Writing a Mini-Lisp Compiler

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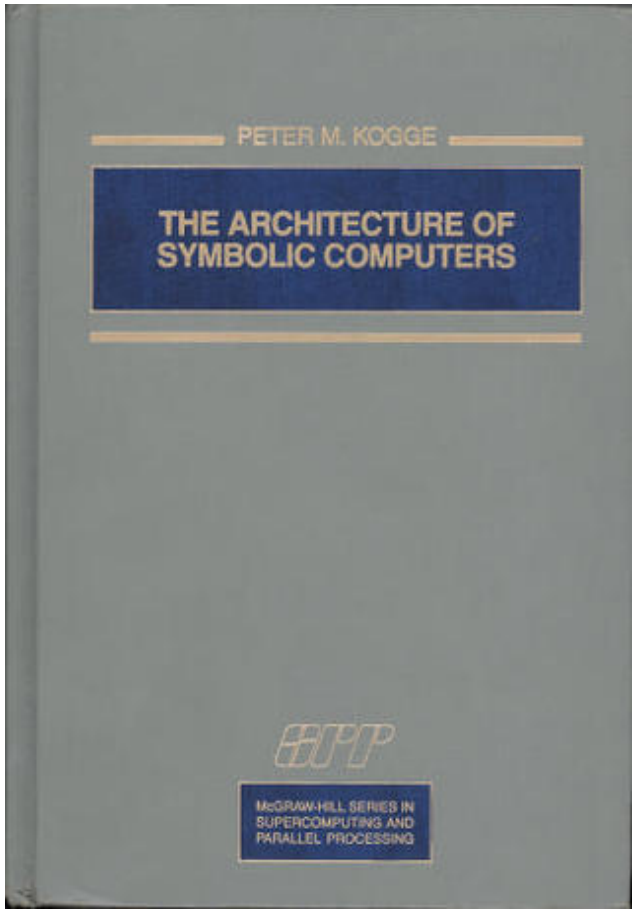
About 13 years ago I did an BSc/BInfTech combined degree.

A few of the IT subjects were fun:

- Computational complexity. NP-complete, etc.
- Operating systems. We wrote our own memory pager in C.
- Functional programming. Gofer on MS-DOS.
- Compilers. We wrote a compiler for a mini-Java language, in C.



The Architecture of Symbolic Computers (Peter M. Kogge, 1991)

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`http://blog.fogus.me/2012/07/25/some-lisp-books-and-then-some/`

“The best Lisp book I’ve ever read and could ever possibly read.”

`http://www.loper-os.org/?p=13`

“The Architecture of Symbolic Computers (Peter M. Kogge) is quite possibly the most useful resource I have come across in my quest thus far. If you are interested in Lisp Machine revival, non-von Neumann computation, or the dark arts of the low-level implementation of functional programming systems, you will not be disappointed.”

Here's the plan:

1. Define a virtual machine: memory, registers, opcodes.
2. Write an emulator.
3. Define a mini-Lisp language (let, lambdas, etc).
4. Write a compiler for mini-Lisp to the virtual machine.

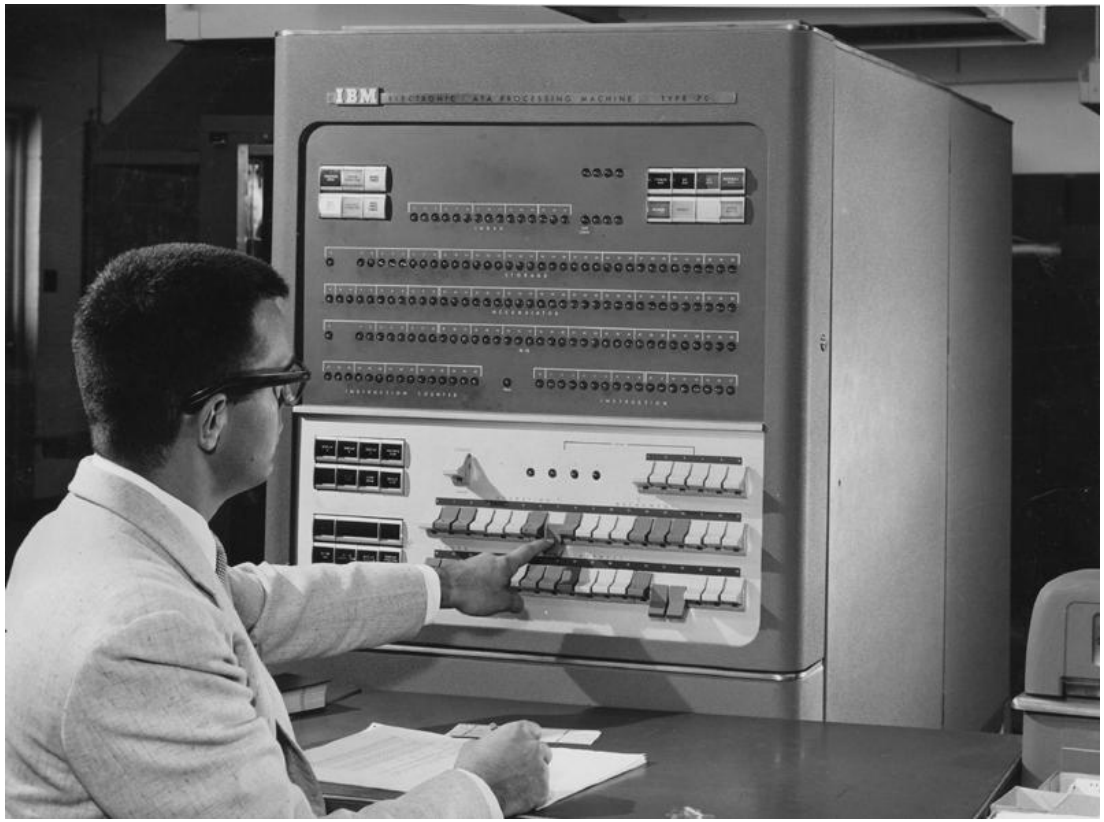
IBM 704/709 - circa 1950

16K per box!

http://www.computer-history.info/Page4.dir/pages/IBM.704.dir/

IBM 704/709 - circa 1950

Operator console.



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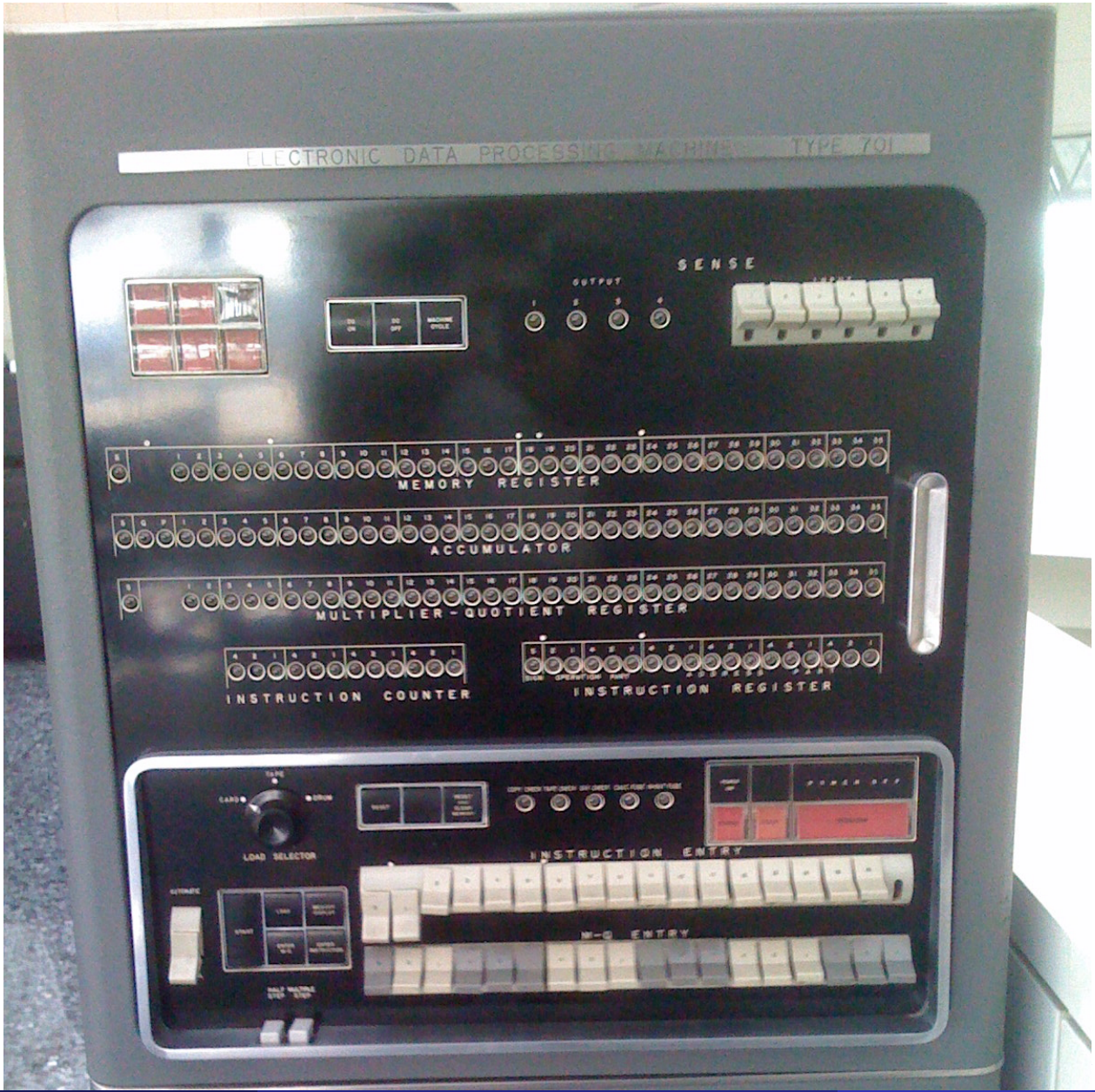
IBM 701 console



The IBM 704 had 36-bit machine words:

- address part: 15 bits
- decrement part: 15 bits
- prefix part: 3 bits
- tag part: 3 bits

Corresponding instructions:

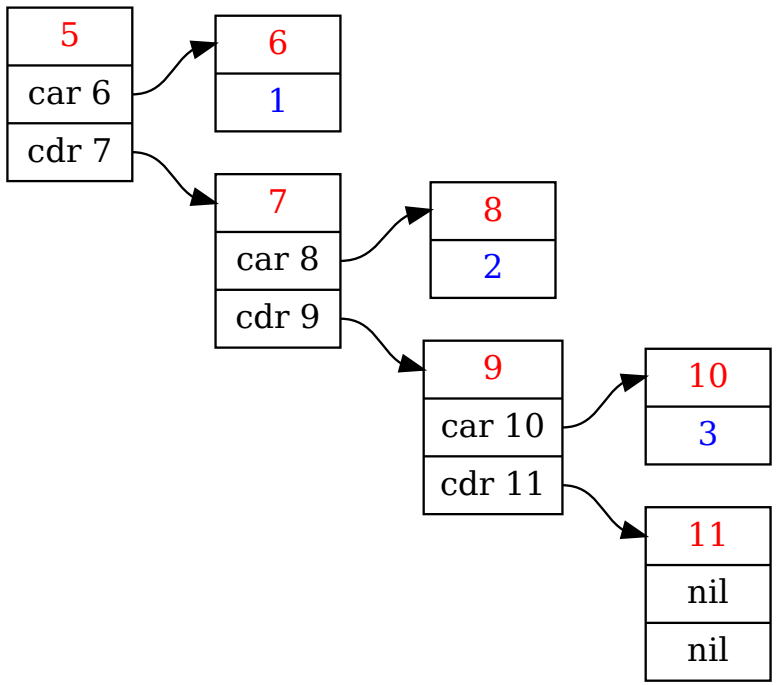
- CAR: Contents of Address part of Register
- CDR: Contents of Decrement part of Register

Think of CAR as head and CDR as tail. Store linked lists with ease.

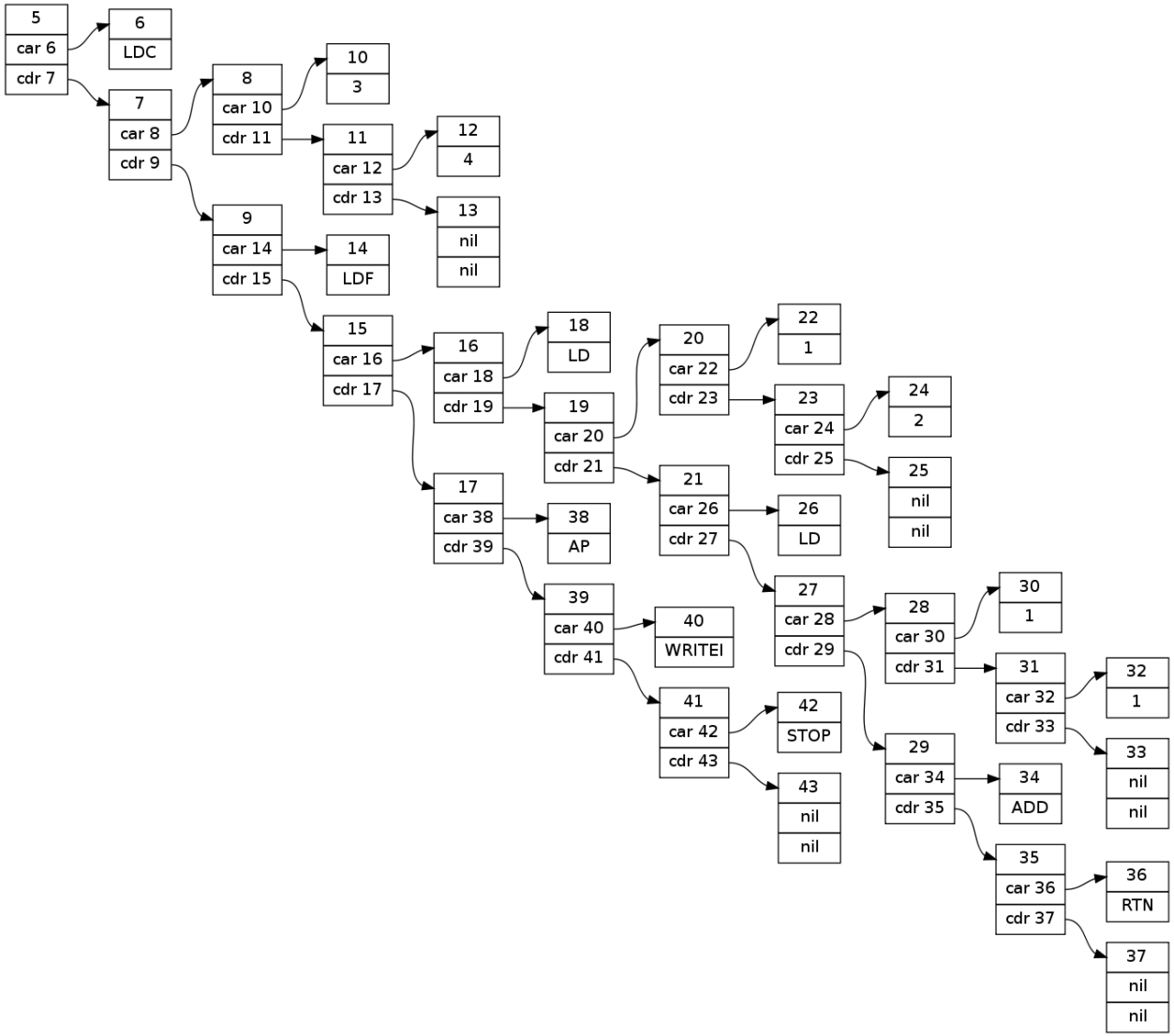
Store this list:

```
[1, 2, 3]
```

```
address  |  value
-----------------------
5        |  (6, 7)
6        |  1
7        |  (8, 9)
8        |  2
9        |  (10, 11)
10       |  3
11       |  (nil, nil)
```



```
[LDC, [3, 4], LDF, [LD, [1, 2], LD, [1, 1], ADD, RTN],
                AP, WRITEI, STOP,]
```



A linked list can represent a stack:

- push: insert at front, return new head.
- pop: remove from front, return cdr (tail) of original head.

We can run simple computations if we have two things:

- A stack for temporary results (like an accumulator register); and
- a pointer to the next instruction to execute.

- S: temporary results stack.
- C: program counter for currently executing code.
- `LDC`: LoaD Constant
- `ADD`: integer ADDition
- `STOP`: STOP the machine

Add 3 and 4:

```
1. S: []        C: [LDC, 3, LDC, 4, ADD, STOP]

2. S: [3]       C: [LDC, 4, ADD, STOP]

3. S: [4, 3]    C: [ADD, STOP]

4. S: [7]       C: [STOP]
```

```
LDC  = 100
ADD  = 101
STOP = 102

S = []
C = [LDC, 3, LDC, 4, ADD, STOP]

def opcode_LDC(S, C):
    assert C[0] == LDC
    C.pop(0)                    # pop LDC
    S.insert(0, C.pop(0)) # push value onto S

def opcode_ADD(S, C):
    assert C[0] == ADD
    C.pop(0)                        # pop ADD
    val1 = S.pop(0)                 # first value
    val2 = S.pop(0)                 # second value
    S.insert(0, val1 + val2) # push result
```

Here's the machine emulator:

```
S = []
C = [LDC, 3, LDC, 4, ADD, STOP]

while True:
    if   C[0] == STOP: break
    elif C[0] == LDC:
        opcode_LCD(S, C)
    elif C[0] == ADD:
        opcode_ADD(S, C)
    else:
        assert False
```

Summary of the machine so far:

- Memory: a cell contains an integer or (car, cdr) tuple.
- Registers: S (stack), C (code).
- Opcodes: `ADD`, `LDC`, `STOP`.

This doesn't do much — we need functions of some sort.

Lambda expressions:

- Python: `(lambda x, y: x + y)(3, 4)`
- Haskell: `(\x y -> x + y) 3 4`
- Haskell': `(\x y -> (+) x y) 3 4`
- Lisp: `((LAMBDA (x y) (+ x y)) (3 4))`

Problems:

- Can't store "x", so remember `x` = first parameter, etc.
- Save environment before call: new register D (dump).
- Store arguments: new register E (environment).
- New opcodes:
  - LD: LoaD identifier. e.g. `[LD, 1]` = load value of `x`.
  - LDF: LoaD Function. Push a closure onto S.
  - AP: APply function. Evaluate a closure.
  - RTN: ReTurN from function. Restore state.

```
S:  []
E:  []
C:  [LDC, [3, 4], LDF, [LD, 2, LD, 1, ADD, RTN], AP, STOP]
D:  []

S:  [[3, 4]]
E:  []
C:  [LDF, [LD, 2, LD, 1, ADD, RTN], AP, STOP]
D:  []

S:  [[LD, 2, LD, 1, ADD, RTN], [3, 4]]   # a closure
E:  []
C:  [AP, STOP]
D:  []
```

```
S:  [ [LD, 2, LD, 1, ADD, RTN] , [3, 4] ]   # a closure
E:  []
C:  [ AP , STOP]
D:  []

S:  []
E:  [ [3, 4] ]
C:  [LD, 2, LD, 1, ADD, RTN]
D:  [[S=[], E=[], C=[STOP]]

S:  [4]
E:  [ [3, 4] ]
C:  [LD, 1, ADD, RTN]
D:  [[S=[], E=[], C=[STOP]]
```

```
S:  [3, 4]
E:  [ [3, 4] ]
C:  [ADD, RTN]
D:  [[S=[], E=[], C=[STOP]]

S:  [7]
E:  [ [3, 4] ]
C:  [RTN]
D:  [[S=[], E=[], C=[STOP]]

S:  [7]
E:  []
C:  [STOP]
D:  []
```

SECD machine summary so far:

- Memory: a cell contains an integer or (car, cdr) tuple.
- Registers: S (stack), E (environment), C (code), D (dump).
- Opcodes: `ADD`, `LDC`, `STOP` `LD`, `LDF`, `RTN`, `AP`.
- Can evaluate lambda expressions.

SECD opcodes

```
ADD     # integer addition
MUL     # integer multiplication
SUB     # integer subtraction
DIV     # integer division

NIL     # push nil pointer onto the stack
CONS    # cons the top of the stack onto the next list
LDC     # push a constant argument
LDF     # load function
AP      # function application
LD      # load a variable
CAR     # value of car cell
CDR     # value of cdr cell

DUM     # setup recursive closure list
RAP     # recursive apply
```

SECD opcodes contd.

```
JOIN    # C = pop dump
RTN     # return from function
SEL     # logical selection (if/then/else)
NULL    # test if list is empty

WRITEI  # write an integer to the terminal
WRITEC  # write a character to the terminal

READC   # read a single character from the terminal
READI   # read an integer from the terminal

ZEROP  # test if top of stack = 0 [nonstandard opcode]
GTOP   # test if top of stack > 0 [nonstandard opcode]
LTOP   # test if top of stack < 0 [nonstandard opcode]

STOP    # halt the machine
```

Final steps...

- Define a simple Lisp language.
- Write a function `compile(x)` to translate Lisp forms into SECD machine code.

Square-bracket Lisp

```
# 3 + 4
[ADD, 3, 4]

# lambda x, y: x + y
[LAMBDA, ['x', 'y'], [ADD, 'x', 'y']]

# (lambda x, y: x + y)(3, 4)
[[LAMBDA, ['x', 'y'], [ADD, 'x', 'y']], 3, 4]

# x = 5; y = 7; x - y
[LET, ['x', 'y'], [5, 7], [SUB, 'x', 'y']]
```

Square-bracket Lisp

```
[ADD, 3, 4]

>>> compile([ADD, 3, 4])
[LDC, 4, LDC, 3, ADD, STOP]

def compile(x):
    if x[0] == ADD:
        x.pop(0)
        arg1 = x.pop(0)
        arg2 = x.pop(0)
        return [LDC, compile(arg1), \
                LDC, compile(arg2),
                ADD] \
                + compile(x)
    elif ...
```

Square-bracket Lisp

```
# lambda x, y: x + y
[LAMBDA, ['x', 'y'], [ADD, 'x', 'y']]

>>> compile([LAMBDA, ['x', 'y'], [ADD, 'x', 'y']])
[LDF, [LD, [1, 2], LD, [1, 1], ADD, RTN]]
```

Square-bracket Lisp

```
# (lambda x, y: x + y)(3, 4)
[[LAMBDA, ['x', 'y'], [ADD, 'x', 'y']], 3, 4]

>>> c = [[LAMBDA, ['x', 'y'], [ADD, 'x', 'y']], 3, 4]
>>> compile(c)
[NIL, LDC, 4, CONS, LDC, 3, CONS,
 LDF, [LD, [1, 2], LD, [1, 1], ADD, RTN],
 AP,
 STOP]
```

Square-bracket Lisp

```
# x = 5; y = 7; x - y
[LET, ['x', 'y'], [5, 7], [SUB, 'x', 'y']]

>>> c = [LET, ['x', 'y'], [5, 7], [SUB, 'x', 'y']]
>>> compile(c)
[NIL, LDC, 7, CONS, LDC, 5, CONS,
 LDF, [LD, [1, 2], LD, [1, 1], SUB, RTN],
 AP,
 STOP]
```

Length of a list?

```
> let f x m = if null x
                then m
                else f (tail x) (m + 1)
> f [1, 2, 3] 0
3
```

```
[LETREC, ['f'], [[LAMBDA, ['x', 'm'],
    [IF, [NULL, 'x'],
         'm',
         ['f', [CDR, 'x'], [ADD, 'm', 1]]]]],
  ['f', [LIST, 1, 2, 3], 0]
```

Square-bracket Lisp:

- Enough to write basic programs: `LET`, `LAMBDA`, `IF`.
- Recursion using `LETREC`.
- No destructive assignment: pure Lisp.
- Closures can be evaluated in the future, always same value.
- Code as data.
- Lambda expressions $\leftrightarrow$ S-expressions.
- Relies on machine to do garbage collection (say what?).

The CURRY chip (Ramsdell, 1986)

- 0.4Mhz
- CPU chip: about 9000 transistors, performed graph reduction (combinators S, K, I).
- Memory chip: garbage collection.
- Timing chip: overall timing and control console.

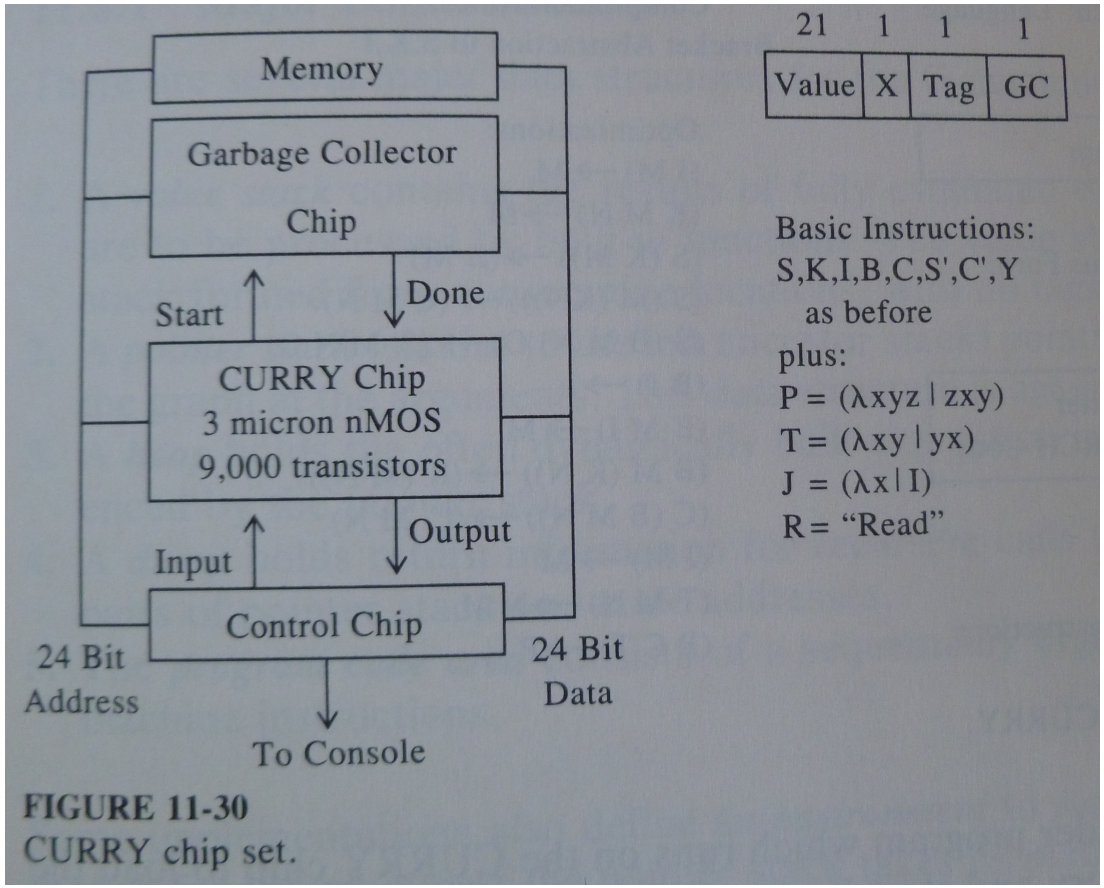


FIGURE 11-30
CURRY chip set.

MultiLISP: parallel Lisp

- Pure lambda calculus $\Rightarrow$ opportunities for parallelism.
- Concert machine at MIT: 24-way Motorola 68000-based shared-memory multiprocessor (early 80s?).
- MultiLISP $\rightarrow$ SECD-like abstract machine called MCODE.
- MCODE interpreter (3000 lines of C).
- Unfortunately slow due to MCODE, but parallel benefits could be measured.
- Used *futures* for evaluation; see also Swift:
  `http://www.ci.uchicago.edu/swift/main/`

Symbolics Lisp Machine

Symbolics Lisp Machine

- Instruction set: stack machine, similar to SECD.
- Hardware support:
  - virtual memory
  - garbage collection
  - data type testing

Symbolics Lisp Machine keyboard

modifier keys: HYPER SUPER META CONTROL

My SECD emulator and mini-Lisp compiler:
`https://github.com/carlohamalainen/pysecd`