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SWEET16: The 6502 Dream Machine

While writing Apple BASIC for a 6502 microprocessor I repeatedly encountered a variant of Murphy's Law. Briefly stated, any routine operating on 16 bit data will require at least twice the code that it should. Programs making extensive use of 16 bit pointers (such as compilers, editors and assemblers) are included in this category. In my case, even the addition of a few double byte instructions to the 6502 would have only slightly alleviated the problem. What I really needed was a hybrid of the MOS Technology 6502 and RCA 1800 architectures, a powerful 8 bit data handler complemented by an easy to use processor with an abundance of 16 bit registers and excellent pointer capability. My solution was to implement a nonexistent 16 bit "metaprocessor" in software, interpreter style, which I call SWEET16. This metaprocessor was sketched at the end of my article in May 1977 BYTE, and the purpose of this article is to fill in the details of SWEET16.

SWEET16 is based around sixteen 16 bit registers called R0 to R15, actually implemented as 32 memory locations. R0 doubles as the SWEET16 accumulator (ACC), R15 as the program counter (PC), and R14 as the status register. R13 holds compare instruction results and R12 is the subroutine return stack pointer if SWEET16 subroutines are used. All other SWEET16 registers are at the user's unrestricted disposal.

SWEET16 instructions fall into register and nonregister categories. The register operations specify one of the 16 registers to be used as either a data element or a pointer to data in memory depending on the specific instruction. For example, the instruction INR R5 uses R5 as data and ST @R7 uses R7 as a pointer to data in memory. Except for the SET instruction, register operations only require one byte. The nonregister operations are primarily 6502 style branches with the second byte specifying a ±127 byte displacement relative to the address of the following instruction. If a prior register operation result meets a specified branch condition, the displacement is added to SWEET16's program counter, effecting a branch.

SWEET16 is intended as a 6502 enhancement package, not a stand alone processor. A 6502 program switches to SWEET16 mode with a subroutine call, and subsequent code is interpreted as SWEET16 instructions. The nonregister operation RTN returns the user program to the 6502's direct execution mode after restoring the internal register contents (A, X, Y, P and S). The example of listing 1 illustrates how to use SWEET16 in some program segment.

```
                300 B9 00 02            LDA  IN, Y      Get a char.
                303 C9 CD               CMP  "M"        "M" for move?
                305 D0 09               BNE  NOMOVE       No, skip move.
                307 20 00 08            JSR  SW16         Yes, call SWEET16.
SWEET16         30A 41          MLOOP   LD   @R1        R1 holds source address.
                30B 52                  ST   @R2        R2 holds dest. address.
                30C F3                  DCR  R3         Decrement length.
                30D 07 FB               BNZ  MLOOP        Loop until done.
                30F 00                  RTN             Return to 6502 mode.
                310 C9 C5       NOMOVE  CMP  "E"        "E" char?
                312 D0 13               BEQ  EXIT         Yes, exit.
                314 C8                  INY               No, continue.
```

Note: Registers A, X, Y, P and S are not disturbed by SWEET16.

Listing 1: Use of SWEET16 within an assembly language program is accomplished by executing a subroutine call to the SWEET16 entry point (address 307 here). This call preserves the processor registers at the time of entry and begins interpretive execution. End of interpretive execution is signaled by a RTN operation code of SWEET16, at which point all the processor registers will be restored.

Instruction Descriptions

The SWEET16 op code list is short and uncomplicated. Excepting relative branch displacements, hand assembly is trivial. All register op codes are formed by combining two hexadecimal digits, one for the op code and one to specify a register. For example,

op codes 15 and 45 both specify register R5 while codes 23, 27 and 29 are all ST (store) operations. Most register operations of SWEET16 are assigned to numerically adjacent pairs to facilitate remembering them. Thus LD and ST are op codes 2n and 3n respectively, while LD @ and ST @ are codes 4n and 5n.

Operation codes 00 to 0C (hexadecimal) are assigned to the 13 nonregister operations. Except for RTN (op code 0), BK (0A), and RS (B), the nonregister operations are 6502 style relative branches. The second byte of a branch instruction contains a ±127 byte displacement value (in two's complement form) relative to the address of the instruction immediately following the branch. If a specified branch condition is met by the prior register operation result, the displacement is added to the program counter effecting a branch. Except for BR (Branch always) and BS (Branch to Subroutine), the branch operation codes are assigned in complementary pairs, rendering them easily remembered for hand coding. For example, Branch if Plus and Branch if Minus are op codes 04 and 05, while Branch if Zero and Branch if NonZero are op codes 06 and 07.

Theory of Operation

SWEET16 execution mode begins with a subroutine call to SW16 (see listing 2, an assembly of SWEET16). The user must insure that the 6502 is in hexadecimal mode upon entry. [*For those unfamiliar with the 6502, arithmetic is either decimal or hexadecimal (binary) depending on a programmable flag. . .*CH] All 6502 registers are saved at this time, to be restored when a SWEET16 RTN instruction returns control to the 6502. If you can tolerate indefinite 6502 register contents upon exit, approximately 30 μs may be saved by entering SWEET16 at location SW16 + 3. Because this might cause an inadvertent switch from hexadecimal to decimal mode, it is advisable to enter at SW16 the first time through.

After saving the 6502 registers, SWEET16 initializes its program counter (R15) with the subroutine return address off the 6502 stack. SWEET16's program counter points to the location preceding the next instruction to be executed. Following the subroutine call are 1 byte, 2 byte, or 3 byte long SWEET16 instructions, stored in ascending

Listing 2: SWEET16 assembly. The SWEET16 program, assembled to reside at location 800 hexadecimal, is presented by this listing. The primary entry point is at the beginning, location SW16. An alternate entry point if there is no need to save processor registers is at location 803 in this assembly, SW16+3.

```
                                SWEET16 INTERPRETER
11:18 A.M., THU, MAY 12, 1977

                    00001 **********************
                    00002 *                    *
                    00003 *   APPLE-II PSEUDO  *
                    00004 * MACHINE INTERPRETER *
                    00005 *                    *
                    00006 *      S. WOZNIAK    *
                    00007 * APPLE COMPUTER INC  *
                    00008 *                    *
                    00009 **********************
                    00010  TITLE "SWEET16 INTERPRETER"
                    00011 R0L       EPZ  $0
                    00012 R0H       EPZ  $1
                    00013 R14H      EPZ  $1D
                    00014 R15L      EPZ  $1E
                    00015 R15H      EPZ  $1F
                    00016 S16PAG    EQU  $F7
                    00017           ORG  $800
0800: 20 74 09      00018 SW16      JSR  SAVE      PRESERVE 6502 REG CONTENTS
0803: 68            00019           PLA
0804: 85 1E         00020           STA  R15L      INIT SWEET16 PC
0806: 68            00021           PLA            FROM RETURN
0807: 85 1F         00022           STA  R15H        ADDRESS
0809: 20 0F 08      00023 SW16B     JSR  SW16C     INTERPRET AND EXECUTE
080C: 4C 09 08      00024           JMP  SW16B     ONE SWEET16 INSTR.
080F: E6 1E         00025 SW16C     INC  R15L
0811: D0 02         00026           BNE  SW16D     INCR SWEET16 PC FOR FETCH
0813: E6 1F         00027           INC  R15H
0815: A9 F7         00028 SW16D     LDA  #S16PAG
0817: 48            00029           PHA            PUSH ON STACK FOR RTS
0818: A0 00         00030           LDY  #$0
081A: B1 1E         00031           LDA  (R15L),Y  FETCH INSTR
081C: 29 0F         00032           AND  #$F       MASK REG SPECIFICATION
081E: 0A            00033           ASL  A         DOUBLE FOR 2-BYTE REG'S
081F: AA            00034           TAX            TO X-REG FOR INDEXING
0820: 4A            00035           LSR  A
0821: 51 1E         00036           EOR  (R15L),Y  NOW HAVE OPCODE
0823: F0 0B         00037           BEQ  TOBR      IF ZERO THEN NON-REG OP
0825: 86 1D         00038           STX  R14H      INDICATE'PRIOR RESULT REG'
0827: 4A            00039           LSR  A
0828: 4A            00040           LSR  A         OPCODE*2 TO LSB'S
0829: 4A            00041           LSR  A
082A: A8            00042           TAY            TO Y-REG FOR INDEXING
082B: B9 58 08      00043           LDA  OPTBL-2,Y LOW-ORDER ADR BYTE
082E: 48            00044           PHA            ONTO STACK
082F: 60            00045           RTS            GOTO REG-OP ROUTINE
0830: E6 1E         00046 TOBR      INC  R15L
0832: D0 02         00047           BNE  TOBR2     INCR PC
0834: E6 1F         00048           INC  R15H
0836: BD 5B 08      00049 TOBR2     LDA  BRTBL,X   LOW-ORDER ADR BYTE
0839: 48            00050           PHA            ONTO STACK FOR NON-REG OP
083A: A5 1D         00051           LDA  R14H      'PRIOR RESULT REG' INDEX
083C: 4A            00052           LSR  A         PREPARE CARRY FOR BC, BNC.
083D: 60            00053           RTS            GOTO NON-REG OP ROUTINE
083E: 68            00054 RTNZ      PLA            POP RETURN ADDRESS
083F: 68            00055           PLA
0840: 20 7F 09      00056           JSR  RESTORE   RESTORE 6502 REG CONTENTS
0843: 6C 1E 00      00057           JMP  (R15L)    RETURN TO 6502 CODE VIA PC
0846: B1 1E         00058 SETZ      LDA  (R15L),Y  HIGH-ORDER BYTE OF CONST
0848: 95 01         00059           STA  R0H,X
084A: 88            00060           DEY
084B: B1 1E         00061           LDA  (R15L),Y  LOW-ORDER BYTE OF CONSTANT
084D: 95 00         00062           STA  R0L,X
084F: 98            00063           TYA            Y-REG CONTAINS 1
0850: 38            00064           SEC
0851: 65 1E         00065           ADC  R15L      ADD 2 TO PC
0853: 85 1E         00066           STA  R15L
0855: 90 02         00067           BCC  SET2
0857: E6 1F         00068           INC  R15H
0859: 60            00069 SET2      RTS
085A: 79            00070 OPTBL     DFB  SET-1     (1X)
085B: 70            00071 BRTBL     DFB  RTN-1     (0)
085C: 7B            00072           DFB  LD-1      (2X)
085D: 14            00073           DFB  BR-1      (1)
085E: 84            00074           DFB  ST-1      (3X)
085F: 15            00075           DFB  BNC-1     (2)
0860: 9C            00076           DFB  LDAT-1    (4X)
0861: 26            00077           DFB  BC-1      (3)
0862: 8D            00078           DFB  STAT-1    (5X)
0863: 29            00079           DFB  BP-1      (4)
0864: BE            00080           DFB  LDDAT-1   (6X)
0865: 30            00081           DFB  BM-1      (5)
0866: C8            00082           DFB  STDAT-1   (7X)
0867: 37            00083           DFB  BZ-1      (6)
0868: A6            00084           DFB  POP-1     (8X)
0869: 40            00085           DFB  BNZ-1     (7)
086A: D2            00086           DFB  STPAT-1   (9X)
086B: 49            00087           DFB  BM1-1     (8)
086C: FC            00088           DFB  ADD-1     (AX)
086D: 54            00089           DFB  BNM1-1    (9)
086E: E5            00090           DFB  SUB-1     (BX)
086F: 7C            00091           DFB  BK-1      (A)
0870: AA            00092           DFB  POPD-1    (CX)
0871: 5F            00093           DFB  RS-1      (B)
0872: E7            00094           DFB  CPR-1     (DX)
0873: 0A            00095           DFB  BS-1      (C)
0874: 95            00096           DFB  INR-1     (EX)
0875: 5E            00097           DFB  NUL-1     (D)
```

Listing 2, continued:

```
0876: DC          00098          DFB  DCR-1     (FX)
0877: 5E          00099          DFB  NUL-1     (E)
0878: 5E          00100          DFB  NUL-1     (UNUSED)
0879: 5E          00101          DFB  NUL-1     (F)
087A: 10 CA       00102 SET      BPL  SETZ      ALWAYS TAKEN
087C: B5 00       00103 LD       LDA  R0L,X
                  00104 BK       EQU  *-1
087E: 85 00       00105          STA  R0L
0880: B5 01       00106          LDA  R0H,X     MOVE RX TO R0
0882: 85 01       00107          STA  R0H
0884: 60          00108          RTS
0885: A5 00       00109 ST       LDA  R0L
0887: 95 00       00110          STA  R0L,X     MOVE R0 TO RX
0889: A5 01       00111          LDA  R0H
088B: 95 01       00112          STA  R0H,X
088D: 60          00113          RTS
088E: A5 00       00114 STAT     LDA  R0L
0890: 81 00       00115 STAT2    STA  (R0L,X)   STORE BYTE INDIRECT
0892: A0 00       00116          LDY  #$0
0894: 84 1D       00117 STAT3    STY  R14H      INDICATE R0 IS RESULT REG
0896: F6 00       00118 INR      INC  R0L,X
0898: D0 02       00119          BNE  INR2      INCR RX
089A: F6 01       00120          INC  R0H,X
089C: 60          00121 INR2     RTS
089D: A1 00       00122 LDAT     LDA  (R0L,X)   LOAD INDIRECT (RX)
089F: 85 00       00123          STA  R0L       TO R0
08A1: A0 00       00124          LDY  #$0
08A3: 84 01       00125          STY  R0H       ZERO HIGH-ORDER R0 BYTE
08A5: F0 ED       00126          BEQ  STAT3     ALWAYS TAKEN
08A7: A0 00       00127 POP      LDY  #$0       HIGH ORDER BYTE = 0
08A9: F0 06       00128          BEQ  POP2      ALWAYS TAKEN
08AB: 20 DD 08    00129 POPD     JSR  DCR       DECR RX
08AE: A1 00       00130          LDA  (R0L,X)   POP HIGH-ORDER BYTE @RX
08B0: A8          00131          TAY            SAVE IN Y-REG
08B1: 20 DD 08    00132 POP2     JSR  DCR       DECR RX
08B4: A1 00       00133          LDA  (R0L,X)   LOW-ORDER BYTE
08B6: 85 00       00134          STA  R0L       TO R0
08B8: 84 01       00135          STY  R0H
08BA: A0 00       00136 POP3     LDY  #$0       INDICATE R0 AS LAST
08BC: 84 1D       00137          STY  R14H           RESULT REG
08BE: 60          00138          RTS
08BF: 20 9D 08    00139 LDDAT    JSR  LDAT      LOW BYTE TO R0, INCR RX
08C2: A1 00       00140          LDA  (R0L,X)   HIGH-ORDER BYTE TO R0
08C4: 85 01       00141          STA  R0H
08C6: 4C 96 08    00142          JMP  INR       INCR RX
08C9: 20 8E 08    00143 STDAT    JSR  STAT      STORE INDIRECT LOW-ORDER
08CC: A5 01       00144          LDA  R0H       BYTE AND INCR RX.  THEN
08CE: 81 00       00145          STA  (R0L,X)   STORE HIGH-ORDER BYTE.
08D0: 4C 96 08    00146          JMP  INR       INCR RX AND RETURN
08D3: 20 DD 08    00147 STPAT    JSR  DCR       DECR RX
08D6: A5 00       00148          LDA  R0L
08D8: 81 00       00149          STA  (R0L,X)   STORE R0 LOW BYTE @RX
08DA: 4C BA 08    00150          JMP  POP3      INDICATE R0 AS LAST
08DD: B5 00       00151 DCR      LDA  R0L,X          RESULT REG
08DF: D0 02       00152          BNE  DCR2      DECR RX
08E1: D6 01       00153          DEC  R0H,X
08E3: D6 00       00154 DCR2     DEC  R0L,X
08E5: 60          00155          RTS
08E6: A0 00       00156 SUB      LDY  #$0       RESULT TO R0
08E8: 38          00157 CPR      SEC            NOTE Y-REG = 13*2 FOR CPR
08E9: A5 00       00158          LDA  R0L
08EB: F5 00       00159          SBC  R0L,X
08ED: 99 00 00    00160          STA  R0L,Y     R0-RX TO RY
08F0: A5 01       00161          LDA  R0H
08F2: F5 01       00162          SBC  R0H,X
08F4: 99 01 00    00163 SUB2     STA  R0H,Y
08F7: 98          00164          TYA            LAST RESULT REG*2
08F8: 69 00       00165          ADC  #$0       CARRY TO LSB
08FA: 85 1D       00166          STA  R14H
08FC: 60          00167          RTS
08FD: A5 00       00168 ADD      LDA  R0L
08FF: 75 00       00169          ADC  R0L,X
0901: 85 00       00170          STA  R0L       R0+RX TO R0
0903: A5 01       00171          LDA  R0H
0905: 75 01       00172          ADC  R0H,X
0907: A0 00       00173          LDY  #$0       R0 FOR RESULT
0909: F0 E9       00174          BEQ  SUB2      FINISH ADD
090B: A5 1E       00175 BS       LDA  R15L      NOTE X-REG IS 12*2!
090D: 20 90 08    00176          JSR  STAT2     PUSH LOW PC BYTE VIA R12
0910: A5 1F       00177          LDA  R15H
0912: 20 90 08    00178          JSR  STAT2     PUSH HIGH-ORDER PC BYTE
0915: 18          00179 BR       CLC
0916: B0 0E       00180 BNC      BCS  BNC2      NO CARRY TEST
0918: B1 1E       00181 BR1      LDA  (R15L),Y  DISPLACEMENT BYTE
091A: 10 01       00182          BPL  BR2
091C: 88          00183          DEY
091D: 65 1E       00184 BR2      ADC  R15L      ADD TO PC
091F: 85 1E       00185          STA  R15L
0921: 98          00186          TYA
0922: 65 1F       00187          ADC  R15H
0924: 85 1F       00188          STA  R15H
0926: 60          00189 BNC2     RTS
0927: B0 EC       00190 BC       BCS  BR
0929: 60          00191          RTS
092A: 0A          00192 BP       ASL  A         DOUBLE RESULT-REG INDEX
092B: AA          00193          TAX            TO X-REG FOR INDEXING
092C: B5 01       00194          LDA  R0H,X     TEST FOR PLUS
092E: 10 E8       00195          BPL  BR1       BRANCH IF SO
0930: 60          00196          RTS
0931: 0A          00197 BM       ASL  A         DOUBLE RESULT-REG INDEX
0932: AA          00198          TAX
0933: B5 01       00199          LDA  R0H,X     TEST FOR MINUS
0935: 30 E1       00200          BMI  BR1
0937: 60          00201          RTS
0938: 0A          00202 BZ       ASL  A         DOUBLE RESULT-REG INDEX
0939: AA          00203          TAX
093A: B5 00       00204          LDA  R0L,X     TEST FOR ZERO
093C: 15 01       00205          ORA  R0H,X     (BOTH BYTES)
093E: F0 D8       00206          BEQ  BR1       BRANCH IF SO
0940: 60          00207          RTS
0941: 0A          00208 BNZ      ASL  A         DOUBLE RESULT-REG INDEX
0942: AA          00209          TAX
0943: B5 00       00210          LDA  R0L,X     TEST FOR NONZERO
0945: 15 01       00211          ORA  R0H,X     (BOTH BYTES)
0947: D0 CF       00212          BNE  BR1       BRANCH IF SO
0949: 60          00213          RTS
094A: 0A          00214 BM1      ASL  A         DOUBLE RESULT-REG INDEX
094B: AA          00215          TAX
094C: B5 00       00216          LDA  R0L,X     CHECK BOTH BYTES
094E: 35 01       00217          AND  R0H,X     FOR $FF (MINUS 1)
```

memory locations like 6502 instructions. The main loop at SW16B repeatedly calls the "execute instruction" routine at SW16C which examines one op code for type and branches to the appropriate subroutine to execute it.

Subroutine SW16C increments the program counter (R15) and fetches the next op code which is either a register operation of the form OP REG (2 hexadecimal digits) with OP between hexadecimal 1 and F, or a nonregister operation of the form 0 OP with OP between hexadecimal 0 and D. Assuming a register operation, the register specification is doubled to account for the 2 byte SWEET16 registers and placed in the X register for indexing. Then the instruction type is determined. Register operations place the doubled register specification in the high order byte of R14 indicating the "prior result register" to subsequent branch instructions. Nonregister operations treat the register specification (right-hand half-byte) as their op code, increment the SWEET16 PC to point at the displacement byte of branch instructions, load the A-Reg with the "prior result register" index for branch condition testing, and clear the Y-Reg.

When Is an RTS Really a JSR?

Each instruction type has a corresponding subroutine. The subroutine entry points are stored in a table which is directly indexed by the op code. By assigning all the entries to a common page, only a single byte of address need be stored per routine. The 6502 indirect jump might have been used as follows to transfer control to the appropriate subroutine:

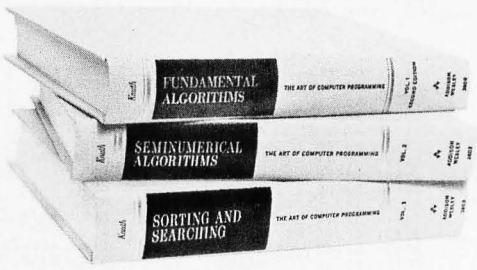
```
LDA #ADRH     High order address byte
STA IND+1
LDA OPTBL,X   Low order byte
STA IND
JMP (IND)
```

To save code the subroutine entry address (minus 1) is pushed onto the stack, high order byte first. A 6502 RTS (ReTurn from Subroutine) is used to pop the address off the stack and into the 6502 program counter (after incrementing by 1). The net result is that the desired subroutine is reached by executing a subroutine return instruction! [*This ironic situation is an example of what is commonly referred to as "cleverness."*]

Op Code Subroutines

The register operation routines make use of the 6502 "zero page indexed by X" and "indexed by X indirect" addressing modes to access the specified registers and indirect data. The "result" of most register ops is left

The Art of Computer Programming



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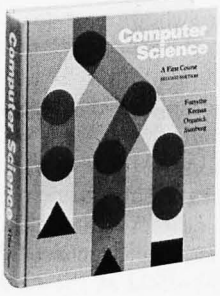

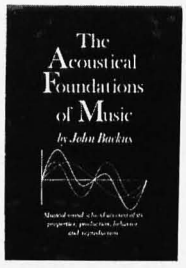

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Listing 2, continued:

```
0950: 49 FF     00218           EOR  #$FF
0952: F0 C4     00219           BEQ  BR1        BRANCH IF SO
0954: 60        00220           RTS
0955: 0A        00221 BNM1      ASL  A          DOUBLE RESULT-REG INDEX
0956: AA        00222           TAX
0957: B5 00     00223           LDA  R0L,X
0959: 35 01     00224           AND  R0H,X      CHK BOTH BYTES FOR NO $FF
095B: 49 FF     00225           EOR  #$FF
095D: D0 B9     00226           BNE  BR1        BRANCH IF NOT MINUS 1
095F: 60        00227 NUL       RTS
0960: A2 18     00228 RS        LDX  #$18       12*2 FOR R12 AS STK PNTR
0962: 20 DD 08  00229           JSR  DCR        DECR STACK POINTER
0965: A1 00     00230           LDA  (R0L,X)    POP HIGH RETURN ADR TO PC
0967: 85 1F     00231           STA  R15H
0969: 20 DD 08  00232           JSR  DCR        SAME FOR LOW-ORDER BYTE
096C: A1 00     00233           LDA  (R0L,X)
096E: 85 1E     00234           STA  R15L
0970: 60        00235           RTS
0971: 4C 3E 08  00236 RTN       JMP  RTNZ
                00237 *
                00238 * REG SAVE/RESTORE ROUTINES
                00239 * FOR NON-APPLE-II SYSTEMS
                00240 *
                00241 ASAV      EPZ  $45
                00242 XSAV      EPZ  $46
                00243 YSAV      EPZ  $47
                00244 PSAV      EPZ  $48
0974: 85 45     00245 SAVE      STA  ASAV
0976: 86 46     00246           STX  XSAV       SAVE 6502 REG CONTENTS.
0978: 84 47     00247           STY  YSAV
097A: 08        00248           PHP
097B: 68        00249           PLA
097C: 85 48     00250           STA  PSAV
097E: 60        00251           RTS
097F: A5 48     00252 RESTORE   LDA  PSAV
0981: 48        00253           PHA
0982: A5 45     00254           LDA  ASAV
0984: A6 46     00255           LDX  XSAV       RESTORE 6502 REG CONTENTS.
0986: A4 47     00256           LDY  YSAV
0988: 28        00257           PLP
0989: 60        00258           RTS
```

Table 1:

SWEET16 OP CODE SUMMARY

Register Ops				Nonregister Ops		
				00	RTN	(Return to 6502 mode)
1n	SET	Rn	Constant (Set)	01	BR ea	(Branch always)
2n	LD	Rn	(Load)	02	BNC ea	(Branch if No Carry)
3n	ST	Rn	(Store)	03	BC ea	(Branch if Carry)
4n	LD	@Rn	(Load indirect)	04	BP ea	(Branch if Plus)
5n	ST	@Rn	(Store indirect)	05	BM ea	(Branch if Minus)
6n	LDD	@Rn	(Load double indirect)	06	BZ ea	(Branch if Zero)
7n	STD	@Rn	(Store double indirect)	07	BNZ ea	(Branch if NonZero)
8n	POP	@Rn	(Pop indirect)	08	BM1 ea	(Branch if Minus 1)
9n	STP	@Rn	(Store pop indirect)	09	BNM1 ea	(Branch if Not Minus 1)
An	ADD	Rn	(Add)	0A	BK ea	(Break)
Bn	SUB	Rn	(Sub)	0B	RS	(Return from Subroutine)
Cn	POPD	@Rn	(Pop double indirect)	0C	BS ea	(Branch to Subroutine)
Dn	CPR	Rn	(Compare)	0D		(Unassigned)
En	INR	Rn	(Increment)	0E		(Unassigned)
Fn	DCR	Rn	(Decrement)	0F		(Unassigned)

SWEET16 Operation Code Summary: Table 1 summarizes the list of SWEET16 operation codes, which are explained in further detail one by one in the descriptions which follow the table. The program of listing 2 implements the execution of these interpretive codes after a call to the entry point SW16. Return to the calling program and normal noninterpretive operation is accomplished with the RTN mnemonic of SWEET16.

SWEET16 – REGISTER OPERATIONS

SET Rn, Constant — [1 n] [low] [high] (Set)

constant

The 2 byte constant is loaded into Rn (n = 0 to F, hexadecimal) and branch conditions set accordingly. The carry is cleared.

Example:

```
15 34 A0        SET   R5, A034      R5 now contains A034
```

LD Rn — [2 n] (Load)

The ACC (R0) is loaded from Rn and branch conditions set according to the data transferred. The carry is cleared and the contents of Rn are not disturbed.

Example:

```
15 34 A0        SET   R5, A034
25              LD    R5            ACC now contains A034
```

in the specified register and can be sensed by subsequent branch instructions since the register specification is saved in the high order byte of R14. This specification is changed to indicate R0 (ACC) for ADD and SUB instructions and R13 for the CPR (compare) instruction.

Normally the high order R14 byte holds the "prior result register" index *times 2* to account for the 2 byte SWEET16 registers, and thus the least significant bit is zero. If ADD, SUB or CPR instructions generate carries, then this index is incremented, setting the least significant bit, which becomes a carry flag.

The SET instruction increments the program counter twice, picking up data bytes for the specified register. In accordance with 6502 convention, the low order data byte precedes the high order byte.

Most SWEET16 nonregister operations are relative branches. The corresponding subroutines determine whether or not the "prior result" meets the specified branch condition and if so update the SWEET16 program counter by adding the displacement value (−128 to +127 bytes).

The RTN operation restores the 6502 register contents, pops the subroutine return stack and jumps indirect through the SWEET16 program counter register. This transfers control to the 6502 at the instruction immediately following the RTN instruction.

The BK operation actually executes a 6502 break instruction (BRK), transferring control to the interrupt handler.

Any number of subroutine levels may be implemented within SWEET16 code via the BS (Branch to Subroutine) and RS (Return from Subroutine) instructions. The user must initialize and otherwise not disturb R12 if the SWEET16 subroutine capability is used since it is utilized as the automatic subroutine return stack pointer.

Memory Allocation and User Modifications

The only storage that must be allocated for SWEET16 variables are 32 consecutive locations in page zero for the SWEET16 registers, four locations to save the 6502 register contents, and a few levels of the 6502 subroutine return address stack. If you don't need to preserve the 6502 register contents, delete the SAVE and RESTORE subroutines and the corresponding subroutine calls. This will free the four page zero locations ASAV, XSAV, YSAV and PSAV.

You may wish to add some of your own

Text continued on page 159

ST Rn | 3 n | (Store)

The ACC (R0) is stored into Rn and branch conditions set according to the data transferred. The carry is cleared and the ACC contents are not disturbed.

Example:

```
25          LD    R5        Copy the contents
36          ST    R6        of R5 to R6.
```

LD @Rn | 4 n | (Load indirect)

The low order ACC byte is loaded from the memory location whose address resides in Rn, and the high order ACC byte is cleared. Branch conditions reflect the final ACC contents which will always be positive and never minus 1. The carry is cleared. After the transfer, Rn is incremented by 1.

Example:

```
15 34 A0    SET   R5, A034
45          LD    @R5       ACC is loaded from
                            memory location A034
                            and R5 is incremented
                            to A035.
```

ST @Rn | 5 n | (Store indirect)

The low order ACC byte is stored into the memory location whose address resides in Rn. Branch conditions reflect the 2 byte ACC contents. The carry is cleared. After the transfer, Rn is incremented by 1.

Example:

```
15 34 A0    SET   R5, A034    Load pointers R5 and R6
16 22 90    SET   R6, 9022    with A034 and 9022.
45          LD    @R5         Move a byte from location
56          ST    @R6         A034 to location 9022. Both
                              pointers are incremented.
```

LDD @Rn | 6 n | (Load double byte indirect)

The low order ACC byte is loaded from the memory location whose address resides in Rn, and Rn is then incremented by 1. The high order ACC byte is loaded from the memory location whose address resides in the (incremented) Rn and Rn is again incremented by 1. Branch conditions reflect the final ACC contents. The carry is cleared.

Example:

```
15 34 A0    SET   R5, A034
65          LDD   @R5       The low order ACC byte is
                            loaded from location A034,
                            the high order byte from
                            location A035. R5 is incre-
                            mented to A036.
```

STD @Rn | 7 n | (Store double byte indirect)

The low order ACC byte is stored into the memory location whose address resides in Rn, and Rn is then incremented by 1. The high order ACC byte is stored into the memory location whose address resides in (the incremented) Rn and Rn is again incremented by 1. Branch conditions reflect the ACC contents which are not disturbed. The carry is cleared.

Example:

```
15 34 A0    SET   R5, A034    Load pointers R5 and R6
16 22 90    SET   R6, 9022    with A034 and 9022. Move
65          LDD   @R5         double byte from locations
76          STD   @R6         A034 and A035 to locations
                              9022 and 9023. Both pointers
                              are incremented by 2.
```

POP @Rn | 8 n | (Pop indirect)

The low order ACC byte is loaded from the memory location whose address resides in Rn *after* Rn is decremented by 1 and the high order ACC byte is cleared. Branch conditions reflect the final 2 byte ACC contents which will always be positive and never minus 1. The carry is cleared. Because Rn is decremented prior to loading the ACC, single byte stacks may be implemented with the ST @Rn and POP @Rn operations (Rn is the stack pointer).

Example:

```
15 34 A0    SET   R5, A034    Init stack pointer.
10 04 00    SET   R0, 4         Load 4 into ACC.
35          ST    @R5         Push 4 onto stack.
10 05 00    SET   R0, 5         Load 5 into ACC.
35          ST    @R5         Push 5 onto stack.
10 06 00    SET   R0, 6         Load 6 into ACC.
35          ST    @R5         Push 6 onto stack.
85          POP   @R5         Pop 6 off stack into ACC.
85          POP   @R5         Pop 5 off stack.
85          POP   @R5         Pop 4 off stack.
```

STP @Rn | 9 n | (Store pop indirect)

The low order ACC byte is stored into the memory location whose address resides in Rn *after* Rn is decremented by 1. Then the high order ACC byte is stored into the memory location whose address resides in Rn after Rn is again decremented by 1. Branch conditions will reflect the 2 byte ACC contents which are not modified. STP @Rn and PLA @Rn are used together to move data blocks beginning at the greatest address and working down. Additionally, single byte stacks may be implemented with the STP @Rn and LDA @Rn ops.

Example:

```
14 34 A0    SET   R4, A034    Init pointers.
15 22 90    SET   R5, 9022
84          POP   @R4         Move byte from A033
95          STP   @R5           to 9021.
84          POP   @R4         Move byte from A032
95          STP   @R5           to 9020.
```

ADD Rn | A n | (Add)

The contents of Rn are added to the contents of the ACC (R0) and the low order 16 bits of the sum restored in ACC. The 17th sum bit becomes the carry and other branch conditions reflect the final ACC contents.

Example:

```
10 34 76    SET   R0, 7634    Init R0 (ACC)
11 27 42    SET   R1, 4227      and R1.
A1          ADD   R1          Add R1 (sum = B85B,
                                carry clear)
A0          ADD   R0          Double ACC (R0) to 70B6
                                with carry set.
```

SUB Rn | B n | (Subtract)

The contents of Rn are subtracted from the ACC contents by performing a two's complement addition:

ACC ← ACC + $\overline{Rn}$ + 1

The low order 16 bits of the subtraction are restored in the ACC. The 17th sum bit becomes the carry and other branch conditions reflect the final ACC contents. If the 16 bit unsigned ACC contents are greater than or equal to the 16 bit unsigned Rn contents then the carry is set, otherwise it is cleared. Rn is not disturbed.

Example:

```
10 34 76    SET   R0, 7634    Init R0 (ACC)
11 27 42    SET   R1, 4227      and R1.
A1          SUB   R1          Subtract R1 (diff = 340D
                                with carry set)
A0          SUB   R0          Clears ACC (R0)
```

POPD @Rn | C n | (POP Double byte indirect)

Rn is decremented by 1 and the high order ACC byte is loaded from the memory location whose address now resides in Rn. Then Rn is again decremented by 1 and the low order ACC byte is loaded from the corresponding memory location. Branch conditions reflect the final ACC contents. The carry is cleared. Because Rn is decremented *prior* to loading each of the ACC halves, double byte stacks may be implemented with the STD @ Rn and POPD @ Rn operations. (Rn is the stack pointer).

Example:

```
15 34 A0        SET   R5, A034     Init stack pointer.
10 12 AA        SET   R0, AA12        Load AA12 into ACC.
75              STD   @R5          Push AA12 onto stack.
10 34 BB        SET   R0, BB34        Load BB34 into ACC.
75              STD   @R5          Push BB34 onto stack.
10 56 CC        SET   R0, CC56        Load CC56 into ACC.
75              STD   @R5
C5              POPD  @R5          Pop CC56 off stack.
C5              POPD  @R5          Pop BB34 off stack.
C5              POPD  @R5          Pop AA12 off stack.
```

CPR Rn | D n | (Compare)

The ACC (R0) contents are compared to Rn by performing the 16 bit binary subtraction ACC-Rn and storing the low order 16 difference bits in R13 for subsequent branch tests. If the 16 bit unsigned ACC contents are greater than or equal to the 16 bit unsigned Rn contents then the carry is set, otherwise it is cleared. No other registers, including ACC and Rn, are disturbed.

Example:

```
15 34 A0        SET   R5, A034     Pointer to memory.
16 BF A0        SET   R6, A0BF     Limit address.
10 00 00  LOOP  SET   R0, 0        Zero data.
75              STD   @R5          Clear 2 locs, incr R5 by 2.
25              LD    R5           Compare pointer R5
D6              CPR   R6              to limit R6.
02 F8           BNC   LOOP         Loop if carry clear.
```

INR Rn | E n | (Increment)

The contents of Rn are incremented by 1. The carry is cleared and other branch conditions reflect the incremented value.

Example:

```
15 34 A0        SET   R5, A034     Init R5 (pointer)
10 00 00        SET   R0, 0        Zero to R0.
55              ST    @R5          Clears loc A034 and incrs
                                      R5 to A035.
E5              INR   R5           Incr R5 to A036
55              ST    @R5          Clears loc A036 (not A035)
```

DCR Rn | F n | (Decrement)

The contents of Rn are decremented by 1. The carry is cleared and other branch conditions reflect the decremented value.

Example: (Clear nine bytes beginning at loc A034)

```
15 34 A0        SET   R5, A034     Init pointer.
14 09 00        SET   R4, 9        Init count.
10 00 00        SET   R0, 0        Zero ACC.
55        LOOP  ST    @R5          Clear a mem byte.
F4              DCR   R4           Decr count.
07 FC           BNZ   LOOP         Loop until zero.
```

SWEET16 Nonregister Instructions

RTN | 0 0 | (Return to 6502 mode)

Control is returned to the 6502 and program execution continues at the location immediately following the RTN instruction. The 6502 registers and status conditions are restored to their original contents (prior entering SWEET16 mode).

BR ea | 0 1 | d d | (Branch Always)

An effective address (ea) is calculated by adding the signed displacement byte (dd) to the program counter. The program counter contains the address of the instruction immediately *following* the BR, or the address of the BR operation plus 2. The displacement is a signed two's complement value from −128 to +127. Branch conditions are not changed. Note that effective address calculation is identical to that for 6502 relative branches.

Some examples:

dd = $80	ea = PC + 2 − 128
dd = $81	ea = PC + 2 − 127
dd = $FF	ea = PC + 2 − 1
dd = $00	ea = PC + 2 + 0
dd = $01	ea = PC + 2 + 1
dd = $7E	ea = PC + 2 + 126
dd = $7F	ea = PC + 2 + 127

Example:

```
$300: 01 50        BR  $352
```

BNC ea | 0 2 | d d | (Branch if No Carry)

A branch to the effective address is taken only if the carry is clear, otherwise execution resumes as normal with the next instruction. Branch conditions are not changed.

BC ea | 0 3 | d d | (Branch if Carry set)

A branch is effected only if the carry is set. Branch conditions are not changed.

BP ea | 0 4 | d d | (Branch if Plus)

A branch is effected only if the prior "result" (or most recently transferred data) was positive. Branch conditions are not changed.

Example: (Clear mem from loc A034 to A03F)

```
15 34 A0          SET   R5, A034     Init pointer.
14 3F A0          SET   R4, A03F     Init limit.
10 00 00  LOOP    SET   R0, 0
55                ST    @R5          Clear mem byte, incr R5.
24                LD    R4           Compare limit to
D5                CPR   R5             pointer.
04 F8             BP    LOOP         Loop until done.
```

BM ea | 0 5 | d d | (Branch if Minus)

A branch is effected only if the prior "result" was minus (negative, MSB = 1). Branch conditions are not changed.

BZ ea | 0 6 | d d | (Branch if Zero)

A branch is effected only if the prior "result" was zero. Branch conditions are not changed.

BNZ ea | 0 7 | d d | (Branch if NonZero)

A branch is effected only if the prior "result" was nonzero. Branch conditions are not changed.

BM1 ea | 0 8 | d d | (Branch if Minus 1)

A branch is effected only if the prior "result" was minus 1 ($FFFF hexadecimal). Branch conditions are not changed.

BNM1 ea | 0 9 | d d | (Branch if Not Minus 1)

A branch is effected only if the prior "result" was not minus 1 ($FFFF hexadecimal). Branch conditions are not changed.

Text continued from page 154

instructions to this implementation of SWEET16. If you use the unassigned op codes $0E and $0F, remember that SWEET16 treats these as 2 byte instructions. You may wish to handle the break instruction as a SWEET16 call, saving two bytes of code each time you transfer into SWEET16 mode. Or you may wish to use the SWEET16 BK (Break) operation as a "CHAROUT" call in the interrupt handler. You can perform absolute jumps within SWEET16 by loading the ACC (R0) with the address you wish to jump to (minus 1) and executing a ST R15 instruction.

And as a final thought, the ultimate modification for those who do not use the 6502 processor would be to implement a version of SWEET16 for some other microprocessor design. The idea of a low level interpretive processor can be fruitfully implemented for a number of purposes, and achieves a limited sort of machine independence for the interpretive execution strings. I found this technique most useful for the implementation of much of the software of the Apple II computer; I leave it to readers to explore further possibilities for SWEET16.■

BRK | 0 A | (Break)

A 6502 BRK (break) instruction is executed. SWEET16 may be reentered non-destructively at SW16D after correcting the stack pointer to its value prior to executing the BRK.

RS | 0 B | (Return from SWEET16 Subroutine)

RS terminates execution of a SWEET16 subroutine and returns to the SWEET16 calling program which resumes execution (in SWEET16 mode). R12, which is the SWEET16 subroutine return stack pointer, is decremented twice. Branch conditions are not changed.

BS ea | 0 C | d d | Branch to SWEET16 Subroutine

A branch to the effective address (PC + 2 + d) is taken and execution is resumed in SWEET16 mode. The current PC is pushed onto a "SWEET16 subroutine return address" stack whose pointer is R12, and R12 is incremented by 2. The carry is cleared and branch conditions set to indicate the current ACC contents.

Example: (Calling a "memory move" subroutine to move A034—A03B to 3000—3007)

```
300: 15 34 A0          SET   R5, A034    Init pointer 1.
303: 14 3B A0          SET   R4, A03B    Init limit 1.
306: 16 00 30          SET   R6, 3000    Init pointer 2.
309: 0C 15             BS    MOVE        Call move subroutine.
       .
       :
320: 45          MOVE  LD    @R5         Move one
321: 56                ST    @R6           byte.
322: 24                LD    R4
323: D5                CPR   R5          Test if done.
324: 04 FA             BP    MOVE
326: 0B                RS                Return.
```