PROGRAMS FOR THE COSMAC ELF INTERPRETERS

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Introduction

This booklet's purpose is to explain the construction and operation of an interpreter for the COSMAC 1802 "ELF". It assumes that the reader has some knowledge of the 1802 instruction set and is able to write simple machine language programs. Mnemonics are not provided because most ELF owners do not have access to assemblers and must work directly in machine language. Instead, programs are explained in a documented, step-by-step fashion, that it is hoped will make the concepts involved easy to follow.

The interpretive language described is "CHIP-8", the language used by RCA Corporation in its "COSMAC VIP" computer. CHIP-8 is a simple language consisting of about 30 instructions. RCA's interpreter is elegant and well thought out; once understood it is easily changed and modified.

This booklet contains five sections; in the first section a simple demonstration interpreter is introduced. This demonstration interpreter runs in the basic 1/4 "ELF" and its instructions are a subset of the full CHIP-8 instruction set. While simple, the demonstration interpreter employs methods similar to those in the full interpreter.

Further sections discuss the full CHIP-8 instruction set, hardware differences between the "VIP" and the "ELF", and provide a listing of a complete ELF interpreter together with suggestions for implementing it on various machines. The final section discusses the extension of the CHIP-8 instruction set. Examples are provided for multiply and divide instructions together with an instruction which displays characters for the 64 six bit ASCII symbols.

I should like to thank RCA Corporation for permission to write about CHIP-8 and to modify it for the ELF. However RCA is not responsible for any of the material in this booklet. The programs described here have been thoroughly tested on a number of versions of the COSMAC "ELF" as described in Popular Electronics articles and are believed to be reliable but there is, of course, still the possibility that they contain unexpected errors. This kind of interpreter is rather hardware dependent and changes in input/output lines or in the use of flag lines will cause failures. An attempt was made to provide sufficient documentation so that the user can make the changes necessary to implement CHIP-8 on a variety of machines.

A Demonstration Interpreter

The surprising power of computers is due to the development of languages which organize programming into different levels of complexity. Perhaps the simplest way to organize programming with a language is to use an interpreter. One can consider an interpreter to be a program that converts the basic instruction set to a new language, a set of instructions that better suits the programmer. Alternately an interpreter can be thought of as a program with a control section and a number of subroutines, the new language now instructs the interpreter as to which subroutines to call and in which order. The subroutines perform "tasks" which are more complicated than those performed by a single machine code operation. The ubiquitous basic interpreter is a good example.

RCA's CHIP-8 language is an interpretive one and it converts the 94 machine language instructions of the 1802 microprocessor to a new set of about 30 more powerful and convenient instructions. Each type of statement in the new language is implemented by a machine code subroutine which carries out the desired operation. It differs from a basic interpreter in that most of the operations carried out by the subroutines are small ones, consisting of only a few machine code instructions, and the language is therefore a simple one without many of the features of basic. However quite powerful programs can be written with a few hundred CHIP-8 instructions.

This section introduces a version of CHIP-8 for the 1/4K Elf. Ten of the instructions are a subset of the full CHIP-8 set and are identical to those in CHIP-8. Two additional instructions, read a byte from the keyboard and display a byte on the hex display, have no exact counterparts in the CHIP-8 set.

CHIP-8 instructions consist of four hex digits. The first hex digit determines the type of instruction; there are therefore 16 basic kinds of CHIP-8 instructions. The next 3 hex digits are used in several different ways. The can be used to specify a memory location, and as there are 3 hex digits available, any memory location from 000 to FFF can be specified. In the demonstration interpreter only the two least significant hex digits are needed for this purpose because it is necessary to address only a single page of memory.

A basic feature of CHIP-8 is that it provides 16 one byte variables, designated V0 through VF. Thus a single hex digit can be used to specify one of these variables. In many pt the CHIP-8 instructions the second most significant hex digit is used for this purpose, leaving the last two hex digits available for other uses. In arithmetic operations the two variables to be added, etc. are specified by the second and third hex digit leaving the last hex digit to designate the type of arithmetic operation to carry out.

Before beginning a discussion of how the interpreter works, it is necessary to have an understanding of the language and its use. The instructions available are shown in Table 1.

Table 1

Demonstration Interpreter Instructions

00MM	do a machine code subroutine at location MM (The machine code subroutine must end with D4)
10MM	go to MM; control is transferred to location MM in the interpretive code
20MM	do an interpreter subroutine at location MM (The interpreter subroutines must end with 009E)
4XKK	skip if VX≠KK; the next interpreter instruction is skipped over if VX does not equal KK
6XKK	set VX=KK; variable X is made equal to KK
8XY0	set VX=VY; variable X is made equal to variable Y
8XY1	set VX=VY or VY; variable X is made equal to the result of VX logically ored against VY (Note that VF is changed)
8XY2	set VX=VX and VY; variable X is made equal to the result of VX logically anded against VY (Note that VF is changed)
8XY3	set VX=VX xor VY; variable X is made equal to the result of VX logically xored against VY (note that VF is changed)
8XY4	set VX=VX+VY; variable X is made equal to the sum of VX and VY (Note that VF becomes 00 if the sum is less than or equal to FF and 01 if the sum is greater than FF)
8XY5	set VX=VX-VY; variable VX is made equal to the difference between VX and VY (Note that VF becomes 00 if VX is less than VY and 01 if VX is greater than or equal to VY)
8XY6	set VX equal to VY shifted right 1 bit position, (Note bit 0 is shifted into VF)
8XY7	set VX=VY-VX; variable VX is made equal to the difference between VY and VX (Note that VF becomes 00 if the

sum is less than or equal to FF and 01 if the sum is greater than FF)

8XYE set VX equal to VY shifted left 1 bit position (Note bit 7 is shifted into VF)

DXKK display VX on the hex display, KK indicates the length of a pause for display

FX00 set VX equal to the switch byte; waits for the input button to be pushed and released

An easy way to see how these instructions are used is to illustrate them with a simple program. The interpreter is listed at the end of the chapter and can be used to run these sample programs.

To start let's look at the following program. It reads 2 switch bytes, displays them, adds them, and displays the result. If overflow occurs, that is also displayed. The program uses only 10 interpreter instructions (The first instruction 3071 is actually machine code and transfers control on entry to the interpreter; It is not part of the interpretive code.) The interpreter has a program counter for interpretive code (R(5)) which is set on entry to the address of the first instruction (M(0002)). The first interpretive language instruction is 63EE which sets variable number 3 equal to EE.

Interpretive Addition Program

Add.	Code	Notes
00	3071	entry to interpreter
02	63EE	set V3 equal to EE
04	F400	set V4 equal to switch byte, waits for in on, off
06	D4FF	display V4 on hex display for about 1.8 seconds
08	F500	set V5 equal to switch byte
0A	D5FF	display V5 on hex display
0C	8454	set V4 equal to V4 + V5
0E	D4FF	display V4, now the sum of V4 + V5
10	4F01	skip next instruction if VF ≠ 01, remember VF will be set to 01 by the 8454 instruction if overflow occurs
12	D3FF	display V3 (V3 was set equal to EE) this instruction is skipped if VF is anything but 01
14	1004	go back to instruction 04 to wait for next number

The above program illustrates most of the demonstration interpreter instructions; an important exception is the interpreter subroutine call. Unlike the SEP register technique used in simple machine code programs, interpreter subroutines do not have to return to the main program but can be called from other subroutines. A stack is employed to store the return address when a subroutine call is made and successive calls to subroutines, without returns, push the stack further down. In the demonstration interpreter the stack pointer, R(2), points to the last location used and is pushed down one before a new byte is added to the stack. Each time a return from a subroutine occurs the stack pointer is incremented by one.

The next program is a simple illustration of the use of an interpreter subroutine. A switch byte is entered and displayed. It is then counted down by three's until underflow occurs. A subroutine is used to implement the counting down by three.

Program to Illustrate Subroutine use

Add.	Code	Notes
00	3071	entry to interpreter
02	F500	set V5 equal to switch byte, waits for in on, off
04	D5FF	display V5 on hex display for about 1.8 seconds
06	200A	call interpreter subroutine at location 0A
08	1002	on return from subroutine go to location 02 to read another switch byte
-	-	begin interpretive subroutine
0A	6603	set V6 equal to 03
0C	8565	set V5 equal to V5 - V6
0E	D540	display V5 for ca 0.4 seconds
10	4F01	skip next instruction if underflow occurs during the subtraction, VF equals 00 on underflow
12	100C	transfer to location 0C to subtract three more
14	009E	return from subroutine

In the above program, the call to the subroutine uses one stack position to store the return address. When the interpreter is entered the stack pointer is set to location 71. On calling the subroutine it is decremented by one, to location 70, and 08, the location the interpreter should execute on return from subroutine, is stored there. If we examine location 70 after running this program 08 will be found there.

Two additional stack locations, 6E and 6F are used by 8565 instruction, these locations become F5 and D3 respectively. An explanation of why this occurs is given in the demonstration interpreter listing.

The interpreter also includes an instruction, 00MM, which executes a machine code subroutine at address MM. This is easily accomplished; the control section of the interpreter treats the machine code subroutine as if it were one of the subroutines written to execute CHIP-8 instruction. All the subroutines which execute CHIP-8 instructions end with a D4 byte.

The following program poses simple addition problems and illustrates most of the demonstration interpreter instructions. It contains a machine language subroutine which generates two random numbers when the in button is pushed. On entry, the program displays AA and the Q light comes on. When the input button is pressed a simple addition problem (base 10) is presented; for example 17AD (for and) 32E0 (for equals) may be displayed. If 00 is entered the problem is shown again, if the correct answer is entered it is displayed followed by AA. However if an incorrect answer is entered EE is shown followed by the correct answer. The program requires 36 interpreter instructions and a machine language subroutine of 25 bytes. An interpreter subroutine is used to generate two random numbers in VD and VE. The displayed numbers are all less than 99 (base 10) to accommodate the hex display and the simple hex to decimal conversion routine which fails for numbers greater or equal to 100 (base 10).

Program for Addition Problems

Add.	Code	Notes
00	3071	entry to interpreter
02	60E0	set V0 equal to E0
04	61EE	set V1 equal to EE
06	62AD	set V2 equal to AD
08	63AA	set V3 equal to AA
0A	D300	display V3 (AA) on the display but no delay for display
0C	004A	call machine language subroutine which generates random numbers in VD and VE when in is pushed
0E	8BE0	set VB equal to VE as preparation for summing the two random numbers
10	8BD4	set VB equal to VD + VE, sum of the two random numbers
12	203A	call the interpreter subroutine which converts from hex to decimal, answer is returned in VA and VB is changed
14	8CA0	save answer on return from subroutine by setting VC equal to VA
16	8BE0	set VB equal to VE, one of the random numbers
18	203A	call subroutine to make VA the decimal equivalent of VB
1A	DAFF	display VA, first random number (base 10)
1C	D2FF	display V2 (AD)
1E	8BD0	set VB equal to VE the other random number
20	203A	call subroutine to make VA the decimal equivalent of VB
22	DAFF	display VA, second random number
24	D0FF	display V0 (E0)
26	F600	make V6 the entered byte
28	4600	skip the next instruction if V6 is equal to 00
2A	1016	here only if V6 is 00, back to 16 to repeat display
2C	D6FF	display V6, the entered byte
2E	86C5	set V6 equal to V6 - VC, VC is the correct answer (base 10)
30	4600	skip next instruction unless V6 equals 00, i.e. skip on wrong answer
32	100A	transfer to 0A to show AA if answer is correct
34	D1FF	display V1 (EE)
36	DCFF	display VC, correct answer
38	100C	transfer to 0C to begin next problem
-	-	end of main, begin hex to decimal conversion subroutine, subroutine adds 06 to VB for every time 0A occurs, argument is passed in

		VB and returned in VA
3A	8AB0	set VA equal to VB
3C	6906	set V9 equal to 06
3E	680A	set V8 equal to 0A
40	8B85	set VB equal to VB - V8, i.e. subtract 0A from VB
42	4F00	skip next instruction if VF equals 00, i.e. skip unless underflow
44	009E	return from subroutine on underflow
46	8A94	set VA equal to VA + V9, i.e. add 06 to VA
48	1040	transfer to location 40 to subtract 0A from VB, this is the end of the subroutine
-	-	start of machine language subroutine, random numbers from 1 through 50 (base 10) are generated in VD and VE, R(6) is used to point to VD and VE, see interpreter listing for a better understanding of how this routine works
4A	7B	entry point, turn Q on
4B	E6	make R(6) the X register
4C	F8 FE A6	load the address of VE to R(6)
4F	F8 33	load 51 (base 10) to D
51	FF 01	subtract 01 from D
53	32 4F	transfer to 4F if D is zero
55	3F 51	transfer to 51 unless in pushed
57	73	here when in pushed, store number in VE point R(6) to VD
58	F8 32	load 50 (base 10) to D
5A	FF 01	subtract 01 from D
5C	32 58	transfer to 58 id D is zero
5E	37 5A	transfer to 5A unless in released
60	56	store number in VD
61	7A D4	turn Q off and return, end of program

The above program illustrates one of the weaknesses of CHIP-8. There is no way to pass arguments to interpreter subroutines except through the variables and we must execute a number of variable transfer instructions to use the hex to decimal interpreter subroutine. This weakness is partly overcome in the full interpreter by the inclusion of instructions which transfer the variables to and from memory. The full interpreter also includes an instruction which generates random numbers and a hex to decimal conversion routine. In the next section this program has been rewritten for the full interpreter.

Now let's look at the listing for the demonstration interpreter. It uses the 16 locations F0 through FF to store the 16 variables. The interpreter examines each instruction in turn and carries out the desired operation by calling the correct subroutine. It uses the following registers:

Demonstration Interpreter Register Use

R(2)	stack pointer
R(3)	set to address of machine code subroutine that carries out instruction, i.e. subroutine program counter
R(4)	program counter for control section of interpreter
R(5)	program counter for interpretive code
R(6)	VX pointer, points to one of 16 variables
R(7)	VY pointer, points to one of 16 variables
R(C)	used to point to a table of addresses

The interpreter is designed for use on a single page of memory and will work in the basic 1/4K Elf as it stands. For expanded systems R(2), R(3), R(4), R(5), R(6), R(7) and R(C) have to have their high order bytes set to the page the interpreter resides on. Perhaps the simplest way to do this initialization for an expanded system is to change the entry point of the interpreter from 71 to 68 and add the following code from locations 68 through 73:

Add.	Code	Notes
68	F8 00	load page number to D, here 00 but interpreter can be on any page
6A	B2 B3 B4	initialize registers
6D	B5 B6 B7 BC	initialize register
71	F8 68 A2	establish top of stack at M(68) instead of at M(71)

Note that the stack pointer is now initialized at location 68 instead of at location 71. Alternately one can place the interpreter on a higher page in memory, do the initialization of the registers on page 00 and then transfer control to the interpreter. If this method is used the interpretive code can start at location 00 and R(5).0, the address of the first interpreter instruction, can be set to 00.

Demonstration Interpreter Listing

Add.	Code	Notes
71	F8 71 A2	establish stack pointer
74	F8 7A A4	R(4) will be program counter for control section of interpreter
77	F8 02 A5	R(5) is program counter for interpretive code, first instruction is at M(02)
7A	D4	establish program counter for control section
7B	E2	make R(2) the X register, this is the entry point for return to control section after completing a subroutine call
7C	45 AF	load first half of instruction and save it in R(F).0
7E	F6 F6 F6 F6	shift right to get most significant digit most significant digit determines type of instruction
82	32 98	if D is zero (type 0 instruction) we have machine code subroutine call, transfer to location 98
84	F9 A0	else or against A0 to get address from table of subroutine locations (see locations A1 to AF)
86	AC	save address in R(C).0
87	8F	bring back instruction
88	F9 F0	or against F0 to get VX address
8A	A6	establish R(6) as VX pointer
8B	05	load second half of instruction, note that R(5) is left pointing to second half of instruction
8C	F6 F6 F6 F6	shift right to get VY pointer
90	F9 F0	or against F0 to get VY address
92	A7	establish R(7) as VY pointer
93	0C A3	pick up subroutine address from table and point R(3) to subroutine
95	D3	call subroutine to do instruction
96	30 7B	on return from subroutine go to 7B for next instruction
98	45 30 94	here for machine code subroutine, load address to D and go to 94 to establish R(3)
-	-	begin subroutine for 6XKK instruction
9B	45 56	load KK to D, store in VX
9D	D4	return to control section
-	-	9E through A0 is a machine code subroutine that restores R(5) on return from interpreter subroutine
9E	42	load return address from stack
9F	A5 D4	restore R(5) and return
-	-	the next 15 bytes are the subroutine locations
A1	B5 B0 E5 B8	i.e. go to B5 for 10MM
A5	E5 9B E5 C0	instructions, go to B0
A9	E5 E5 E5 E5	for 20MM instructions,
AD	E7 E5 DD	etc. illegal instructions go to E5 where they are ignored
-	-	subroutine for 20MM instructions
B0	15 85	load return address to D
B2	22 52	save on stack, push stack down first
B4	25	restore R(5) so that it points to MM
-	-	rest of this subroutine is shared with 10MM instructions
B5	45 A5	load MM change R(5) to point to new address
B7	D4	return
-	-	begin subroutine for 4XKK instruction
B8	45	load KK to D
B9	E6	make R(6) the X register, the VX pointer
BA	F3	x'or VX against KK

BB	32 BF	return immediately if D equals 0, i.e. if VX equals KK
BD	15 15	else increment instruction program counter twice
BF	D4	return
-	-	here begin the 8XYN instructions
C0	45	load YN to D
C1	FA 0F	and off N to get 0N in D
C3	3A C8	go to C8 unless N is zero
C5	07 56	load VY, write to VX
C7	D4	return
-	-	here on other 8XYN instructions, makes up FN D3 on stack, transfers control to stack and obeys the two instructions, uses R(2) as program counter
C8	AF	save 0N
C9	22	push stack down
CA	F8 D3 73	load D3 to D, write to stack
CD	8F F9 F0	load 0N, or against F0 to get F1, F2, F3, F4, F5, F6, F7, or FE
D0	52	write to stack
D1	E6	make VX pointer the X register
D2	07	load VY to D
D3	D2	go to stack to obey FN D3 instructions
D4	56	on return save result as VX
D5	F8 FF A6	point R(6) to VF
D8	F8 00	clear D
DA	7E 56	shift DF into D and save as VF
DC	D4	return
-	-	begin FX00 subroutine
DD	7B	Q on to indicate waiting for byte
DE	3F DE	wait for in on
E0	37 E0	wait for in off
E2	E6	make VX pointer the X register
E3	6C	switch byte to VX
E4	7A	turn Q off
E5	45 D4	advance instruction counter, return – also used for illegal instructions
-	-	begin DXKK subroutine
E7	E6	make VX pointer the X register
E8	64	display VX
E9	45 BF	load KK to R(F).1
EB	2F 9F	decrement R(F), load R(F).1
ED	3A EB	go to EB unless D is zero, delay loop
EF	D4	return – end of interpreter
F0-FF	-	locations where the 16 interpreter variables are stored

The Chip-8 Language

This section contains a brief discussion of the CHIP-8 language and a list of the available instructions. Further information about RCA's VIP machine and about CHIP-8 can be found in two articles by Joseph Weisbecker ("COSMAC VIP, the RCA Fun Machine", in the August, 1977 Byte magazine p. 30, and "An Easy Programming System", in the December, 1978 Byte magazine p.108) and in RCA's literature. The full CHIP-8 instruction set is listed in the table at the end of this chapter.

Many of the basic features of the CHIP-8 language are explained and illustrated in section 2 and the demonstration interpreter contains ten instructions which are identical to those in the full CHIP-8 set. The complete language is designed for use with low resolution graphics and the display subroutine is the longest and most complex of the subroutines in the interpreter. A number of TV games have been written with CHIP-8 and it is well suited for this purpose. The display instruction is used in conjunction with a memory pointer and the CHIP-8 variables and has the form DXYN. The values of VX and VY indicate where on the video display to show information, and the value of N indicates how many bytes to display. A memory pointer, called I, gives the starting address of the information to be displayed and must be set by other instructions. Positions in the display field are determined by a rectangular coordinate system with the origin in the upper left corner; 64 horizontal positions, designated by VX and 32 vertical positions designated by VY, are available. The bytes to be displayed are exclusively ored against the display field; an important feature for TV games. Portions of memory bytes which extend beyond the display field on the right or at the bottom are truncated, there is no wrap around.

Another important feature of the language is the 16 one byte variables, V0 through VF, which are held in random access memory. Two of these variables V0 and VF are used for special purposes. V0 is used in a kind of computed go statement, the BMMM instruction. Control is transferred to location MMM to which has been added the value of V0. As in the demonstration interpreter, VF is used to indicate overflow in arithmetic operations. It is also used to indicate when a display instruction attempts to show a position which is already being displayed. As the display instruction exclusively or's the data to be displayed against the display field, such an attempt turns off the displayed position. VF is set to 01 to indicate this occurrence. This serves as a simple way to determine if a missile has struck a target in a TV game.

A third important feature of CHIP-8, already mentioned in the discussion of the display routine, is the memory pointer, I. The memory pointer can be set both directly and indirectly; besides its use as a display pointer, it also serves as a pointer for transferring variables to and from memory.

The full CHIP-8 instruction set has six skip instructions all of which follow the principle of the skip instruction included in the demonstration interpreter. That is, the next interpreter instruction is skipped over if on testing a condition it is found to be true.

The instructions which have 8 as the first hexadecimal digit perform arithmetic and logic operations and are all included in the demonstration interpreter. Note again that VF is used to indicate overflow and that the value of VF is changed by 8XY1, 8XY2, 8XY3, 8XY4, 8XY5, 8XY6, 8XY7, and 8XYE instructions.

A number of instructions which are not included in the demonstration interpreter are the "F" instructions. Several of these are used in conjunction with the memory pointer. For example the FX29 instruction points I at a 5 byte memory pattern which corresponds to the least significant hex digit of VX. If V7 were 38 and F729 instruction were executed I would point to the first byte of the series F0, 90, F0, 90, F0 (a pattern for the symbol "8") and DXY5 instruction would show an "8" on the display. The FX33 instruction is a binary to decimal conversion routine. The value of VX is converted to a 3 digit decimal number with the hundreds digit stored at location I, the tens digit at location I + 1, and the units digit at location I + 2. The FX55 and FX56 instructions use the memory pointer to transfer values from memory to the variables , respectively.

Other "F" instructions include a settable tone generator (FX18) (see the section on Hardware Differences), an instruction to set a timer (FX15), an instruction to read the timer (FX07), and an instruction to read the keyboard (FX0A). An additional "F" instruction has been added for the Elf; FX75, which displays the value of VX on the hex display.

Other useful instructions which are not present in the demonstration interpreter include a random number generator (CXKK where KK is anded against a random byte before being transferred to VX), and an instruction which adds a byte to one of the variables, 7XKK. Two of the CHIP-8 instructions 00E0 (erase display) and 0DEE (return from a CHIP-8 subroutine) are implemented as machine code subroutines resident in the interpreter itself. They are therefore dependant upon the page where CHIP-8 is located and will have to be changed if CHIP-8 is relocated. This also is the reason that the return from a subroutine is 009E in the demonstration interpreter and 00EE in the full CHIP-8 interpreter.

To illustrate the use of the full instruction set, let's rewrite one of the programs that used the demonstration interpreter, the one involving addition problems. The following program constructs simple addition problems using two randomly chosen numbers between 0 and 127. On entry to the program a problem is presented, e.g. 076 + 093 = ?. An answer is entered through the keyboard one digit at a time (i.e. 1, 6, 3) and when the last digit is entered 163 is displayed. A C flows the entered number if it is correct and an E if it is incorrect. In the case of an incorrect answer the correct answer is also shown. Another problem is given when any key is entered. The program consists of 67 CHIP-8 instructions and also uses 32 bytes for constants and work space.

Program for Addition Problems

Add.	Code	Notes
0200	00E0	erase display
-	-	first set up problems and answer
0202	CD7F	VD equals random number
0204	CE7F	VE equals random number
0206	8CD0	VC = VD
0208	8CE4	VC = VD + VE (the answer)
-	-	next convert to decimal and display the problem
020A	A2A2	point I to work space

020C	6A00	set VA = 00, display pointer
020E	6B00	set VB = 00, display pointer
0210	FD33	M(I) equals 3 digit decimal equivalent of VD
0212	F265	V0, V1, V2 equals M(I)
0214	2276	call CHIP-8 subroutine (displays 3 digit number in V0, V1, and V2)
0216	A288	point I to + pattern
0218	7A07	VA = VA + 07, display pointer
021A	DAB5	display + pattern
021C	A2A2	point I to work space
021E	7A08	VA = VA + 08, display pointer
0220	FE33	M(I) equals 3 digit decimal equivalent of VE
0222	F265	V0, V1, V2 equals M(I)
0224	2276	call subroutine to display VE
0226	A28E	point I to = pattern
0228	7A07	VA = VA + 07, display pointer
022A	DAB4	display = pattern
022C	A292	point I to ? pattern
022E	6A18	set VA = 18, display pointer
0230	6B08	set VB = 08, display pointer
0232	DABF	display ? pattern
-	-	now read in possible answer
0234	F00A	V0 = least significant digit of switch byte
0236	F10A	V1 = switch byte (LSD)
0238	F20A	V2 = switch byte (LSD)
023A	DABF	display ? pattern (erases it)
023C	6A15	set VA = 15, display pointer
023E	2276	call subroutine to display entered answer
-	-	now compute answers, right to 025c, wrong to 0262
0240	A2A5	point I to work space
0242	F255	V0, V1, V2 – correct answer
0244	A2A2	V3, V4, V5 – entered answer
0246	FC33	V3 = V3 – V0
0248	F565	skip to 0262, error
024A	8305	V4 = V4 – V1
024C	3300	skip if V3 = 00
024E	1262	go to 0262, error
0250	8415	V4 = V4 – V1
0252	3400	skip if V4 = 00
0254	1262	go to 0262, error
0256	8525	V5 = V5 – V2
0258	3500	skip if V5 = 00
025A	1262	go to 0262, error
-	-	here if answer correct
025C	660C	set V6 = 0C
025E	F618	set tone duration (reward)
0260	126A	go to 026A
-	-	here if answer wrong
0262	6A15	set VA = 15, display pointer
0264	6B10	set VB = 10, display pointer
0266	2276	call subroutine to display correct answer
0268	660E	V6 = 0E
026A	6A26	VA = 26, display pointer
026C	6B08	VB = 08, display pointer
026E	F629	point I to C or E pattern
0270	DAB5	display C or E
0272	F00A	wait for any input
0274	1200	to 0200 for next problem
-	-	subroutine to display 3 digit number held in V0, V1, V2
0276	F029	point I to pattern for V0
0278	DAB5	display it
027A	7A05	VA = VA + 05, display pointer
027C	F129	point I to pattern for V1
027E	DAB5	display it
0280	7A05	VA = VA + 05, display pointer
0282	F229	point I to pattern for V1
0284	DAB5	display it
0286	00EE	return from subroutine
-	-	patterns and work space
0288	2020	pattern for + sign
028A	F820	
028C	2000	
028E	00FF	pattern for ? sign
0290	00FF	
0292	FFFF	
0294	0303	
0296	03FF	
0298	FFC0	
029A	C0C0	
029C	C0C0	
029E	00C0	
02A0	C000	
02A2	-	work space
02A4	-	
02A6	-	

Table 2

Full Interpreter Instructions

0MMM	do a machine code subroutine at location 0MMM (The machine code subroutine must end with D4)
1MMM	go to 0MMM; control is transferred to location 0MMM in the interpretive code

2MMM	do an interpreter subroutine at location 0MMM (the interpreter subroutine must end with 00EE)
3XKK	skip if VX = KK; the next interpreter instruction is skipped over if VX equals KK
4XKK	skip if VX ≠ KK; the next interpreter instruction is skipped over if VX does not equal KK
5XY0	skip if VX = VY; the next interpreter instruction is skipped over if VX equals VY (see 9XY0)
6XKK	set VX = KK; variable X is made equal to KK
7XKK	set VX = VX + KK; add KK to variable X
8XY0	set VX = VY; variable X is made equal to variable Y
8XY1	set VX = VX or VY; variable X is made equal to the result of VX logically or'ed against VY (Note that VF is changed)
8XY2	set VX = VX and VY; variable X is made equal to the result of VX logically anded against VY (Note that VF is changed)
8XY3	set VX = VX xor VY; variable X is made equal to the result of VX logically xor'ed against VY (Note that VF is changed)
8XY4	set VX = VX + VY; variable X is made equal to the sum of VX and VY (Note that VF becomes 00 if the sum is less than or equal to FF and 01 if the sum is grater than FF)
8XY5	set VX = VX – VY; variable X is made equal to the difference between VX and VY (Note that VF becomes 00 if VX is less than VY and 01 if VX is greater than or equal to VY)
8XY6	set VX = VY shifted right 1 bit position (Note bit 0 is shifted into VF)
8XY7	set VX = VY - VX; variable X is made equal to the difference between VY and VX (Note that VF becomes 00 if VY is less than VX and 01 if VY is greater than or equal to VX)
8XYE	set VX = VY shifted left 1 bit position (Note bit 0 is shifted into VF)
9XY0	skip if VX ≠ VY; the next interpreter instruction is skipped over if VX does not equal VY (see 5XY0)
AMMM	point I at 0MMM; the memory pointer is set to 0MMM
BMMM	go to 0MMM + V0, the value of V0 is added to 0MMM and control is transferred to the resulting location
CXKK	set VX to a random byte; random byte is anded against KK first
DXYN	display N byte pattern at coordinates VX, VY; I (memory pointer) gives starting locations to be displayed. The displayed locations are exclusively ored against display field. VF becomes 01 if some of the display field is already set, 00 if it is not.
EX9E	skip if VX = hex key; skip next instruction if the least significant digit of VX equals the least significant digit of the keyboard.
EXA1	skip if VX ≠ hex key; skip next instruction if the least significant digit of VX does nor equal the least significant digit of the keyboard
FX07	set VX to the value of the timer; timer is counted down in interrupt routine
FX0A	set VX = hex key; sets VX equal to the least significant digit of the keyboard, waits for in on, off
FX15	set timer to VX; timer is counted down in interrupt routine so 01 is ca. 1/60th second
FX18	set tone duration to VX; turns Q on for duration specified by VX, 01 is ca. 1/60th second
FX1E	set I to I + VX; add the value of VX to the memory pointer
FX29	point I to pattern for least significant digit of VX
FX33	convert VX to decimal; 3 decimal digits are stored at M(I), M(I + 1), and M(I + 2), I does not change
FX55	save V0 through VX in memory at locations specified by I, V0 at M(I), V1 at M(I+1), etc, I becomes I + X + 1
FX65	transfer memory locations specified by I to variables V0 through VX, V0 becomes M(I), V(1) becomes M(I + 1), etc, I becomes I + X + 1
FX75	display the value of VX on the hex display

00E0	erase the display (actually a machine language subroutine resident in the interpreter)

Hardware Differences between 1802 Computers

The most important difference between the various versions of the CCOSMAC ELF and the COSMAC VIP is the keyboard. The COSMAC VIP has a hex keyboard; however it is not connected to an input port,. Instead the least significant 4 bits of a bus output byte (Out 2, 62) are decoded and the 16 output lines connected to the corresponding hex keys. Each key is connected to one of the flag lines (EF3). To determine which key is depressed requires a software routine which scans the keyboard. Scanning is done by repeatedly outputting the 16 possible least significant hex digits and examining the flag line to see which digits cause it to be pulled low. Debouncing is also carried out within the software routines; there is an approximately 1/15 second software delay to debounce both opening and closing of a keyboard switch.

COSMAC ELF computers on the other hand are variable in design and have a variety of ways to input information from keyboards or switches. Indeed the September, 1976 issue of Popular Electronics describes a way to connect a scanned hex keyboard, much like that contained in the VIP, to the ELF. However most of the commercially available ELFs (e.g. Super Elf and Elf-2) have latched hex keyboards with roll-over. The latches are connected to an input port and one can examine the contents of these latches at any time under software control. A hardware debounced button (the in button) can be used as a device to indicate to a software routine that we wish the switch latches read. An additional feature of the Elf is the ability to carry out direct memory access input from the keyboard by depressing the in button when the computer is in the load mode. This feature is not required by the VIP which has an operating system in ROM.

These different methods in inputting information from the keyboard have different advantages and disadvantages, neither is really totally satisfactory. The VIP's keyboard has one significant advantage. All of the keys are connected directly to a flag line and it is possible to tell, with software, when a key is being depressed and if so which one. A quick response to keyboard entry is therefore possible and this property is particularly desirable for TV games. It also makes possible an operating system which enters bytes directly from the keyboard to memory without the necessity of pushing an in button. These features are more difficult with a roll-over latched keyboard like that found in many ELFs. Entered bytes can only be read from latches and there is no way, with software, to determine when a single key is repeatedly entered; that is we could never determine if B, B, B, B was entered because the contents of the latches would never change. This difficulty could, of course, be overcome with some simple hardware changes to the ELF.

The advantage of the ELF keyboard is that the contents of the keyboard latches can be transferred directly to memory by instituting a direct memory access cycle. This, in fact, is what makes the ELF a viable machine without read only memory. However the ELF would be easier to use if the contents of the keyboard latches were displayed and if a signal were provided which made it unnecessary to push the in button.

Another hardware difference is in the treatment of the Q line. In the VIP the Q line is attached to a simple oscillator, and this in turn can be connected to a speaker. Hence in the VIP when the Q line is turned on, a tine is heard in the loudspeaker. This feature can be added to an ELF without much difficulty. It should perhaps be mentioned that the VIP has room on board for one input and one output port, the output uses out-3 (63), and the input port uses in-3 (6B).

Rather than attempt to change the ELF to a VIP by making hardware changes, this booklet accepts the ELF's as they are and makes the software changes in CHIP-8 to accommodate ELFs. Unfortunately ELF's are not built to a standard design like the VIP and it is therefore difficult to write software which will suit all ELF users. To compensate for this a detailed listing of the interpreter is presented in the next section. It is hoped that sufficient information is given so that those with ELF's which differ from commercially available machines will be able to modify the interpreter to suit their machines.

A Complete Elf CHIP-8 Interpreter

This section provides a listing and a discussion of a version of CHIP-8 for COSMAC ELF's. The main listing of the interpreter is designed for a 4K Elf with memory pages 00 through 0F, the configuration most commonly used by the commercially available ELF's. It is also possible to use CHIP-8 in the 1 1/4K ELF's described in the articles in Popular Electronics, but to do so is very tedious unless the switches are replaced with a latched decoded keyboard. This machine has memory pages 00, 04, 05, 06, and 07 and a version of CHIP-8 for such a machine will also be described. The necessary changes to CHIP-8 will be discussed in the notes included with the full interpreter listing. Similar changes are required when CHIP-8 is relocated in memory and this example may aid those with other styles of machines.

The first consideration in modifying CHIP-8 for use on the ELF is page use. The following page use was chosen for the 4K Elf's with memory pages 00 through 0F:

Page	Use
00	first half of interpreter
01	second half of interpreter
02 – 0D	reserved for interpretive code
0E(first half)	character table and interrupt routine
0E(second half)	variables, work space and stack
0F	display page

This choice of page usage maximizes the similarity of ELF CHIP-8 and VIP CHIP-8. However it is possible to relocate the code to other places in memory and it might be better to accept the changes in CHIP-8 and place the interpreter on pages 0C and 0D. Relocation is necessary to implement the 1 1/4K version. Because of this, some changes in the language are necessary for the 1 1/4K version and the instruction 00E0 becomes 04E0 and 00EE becomes 04EE. Page use for the 1 1/4 K version is as follows:

Page	Use
00	display page
04	first half of interpreter
05	second half of interpreter
06 (first half)	character table and interrupt routine
06 (second half)	variables, work space and stack (There is room for a small operating system in the middle of page 6)
07	interpretive code

Register use is the same as it is in the VIP version of CHIP-8 as follows:

Use of Registers

	High	Low
R(0)		DMA address
R(1)		interrupt address
R(2)		stack, sometimes X register
R(3)		program counter for interpreter subroutines
R(4)		program counter for control section of interpreter
R(5)		CHIP-8 instruction program counter
R(6)		variable pointer, the VX pointer
R(7)		variable pointer, the VY pointer
R(8)	timer	timer
R(9)	random numbers	random numbers
R(A)		the I pointer
R(B)		display page pointer
R(C)	used for scratch but available for machine code subroutines	
R(D)	used for scratch but available for machine code subroutines	
R(E)	used for scratch but available for machine code subroutines	
R(F)	used for scratch but available for machine code subroutines	

Complete CHIP-8 Interpreter Listing

Add.	Code	Notes
-	-	first initialize the registers
0000	F8 0E B1	high order interrupt address
03	F8 46 A1	low order interrupt address replace 00E with 06 for 1 1/4K Elf
06	F8 0F BB	establish display page, replace 0F with 00 for 1 1/4K Elf
09	F8 0E B2	establish a high order stack address replace 0E with 06 for 1 1/4K Elf
0C	B6	establish page for variables, work space (same as stack page)
0D	F8 CF A2	establish low order stack address
10	F8 01 B5	high order address for first CHIP-8 instruction, replace 01 with 05 for 1 1/4K Elf

13	F8 FC A5	low order address for first CHIP-8 instruction, replace FC with FA for 1 1/4K Elf
16	F8 00 B4	establish control section program counter, replace 00 with 04 for a 1 1/4K Elf
19	F8 1C A4	establish low order address for control section program counter
1C	D4	make R(4) the program counter, this ends initialization of registers
-	-	begin control section of interpreter, on return from interpreter subroutine location 1D is entered
1D	96 B7	establish high order VY pointer
1F	E2	establish x-register
20	94 BC	make R(C).1 the current page
22	45	load first byte of a CHIP-8 instruction in R(F).1
23	AF	save 1st byte of instruction to R(F).0
24	F6 F6 F6 F6	shift right 4 times to get most significant digit
28	32 44	go to 44 if most significant digit is 0, we have a machine language subroutine
2A	F9 50	else or immediate against 50 to make pointer to table of subroutine locations
2C	AC	save result in R(C).0, the register used as a pointer
2D	8F	bring back 1st byte of instruction
2E	F9 F0	or immediate against F0 to make VX pointer
30	A6	save in R(6).0, the VX pointer
31	05	load 2nd byte of instruction
32	F6 F6 F6 F6	shift right to get most significant digit
36	F9 F0	or immediate against F0 to make VY pointer

38	A7	save in R(7).0, the VY pointer
39	4C B3	interpreter high order subroutine address from table to R(3).1
3B	8C FC 0F AC	set up pointer to table of low order subroutine addresses
3F	0C A3	low order subroutine address from table to R(3).0, R(3) now points to correct interpreter subroutine
41	D3	change to subroutine program counter
42	30 1D	subroutines end with D4, return here and go back to treat another interpreter instruction
-	-	comes to location 44 for machine code subroutines
44	8F	reload 1st byte of CHIP-8 instruction
45	B3	save in R(3).1, high order machine code subroutine address
46	45	load advance – 2nd byte of interpreter instruction
47	30 40	go to location 40 to set R(3).0 and call subroutine
-	-	end of control section, except see tables of addresses
49	22 69 12 D4	these 4 bytes are a machine code subroutine to turn on 1861 (TV) – obeyed in usual way as a machine code subroutine
4D	00 00 00 00	unused
-	-	next 15 bytes are high order addresses for interpreter subroutines, notes show most significant digit of instruction (note add 04 to each address for 1 1/4K Elf)
51	01 01 01 01	1 2 3 4
55	01 00 01 01	5 6 7 8
59	01 01 01 01	9 A B C
5D	00 01 01	D E F
60	00	unused

-	-	low order addresses – same for 1 1/4K Elf
61	7F 78 86 8E	1 2 3 4
65	98 FC 00 C2	5 6 7 8
69	94 F1 B2 DF	9 A B C
6D	70 9C 05	D E F
-	-	Now starts the remainder of the interpreter subroutines
-	-	entry to the display subroutine instruction, DXYN, review material in section 3 to see what it does. R(6) is used to point to work space, R(A) is I (the memory pointer), R(7).0 and R(D),0 are used to store N the number of bytes to display, and R(C) is used as pointer in to display page
70	06 BE	load VX, save in R(E).1
72	FA 3F	and against 3F (only 64 positions across display field)
74	F6 F6 F6	shift right 3 times (gets row address, i.e. 0-7 in display page)
77	22 52	save word address on stack
79	07	load VY
7A	FE FE FE	shift left 3 times to make space for row address
7D	F1	or on row address by setting R(C).1 to display page address
7E	AC	save in R(C).0
7F	9B BC	complete address by setting R(C).1 to display page address
81	45	load advance, 2nd half of instruction
82	FA 0F	and off number of bytes to display
84	AD A7	save in R(D).0 and R(7).0
86	F8 D0	load starting address of work space
88	A6	R(6) now points to work space
89	F8 00 AF	establish R(F).0 as a source of 00
8C	87	load number of bytes to display (a reentry point)

8D	32 F3	to location F3 for housekeeping if all done or if no bytes to display
8F	27	decrement number of bytes to display
90	4A BD	load advance, load display byte and save in R(D).1
92	9E	reload VX
93	FA 07 AE	and against 07, save in R(E).0, this is position in word – say R(A) pointed to a location containing FF (1111 1111) and least significant 3 bits of VX were (011) – routine from here to A9 would make two adjacent work locations (0001 1111) and (1110 0000) i.e. it would shift the word to be displayed over by 3 bits and fill in to the left and right with 0.
96	8E	load word position
97	32 A2	to A2 if 00, no shift needed
99	9D F6 BD	shift 1 bit to DF, 0 to MSB of D
9C	8F 76 AF	transfer DF to R(F).0, DF to MSB, LSB to DF
9F	2E 30 96	repeat number of times in word address
A2	9D 56	save 1st word in work
A4	16 8F 56	save 2nd word in work
A7	16	point R(6) to next work space
A8	30 89	repeat till all display words treated
AA	00	idles here after housekeeping, sees locations F3 through FB, still here to transfer work to display – R(C) points to first word to change in display field
AB	EC	make R(C) the X register
AC	F8 D0	load starting address of work
AE	A6	R(6) points to work
AF	F8 00 A7	00 to R(7).0 and eventually to VF

B2	8D	load number of bytes to display, reenters here until done
B3	32 D8	all done?, to D8 to set VF and exit
B5	06	load byte from work
B6	F2	and against display field
B7	2D	decrement bytes to display
B8	32 BD	to BD if result of and is 00, i.e. no points already set
BA	F8 01 A7	if points set make R(7).0 and eventually VF, 01
BD	46	reload work to D (load advance)
BE	F3	x'or against display field
BF	5C	write result to display field
C0	02	reload VX
C1	FB 07	are we at the end of the row?
C3	32 D1	if we are quit, no wrap around
C5	1C	else increment R(C)
C6	06	load next word from work
C7	F2 32 CD	repeat test for already set bits
CA	F8 01 A7	01 to R(7).0 if bits set
CD	06	load from work again
CE	F3 5C	x'or against filed and write to field
D0	2C 16	decrement R(C), increment R(6)
D2	8C FC 08	load R(C).0 add 08
D3	AC	load new address to R(C).0
D6	3B B2	if DF is 0 go to B2 to do more, else we've run over bottom and should return
-	-	comes here when all done
D8	F8 FF A6	load VF address to R(6).0
DB	87 56	load R(7).0 (either 00 or 01) and store in VF
DD	12 D4	fix up stack and return to control section
DF	00	unused – done with main part of display routine se F3 – FB, a patch for housekeeping
-	-	entry point for 00E0 instruction (04E0 for 1 1/4k Elf) a machine code subroutine that erases the display page
E0	9B BF	load display page address to R(F).1
E2	F8 FF AF	load FF to R(F).0
E5	F8 00	load 00 to D
E7	5F	store via F
E8	8F 32 DE	load R(F).0, return from subroutine if D is 00, all done
EB	2F 30 E5	else decrement R(F) and go back to blank another memory location
-	-	entry point for 00EE instruction (04EE for 1 1/4k Elf) retrieves interpretive code address from stack
EE	42 B5	retrieve high order address
F0	42 A5	then low order address R(5) now set
F2	D4	return to control section
-	-	part of display routine, resets memory pointer
F3	8D A7	load number bytes to display, save in R(7).0
F5	87	load R(7).0 to D
F6	32 AA	if 00 done, go to AA to wait for DMA
F8	2A 27	decrement R(A) (memory pointer) and R(7)
FA	30 F5	go back to check if done
-	-	entry for 6XKK subroutine
FC	45	load KK to D
FD	56 D4	write to VX and return
FF	00	unused, end of page 00 (04 for 1 1/4k Elf)
-	-	begin page 01 (05 for 1 1/4k Elf)
-	-	entry for 7XKK subroutine
0100	45	load KK to D
01	E6	make R(6), VX, the X register

02	F4	add KK to VX
03	56	write result to VX
04	D4	return to control section
-	-	all F instructions enter here and are set to correct subroutines by changing R(3)
05	45	load advance – 2nd byte of F instruction is location to transfer to on this page
06	A3	change R(3) subroutine program counter to correct address
-	-	entry for FX07 subroutine
07	98	load timer value to D (see interrupt routine)
08	56 D4	write VX and return
-	-	entry for FX0A subroutine
0A	3F 0A 37 0C	wait for in on, off
0E	22	push down stack
0F	6C	read switch byte
10	FA 0F	and against 0F to get least significant digit (This corresponds to original Chip-8, could and against FF to read complete byte)
12	12 56	restore stack, write to VX
14	D4	return to control section
-	-	entry for FX15 subroutine
15	06	load VX to D
16	B8 D4	save in R(8).1 and return
-	-	entry for FX18 subroutine
18	06	load VX to D
19	A8 D4	save in R(8).1 and return (see interrupt routine for FX15 and FX18 explanation)
-	-	the next 3 bytes are used by the FX33 subroutine
1B	64	100 (base 10)
1C	0A	10 (base 10)
1D	01	1 (base 10)
-	-	entry for FX1E subroutine
1E	E6	make R(6), VX pointer, the X register
1F	8A	load low order memory pointer address
20	F4 AA	add VX, restore R(A)
22	3B 28	to 28 if DF is zero, no overflow, exit
24	9A FC 01	else increment high order I address
27	BA D4	restore it and return
-	-	entry for FX29 subroutine, table of display patterns is on page with interrupt routine, pointer into table are at the beginning of the page
29	91 BA	load interrupt page address to R(A).1
2B	06	load VX to D
2C	FA 0F	and against 0F to get least significant digit
2E	AA 0A AA	get low order R(A) address from table of pointers
31	D4	return
32	00	unused
-	-	entry for FX33 subroutine (hex to decimal conversion)
33	E6	make R(6), VX pointer, the X register
34	06 BF	save VX in R(F).1
36	93 BE	point R(E) to 011B, first
38	F8 1B AE	entry of table
3B	2A	decrement memory pointer
3C	1A	increment memory pointer, later enter here
3D	F8 00 5A	write 00 to M(R(A))
40	0E	load table entry to D
41	F5	subtract VX
42	3B 4B	if overflow go to 4B
44	56	else write remainder to V6,
45	0A FC 01 5A	add 01 to M(R(A)),
49	30 40	and repeat
4B	4E	here if overflow – load advance table entry
4C	F6	shift right - if table entry is 01 DF is set
4D	3B 3C	back to do another digit unless DF is set
4F	9F 56	here if done - restore VX
51	2A 2A	restore memory pointer
53	D4	return to control section

54	00	unused
-	-	entry for FX55 subroutine transfer variables to memory
55	22	push down stack
56	86 52	load contents of R(6).0 to stack (one of F0-FF)
58	F8 F0 A7	point R(7) to V0
5B	07	load V0, on later entry V1, etc.
5C	5A	write to M(R(A))
5D	87 F3	load R(7).0 and x'or against stack byte - passed VX pointer - if result is 00 we're done
5F	17 1A	increment R(7) and memory pointer
61	3A 5B	go to 5B to transfer next VX unless done
63	12 D4	else restore stack pointer, return
-	-	entry for FX65 subroutine transfer memory to variables
65	22	push down stack
66	86 52	transfer contents of R(6).0 to stack, on of F0-FF
68	F8 F0 A7	point R(7) to V0
6B	0A	load M(R(A)) to D, enters here later
6C	57	write in V0, V1, V2, etc.
6D	87 F3	load R(7).0 and x'or against stack byte - if result is 00 we're done
6F	17 1A	increment R(7) and memory pointer
71	3A 6B	go to 5B to transfer next byte unless done
73	12 D4	else restore stack pointer, return
-	-	entry for FX75 subroutine transfer VX to hex display
75	E6	make VX pointer the X register
76	12 D4	output VX and return
-	-	entry for 2MMM subroutine, go to interpreter subroutine
78	15 85	store return interpreter code
7A	22 73	address on stack
7C	95 52	
7E	25	restore R(5) to point to 2nd half of instruction
-	-	entry for 1MMM subroutine rest of code through location 85 is shared
7F	45 A5	load MM to D and transfer to R(5).0
81	86 FA 0F	retrieve M (most significant part) from R(6).0
84	B5 D4	set R(5).1 and return
-	-	entry for 3XKK subroutine - skip if VX equals KK
86	45	load KK to D
87	E6 F3	make VX pointer X register, x'or VX against KK
89	3A 8D	return if D does not equal zero
8B	15 15	else skip
8D	D4	return to control section
-	-	entry for 4XKK subroutine
8E	45	load KK to D
8F	E6 F3	make VX pointer X register, x'or VX against KK
91	3A 8B	skip if D does not equal zero
93	D4	else return
-	-	entry for 9XY0 subroutine, skip if VX does not equal VY
94	45	set R(5) to next instruction
95	07	load VY to D
96	30 8F	transfer to 8F to complete instruction
-	-	entry for 5XY0 subroutine
98	45	set R(5) to next instruction
99	07	load VY to D
9A	30 87	transfer to 87 to complete instruction

-	-	entry for E subroutine EX9E - skip if VX equals keys (LSD), EXA1 - skip if VX does not equal keys (LSD), see Section 4 Hardware Differences. Designed to be as close as possible to original use in VIP
9C	22	push down stack
9D	6C	switch byte to stack, D
9E	06 F3	load VX, x'or against switch byte
A0	FA 0F	and off least significant digit of answer
A2	52	write result to stack
A3	45 F6	load advance - shift right 0 to DF for EX9E instruction, I to DF for EXA1 instruction
A5	42	load back stack byte, restore stack
A6	3B AD	to AD for EX9E instruction, carry on for EXA1 instruction
A8	3F 8B	skip if in not depressed
AA	3A 8B	skip if in depressed but wrong key
AC	D4	else return
AD	3F B1	skip if in not depressed
AF	32 8B	skip if in depressed but wrong key
B1	D4	else return
-	-	entry for BMMM instruction, go to 0MMM plus V0
B2	F8 F0 A7	point R(7) to V0
B5	E7	make R(7) the X register
B6	45	load MM
B7	F4	add V0 and D
B8	A5	save it in R(5).0
B9	86 FA 0F	load R(6).0 to retrieve most significant part of MMM, and off
BC	3B C0	to C0 if no overflow on addition, all done
BE	FC 01	else add 01 to D
C0	B5 D4	set R(5).1 and return
-	-	entry for 8XYN instructions, identical to those in demonstration interpreter
C2	45	load YN to D
C3	FA 0F	and off N to get 0N
C5	3A CA	go to CA unless N is zero
C7	07 56 D4	if N is 00 load VY, write to VX, return
-	-	here on other *XYN instructions, see demonstration interpreter for method used
CA	AF 22	save 0N in R(F),0, push down stack
CC	F8 D3 73	load D3, write to stack
CF	8F F9 F0	load 0N, or against F0
D2	52	write one of F1, F2, F3, F4, F5, F6, F7, or FE to stack
D3	E6	make VX pointer, X register
D4	07 D2	load VY and go to stack
D6	56	on return save result as VX
D7	F8 FF A6	point R(6) at VF
DA	F8 00	make D equal 00
DC	7E 56	shift DF into D and write to VF
DE	D4	return
-	-	entry for CXKK subroutine, random number generator
DF	19	increment R(9) - random byte - see interrupt routine
E0	89 AE 93 BE	pint R(E) to some byte on this page
E4	99	load R(9).1 - random byte from interrupt
E5	EE	make R(E) the X register
E6	F4 56	add the two random bytes, save in VX
E8	76	shift right with carry - scramble D
E9	E6	make VX pointer the X register
EA	F4 B9	add, use result to change R(9).1 as it isn't changed often in interrupt routine
EC	56	save result to VX
ED	45 F2	load KK and and against VX
EF	56 D4	save result as VX and return
-	-	entry for AMMM subroutine, set I pointer

F1	45 AA	load MM - transfer to R(A).0
F3	86 FA 0F	retrieve M from R(6),o (MSD)
F6	BA	complete memory pointer
F7	D4	end of interpreter subroutines
-	-	remaining 8 locations are used for interpretive code, starting address of interpretive code is 01 FC for 4k interpreter, 05FA for 1 1/4 interpreter
F8	00 00	unused, this is 4K version
FA	00 00	unused
FC	00 E0	erase display page
FE	00 49	turn on TV
02 00	-	start of interpreter code
-	-	for 1 1/4k version
05 F8	00 00	unused
FA	04 E0	erase display page
FC	04 49	turn on TV
FE	17 00	transfer to page 7 for interpreter code

Character Table and Interrupt Routine

Add.	Code	Notes
-	-	This code could go on any page, as written it is on page 0E for the 4k version and page 06 for the 1 1/4k version
-	-	first 16 bytes are pointers for the characters 0-F
0E 00	30 39 22 2A	pointers to 0, 1, 2, 3
04	3E 20 24 34	pointers to 4, 5, 6, 7
08	26 28 2E 18	pointers to 8, 9, A, B
0C	14 1C 10 12	pointers to C, D, E, F
-	-	next 51 bytes are the display symbols for the characters, 5 bytes/symbol
10	F0 80	start E display
12	F0 80	start F display
14	F0 80	start C display
16	80 80	
18	F0 50	start B display
1A	70 50	
1C	F0 50	start D display
1E	50 50	
20	F0 80	start 5 display
22	F0 10	start 2 display
24	F0 80	start 6 display
26	F0 90	start 8 display
28	F0 90	start 9 display
2A	F0 10	start 3 display
2C	F0 10	
2E	F0 90	start A display
30	F0 90	start 0 display
32	90 90	
34	F0 10	start 7 display
36	10 10	
38	10 60	start 1 display (starts at 39)
3A	20 20	
3C	20 70	
3E	A0 A0	start 4 display
40	F0 20	
42	20	end of display characters
-	-	begin interrupt routine, entry point is 0E 46 (06 46 for 1 1/4k Elf)
43	7A	Q (tone) off
44	42 70	restore D and return from interrupt
46	22	push stack down, entry to interrupt
47	78 22 52	save X, P; push, save D
4A	C4	no op, necessary 3 cycle instruction
4B	19	increment R(9), random number (see instruction CXKK)
4C	F8 00 A0	set low order address of DMA pointer
4F	9B B0	set high order address of DMA pointer
51	E2 E2	make up necessary 29 machine cycles
53	80 E2	load R(0).0 to D
-	-	DMA 1
55	E2 20 A0	restore DMA address
-	-	DMA 2
58	E2 20 A0	restore DMA address
-	-	DMA 3
5B	E2 20 A0	restore DMA address
-	-	DMA 4
5E	3C 53	continue till done
60	9B	R(8).1 is timer, load it (see FX07 and FX15 instructions)
61	32 67	if D is zero go to 67, timer is timed out, leave alone

63	AB 2B 8B B8	else subtract 01 from timer, method used does not disturb the DF flag. DF is not changed by the interrupt routine
67	88	load R(8).0 tone duration, see FX18 instruction
68	32 43	if tome duration is over go to 43
6A	7B	continue with or start tone
6B	28	decrement R(8).0, tone duration
6C	30 44	return, leaving tone on
-	-	end of interpreter

Extending the CHIP-8 Instruction Set

The CHIP-8 interpreter is well organized and constructed and as a result it is easy to modify and extend. If a specific task, for example the control of a robot, is to be programmed the interpretive language can be changed to suit the application. Let's look at how we might extend the current CHIP-8 instructions. There are two main types of instructions one might wish to add, those which involve pointers to two of the CHIP-8 variables, (e.g. like 8XYN) and those which require a ;pointer to a single CHIP-8 variable (e.g. 6XKK).

The first group of instructions might be created by expanding either the 5XY0 instruction or the 9XY0 instruction. Say we chose to expand the 5XY0 instruction. The entry point for the 5XY0 instruction would be changed to point to a third CHIP-8 page. The least significant hex digit of the instruction would be examined and if it was 00 the instruction would have its usual meaning. However if the last hex digit was 1, 2, etc., the new operations would be performed.

As an example let's expand the 5XY0 instruction to the following set:

5XY0	skip if VX=VY; the next interpreter instruction is skipped over if VX equals VY (original meaning)
5XY1	skip if VX>VY; the next interpreter instruction is skipped over if VX is greater than VY
5XY2	skip if VX<VY; the next interpreter instruction is skipped over if VX is less than VY
5XY3	skip if VX≠VY; the next interpreter instruction is skipped over if VX does not equal VY

We will place the new subroutines in the middle of page 0E between the interrupt routine and the bottom of the CHIP-8 stack. The entry point of the new interpreter subroutine will be 0E 70 (06 70 for the 1 1/4k Elf). CHIP-8 must be modified so that the 5 instructions transfer control to this address in the interpreter. Replace the 01 at location 00 55 with 0E (06 in the corresponding place for the 1 1/4k Elf) and replace the 98 at location 00 65 with 70.

Additional Skip Instructions
Expansion of the 5XY0 Instruction

Add.	Code	Notes
0E 70	93 BC	set R(C).1 to current page
72	45	load advance 2nd CHIP-8 byte, now VY
73	FA 03	and off 00, 01, 02, or 03 depending on instruction
75	FC 7D	add starting address of table of locations
77	AC	point R(C) to proper entry in table
78	0C AC	pick up table entry, point R(C) to proper subroutine address
7A	07 E6	load VY, make R(6) the X register
7C	DC	go to one of four subroutines
7D	81	address for 5XY0 instruction
7E	8B	address for 5XY1 instruction
7F	8F	address for 5XY2 instruction
80	87	address for 5XY3 instruction
-	-	entry for 5XY0
81	F3	x'or VX against VY
82	3A 86	return if D does not equal 00
84	15 15 D4	else skip and return
-	-	entry for 5XY3
87	F3	x'or VX against VY
88	3A 84	skip if D does not equal 00
8A	D4	else return
-	-	entry for 5XY1
8B	F7	subtract VX from VY
8C	3B 84	skip if DF equals zero
8E	D4	else return
-	-	entry for 5XY2
8F	F5	subtract VY from VX
90	3B 84	skip if DF equals zero

92	D4	else return, end of 5XYN subroutines

Among the instructions that the interpreter lacks are simple multiply and divide instructions to go along with its addition and subtraction instructions. Let's expand the 9XY0 instruction to add these instructions to CHIP-8. Multiply and divide instructions are necessarily 16 bit ones, the product of two 8 bit numbers may be up to 16 bit long and of course we need 16 bits to represent the quotient and remainder from the division of two 8 bit numbers. An additional variable will be required to hold the most significant byte from a multiplication and the remainder form a division. VF is already a special variable and will be used to hold the most significant [art of the product in a multiplication and the remainder in division. As well it would be nice to be able to represent the product of a multiplication as a decimal number and a 16 bit hex to decimal conversion routine will also be added.

The new "9" instructions will be located starting at the beginning of page 0D and we shall have to change the address of the "9" instructions in the interpreter. Memory location 00 59 should be changed from 01 to 0D and memory location 00 69 should be changed from 94 to 00.

The new instructions are:

9XY0	skip if VX≠VY; the next interpreter instruction is skipped over VX does not equal VY (unchanged)
9XY1	set VF, VX equal to VX times VY where VF is the most significant part of a 16 bit word
9XY2	set VX equal to VX divided by VY where VF is the remainder
9XY3	let VX, VY be treated as a 16 bit word with VX the most significant part and convert to decimal; 5 decimal digits are stored at M(I), M(I+1), M(I+2), M(I+3), and M(I+4), I does not change

Multiply, Divide and 16 Bit Display Instructions Expansion of 9XY0 Instruction

Add.	Code	Notes
0D 00	93 BC	set R(C).1 to current page
02	45	load 2nd CHIP-8 byte, YN
03	FA 03	and off 00, 01, 02, or 03
05	FC 18	add starting address of table of locations
07	AC	point R(C) to proper entry in table
08	0C AC	pick up table entry , point R(C) to proper subroutine address
-	-	before calling subroutine get ready for multiply and divide
0A	E7	R(7), VY pointer the X register
0B	96 BE	point R(E) to VF
0D	F8 FF AE	
10	F8 00 5E	set VF to 00
13	F6	clear DF flag
14	F8 09 AD	initialize counter for shifts to 09
-	-	now call subroutines
17	DC	go to one of 4 subroutines
18	80	address for 9XY0 instruction
19	1C	address for 9XY1 instruction, multiply
1A	2D	address for 9XY2 instruction, divide
1B	46	address for 9XY3 instruction, hex to decimal conversion
-	-	multiply routine entry, works by shift and add method like pencil and paper multiplication
1C	0E 76 5E	shift double length
1F	06 76 56	bit to the left
22	2D 8D	decrement and load counter
24	32 34	done when counted out
26	3B 1C	back if DF is 00, nothing to add
28	0E F4 5E	else add VY to VF,
2B	30 1C	before going back
-	-	end of multiply routine, begin divide routine - first check for division by zero
2D	07	load VY to D
2E	3A 35	if not equal to zero go on
30	F8 FF	else set quotient and remainder to FF and
32	56 5E D4	return
-	-	here if divisor greater than 0, division method similar to multiplication
35	0E F7	load VF, subtract VY
37	3B 3A	to 3A on overflow

39	5E	else save result in VF
3A	06 7E 56	shift one bit left
3D	2D 8D	decrement, load counter
3F	32 34	return when counted out
41	0E 7E 5E	shift one bit left
44	30 35	return to 35 for next subtraction
-	-	entry to 9XY3 subroutine, hex to decimal conversion (5 decimal digits) method is similar to that for FX33 instruction
46	06 BF	save VX
48	07 AF	save VY
4A	9C BE	point R(E) to 1 less than starting address
4C	F8 75 AE	of table of powers of 10
4F	2A	decrement memory pointer
50	1A 1E	increment memory pointer, table pointer
52	F8 00 5A	set memory pointer location to 00
55	E7	VY pointer (least significant byte) is the X register
56	4E F5	load table entry, subtract from VY
58	E6	VX pointer (most significant byte) is the X register
59	0E 75	load table entry, subtract with carry
5B	2E	decrement table pointer
5C	3B 69	to 69 if overflow done with this digit
5E	56	else update VX
5F	E7 0E F5 57	and update VY
63	0A FC 01 5A	increment memory pointer location
67	30 55	and go back till overflow
-	-	here on overflow
69	4E F6	load table entry, check for done
6B	3B 50	if not done to 50 for next digit
-	-	here when done
6D	9F 56	restore VX
6F	8F 57	restore VY
71	2A 2A 2A 2A	restore memory pointer
75	D4	return
-	-	table entries
76	10 27	10000 (base 10) 2710 (base 16)
78	E8 03	1000 (base 10) 03E8 (base 16)
7A	64 00	100 (base 10) 0064 (base 16)
7C	0A 00	10 (base 10) 000A (base 16)
7E	01 00	1 (base 10) 0001 (base 16)
-	-	entry for (XY0 subroutine (original instructions)
80	07	load VY
81	E6	make VX pointer the X register
82	F3	x;or VY against VX
83	3A 86	if D not equal to zero, skip
85	D4	else return
86	15 15 D4	skip and return

If one has an ASCII device connected to an ELF, perhaps a keyboard, it would be convenient to have a CHIP-8 instruction which would create symbols for the characters in ASCII code. Such an instruction is presented last, the FX94 instruction. This instruction uses the space left unused in the interpreter by the expansion of the "5" and "9" instructions and creates symbols for the 64 characters in 6 bit ASCII. In operation it works exactly like the FX29 instruction except that the memory pointer is set to the address of one of the 64 ASCII symbols corresponding to VX instead of to the address of one of the 16 symbols 0-F. If the "5" and "9" instructions have not been expanded this instruction can, as well, replace the FX29 instruction and ways to implement either alternative will be given.

The instruction fits on a single page; each of the 64 ASCII symbols are coded by 3 bytes which requires 192 memory locations and the remainder of the subroutine fits in the 64 locations remaining. The construction of this instruction is quite simple. The first 16 locations on the page are patterns which are available to construct the symbols. Each ASCII symbol is designated by 5 hex digits which correspond to the patterns needed to construct the symbol. The sixth hex digit in the three words used to code each symbol serves as an indicator of the length of the symbol. When an FX94 (FX29) instruction is carried out this value is transferred to V0 where it can be used to get a pleasing spacing of the symbols.

The symbols are relatively crude, both because of the poor resolution of the ELF graphics and also because they consist of combinations of only 16 patterns. However they are easily recognized and make the presentation of ASCII data relatively with the aid of a very simple interpreter program.

The method used to transfer control from the interpreter to the new subroutine is to change the program counter from R(3) to R(C). This change has to be done in the interpreter and the address of the new subroutine must first be loaded to R(C). If the ASCII subroutine is located on page 0C the proper entry point is 0C D0. To make an FX94 instruction add the following code to the interpreter on page 01 (4k version):

Add.	Code	Notes
01 94	F8 D0 AC	point R(C).0 to D0
97	F8 0C BC	point R(C).1 to page 0C
9A	DC	make R(C) the program counter

This code overwrites the locations which were used for the "5" and "9" instructions. The same code, but located starting at address 01 29, would change the FX29 instruction to the ASCII instruction.

Six-Bit ASCII Symbols Subroutine

Add.	Code	Notes
-	-	subroutine can reside on any page, here it is on page 0C
-	-	the first 16 locations are the patterns available to make up the symbols
0C 00	00	(blank)
01	10	*
02	20	*
03	88	* *
04	A8	* * *
05	50	* *
06	F8	*****
07	70	***
08	80	*
09	90	* *
0A	A0	* *
0B	B0	* **
0C	C0	**
0D	D0	** *
0E	E0	***
0F	F0	****
-	-	locations 10 through CF are codings for the 64 ASCII symbols, 3 bytes to a symbol

-	-	A diagram giving the order in which the patterns are assembled from the bytes is:
		XX XX XX
		45 23 61
		where the 6th hex digit contains the width of the character, at most 5 bits. The first ASCII character (hex 00) is @, its coding is 46, 3E, 56 which gives:
		`pattern 6 - *****`
		`pattern 3 - *   *`
		`pattern E - ***`
		`pattern 4 - * * *`
		`pattern 6 - *****`
		The character is 5 bits long

10	46 3E 56	00 - @
13	99 9F 4F	01 - A
16	5F 57 4F	02 - B
19	8F 88 4F	03 - C
1C	5F 55 4F	04 - D
1F	8F 8F 4F	05 - E
22	88 8F 4F	06 - F
25	9F 8B 4F	07 - G
28	99 9F 49	08 - H
2B	27 22 47	09 - I
2E	AE 22 47	0A - J
31	A9 AC 49	0B - K
34	8F 88 48	0C - L
37	43 64 53	0D - M
3A	99 DB 49	0E - N
3D	9F 99 4F	0F - O
40	88 9F 4F	10 - P
43	9F 9B 4F	11 - Q
46	A9 9F 4F	12 - R
49	1F 8F 4F	13 - S
4C	22 22 56	14 - T
4F	9F 99 49	15 - U
52	22 55 53	16 - V
55	55 44 54	17 - W
58	53 52 53	18 - X
5B	22 52 53	19 - Y
5E	CF 12 4F	1A - Z
61	8C 88 3C	1B - [
64	10 C2 40	1C - \
67	2E 22 3E	1D -]
6A	30 25 50	1E - ^
6D	06 00 50	1F - _
70	00 00 40	20 - space
73	0C CC 2C	21 - !
76	00 50 45	22 - "
79	65 65 55	23 - #
7C	46 46 56	24 - $

7F	DF BF 4F	25 - %
82	5F AF 4E	26 - &
85	00 80 18	27 - '
88	21 22 41	28 - (
8B	12 11 42	29 -)
8E	53 56 53	2A - *
91	22 26 52	2B - +
94	2E 00 30	2C - ,
97	00 06 50	2D - -
9A	CC 00 20	2E - .
9D	C0 12 40	2F - /
A0	9F 99 4F	30 - 0
A3	22 22 32	31 - 1
A6	8F 1F 4F	32 - 2
A9	1F 1F 4F	33 - 3
AC	22 AF 4A	34 - 4
AF	1F 8F 4F	35 - 5
B2	9F 8F 4F	36 - 6
B5	11 11 4F	37 - 7
B8	9F 9F 4F	38 - 8
BB	1F 9F 4F	39 - 9
BE	80 80 10	3A - :
C1	2E 20 30	3B - ;
C4	21 2C 41	3C - <
C7	E0 E0 30	3D - =
CA	2C 21 4C	3E - >
CD	88 1F 4F	3F - ?
-	-	end of character table, entry point for ASCII display subroutine
-	-	first point R(a), memory pointer to a scratch place in random access memory - here at bottom of stack
D0	F8 0E BA	point R(A).1 to page 0E
D3	F8 9F AA	point R(A).0 to 9F, just below stack, R(A).0 points to 9B when returning from subroutine
D6	9C	load page number to D
D7	B3 BD	point R(3).1 and R(D).1 to this page
D9	F9 F0 A7	point R(7) to V0
DC	Ea	make R(A), memory pointer, the X register
DD	06 FA 3F	load VX, and off 6 bits
E0	5A F4 F4	write to M(R(X)), add twice to get number times 3
E3	FC 10	add starting address of character table
E5	AD	R(D) now points to correct location in large table
-	-	entry point for successive table bytes
E6	0D FA 0F	load table entry, and off least significant digit
E9	A3	point R(3) to correct entry in table of patterns (small table)
EA	03 73	pick up pattern, write to random access memory, decrement I
EC	4D	pick up byte again, this time advance R(D)
ED	F6 F6 F6 F6	shift right to get most significant digit
F1	A3	point R(3) to correct entry
F2	8A	load R(A).0
F3	FB 9A	check, have we done 5 patterns?
F5	32 FB	if D is 00 we're done, go to set V0 and return
F7	03 73	else pick up pattern, write to random access memory
F9	30 E6	and return for next table entry
-	-	here on return
FB	83	retrieve length of symbol from R(3).0
FC	57	write to V0
FD	1A D4	fix up R(A) and return

The reader would probably like to see what these characters look like when displayed. Here is an interpretive program which can be used to display all of the ASCII symbols. The program waits for a switch byte (0-F) and when it is entered displays the corresponding ASCII symbol in the upper left of the screen followed by as many ASCII symbols as the screen has room for. If the byte in the interpreter (4K) at location 01 11 is changed from 0F to FF complete switch bytes (00-FF) can be entered.

Program to Display ASCII Characters

Add.	Code	Notes
0200	F50A	V5 equals keys - waits for in button
02	6600	V6 = 00
04	6700	V7 = 00, display pointers
06	6B3F	VB = 3F, line length
08	F594	(F529?) set I to V5 ASCII symbol, V0 = symbol length
0A	7501	V5 = V5 + 01

0C	D675	display the symbol at V6, V7
0E	8604	V6 = V6 + V0
10	7601	V6 = V6 + 01, space between symbols
12	8D60	VD = V6
14	F594	(F529?) set I, V0 for next symbol
16	8DD4	VD = VD + V0, add length of next symbol to VD
18	8DB5	VD = VD - VB, check will it extend past line end?
1A	3F01	skip if VF is 01, over the end of line
1C	1208	O.K. go back and display
1E	6600	reset to new line
20	7706	V7 = V7 + 06, set line down
22	471E	skip unless V7 is 1E, we're off bottom
24	1224	stop - screen is full
26	1208	return to do another line

It is hoped that these examples demonstrate the ease with which the CHIP-8 interpreter can be extended and modified. One of the limitations of CHIP-8, the fact that only memory locations 0000 through 0FFF are available to it, can be overcome by redesigning the interpreter to address memory in 4k fields. A field designation instruction is used to change from one 4k field to another. A relocatable 1k interpreter which includes all of the material presented in this booklet, as well as a field instruction, is listed in the Appendix. The field instruction is a four byte one which has the form, FFFF, MMMM. M is the new field and MMM is the address of the first instruction to be obeyed in the new field. For example to transfer to a new field:

Add.	Code	Notes
0FD0	6300	set V3 to 0D
D2	6400	set V4 to 00
D4	650a	set V5 to 0A
D6	FFFF	field instruction go to
D8	1004	field 1, 004
-	-	
10 04	F529	point to symbol for A
06	D345	display A
-	-	etc.

More ambitious programs can be written with the 4K memory restraint removed. The field designation is stored in R(B).0 and is set on entry to the interpreter, if less than 4k of memory is available it can be ignored.

Appendix

The interpreter listed below is relocatable and can be placed on any four contiguous pages (e.g. 0A00 - 0DFF for 4k Elf). It *must* be entered with R(3) as the program counter. Enter at location 0000 for default values for the first interpreter instruction (01FE), the display page (0F), and the page for variables and constants (0E). To change the default values set R(5) to the address of the first interpreter instruction, set R(B).1 to the display page, set R(6).1 to the page for variables and constants, and enter the interpreter at location 000C. The default value for the location of the first interpreter instruction (01FE) allows space for an erase display instruction (00E0) before a program which starts at location 0200. The FX29 instruction in this interpreter does not alter the value of V0.

```
0000   F8 01 B5 F8    FE A5 F8 0F
0008   BB F8 0E B6    95 FA F0 AB
0010   96 B2 F8 CF    A2 E3 70 23
0018   93 B4 FC 02    B1 F8 D3 A1
0020   F8 25 A4 69    D4 96 B7 45
0028   AF F6 F6 F6    F6 32 4D FC
0030   69 AC 8F F9    F0 A6 05 F6
0038   F6 F6 F6 F9    F0 A7 94 BC
0040   EC F4 B3 8C    FC 0F AC 0C
0048   A3 E2 D3 30    25 8F 32 54
0050   B3 45 30 48    94 FC 02 B3
0058   05 FB EE 32    66 FB 0E 32
0060   64 8F 30 50    FC 05 FC 07
0068   30 48 01 01    02 02 02 02
0070   01 01 02 01    01 01 00 01
0078   01 7F 78 1B    1F 27 23 00
0080   C4 4F F3 AD    E1 88 96 05
0088   06 BE FA 3F    F6 F6 F6 22
0090   52 07 FE FE    FE F1 AC 9B
0098   BC 45 FA 0F    AD A7 F8 D0
00A0   A6 F8 00 AF    87 32 F7 27
00A8   4A BD 9E FA    07 AE 8E 32
00B0   BA 9D F6 BD    8F 76 AF 2E
00B8   30 AE 9D 56    16 8F 56 16
00C0   30 A1 00 EC    F8 D0 A6 F8
00C8   00 A7 8D 32    F0 06 F2 2D
00D0   32 D5 F8 01    A7 46 F3 5C
00D8   02 FB 07 32    E9 1C 06 F2
00E0   32 E5 F8 01    A7 06 F3 5C
00E8   2C 16 8C FC    08 AC 3B CA
00F0   F8 FF A6 87    56 12 D4 8D
00F8   A7 87 32 C2    2A 27 30 F9
0100   45 E6 F4 56    D4 45 A3 98
0108   56 D4 3F 0A    37 0C 22 6C
0110   FA 0F 12 56    D4 06 B8 D4
0118   06 A8 D4 64    0A 01 E6 8A
0120   F4 AA 3B 28    9A FC 01 BA
0128   D4 F8 B0 30    8E 00 00 00
0130   15 15 D4 E6    06 BF 93 BE
0138   F8 1B AE 2A    1A F8 00 5A
0140   0E F5 3B 4B    56 0A FC 01
0148   5A 30 40 4E    F6 3B 3C 9F
0150   56 2A 2A D4    00 22 86 52
0158   F8 F0 A7 07    5A 87 F3 17
0160   1A 3A 5B 12    D4 22 86 52
0168   F8 F0 A7 0A    57 87 F3 17
0170   1A 3A 6B 12    D4 E6 64 D4
0178   15 95 22 73    85 52 25 45
0180   A5 86 FA 0F    22 52 8B F1
0188   B5 12 D4 00    F8 C0 AC 93
0190   FC 02 BC DC    30 BC 22 6C
0198   06 F3 FA 0F    52 45 F6 42
01A0   3B A7 3F 30    3A 30 D4 3F
01A8   AB 32 30 D4    00 F8 F0 A7
01B0   E7 45 F4 A5    86 FA 0F 3B
01B8   BB FC 01 E2    22 52 8B F1
01C0   B5 12 D4 00    45 FA 0F 3A
01C8   CC 07 56 D4    AF 22 F8 D3
01D0   73 8F F9 F0    52 E6 07 D2
01D8   56 F8 FF A6    F8 00 7E 56
01E0   D4 19 89 AE    93 BE 99 EE
01E8   F4 56 76 E6    F4 B9 56 45
01F0   F2 56 D4 45    AA 86 FA 0F
01F8   22 52 8B F1    BA 12 D4 45
```

```
0200   22 73 FA F0   AB 05 52 42
0208   A5 42 B5 D4   15 9B BF F8
0210   FF AF F8 00   5F 8F 32 0B
0218   2F 30 12 45   E6 30 38 45
0220   E6 30 3E 45   56 D4 00 93
0228   BC 45 FA 03   FC 34 AC 0C
0230   AC 07 E6 DC   38 42 46 3E
0238   F3 3A 3D 15   15 D4 F3 3A
0240   3B D4 F7 3B   3B D4 F5 3B
0248   3B D4 07 E6   30 3E 00 93
0250   BC 45 FA 03   32 4A FC 68
0258   AC 0C AC E7   96 BE F8 FF
0260   AE F8 00 5E   F6 F8 09 AD
0268   DC 6C 7D 96   0E 76 5E 06
0270   76 56 2D 8D   32 84 3B 6C
0278   0E F4 5E 30   6C 07 3A 85
0280   F8 FF 56 5E   D4 0E F7 3B
0288   8A 5E 06 7E   56 2D 8D 32
0290   84 0E 7E 5E   30 85 06 BF
0298   07 AF 9C BE   F8 C5 AE 2A
02A0   1A 1E F8 00   5A E7 4E F5
02A8   E6 0E 75 2E   3B B9 56 E7
02B0   0E F5 57 0A   FC 01 5A 30
02B8   A5 4E F6 3B   A0 9F 56 8F
02C0   57 2A 2A 2A   2A D4 10 27
02C8   E8 03 64 00   0A 00 01 00
02D0   7A 42 70 22   78 22 52 C4
02D8   19 F8 00 A0   9B B0 E2 E2
02E0   80 E2 E2 20   A0 E2 20 A0
02E8   E2 20 A0 3C   E0 22 76 52
02F0   98 32 F6 FF   01 B8 42 7E
02F8   88 32 D0 7B   28 30 D1 00
0300   00 10 20 88   A8 50 F8 70
0308   80 90 A0 B0   C0 D0 E0 F0
0310   46 3E 96 F9   F9 5F 57 FF
0318   88 F8 5F 55   FF F8 F8 88
0320   8F FF B9 F8   99 9F 79 22
0328   72 AE 22 97   CA 9A 8F 88
0330   38 44 36 99   DB F9 99 F9
0338   88 9F FF B9   F9 A9 9F FF
0340   F1 F8 22 22   F6 99 99 22
0348   55 53 45 44   53 52 23 22
0350   35 CF 12 CF   88 C8 10 C2
0358   E0 22 E2 30   25 60 00 00
0360   00 00 C0 C0   CC 00 50 55
0368   56 56 46 46   F6 FD FB 5F
0370   AF 0E 00 88   21 22 21 11
0378   21 53 56 23   62 22 2E 00
0380   00 6D 00 CC   00 00 2C 01
0388   9F 99 2F 22   22 8F 1F FF
0390   F1 F1 22 AF   FA F1 F8 9F
0398   8F 1F 11 F1   9F 9F FF F1
03A0   F9 80 80 E0   02 02 21 2C
03A8   01 0E 0E 2C   21 8C F8 F1
03B0   06 AF FA 0F   F9 30 56 FD
03B8   39 33 C2 FD   40 56 30 C2
03C0   06 AF 96 BA   F8 9F AA 9C
03C8   B3 BD EA 06   FA 3F 5A F4
03D0   F4 F4 F4 76   3B DB FC 10
03D8   AD 30 E9 FC   10 AD 0D FA
03E0   0F A3 8A FB   9A 32 F8 03
03E8   73 4D F6 F6   F6 F6 A3 8A
03F0   FB 9A 32 F8   03 73 30 DE
03F8   8F 56 1A D4   00 00 00 00
```

Notes

The FX00 and FX75 instructions cause failures when X is F because R(6) "turns" a page; R(6) should be decremented after the use of an output (64) instruction.

When using the relocatable interpreter place all the machine code subroutines in field 0 (0000 to 0FFF); they are accessible to calls from any of the 16 fields.

Notes

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