)
          (append (cdr lst1) lst2))))
(define lst1 '(3 4))
(define lst2 '(5 6 7))
(define lst3 (append lst1 lst2))
lst3                  → (3 4 5 6 7)
```



Sharing list substructures is common, and safe if no side-effects

Side effect special forms

`set!`: rebind a variable to refer to a different value

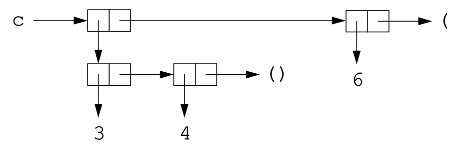
```
(define x 5)
(set! x '(6 7))
x                  → (6 7)

(define (test lst)
  (set! lst (cons 1 lst))
  lst)
(test '(2 3))      → (1 2 3)
```


Side effects on cons cells

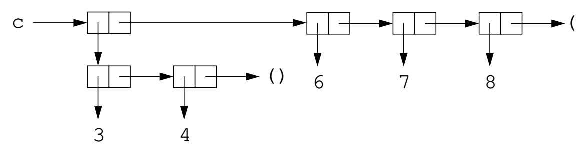
`set-car!`, `set-cdr!`: rebind head, tail of cons cell

```
(define c (list 5 6))
(set-car! c (list 3 4))
```




```
c                          → ((3 4) 6)

(set-cdr! (cdr c) (list 7 8))
```



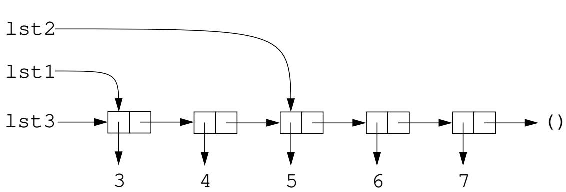

```
c                          → ((3 4) 6 7 8)
```


Example

`append!`: destructive `append`

```
(define (append! lst1 lst2)
  (cond ((null? lst1) lst2)
        ((null? (cdr lst1))
              (set-cdr! lst1 lst2)
              lst1)
        (else (append! (cdr lst1) lst2)
              lst1)))

(define lst1 '(3 4))
(define lst2 '(5 6 7))
(define lst3 (append! lst1 lst2))
lst3                → (3 4 5 6 7)
```



`append!` more efficient than `append`, but
more complicated to use correctly in face of rampant sharing

Recursion vs. iteration

Recursion more general than iteration

- equivalent to iteration plus a stack

Recursion often considered less efficient (both time and space) than iteration

- procedure calls and stack allocation/deallocation on each "iteration"

Tail recursion: recursive call is last operation before returning

- Scheme requires tail recursion to be implemented just as efficiently as iteration

Examples:

```
(define (last lst)
  (if (null? (cdr lst)) (car lst)
      (last (cdr lst))))

(define (member x lst)
  (cond ((null? lst) #f)
        ((eqv? x (car lst)) #t)
        (else (member x (cdr lst)))))
```

Converting to tail recursive form

This isn't tail recursive:

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

but we can define a tail-recursive version
using a helper procedure with an "accumulator" argument:

```
(define (factorial n)
  (define (fact-iter k result)
    (if (zero? k) result
      (fact-iter (- k 1) (* k result))))
  (fact-iter n 1))
```


First-class functions

Functions are themselves data values that can be passed around and called later

- function to call is a full-fledged expression

Enables a powerful form of abstraction where procedures can take other procedures as parameters to customize their behavior

- parameterized procedures sometimes called functionals

Example: a find functional with a comparison parameter function

```
(define (find pred-fn lst)
  (if (null? lst) #f
    (if (pred-fn (car lst)) (car lst)
      (find pred-fn (cdr lst)))))
```

To find first positive number in list:

```
(define (is-positive? n) (> n 0))
is-positive?               → #[compiled proc]
(find is-positive? '(-3 -4 5 7)) → 5
```

To find first nested list in list:

```
(find pair? '(3 (4 5) 6))        → (4 5)
```


More functionals

`map`: apply a function to each element of a list, collecting results into a new equal-length list

```
(define (map fn lst)
  (if (null? lst) ()
    (cons (fn (car lst))
          (map fn (cdr lst)))))
```

```
(map square '(3 4 5))  → (9 16 25)
(map is-positive? '(3 -4 5))  → (#t #f #t)
```

`map2`: take two lists and apply a binary function to corresponding elements, collecting results into a result list

```
(define (map2 fn lst1 lst2)
  (if (or (null? lst1) (null? lst2)) ()
    (cons (fn (car lst1) (car lst2))
          (map2 fn (cdr lst1) (cdr lst2)))))
```

```
(map2 + '(3 4 5) (6 7 8 9))  → (9 11 13)
(map2 list '("Seattle" "Boston")
           '(98195 02115))
     → (("Seattle" 98195) ("Boston" 02115))
```


Anonymous function literals

To exploit functionals better, can write a function in-line as an argument expression, without having to give it a global name

Syntax:

```
Literal ::= ...
         | (lambda (id_formal1 ... id_formalN)
              Expr)
```

Examples:

```
(map (lambda (n) (* n n)) '(3 4 5)) → (9 16 25)
(map2 (lambda (x y) (if (= y 0) 0 (/ x y)))
  '(3 4 5) '(-1 0 2))   → (-3 0 2)
```

Define for functions is "syntactic sugar" around a `lambda`

E.g.

```
(define (square n) (* n n))
```

is really just

```
(define square (lambda (n) (* n n)))
```

`cond`, `let`, `let*`, `and`, `or` are also syntactic sugars

More functionals

`reduce`: take a binary operator and apply it to pairs of list elements (like an infix operator) to compute a result

- left-to-right or right-to-left reduction?
- provide base value, or require non-empty input list and symmetric operator?

Right-to-left reduction, starting from base value:

```
(define (reduce fn base lst)
  (if (null? lst) base
    (fn (car lst)
        (reduce fn base (cdr lst)))))
```

Examples of use:

```
(define (sum lst) (reduce + 0 lst))
(define (prod lst) (reduce * 1 lst))
(define (length lst)
  (reduce (lambda (elem sum-rest)
            (+ 1 sum-rest))
          0 lst))
```


Another functional

`filter`: return a list of only those elements that pass a predicate

```
(define (filter pred lst)
  (reduce
     (lambda (val rest)
       (if (pred val) (cons val rest) rest)))
     nil lst))
```

Examples:

```
(filter is-positive '(3 -4 5 -6))   → (3 5)
```


Returning functions from functions

If functions are first-class, then should be able to return them, store them in data structures, etc.

Example: function composition

```
(define (compose f g)
  (lambda (x) (f (g x))))

(define double-square (compose double square))
```


Currying

A curried function takes some of its arguments and returns a function which takes the remaining arguments

- the result function can be applied to many different arguments, without having to pass in the first arguments again

```
(define (mapc fn) (lambda (lst) (map fn lst)))

(define squarer (mapc square))
(squarer '(3 4 5))  → (9 16 25)
(define sum-of-squares (compose sum squarer))

(define (map2c fn) (lambda (lst1 lst2) ...))

(define (reducec fn base) (lambda (lst) ...))
(define sum (reducec + 0))
(define prod (reducec * 1))

(define (filterc pred) (lambda (lst) ...))
(define positives (filterc is-positive))
(define negatives
  (filterc (lambda (x) (< x 0))))
```

Lexical scoping and block structure

Scheme has a hierarchy of nested scopes of name bindings

- global scope for all top-level names (from `define`)
- `lambda`, `let`, `let*` introduce nested scopes
  - `define` of a function introduces a nested scope, since it's sugar for `lambda`

The same name can be bound only once in a given scope, but can occur in many different scopes

For a given reference to a name, which binding is meant?

Lexical scoping (a.k.a. static scoping):
search from use *outwards through static program text* to first matching declaration

Dynamic scoping:
search from use *upwards through call stack* to first matching declaration

(There are some subtleties -- while we can find the *declaration* statically, we can't always find the *instance* of the identifier statically. See below.)

Example

```
(define x 40)

(define (clam x)
  (squid 3))

(define (squid y)
(+ x y))

(clam 1) => 43
```

Under dynamic scoping (as in older Lisps and some other bizzarre languages):

`(clam 1)` $\rightarrow$ 4

Easier to reason about non-local references with lexical scoping (MacLennan's Structure Principle)

The same example, but with a nested procedure

```
(define x 40)

(define (clam x)
  (define (squid y)
    (+ x y))
  (squid 3))

(clam 1) => 4
```


More static scoping

```
(define n 0)

(define (test n)
  (lambda (x) (+ x n)))

(test 100) => a procedure

((test 100) 5) => 105
((test 200) 5) => 205

n => 0
```

Interaction of Static Scoping and Recursion

```
(define (test n func)
  (cond
    ((= n 10) (func n))
    ((= n 5) (test (+ n 1) (lambda (k) (+ n k))))
    (else (test (+ n 1) func))))

(test 0 (lambda (a) 10)) => 15
```


First-class procedures and scoping

Lexical scoping is interesting if returning a function with nonlocal variables

- how to remember bindings of nonlocal variables?

```
(define (compose f g)
  (lambda (x) (f (g (x)))))

(define double-square (compose double square))
(define square-double (compose square double))

(double-square 5)
(square-double 5)
```

Where do bindings for `f` and `g` come from?
How are these two calls distinguished?

All curried functions have nonlocal variables like this
Many anonymous lambda arguments have nonlocal variables

Closures

To support lexically nested procedures which can be returned out of their enclosing scope, must represent as a **closure**: a pair of code address and **environment**

- environment records bindings of free variables
- closure no longer dependent on enclosing scope
- pair and environment must be heap-allocated
- e.g. Scheme, ML, Haskell, Smalltalk, Cecil

If only allow to pass nested procedures down, not return them, then can implement more cheaply

- environment can be stack-allocated, not heap-allocated
- e.g. Pascal, Modula-3

If allow nested procedures but not first-class procedures, then cheaper still

- do not need pair, just extra implicit environment argument
- e.g. Ada

If allow first-class procedures but no nesting, then can implement with just a code address

- e.g. C, C++