(An ((Even Better) Lisp) Interpreter (in Python))

In a previous essay I showed how to write a simple Lisp interpreter in 90 lines of Python: lis.py. In this essay I make the implementation, lispy.py, three times more complicated, but more complete. Each section handles an addition.

(1) New data types: string, boolean, complex, port

Adding a new data type to Lispy has three parts: the internal representation of the data, the procedures that operate on it, and the syntax for reading and writing it. Here we add four types (using Python's native representation for all but input ports):

- strings: string literals are enclosed in double-quotes. Within a string, a \n means a newline and a \" means a double-quote.
- booleans: The syntax is `#t` and `#f` for True and False, and the predicate is `boolean?`.
- complex numbers: we use the functions in the `cmath` module rather than the `math` module to support complex numbers. The syntax allows constants like `3+4i`.
- ports: No syntax to add, but procedures `port?`, `load`, `open-input-file`, `close-input-port`, `open-output-file`, `close-output-port`, `read`, `read-char`, `write` and `display`. Output ports are represented as Python file objects, and input ports are represented by a class, `InputPort` which wraps a file object and also keeps track of the last line of text read. This is convenient because Scheme input ports need to be able to read expressions as well as raw characters and our tokenizer works on a whole line, not individual characters.

Now, an old data type that becomes new:

- symbol: In the previous version of Lispy, symbols were implemented as strings. Now that we have strings, symbols will be implemented as a separate class (which derives from `str`). That means we no longer can write `if x[0] == 'if'`, because `'if'` is now a string, not a symbol. Instead we write `if x[0] is _if` and define `_if` as `Sym('if')`, where `Sym`manages a symbol table of unique symbols.

Here is the implementation of the new `Symbol` class:

```
class Symbol(str): pass

def Sym(s, symbol_table={}):
    "Find or create unique Symbol entry for str s in symbol table."
    if s not in symbol_table: symbol_table[s] = Symbol(s)
    return symbol_table[s]

_quote, _if, _set, _define, _lambda, _begin, _definemacro, = map(Sym,
"quote   if   set!  define   lambda   begin   define-macro".split())

_quasiquote, _unquote, _unquotesplicing = map(Sym,
"quasiquote   unquote   unquote-splicing".split())
```

We'll show the rest soon.

(2) New syntax: strings, comments, quotes, # literals

The addition of strings complicates tokenization. No longer can spaces delimit tokens, because spaces can appear inside strings. Instead we use a complex regular expression to break the input into tokens. In Scheme a comment consists of a semicolon to the end of line; we gather this up as a token and then ignore the token. We also add support for six new tokens:`#t #f ' ` , ,@`

The tokens `#t` and `#f` are the True and False literals, respectively. The single quote mark serves to quote the following expression. The syntax `'exp` is completely equivalent to `(quote exp)`. The backquote character ` is called quasiquote in Scheme; it is similar to ' except that within a quasiquoted expression, the notation `,exp` means to insert the value of exp(rather than the literal exp), and `,@exp` means that exp should evaluate to a list, and all the items of the list are inserted.

In the previous version of Lispy, all input was read from strings. In this version we have introduced ports (also known as file objects or streams) and will read from them. This makes the read-eval-print-loop (repl) much more convenient: instead of insisting that an input expression must fit on one line, we can now read tokens until we get a complete expression, even if it spans several lines. Also, errors are caught and printed, much as the Python interactive loop does. Here is the `InPort`(input port) class:

```
class InPort(object):
    "An input port. Retains a line of chars."
    tokenizer = r'''\s*(,@|[('`,)]|"(?:[\\].|[^\\"])*"|;.*|[^\s('"`,;)]*)(.*)'''
    def __init__(self, file):
        self.file = file; self.line = ''
    def next_token(self):
        "Return the next token, reading new text into line buffer if needed."
        while True:
            if self.line == '': self.line = self.file.readline()
            if self.line == '': return eof_object
            token, self.line = re.match(InPort.tokenizer, self.line).groups()
            if token != '' and not token.startswith(';'):
                return token
```

The basic design for the `read` function follows a suggestion (with working code) from Darius Bacon (who contributed several other improvements as well).

```
eof_object = Symbol('#<eof-object>') # Note: uninterned; can't be read

def readchar(inport):
    "Read the next character from an input port."
    if inport.line != '':
        ch, inport.line = inport.line[0], inport.line[1:]
        return ch
    else:
        return inport.file.read(1) or eof_object

def read(inport):
    "Read a Scheme expression from an input port."
    def read_ahead(token):
        if '(' == token:
            L = []
            while True:
                token = inport.next_token()
                if token == ')': return L
                else: L.append(read_ahead(token))
        elif ')' == token: raise SyntaxError('unexpected )')
        elif token in quotes: return [quotes[token], read(inport)]
        elif token is eof_object: raise SyntaxError('unexpected EOF in list')
        else: return atom(token)
    # body of read:
    token1 = inport.next_token()
    return eof_object if token1 is eof_object else read_ahead(token1)

quotes = {"'":_quote, "`":_quasiquote, ",":_unquote, ",@":_unquotesplicing}

def atom(token):
    'Numbers become numbers; #t and #f are booleans; "..." string; otherwise Symbol.'
    if token == '#t': return True
    elif token == '#f': return False
    elif token[0] == '"': return token[1:-1].decode('string_escape')
    try: return int(token)
    except ValueError:
        try: return float(token)
        except ValueError:
            try: return complex(token.replace('i', 'j', 1))
            except ValueError:
                return Sym(token)
```

```
def to_string(x):
    "Convert a Python object back into a Lisp-readable string."
    if x is True: return "#t"
    elif x is False: return "#f"
    elif isa(x, Symbol): return x
    elif isa(x, str): return '"%s"' % x.encode('string_escape').replace('"',r'\"')
    elif isa(x, list): return '('+' '.join(map(to_string, x))+')'
    elif isa(x, complex): return str(x).replace('j', 'i')
    else: return str(x)

def load(filename):
    "Eval every expression from a file."
    repl(None, InPort(open(filename)), None)

def repl(prompt='lispy> ', inport=InPort(sys.stdin), out=sys.stdout):
    "A prompt-read-eval-print loop."
    sys.stderr.write("Lispy version 2.0\n")
    while True:
        try:
            if prompt: sys.stderr.write(prompt)
            x = parse(inport)
            if x is eof_object: return
            val = eval(x)
            if val is not None and out: print >> out, to_string(val)
        except Exception as e:
            print '%s: %s' % (type(e).__name__, e)
```

Here we see how the read-eval-print loop is improved:

```
>>> repl()
Lispy version 2.0
lispy> (define (cube x)
          (* x (* x x))) ; input spans multiple lines
lispy> (cube 10)
1000
lispy> (cube 1) (cube 2) (cube 3) ; multiple inputs per line
1
lispy> 8
lispy> 27
lispy> (/ 3 0) ; error recovery
ZeroDivisionError: integer division or modulo by zero
lispy> (if 1 2 3 4 5) ; syntax error recovery
SyntaxError: (if 1 2 3 4 5): wrong length
lispy> (defun (f x)
          (set! 3 x)) ;; early syntax error detection
SyntaxError: (set! 3 x): can set! only a symbol
lispy>
```

(3) Macros: user-defined and builtin derived syntax

We also add a facility for defining macros. This is available to the user, through the `define-macro` special form (which is slightly different than standard Scheme), and is also used internally to define so-called derived expressions, such as the`and` form. Macros definitions are only allowed at the top level of a file or interactive session, or within a `begin` form that is at the top level.

Here are definitions of the macros `let` and `and`, showing the backquote, unquote, and unquote-splicing syntax:

```
def let(*args):
    args = list(args)
    x = cons(_let, args)
    require(x, len(args)>1)
    bindings, body = args[0], args[1:]
    require(x, all(isa(b, list) and len(b)==2 and isa(b[0], Symbol)
                   for b in bindings), "illegal binding list")
    vars, vals = zip(*bindings)
    return [[_lambda, list(vars)]+map(expand, body)] + map(expand, vals)
```

```
_append, _cons, _let = map(Sym("append cons let".split))

macro_table = {_let:let} ## More macros can go here

eval(parse("""(begin

(define-macro and (lambda args
   (if (null? args) #t
       (if (= (length args) 1) (car args)
           `(if ,(car args) (and ,@(cdr args)) #f)))))

;; More macros can go here

)"""))
```

(4) Better `eval` with tail recursion optimization

Scheme has no `while` or `for` loops, relying on recursion for iteration. That makes the language simple, but there is a potential problem: if every recursive call grows the runtime stack, then the depth of recursion, and hence the ability to loop, will be limited. In some implementations the limit will be as small as a few hundred iterations. This limitation can be lifted by altering `eval` so that it does not grow the stack on all recursive calls--only when necessary.

Consider the evaluation of `(if (> v 0) (begin 1 (begin 2 (twice (- v 1)))))` when `v` is 1 and `twice` is the procedure `(lambda (y) (* 2 y))`. With the version of `eval` in lis.py, we would get the following trace of execution, where each arrow indicates a recursive call to `eval`:

```
⇒ eval(x=(if (> v 0) (begin 1 (begin 2 (twice (- v 1))))),      env={'v':1})
    ⇒ eval(x=(begin 1 (begin 2 (twice (- v 1)))),               env={'v':1})
        ⇒ eval(x=(begin 2 (twice (- v 1)))),                    env={'v':1})
            ⇒ eval(x=(twice (- v 1)))),                         env={'v':1})
                ⇒ eval(x=(* 2 y),                               env={'y':0})
                ⇐ 0
```

But note that the recursive calls are not necessary. Instead of making a recursive call that returns a value that is then immediately returned again by the caller, we can instead alter the value of `x` (and sometimes `env`) in the original invocation of`eval(x, env)`. We are free to do that whenever the old value of `x`is no longer needed. The call sequence now looks like this:

```
⇒ eval(x=(if (> v 0) (begin 1 (begin 2 (twice (- v 1))))),      env={'v':1})
   x = (begin 1 (begin 2 (twice (- v 1))))
   x = (begin 2 (twice (- v 1))))
   x = (twice (- v 1))))
   x = (* 2 y);                                                 env = {'y':0}
⇐ 0
```

Here is an implementation of `eval` that works this way. We wrap the body in a `while True` loop, and then for most clauses, the implementation is unchanged. However, for three clauses we update the variable `x` (the expression being evaluated): for `if`, for `begin`, and for procedure calls to a user-defined procedure (in that case, we not ony update `x` to be the body of the procedure, we also update `env` to be a new environment that has the bindings of the procedure parameters). Here it is:

```
def eval(x, env=global_env):
    "Evaluate an expression in an environment."
    while True:
        if isa(x, Symbol):       # variable reference
            return env.find(x)[x]
        elif not isa(x, list):   # constant literal
            return x
        elif x[0] is _quote:     # (quote exp)
            (_, exp) = x
            return exp
        elif x[0] is _if:        # (if test conseq alt)
```

```
            (_, test, conseq, alt) = x
            x = (conseq if eval(test, env) else alt)
        elif x[0] is _set:       # (set! var exp)
            (_, var, exp) = x
            env.find(var)[var] = eval(exp, env)
            return None
        elif x[0] is _define:    # (define var exp)
            (_, var, exp) = x
            env[var] = eval(exp, env)
            return None
        elif x[0] is _lambda:    # (lambda (var*) exp)
            (_, vars, exp) = x
            return Procedure(vars, exp, env)
        elif x[0] is _begin:     # (begin exp+)
            for exp in x[1:-1]:
                eval(exp, env)
            x = x[-1]
        else:                    # (proc exp*)
            exps = [eval(exp, env) for exp in x]
            proc = exps.pop(0)
            if isa(proc, Procedure):
                x = proc.exp
                env = Env(proc.parms, exps, proc.env)
            else:
                return proc(*exps)

class Procedure(object):
    "A user-defined Scheme procedure."
    def __init__(self, parms, exp, env):
        self.parms, self.exp, self.env = parms, exp, env
    def __call__(self, *args):
        return eval(self.exp, Env(self.parms, args, self.env))
```

This implementation makes it possible to write procedures that recurse arbitrarily deeply without running out of storage. However, it may require some restructring of procedures to make this work. Consider these two implementations of a function to sum the integers from 0 to n:

```
(define (sum-to n)
  (if (= n 0)
      0
      (+ n (sum-to (- n 1)))))

(define (sum2 n acc)
  (if (= n 0)
      acc
      (sum2 (- n 1) (+ n acc))))
```

The first is more straightforward, but it yields a "RuntimeError: maximum recursion depth exceeded" on `(sum-to 1000)`. The second version has the recursive call to `sum2` in the last position of the body, and thus you can safely sum the first million integers with `(sum2 1000000 0)` and get 500000500000. Note that the second argument, `acc`, accumulates the results computed so far. If you can learn to use this style of accumulators, you can recurse arbitrarily deeply.

(5) Call-with-current-continuation (`call/cc`)

We have seen that Scheme handles iteration using recursion, with no need for special syntax for `for` or `while` loops. But what about non-local control flow, as is done with `try/except` in Python or `setjmp/longjmp` in C? Scheme offers a primitive procedure, called `call/cc` for "call with current continuation". Let's start with some examples:

```
lispy> (call/cc (lambda (throw)
         (+ 5 (* 10 (call/cc (lambda (escape) (* 100 (escape 3))))))))
35

lispy> (call/cc (lambda (throw)
         (+ 5 (* 10 (call/cc (lambda (escape) (* 100 (throw 3))))))))
3
```

In the first example, evaluating (escape 3) causes Scheme to abort the current calculation and return 3 as the value of the enclosing call to call/cc. The result is the same as (+ 5 (* 10 3))or 35.

In the second example, (throw 3) aborts up two levels, throwing the value of 3 back to the top level. In general, call/cc takes a single argument, proc, which must be a procedure of one argument. proc is called, passing it a manufactured procedure which we will call throw. If throw is called with a single argument, then that argument is the value of the whole call tocall/cc. If throw is not called, the value computed by proc is returned. Here is the implementation:

```
def callcc(proc):
    "Call proc with current continuation; escape only"
    ball = RuntimeWarning("Sorry, can't continue this continuation any longer.")
    def throw(retval): ball.retval = retval; raise ball
    try:
        return proc(throw)
    except RuntimeWarning as w:
        if w is ball: return ball.retval
        else: raise w
```

This implementation allows for non-local escape from procedures. It does not, however, implement the full power of a real Scheme call/cc, with which we can not only call the continuation to return a value, we can also store the continuation away and call it multiple times, each time returning to the same place.

(6) Procedures with arbitrary number of arguments

The standard Scheme procedure list can be called with any number of arguments: (list 1 2), (list 1 2 3), etc. In Scheme a user can define a procedure like this using the syntax (lambda args body)where args is a single symbol representing the parameter that is bound to the list of arguments supplied in a procedure call, and body is the body of the procedure. The implementation takes just one small change in Env.__init__ to check if parms is a Symbol rather than a list:

```
class Env(dict):
    "An environment: a dict of {'var':val} pairs, with an outer Env."
    def __init__(self, parms=(), args=(), outer=None):
        # Bind parm list to corresponding args, or single parm to list of args
        self.outer = outer
        if isa(parms, Symbol):
            self.update({parms:list(args)})
        else:
            if len(args) != len(parms):
                raise TypeError('expected %s, given %s, '
                                % (to_string(parms), to_string(args)))
            self.update(zip(parms,args))
    def find(self, var):
        "Find the innermost Env where var appears."
        if var in self: return self
        elif self.outer is None: raise LookupError(var)
        else: return self.outer.find(var)
```

If parms is a Symbol, we bind it to the list or arguments. Otherwise we bind each parm to the corresponding arg. Real Scheme also has the syntax (lambda (arg1 arg2 . rest) ...). We can't do that because we're using Python lists, and don't have dotted pairs.

(7) Earlier error detection and extended syntax

Consider the following erroneous code:

```
(define f (lambda (x) (set! 3 x)))
(define g (lambda (3) (if (x = 0))))
(define h (lambda (x) (if (x = 0) 1 2 3)))
```

In the first version of Lispy, evaluating these definitions would not yield any complaints. But as soon as any of the functions were called, a runtime error would occur. In general, errors should be reported as early as possible, so the new version of Lispy would give appropriate error messages as these functions are defined, not waiting for them to be called.

We do this by improving the procedure `parse`. In the first version of Lispy, `parse` was implemented as `read`; in other words, any expression at all was accepted as a program. The new version checks each expression for validity when it is defined. It checks that each special form has the right number of arguments and that `set!` and `define` operate on symbols. It also expands the macros and quasiquote forms defined in section (2) above. It accepts a slightly more generous version of Scheme, as described in the table below. Each of the expressions on the left would be illegal in the first version of Lispy, but are accepted as equivalent to the corresponding expressions on the right in the new version:

Extended Expression	Expansion
(begin)	None
(if test conseq)	(if test conseq None)
(define (f arg...) body...)	(define f (lambda (arg...) body...)
(lambda (arg...) e1 e2...)	(lambda (arg...) (begin e1 e2...))
`exp (quasiquote exp)	expand , and ,@ within exp
(macro-name arg...)	expansion of (macro-name arg...)

Here is the definiiton of `parse`:

```
def parse(inport):
    "Parse a program: read and expand/error-check it."
    # Backwards compatibility: given a str, convert it to an InPort
    if isinstance(inport, str): inport = InPort(StringIO.StringIO(inport))
    return expand(read(inport), toplevel=True)
```

And here is the definition of `expand`. It may seem odd that `expand`is twice as long as `eval`. But `expand` actually has a harder job: it has to do almost everything eval does in terms of making sure that legal code has all the right pieces, but in addition it must deal with illegal code, producing a sensible error message, and extended code, converting it into the right basic form.

```
def expand(x, toplevel=False):
    "Walk tree of x, making optimizations/fixes, and signaling SyntaxError."
    require(x, x!=[])                    # () => Error
    if not isa(x, list):                 # constant => unchanged
        return x
    elif x[0] is _quote:                 # (quote exp)
        require(x, len(x)==2)
        return x
    elif x[0] is _if:
        if len(x)==3: x = x + [None]     # (if t c) => (if t c None)
        require(x, len(x)==4)
        return map(expand, x)
    elif x[0] is _set:
        require(x, len(x)==3);
        var = x[1]                       # (set! non-var exp) => Error
        require(x, isa(var, Symbol), "can set! only a symbol")
        return [_set, var, expand(x[2])]
    elif x[0] is _define or x[0] is _definemacro:
        require(x, len(x)>=3)
        _def, v, body = x[0], x[1], x[2:]
        if isa(v, list) and v:           # (define (f args) body)
            f, args = v[0], v[1:]        #  => (define f (lambda (args) body))
            return expand([_def, f, [_lambda, args]+body])
        else:
            require(x, len(x)==3)        # (define non-var/list exp) => Error
            require(x, isa(v, Symbol), "can define only a symbol")
            exp = expand(x[2])
            if _def is _definemacro:
```

```
                require(x, toplevel, "define-macro only allowed at top level")
                proc = eval(exp)
                require(x, callable(proc), "macro must be a procedure")
                macro_table[v] = proc    # (define-macro v proc)
                return None              #  => None; add v:proc to macro_table
            return [_define, v, exp]
    elif x[0] is _begin:
        if len(x)==1: return None        # (begin) => None
        else: return [expand(xi, toplevel) for xi in x]
    elif x[0] is _lambda:                # (lambda (x) e1 e2)
        require(x, len(x)>=3)            #  => (lambda (x) (begin e1 e2))
        vars, body = x[1], x[2:]
        require(x, (isa(vars, list) and all(isa(v, Symbol) for v in vars))
                or isa(vars, Symbol), "illegal lambda argument list")
        exp = body[0] if len(body) == 1 else [_begin] + body
        return [_lambda, vars, expand(exp)]
    elif x[0] is _quasiquote:            # `x => expand_quasiquote(x)
        require(x, len(x)==2)
        return expand_quasiquote(x[1])
    elif isa(x[0], Symbol) and x[0] in macro_table:
        return expand(macro_table[x[0]](*x[1:]), toplevel) # (m arg...)
    else:                                #        => macroexpand if m isa macro
        return map(expand, x)            # (f arg...) => expand each

def require(x, predicate, msg="wrong length"):
    "Signal a syntax error if predicate is false."
    if not predicate: raise SyntaxError(to_string(x)+': '+msg)

def expand_quasiquote(x):
    """Expand `x => 'x; `,x => x; `(,@x y) => (append x y) """
    if not is_pair(x):
        return [_quote, x]
    require(x, x[0] is not _unquotesplicing, "can't splice here")
    if x[0] is _unquote:
        require(x, len(x)==2)
        return x[1]
    elif is_pair(x[0]) and x[0][0] is _unquotesplicing:
        require(x[0], len(x[0])==2)
        return [_append, x[0][1], expand_quasiquote(x[1:])]
    else:
        return [_cons, expand_quasiquote(x[0]), expand_quasiquote(x[1:])]
```

(8) More primitive procedures

Here we augment add_globals with some more primitive Scheme procedures, bringing the total to 75. There are still around 80 missing ones; they could also be added here if desired.

```
def is_pair(x): return x != [] and isa(x, list)

def add_globals(self):
    "Add some Scheme standard procedures."
    import math, cmath, operator as op
    self.update(vars(math))
    self.update(vars(cmath))
    self.update({
     '+':op.add, '-':op.sub, '*':op.mul, '/':op.div, 'not':op.not_,
     '>':op.gt, '<':op.lt, '>=':op.ge, '<=':op.le, '=':op.eq,
     'equal?':op.eq, 'eq?':op.is_, 'length':len, 'cons':lambda x,y:[x]+list(y),
     'car':lambda x:x[0], 'cdr':lambda x:x[1:], 'append':op.add,
     'list':lambda *x:list(x), 'list?': lambda x:isa(x,list),
     'null?':lambda x:x==[], 'symbol?':lambda x: isa(x, Symbol),
     'boolean?':lambda x: isa(x, bool), 'pair?':is_pair,
     'port?': lambda x:isa(x,file), 'apply':lambda proc,l: proc(*l),
     'eval':lambda x: eval(expand(x)), 'load':lambda fn: load(fn), 'call/cc':callcc,
     'open-input-file':open,'close-input-port':lambda p: p.file.close(),
     'open-output-file':lambda f:open(f,'w'), 'close-output-port':lambda p: p.close(),
     'eof-object?':lambda x:x is eof_object, 'read-char':readchar,
     'read':read, 'write':lambda x,port=sys.stdout:port.write(to_string(x)),
     'display':lambda x,port=sys.stdout:port.write(x if isa(x,str) else to_string(x))})
    return self
```

```
isa = isinstance

global_env = add_globals(Env())
```

(9) Testing

Complicated programs should always be accompanied by a thorough test suite. We provide the program lispytest.py, which tests both versions of Lispy:

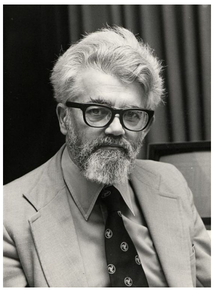
```
bash$ python lispytest.py
python lispytest.py
(quote (testing 1 (2.0) -3.14e159)) => (testing 1 (2.0) -3.14e+159)
(+ 2 2) => 4
(+ (* 2 100) (* 1 10)) => 210
(if (> 6 5) (+ 1 1) (+ 2 2)) => 2
(if (< 6 5) (+ 1 1) (+ 2 2)) => 4
(define x 3) => None
x => 3
(+ x x) => 6
(begin (define x 1) (set! x (+ x 1)) (+ x 1)) => 3
((lambda (x) (+ x x)) 5) => 10
(define twice (lambda (x) (* 2 x))) => None
(twice 5) => 10
(define compose (lambda (f g) (lambda (x) (f (g x))))) => None
((compose list twice) 5) => (10)
(define repeat (lambda (f) (compose f f))) => None
((repeat twice) 5) => 20
((repeat (repeat twice)) 5) => 80
(define fact (lambda (n) (if (<= n 1) 1 (* n (fact (- n 1)))))) => None
(fact 3) => 6
(fact 50) => 30414093201713378043612608166064768844377641568960512000000000000
(define abs (lambda (n) ((if (> n 0) + -) 0 n))) => None
(list (abs -3) (abs 0) (abs 3)) => (3 0 3)
(define combine (lambda (f)
    (lambda (x y)
      (if (null? x) (quote ())
          (f (list (car x) (car y))
             ((combine f) (cdr x) (cdr y))))))) => None
(define zip (combine cons)) => None
(zip (list 1 2 3 4) (list 5 6 7 8)) => ((1 5) (2 6) (3 7) (4 8))
(define riff-shuffle (lambda (deck) (begin
    (define take (lambda (n seq) (if (<= n 0) (quote ()) (cons (car seq) (take (- n 1) (cdr seq))))))
    (define drop (lambda (n seq) (if (<= n 0) seq (drop (- n 1) (cdr seq)))))
    (define mid (lambda (seq) (/ (length seq) 2)))
    ((combine append) (take (mid deck) deck) (drop (mid deck) deck))))) => None
(riff-shuffle (list 1 2 3 4 5 6 7 8)) => (1 5 2 6 3 7 4 8)
((repeat riff-shuffle) (list 1 2 3 4 5 6 7 8)) => (1 3 5 7 2 4 6 8)
(riff-shuffle (riff-shuffle (riff-shuffle (list 1 2 3 4 5 6 7 8)))) => (1 2 3 4 5 6 7 8)
********************************************* lis.py: 0 out of 29 tests fail.
(quote (testing 1 (2.0) -3.14e159)) => (testing 1 (2.0) -3.14e+159)
(+ 2 2) => 4
(+ (* 2 100) (* 1 10)) => 210
(if (> 6 5) (+ 1 1) (+ 2 2)) => 2
(if (< 6 5) (+ 1 1) (+ 2 2)) => 4
(define x 3) => None
x => 3
(+ x x) => 6
(begin (define x 1) (set! x (+ x 1)) (+ x 1)) => 3
((lambda (x) (+ x x)) 5) => 10
(define twice (lambda (x) (* 2 x))) => None
(twice 5) => 10
(define compose (lambda (f g) (lambda (x) (f (g x))))) => None
((compose list twice) 5) => (10)
(define repeat (lambda (f) (compose f f))) => None
((repeat twice) 5) => 20
((repeat (repeat twice)) 5) => 80
(define fact (lambda (n) (if (<= n 1) 1 (* n (fact (- n 1)))))) => None
(fact 3) => 6
(fact 50) => 30414093201713378043612608166064768844377641568960512000000000000
(define abs (lambda (n) ((if (> n 0) + -) 0 n))) => None
(list (abs -3) (abs 0) (abs 3)) => (3 0 3)
```

```
(define combine (lambda (f)
    (lambda (x y)
      (if (null? x) (quote ())
          (f (list (car x) (car y))
             ((combine f) (cdr x) (cdr y))))))) => None
(define zip (combine cons)) => None
(zip (list 1 2 3 4) (list 5 6 7 8)) => ((1 5) (2 6) (3 7) (4 8))
(define riff-shuffle (lambda (deck) (begin
    (define take (lambda (n seq) (if (<= n 0) (quote ()) (cons (car seq) (take (- n 1) (cdr seq))))))
    (define drop (lambda (n seq) (if (<= n 0) seq (drop (- n 1) (cdr seq)))))
    (define mid (lambda (seq) (/ (length seq) 2)))
    ((combine append) (take (mid deck) deck) (drop (mid deck) deck))))) => None
(riff-shuffle (list 1 2 3 4 5 6 7 8)) => (1 5 2 6 3 7 4 8)
((repeat riff-shuffle) (list 1 2 3 4 5 6 7 8)) => (1 3 5 7 2 4 6 8)
(riff-shuffle (riff-shuffle (riff-shuffle (list 1 2 3 4 5 6 7 8)))) => (1 2 3 4 5 6 7 8)
() =raises=> SyntaxError (): wrong length
(set! x) =raises=> SyntaxError (set! x): wrong length
(define 3 4) =raises=> SyntaxError (define 3 4): can define only a symbol
(quote 1 2) =raises=> SyntaxError (quote 1 2): wrong length
(if 1 2 3 4) =raises=> SyntaxError (if 1 2 3 4): wrong length
(lambda 3 3) =raises=> SyntaxError (lambda 3 3): illegal lambda argument list
(lambda (x)) =raises=> SyntaxError (lambda (x)): wrong length
(if (= 1 2) (define-macro a 'a)
    (define-macro a 'b)) =raises=> SyntaxError (define-macro a (quote a)): define-macro only allowed at top level
(define (twice x) (* 2 x)) => None
(twice 2) => 4
(twice 2 2) =raises=> TypeError expected (x), given (2 2),
(define lyst (lambda items items)) => None
(lyst 1 2 3 (+ 2 2)) => (1 2 3 4)
(if 1 2) => 2
(if (= 3 4) 2) => None
(define ((account bal) amt) (set! bal (+ bal amt)) bal) => None
(define a1 (account 100)) => None
(a1 0) => 100
(a1 10) => 110
(a1 10) => 120
(define (newton guess function derivative epsilon)
    (define guess2 (- guess (/ (function guess) (derivative guess))))
    (if (< (abs (- guess guess2)) epsilon) guess2
        (newton guess2 function derivative epsilon))) => None
(define (square-root a)
    (newton 1 (lambda (x) (- (* x x) a)) (lambda (x) (* 2 x)) 1e-8)) => None
(> (square-root 200.) 14.14213) => #t
(< (square-root 200.) 14.14215) => #t
(= (square-root 200.) (sqrt 200.)) => #t
(define (sum-squares-range start end)
         (define (sumsq-acc start end acc)
            (if (> start end) acc (sumsq-acc (+ start 1) end (+ (* start start) acc))))
         (sumsq-acc start end 0)) => None
(sum-squares-range 1 3000) => 9004500500
(call/cc (lambda (throw) (+ 5 (* 10 (throw 1))))) ;; throw => 1
(call/cc (lambda (throw) (+ 5 (* 10 1)))) ;; do not throw => 15
(call/cc (lambda (throw)
         (+ 5 (* 10 (call/cc (lambda (escape) (* 100 (escape 3)))))))) ; 1 level => 35
(call/cc (lambda (throw)
         (+ 5 (* 10 (call/cc (lambda (escape) (* 100 (throw 3)))))))) ; 2 levels => 3
(call/cc (lambda (throw)
         (+ 5 (* 10 (call/cc (lambda (escape) (* 100 1))))))) ; 0 levels => 1005
(* 1i 1i) => (-1+0i)
(sqrt -1) => 1i
(let ((a 1) (b 2)) (+ a b)) => 3
(let ((a 1) (b 2 3)) (+ a b)) =raises=> SyntaxError (let ((a 1) (b 2 3)) (+ a b)): illegal binding list
(and 1 2 3) => 3
(and (> 2 1) 2 3) => 3
(and) => #t
(and (> 2 1) (> 2 3)) => #f
(define-macro unless (lambda args `(if (not ,(car args)) (begin ,@(cdr args))))) ; test ` => None
(unless (= 2 (+ 1 1)) (display 2) 3 4) => None
2
(unless (= 4 (+ 1 1)) (display 2) (display "\n") 3 4) => 4
(quote x) => x
(quote (1 2 three)) => (1 2 three)
'x => x
```

```
'(one 2 3) => (one 2 3)
(define L (list 1 2 3)) => None
`(testing ,@L testing) => (testing 1 2 3 testing)
`(testing ,L testing) => (testing (1 2 3) testing)
`,@L =raises=> SyntaxError (unquote-splicing L): can't splice here
'(1 ;test comments '
     ;skip this line
     2 ; more ; comments ; ) )
     3) ; final comment => (1 2 3)
********************************************** lispy.py: 0 out of 81 tests fail.
```

(Appendix) Brought to you by

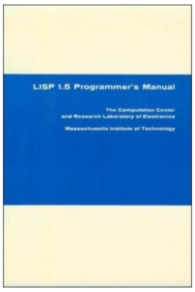

[Alonzo Church]

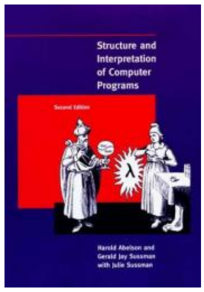

[John McCarthy]


[Steve Russell]


[Guy Steele]


[Gerald Jay Sussman]





Alonzo Church defined the lambda calculus in 1932. John McCarthy proposed that the calculus could be used as the basis of a programming language in late 1958; in 1959 Steve Russell had coded the first Lisp interpreter in assembler for the IBM 704. In 1975, Gerald Jay Sussman and Guy Steele invented the Scheme dialect of Lisp.

(Note: it may seem perverse to use `lambda` to introduce a procedure/function. The notation goes back to Alonzo Church, who in the 1930's started with a "hat" symbol; he wrote the square function as "$\hat{y} . y \times y$". But frustrated typographers moved the hat to the left of the parameter and changed it to a capital lambda: "$\Lambda y . y \times y$"; from there the capital lambda was changed to lowercase, and now we see "$\lambda y . y \times y$" in math books and `(lambda (y) (* y y))` in Lisp. If it were up to me, I'd use `fun` or maybe `^`.)

[Peter Norvig]