Notes on Laning's 1953 Whirlwind program. D Knuth 12 Aug 76 – 14 Aug 76

Whirlwind opcodes (as deduced from this program, not having a manual available at this time) 16-bit words; 5 bits for the opcode

ad ac ← ac + (m). Set toggle iff result ≤ 0 or something like this. [−1+1 sets it; 0−0 does too].
ao equiv to ca m, ad = 1=, ts m.
ca ac ← (m). toggle apparently not set? see 15a1; but yes, set: see 3a15.
ck clc stop
cp jump if toggle.
cs ac ← −(m) also seems to set toggle, see 21a13
dv divide [used for interpreter call only]
ex ac ⟷ (m)
mr multiply [used for interpreter call only]
p decimal integer constant or (no-op.)
rd read a character in Flexowriter code into ac. [6-bit code]
rc
sf normalize ac and store number of shifts in (m) [I guess; used only once, 24a1].
si unknown; something about I/O?
sl shift left
sp jump and set J register to address of following instruction
sr* shift right into extension of accumulator
su ac ← ac − (m), toggle iff result ≤ 0
ta address (m) ← J register.
td address (m) ← address (ac)
ts (m) ← ac

Assembly language 4a3 means location of a3 plus 4; 2r means location of current routine plus 2; octal constants 0,77410.
Location 0 contains 0.

There is a 128-place switching table (unused positions are filled with miscellaneous constants and snatches of code), divided between lower case and upper case. The codes are:

a, b, …, z → letter [50a4]
0, 1, …, 9 → 1, 2, …, 10
⁰, ¹, …, ⁹ → 11, 12, …, 20
space, backspace, tab, cr, stop, null, • → next [2a1].
= → equals [10a10] + → plus [52a4] − → minus [55a4] / → divide [0a9] (→ lpren [0a11]) → rpren [0a12]
• → 0 or period [8a2], a switch initially set 0
g → comma [14a10] or next or spcomma, a switch initially set to comma.
uc → upper [42a4] lc → lower [0a4] S → ucs [40a10] C → ucc [50a10] ⁻ → expminus [10a9].
P → print1 [0a2] or print2 [2a2] a switch initially set to print 1

The code uses switched instructions, I'll use Boolean flags all initially false

cflag: upper case?
mflag: processing a constant? if so, z = number [0a5] or exponent [0a6]
nflag: constant is not a label
pflag: decimal point occurred?
tflag: implied multiplication in effect rather than numeric label. actually tflag = nflag, so drop it.
rflag: processing a negative exponent
eflag: exponent should be negative (or positive if in the denominator)

mem[j] = memory loc j (shared by compiler and object code and interpretive routines) oppart[j] = opcode field of mem[j]
addrpart[j] = address field of mem[j].
flac = floating point accumulator [initially 0.0]. ldigits, rdigits = counters initially zero,
addr = next avail prog address [initially 32] caddr = last address used for constants [initially 197].
op = operation code initially "mr" ; op1 initially "dv" [always the opposite of op]
k = parenthesis level

```
0a1  start:    "si 128";   whatever that means
2a1  next:     c ← read next char; if cflag then x ← uppercasecode[c] else x ← lowercasecode[c];
9a1            if x is a label then (if mflag then (mflag ← false; go to z) else go to x);
12a1           mflag ← nflag; if x=0 [code for period] then (pflag ← true; go to next);
17a1           if x≤10 then (z ← number; d ← x−1) else (z ← exponent; d ← x−11);
23a1           fd ⇐ float(d);  flac ⇐ flac ⊗ 10.0 ⊕ fd;          [⇐ means double word
36a1           if pflag then rdigits ← rdigits+1 else ldigits ← ldigits+1;   ⊕ means floating add etc
37a1           go to next;                                          all done interpretively]
50a4  letter:  if nflag then (compile(op, c); go to next);
28a10 label:   ~~tflag ← true;~~ nflag ← true;
32a10 [19a6]   n ← decode;        decode = return(unfloat(if eflag then −flac else flac))
33a10          mem[switchtable + n] ← ("sp", addr);   comment n=0 not allowed, since 0 always implied as default label;
9a6  reset:    flac ⇐ 0.0; ldigits ← rdigits ← 0; pflag ← false;
17a6           if rflag then (eflag ← ¬eflag; rflag ← false);
38a4           go to x;
10a10 [0a10] equals:  l ← eqsub;   eqsub = (compile("sp", eqroutine); stack2[k] ← addr−1; stack1[k] ← addr−2;
[8a10]                   tmp ← addrpart[addr−2]; mem[addr−2] ← "sp"; return address of this call of eqsub;
                                                                    ↑ garbage
                         return(tmp) )
12a10          resetdvexp; go to next;
18a9                  resetdvexp = (eflag ← false; op ← "mr"; op1 ← "dv")
14a10 comma:   compile("ad", "temp"); compile("ts", l);
18a10          addrpart[stack1[0]] ← stack2[0];
22a10          resetdvexp; ~~xflag ← false;~~ nflag ← false; go to next;
```

What we have seen so far gives enough information to see how the formula "a = b," is compiled. [Except compile subroutine appears below]

```
Scanned symbol   actions  here (j) = loc of jth compiled instruction
   a             mem[switchtable] ← sp (1)     mem[(1)] ← mr a
   =             mem[(2)] ← sp eqroutine       mem[(1)] ← sp ~~~     stack1[0] ← (1)   stack2[0] ← (2)   l ← a
   b             mem[(3)] ← mr b
   ,             mem[(4)] ← ad temp            mem[(5)] ← ts a       mem[(1)] ← sp (2)
```

So the compiled code is:

```
jump to *+1
jump to eqroutine
multiply by b   ]  these are interpreted at run time to refer to floating pt accumulator
add temp        ]     i.e. flac ⇐ flac ⊗ b; flac ⇐ flac ⊕ temp; a ⇐ flac
store in a      ]
```

The eqroutine does just what is needed, namely "temp ⇐ 0.0; flac ⇐ 1.0; return"!
Now let's look at routines needed for slightly more complex expressions $a = 3.1b - c/d^{-2}$ etc.:

```
0a5  number:    while rdigits > 0 do (flac ⇐ flac ⊘ 10.0; rdigits ← rdigits−1);
4a5             j ← alloc; mem[j], mem[j+1] ⇐ flac;
9a5             compile(op, j); go to reset;
0a6  exponent:  tmp ← addrpart[addr−1]; mem[addr−1] ← ("sp", exproutine);
4a6             compile(0, tmp); compile(0, decode); go to reset;
52a4 plus:      resetdvexp; compile("sp", plroutine); go to next;   {tricky use of rJ here. MIX equivalent is:
55a4 minus:     resetdvexp; compile("sp", mnroutine); go to next;    PLUS  JMP 1F        | MINUS JMP 1F        | 1H STJ *+2
0a9  divide:    op ↔ op1;                                                  JMP PLROUTINE |       JMP MNROUTINE |    JMP RESETDV
                eflag ← not(eflag); go to next;                                                                     LDA *
29a4 expminus:  eflag ← not(eflag); rflag ← true; go to next;                                                       JMP COMPILE
                                                                                                                    JMP NEXT
```

Here are the subroutines for compilation and storage allocation:

```
9a8      compile(x,y) = (mem[addr] ← (x,y);
11a8                     addr ← addr+1;
12a8                     if addr > caddr then errorstop);
0a8      alloc = (caddr ← caddr − 2;
4a8                     if addr > caddr then errorstop;
6a8                     return(caddr) )
```

Here are the floating-point routines used at run time:

```
0a13     eqroutine = (temp ⇐ 0.0; flac ⇐ 1.0)
5a13     plroutine = (temp ⇐ temp ⊕ flac; flac ⇐ 1.0)
10a13    mnroutine = (temp ⇐ temp ⊕ flac; flac ⇐ −1.0)
15a13    exproutine(x,n): (if n ≥ 0 then pwrflag ← false else (pwrflag ← true; n ← −n);
29a13                    while n>0 do (if pwrflag then flac ⇐ flac ⊘ x else flac ⇐ flac ⊗ x; n ← n−1))
```

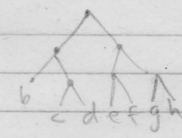
Note bug: a = −b comes out the same as a = 1−b. [See Laning's letter.]

Now, parentheses:

```
0al1  lpren:  compile (0,0);
1al1          k ← k+1;
3al1          eqsub;
4al1          stack3[k] ← alloc;
7al1          if op < op1 then go to next;          comment: "mr" < "dv";
11al1         stack1[k] ← stack1[k] + 2";
12al0         resetdvexp; go to next;
0al2  rpren:  j ← stack1[k] mod 2^11;
6al2          if stack1[k] < 2^21 then resetdvexp
28a9               else (eflag ← true; op ← "dv"; op1 ← "mr");
9al2          compile ("ad", temp); compile ("ts", stack3[k]);
19al2         stack2[k] ↔ stack2[k-1]; compile ("sp", stack2[k]);
28al2         addrpair[j] ← addr;
30al2         compile (op, stack3[k]); k ← k-1; go to next;
```

Interpretation is stack3[k] is location to hold contents of this parenthesis pair
stack1[k] is location of instruction "sp ——" just preceding the code for this parenthesis pair, it will later jump to an instruction that uses the contents of the parenthesis after evaluation [exc k = 0 → it will evaluate the exp]
stack2[k] is location of instruction to begin the evaluation of the parenthesized expression.

Example a = ((b(cd))((ef)(gh))),



leads to:

```
Scanned symbol  ①⑬ ②⑭ ③⑮ ④⑯ ⑤⑰ ⑥⑱ ⑦⑲ ⑧⑳ ⑨㉑ ⑩㉒ ⑪㉓ ⑫㉔            stack1        stack2        stack3
a    mr a
=    sp •  sp ⊜                                                    ①            ②
(          sp • sp ⊜                                               ①③          ②④           [1]
(                sp • sp ⊜                                         ①③⑤        ②④⑥         [1][2]
b                         mr b
(                              sp • sp ⊜                           ①③⑤⑧      ②④⑥⑨       [1][2][3]
c                                          mr c
d                                               mr d
)    ts[3]  sp⑥  mr[3]            sp⑮                ad tmp        ①③⑤        ②④⑨         [1][2]
)    ad tmp ts[2] sp④ mr[2]  sp⑲                                   ①③          ②⑨           [1]
(                                   sp •  sp ⊜                     ①③⑳        ②⑨㉑         [1][4]
(                                               sp •  sp ⊜         ①③⑳㉒      ②⑨㉑㉓       [1][4][5]
e                                                          mr e
f
)                                                                  ①③⑳        ②⑨㉓         [1][4]
(                                                                  ①③⑳㉚      ②⑨㉓…       [1][4][6]
g
h
)                                                                  ①③⑳        ②⑨㉛         [1][4]
)                                                                  ①③          ②㉛           [1]
)                                                                  ①            ㉛
;
```

Final code:

```
        ①      ②      ③      ④      ⑤      ⑥       ⑦      ⑧      ⑨      ⑩
        sp㉛   sp⊜    sp(45)  sp⊜    sp⑲    sp⊜     mr b   sp⑮    sp⊜    mr c
10+:    mr d   ad tmp ts[3]  sp⑥    mr[3]  ad tmp  ts[2]  sp④    mr[2]  sp(41)
20+:    sp⊜    sp㉙   sp⊜    mr e   mr f   ad tmp  ts[5]  sp㉑    mr[5]  sp㉛
30+     sp⊜    mr g   mr h   ad tmp ts[6]  sp㉓    mr[6]  ad tmp ts[4]  sp⑨
40      mr[4]  ad tmp ts[1]  sp②    mr[1]  ad tmp  ts a
```

which is equiv to:

1×g×h+0 → [6]
1×e×f+0 → [5]
1×[5]×[6]+0 → [4]
1×c×d+0 → [3]
1×b×[3]+0 → [2]
1×[2]×[4]+0 → [1]
1×[1]+0 → a

Finally, control flow:

```
?a2 print1:  lower casecode [","] ← next; lowercasecode ["P"] ← print2; lowercasecode ["."] ← period; go to label;
?a2 print2:  compile ("sp", prntroutine); for j ← 1 until 4 do trash ← read next char;   comment R, I, N, and T;
7a2          go to next;
?a2 period:  lower casecode [","] ← comma; lowercasecode ["P"] ← print1; lowercasecode ["."] ← 0; nflag ← false; go to next;

40a10 ucs:   scop ← "sp"; go to ucsc;   comment SP and CP can't be labeled;
50a10 ucc:   scop ← "cp";
42a10 ucsc:  c ← read next char; if c = "R" then go to 0; comment "provision for future SR, CR instructions";
45a10        if c = "T" then go to 32; comment START the object program;
47a10        lowercasecode [","] ← spcomma1; go to next;
53a10 spcomma1: lowercase code [","] ← spcomma2; compile (scop, switchtable + decode); go to reset;
54a10 spcomma2: lowercasecode [","] ← comma; go to next;
```

Runtime print routine:

```
0a15   prntroutine:  "si 149"; j ← location of first parameter;
3a15     while oppart[j] ≠ "sp" do ( print character (addrpart[j]); print character ("=");
                                   floating point print (mem[j]); j ← j+1 );
7a15     go to j;
42a4   upper:  cflag ← true; go to next;
0a4    lower:  cflag ← false; go to next
```

Total length of compiler 45+20+64+64+19+26+6+19+34+78+19+38+13 words = 445
(incl 15 for stack storage)
plus runtime routines 43+19 = 62.

object program goes into locs 32-196; 210-221 is switchtable
subscripted variables, drum overlay usage, D operator: not yet implemented.