Laurence Scotford
A miscellany of stuff that interests me

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Chip-8 on the COSMAC VIP: Drawing Sprites

Posted on August 24, 2013 by laurence

This is part of a series of posts analysing the Chip-8 interpreter on the RCA COSMAC VIP computer. These posts may be useful if you are building a Chip-8 interpreter on another platform or if you have an interest in the operation of the COSMAC VIP. For other posts in the series refer to the index or instruction index.

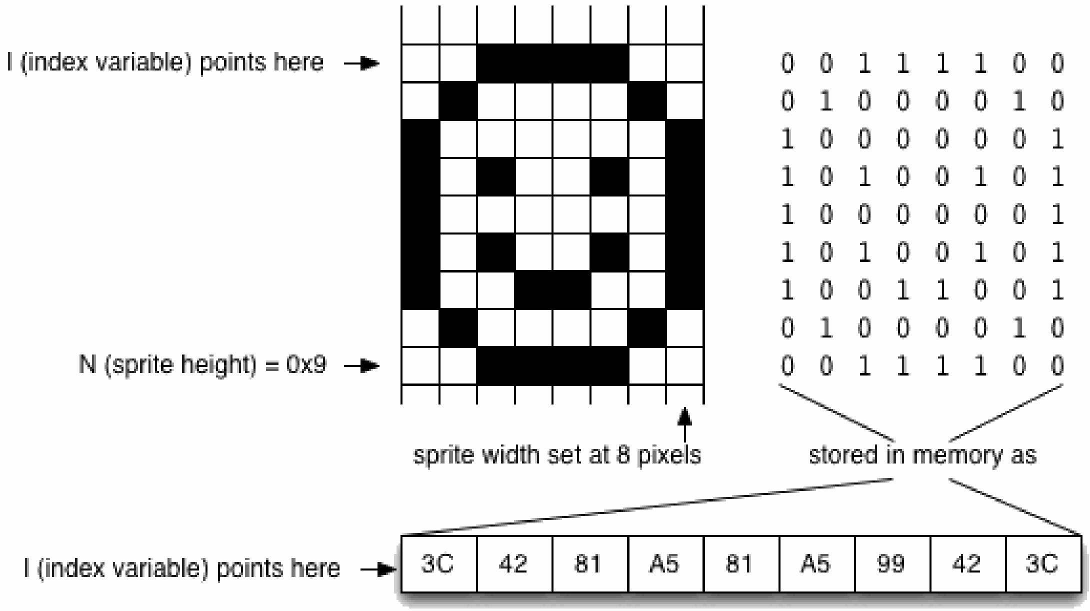
INSTRUCTION GROUP: DXYN
Draw the N byte sprite stored at the address pointed to by I on the display at location X and Y. Set VF to 0x01 if any set pixel in the sprite overwrites an existing set pixel on the display, otherwise set VF to 0x00

Chip-8 has only one instruction for getting data onto the display. Fundamentally it works by reading sprite data stored in memory and writing it to the display memory (It's actually a little more complicated than that, but we'll get onto that in a moment). Then, when the next interrupt occurs, the display control will read this memory and draw it to the display as a series of pixels. I analysed the interrupt and screen refresh mechanism in an earlier post.

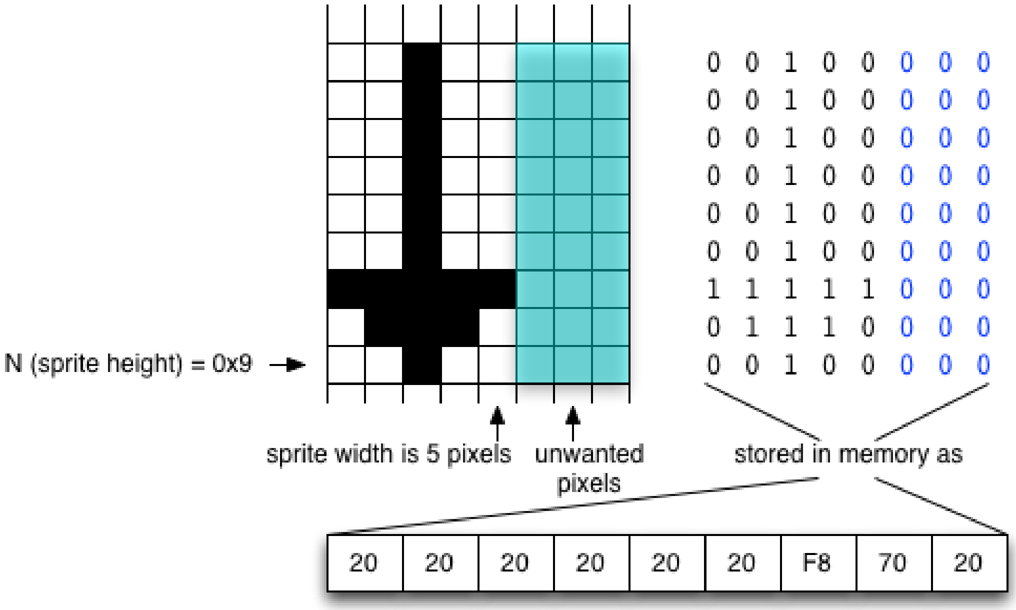
The draw instruction expects the index register, I to be pointing to the memory location of the first row of pixels in the sprite. You can set I with either the AMMM instruction, which simply sets I to the address 0x0MMM, or with the FX29 instruction, which I will analyse in a later post.

Each bit in the sprite represents a single pixel. As Chip-8 uses a black and white display, pixels can either be on (1) or off (0). Each row of pixels is stored sequentially.

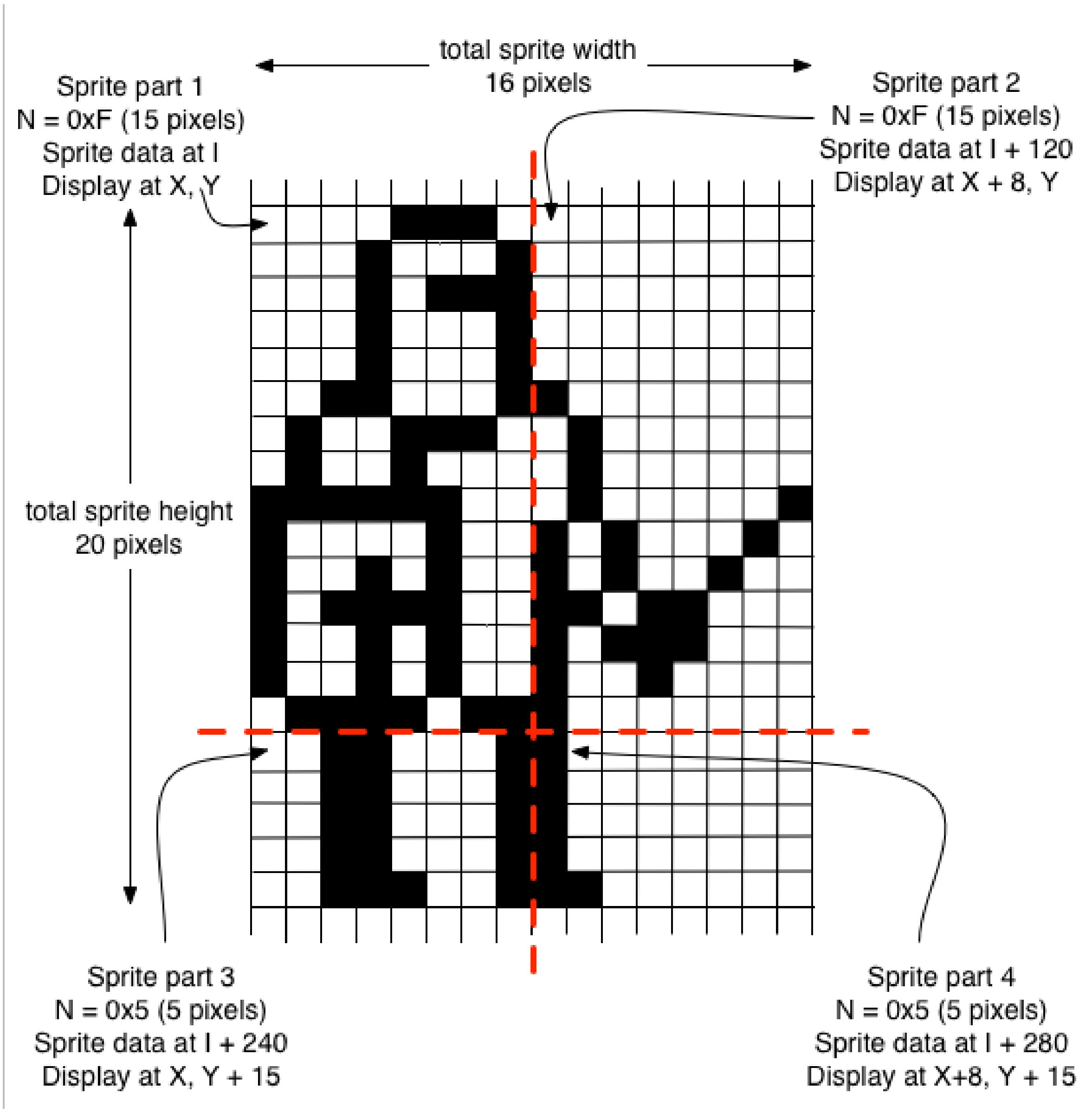
Chip-8 allows you to set the height of the sprite in the final hex digit of the instruction, so sprites can be between one and 15 pixels high. The width of the sprite is fixed at eight pixels (one byte).



This is not really as restrictive as it sounds. If you want a sprite that is narrower than eight pixels, simply set the unwanted pixels to the right of the image to 0, as shown below:

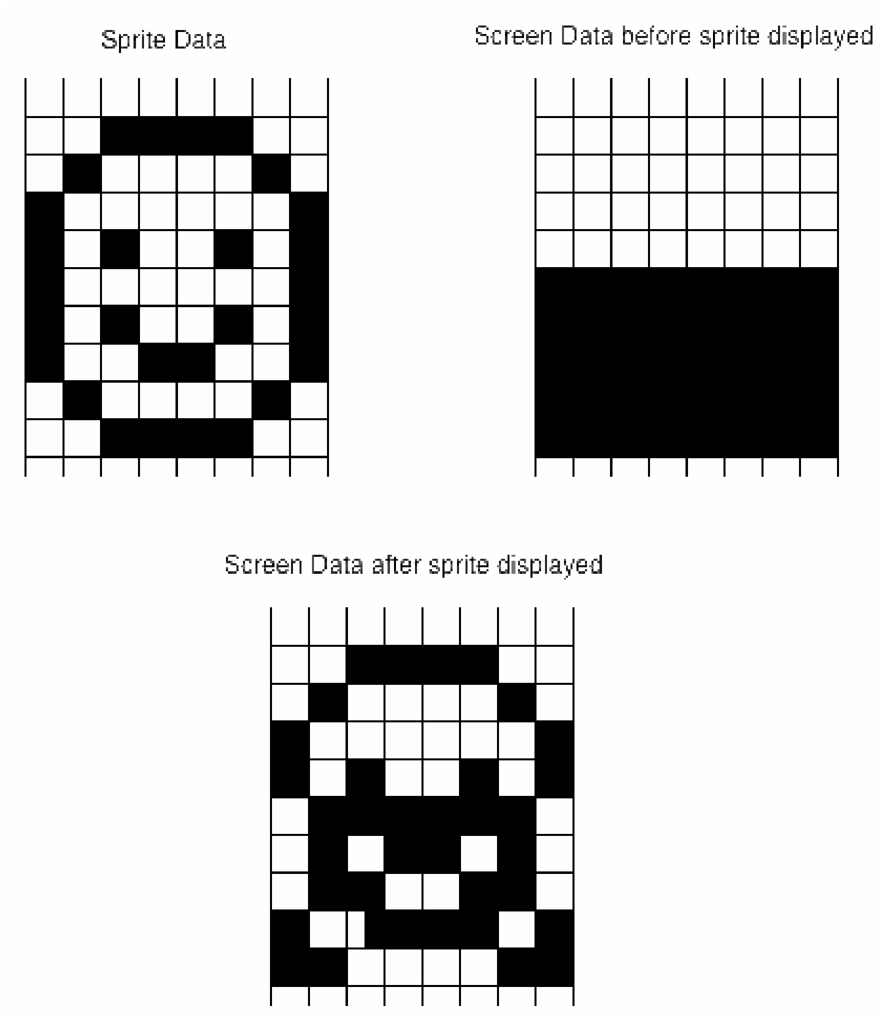


Because of the way Chip-8 sprites are drawn, the unset pixels will have no effect on the display memory. If you want a sprite that is wider than eight pixels and/or higher than 15 pixels, then you should break it into smaller sprites and then draw each part individually, resetting the position appropriately each time.



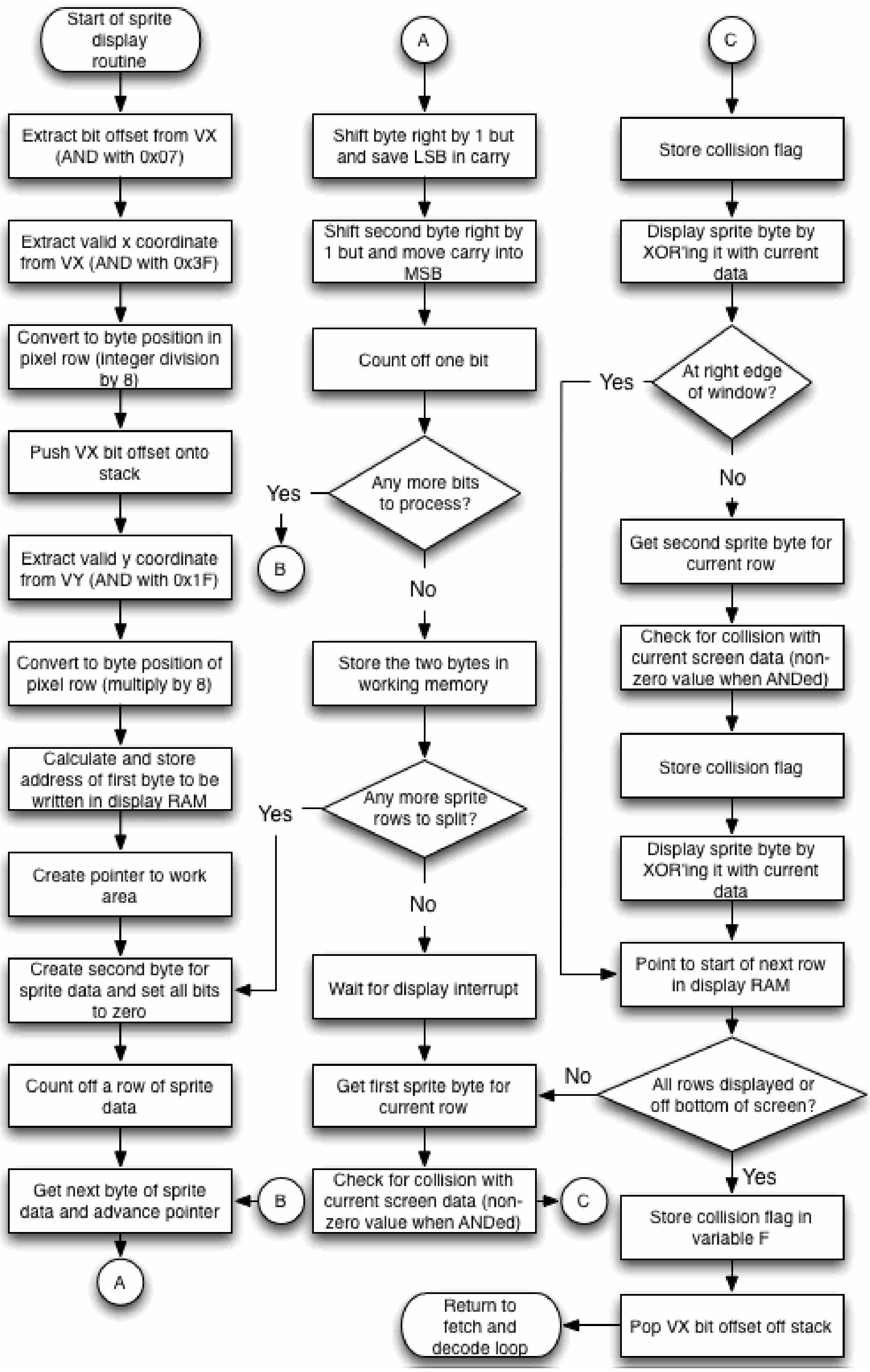
One thing you have to remember if you use this technique is to check for collision after you have drawn each part of the sprite, as the collision flag will only be valid for the part that has just been drawn.

The reason you can have a narrower sprite simply by leaving some columns of pixels blank is because Chip-8 sprites are XOR'd with the current data on screen. So an unset pixel in a sprite will have no effect on the data currently on screen. A set pixel in a sprite will cause the pixel on screen to be set if it is currently unset, or unset if it is currently set. In the latter case, a collision flag will also be set to show the sprite data overlapped with existing data on screen.



Using this technique, it is possible to erase a sprite simply by re-drawing the same sprite at the same coordinates because drawing the sprite for the second time will unset the pixels that were set by the first drawing and vice versa. Of course in that situation you'd want to ignore the collision flag as the sprite would record a collision with itself.

Here's the flowchart for the routine that draws sprites:



Here's the code for the sprite drawing routine:

Address (hex)	Code (hex)	Labels	Assembly	Comments
0070	06	DRAW_ SPRITE:	LDN 6	Get VX(stored at address in R6)
0071	FA 07		ANI 0x07	Mask with 0x07 to save only least significant three bits. These indicate the bit offset of the first bit of sprite data
0073	BE		PHI E	Save these in RE.1
0074	06		LDN 6	Get VX

0075	FA 3F		ANI 0x03F	Mask with 0x3F to save the six least significant bits (max value of X position is 63, which requires only six bits)
0077	F6		SHR	The next three instructions perform an integer division of VX by eight, which gives the position in the pixel row of the first byte that will contain sprite data
0078	F6		SHR	
0079	F6		SHR	
007A	22		DEC 2	Decrement the stack pointer (R2) ready for a push
007B	52		STR 2	Push accumulator (containing most significant three bits of VX) onto the stack
007C	07		LDN 7	Get VY (stored at address in R7)
007D	FA 1F		ANI 0x1F	Mask with 0x1F to save the five least significant bits (max value of Y position is 31, which requires only five bits)
007F	FE		SHL	The next three instructions perform a multiplication of VY by eight, which gives the position in display memory of the first row that will contain sprite data
0080	FE		SHL	
0081	FE		SHL	
0082	F1		OR	OR the result with the top of the stack. This gives the position in display memory of the first byte that will contain pixel data from the sprite
0083	AC		PLO C	Put the result in RC0
0084	9B		GHI B	Get high order byte of address of display memory
0085	BC		PHI C	Put this in RC1. RC now holds the address of the first byte that will have sprite data written to it
0086	45		LDA 5	Get the second byte of the Chip-8 instruction and advance the Chip-8 programme counter
0087	FA 0F		ANI 0x0F	Mask off the least significant hex digit. This contains the number of bytes (rows) in the sprite pattern
0089	AD		PLO D	Save it in RD – this will be used as a display row counter
008A	A7		PLO 7	Save it in R7 – this will be used as a sprite row counter
008B	F8 D0		LDI 0xD0	0xD0 is the low order byte of the address of the area of RAM set aside as a Chip-8 work area. This will be used to assemble a two-byte wide copy of the sprite with the sprite data shifted to the correct offset for the position at which the sprite will be displayed
008D	A6		PLO 6	Put this into R6.0 As R6 is normally used as the VX pointer and the variables are stored in the same page, R6.1 will already be set correctly
008E	93	NEXT_ SPRITE_ ROW:	GHI 3	R3.1 is used as a convenient source of the constant 0x0
008F	AF		PLO F	Set RF.0 to 0x0. The right-hand (2nd) byte of the reconstructed sprite will be initially assembled here
0090	87		GLO 7	Get the number of rows left to assemble
0091	32 F3		BZ RESET_ I_ PTR	Branch to the next stage if they are all done
0093	27		DEC 7	Count off one row of sprite data
0094	4A		LDA A	Get one byte of sprite data from the address pointed at by I (RA) and advance I to next byte
0095	BD		PHI D	Save this in RD.1
0096	9E		GHI E	Get the bit offset for the first bit of sprite data (this was saved in RE.1 earlier)

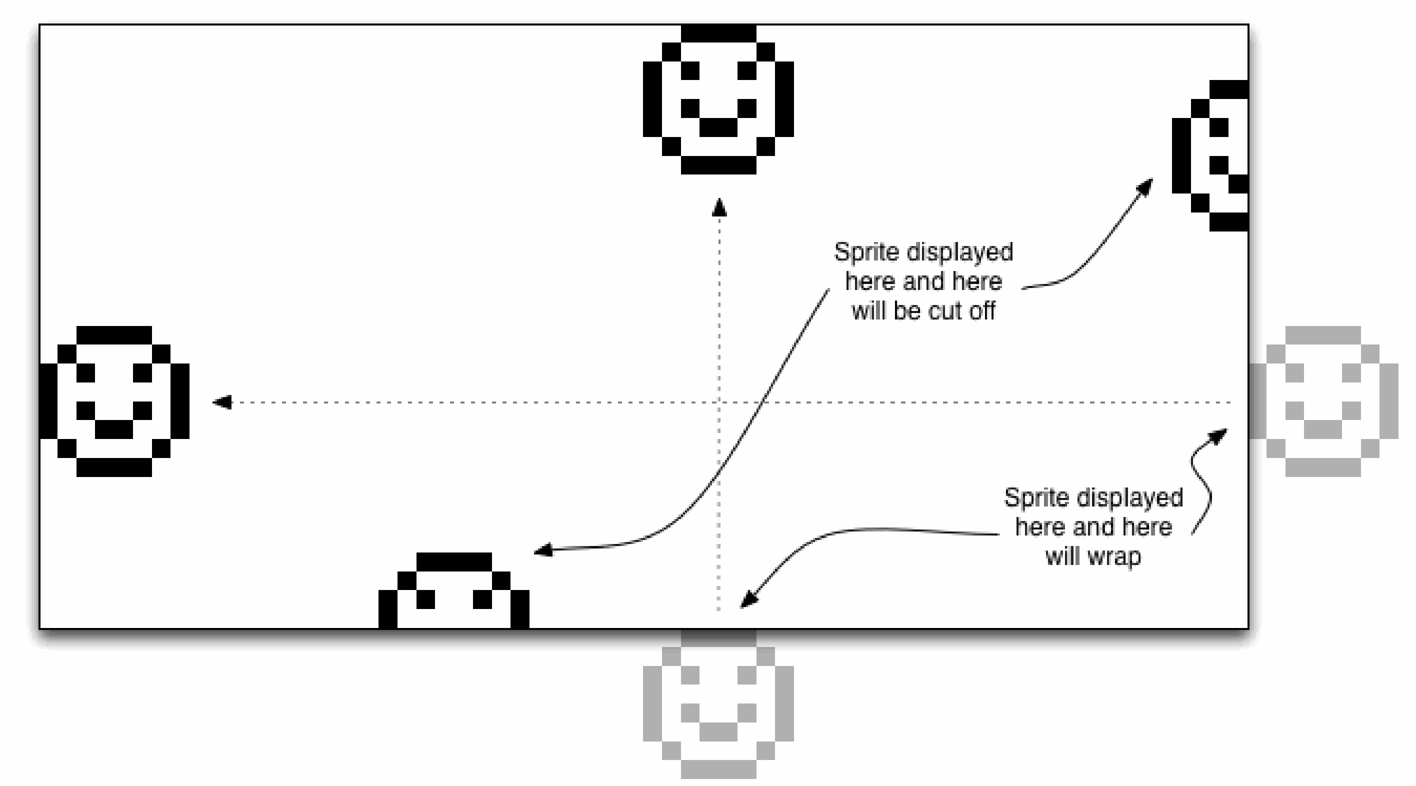
0097	AE		PLO E	Put these in RE.0. This will be used as a bit counter
0098	8E	SPLIT_ SPRITE_ ROW:	GLO E	Get the current bit count
0099	32 A4		BZ STORE_ SPRITE_ ROW	Branch when the bit count is zero, indicating that the sprite data for that row is now correctly split across two bytes (note that this could be immediately if the sprite is positioned at the start of a byte)
009B	9D		GHI D	Get byte to be displayed
009C	F6		SHR	Shift right by 1 bit. This will move a zero into the most significant bit, shift everything else along and move the least significant bit into the carry flag
009D	BD		PHI D	Store shifted byte back in RD.1
009E	8F		GLO F	Get current pattern in second byte
009F	76		SHRC	Shift with carry to the right by one bit. This will move the discarded bit from the first byte into the most significant bit position and shift everything else along
00A0	AF		PLO F	Store the result back in RF.0
00A1	2E		DEC E	Count off another bit
00A2	30 98		BR SPLIT_ SPRITE_ ROW	Branch back to top of loop
00A4	9D	STORE_ SPRITE_ ROW:	GHI D	Get lefthand byte of sprite row to be displayed
00A5	56		STR 6	Store it in the working area in memory
00A6	16		INC 6	Point to the next byte in the working area
00A7	8F		GLO F	Get the righthand byte of the sprite row to be displayed
00A8	56		STR 6	Store it in the working area in memory
00A9	16		INC 6	Point to the next byte in the working area
00AA	30 8E		BR NEXT_ SPRITE_ ROW	Loop back and do the next row
00AC	00	DISPLAY_ SPRITE:	IDL	Wait until the next display interrupt has completed (This is a precaution to prevent sprite tearing)
00AD	EC		SEX C	Set the pointer to display memory (RC) to be used for register indirect addressing memory operations
00AE	F8 D0		LDI 0xD0	0xD0 is the low order byte of the address of the area of RAM set aside as a Chip-8 work area. This is where the offset sprite has been assembled
00B0	A6		PLO 6	R6 now points to assembled offset sprite
00B1	93		GHI 3	R3.1 (high-order byte of interpreter programme counter) is a convenient source of the constant 0x0
00B2	A7		PLO 7	Set R7.0 to zero. This will be used to temporarily store the collision status
00B3	8D	SPRITE_ DISPLAY_ LOOP:	GLO D	Get the number of rows left to display
00B4	32 D9		BZ SAVE_ COLLISION_ FLAG	Branch to next stage if all rows done
00B6	06		LDN 6	Get the lefthand byte of sprite data
00B7	F2		AND	AND it with the current byte in display memory at the target position. This will put a 1 in any bit where a set bit overlaps in both the display memory and the sprite data. So any non-zero

				result indicates that a collision has occurred
00B8	2D		DEC D	Count off one row
00B9	32 BE		BZ DISPLAY_ LEFT_ BYTE:	Branch forward if no collision occurred
00BB	F8 01		LDI 0x01	Construct a collision flag
00BD	A7		PLO 7	Store this in R7.0
00BE	46		LDA 6	Get the lefthand byte of sprite data and advance the pointer
00BF	F3		XOR	XOR it with the current byte in display RAM
00C0	5C		STR C	Now write it to the display by storing the modified byte back in the display RAM
00C1	02		LDN 2	Get the x position of the sprite (in bytes) from the stack
00C2	FB 07		XRI 0x07	XOR it with 0x07 to see if it is at position 7 (i.e. the last byte in the row)
00C4	32 D2		BZ DISPLAY_ NEXT_ ROW	If it is at the right edge of the window, then the second byte would be off screen and there is no point in trying to display it, so skip to the next row
00C6	1C		INC C	Point to the next byte in the display memory
00C7	06		LDN 6	Get the righthand byte of sprite data
00C8	F2		AND	AND it with the current byte in display memory at the target position. This will put a 1 in any bit where a set bit overlaps in both the display memory and the sprite data. So any non-zero result indicates that a collision has occurred
00C9	32 CE		BZ DISPLAY_ RIGHT_ BYTE:	Branch forward if no collision occurred
00CB	F8 01		LDI 0x01	Construct a collision flag
00CD	A7		PLO 7	Store this in R7.0
00CE	06		LDN 6	Get the righthand byte of sprite data
00CF	F3		XOR	XOR it with the current byte in display RAM
00D0	5C		STR C	Now write it to the display by storing the modified byte back in the display RAM
00D1	2C		DEC C	Reset RC so it points to the first byte in the row with sprite data
00D2	16	DISPLAY_ NEXT_ ROW:	INC 6	Point R6 the next byte of sprite data
00D3	8C		GLO C	Get the low-order byte of the current position in display RAM
00D4	FC 08		LDI 0x08	Add 0x08 to move it down one row
00D6	AC		PLO C	Put the result back in RC.0
00D7	3B B3		BNF SPRITE_ DISPLAY_ LOOP	Only display the next row if it is not off the bottom of the screen. This will be indicated because adding 0x08 to the display RAM address will cross a page boundary and generate a carry condition
00D9	F8 FF	SAVE_ COLLISION_ FLAG:	LDI 0xFF	0xFF is the low order byte of the address of variable F, where the collision flag will be stored
00DB	A6		PLO 6	R6 now points to variable F
00DC	87		GLO 7	Get the collision flag
00DD	56		STR 6	Store it in variable F

00DE	12		INC 2	Clean up by popping the least significant three bits of the x position off the stack
00DF	D4		SEP 4	Return to the fetch and decode routine
00E5 – 00F2				*The clear screen and return from subroutine routines are placed here in the interpreter*
00F3	8D	RESET_ I_ PTR:	GLO D	This is part of the display routine used to reset the I pointer to its original value (pointing at the start of the sprite) Get the total number of sprite rows
00F4	A7		PLO 7	Make this into a counter in R7.0
00F5	87	RESET_ I_ LOOP:	GLO 7	Get number of rows remaining
00F6	32 AC		BZ DISPLAY_ SPRITE	If all rows are done (I pointer has been restored), branch back to sprite display routine
00F8	2A		DEC A	Decrement I pointer (RA)
00F9	27		DEC 7	Decrement row counter
00FA	30 F5		BR RESET_ I_ LOOP	Branch back to top of the loop

There are several things to note about this routine, which is the largest and most complex of all the routines in the Chip-8 interpreter. First is that I, VX and VY are all altered by this routine, so the Chip-8 programmer should not expect them to be available for reuse with their original values. These would have to be explicitly set again.

Secondly, any part of a sprite that is off the right edge or bottom edge of the display will simply not be displayed. Fragments of sprites do not wrap around to the other side of the display. However, if the programmer attempts to display the entire sprite off the right edge or bottom edge of the display, it will wrap around. So setting 0x20 for the y coordinate is equivalent to setting 0x0, setting 0x21 is equivalent to 0x1 and so on. It will wrap again at all multiples of 0x20. The same will happen with the x coordinate. Setting it to 0x40 is equivalent to setting it to 0x0, and it will wrap again at all multiples of 0x40.



The timing for this routine gets a little bit complicated because it depends on a number of factors:

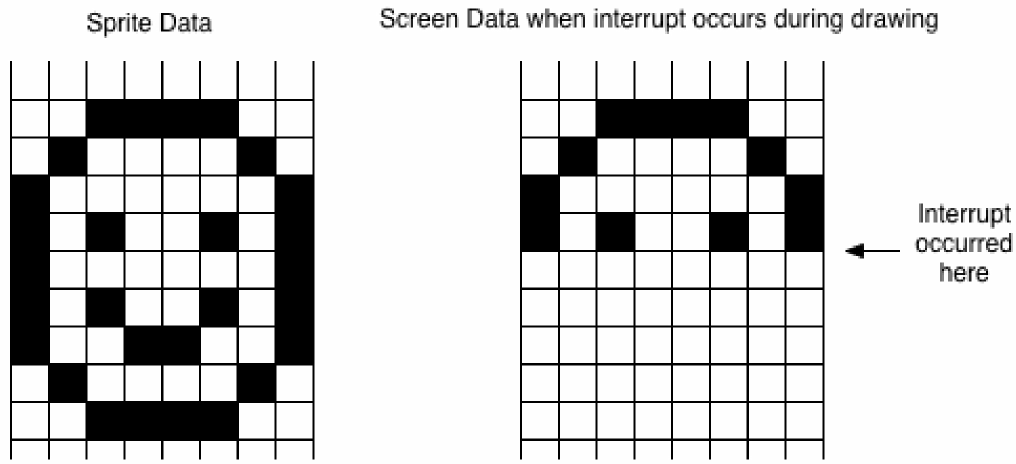
- How many rows the sprite has
- By how many pixels the sprite data is offset from the screen data

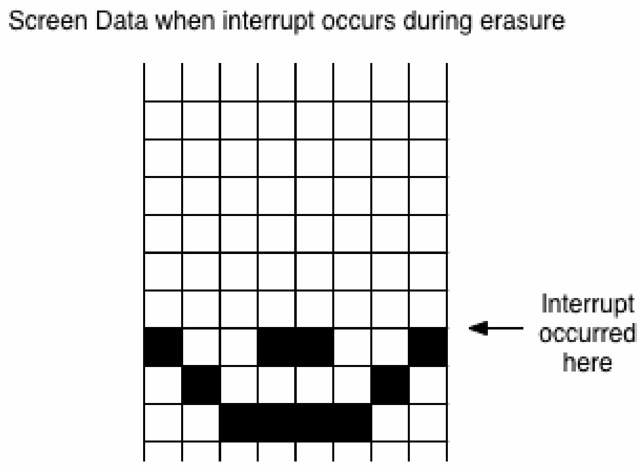
- How many collisions occur
- Whether the sprite is partly off the right edge or bottom edge of the screen

In terms of the time taken to run the actual code, if you ignore the case when the sprite height is zero (why would you ever want to do that?), then the shortest scenario, which is one row of sprite data, no pixel offset, no collisions, and sprite is at bottom right edge of screen is 170 cycles (771.8 microseconds). The worst case scenario (15 rows of sprite data, offset by seven pixels, collisions on every row and the whole sprite is on screen) requires a massive 3812 machine cycles (17306.48 microseconds).

That's not the end of the story though. Just before it enters the part of the routine that actually draws the sprite to the display memory, this routine executes an IDL instruction. Effectively this tells the 1802 processor to sit around and do nothing until the next interrupt occurs. At that point the interrupt routine occurs (during which the display is refreshed). Only once control has returned from the interrupt routine does the sprite drawing routine continue and draw the sprite to screen memory. The best case scenario for this is that the interrupt occurs immediately after the IDL instruction has been executed. In this case it will add an overhead of around 2355 cycles (I saw around because it might be slightly less than that if the general purpose and sound timers are inactive). The worst case scenario is that an interrupt has just occurred immediately before the IDL instruction. In this case the sprite drawing routine will have to hang around for almost a whole TV frame (3666 cycles or 16643.64 microseconds) before it can continue.

You may be wondering why it's necessary to wait for the screen refresh at all. Why not just write the sprite to the display memory as soon as possible and then carry on? The answer is to avoid an effect known as sprite tearing. If the sprite display routine is allowed to write to the display memory whenever it wants, there are going to be occasions when the screen refresh interrupt occurs while the sprite routine is midway through drawing. If you are erasing a sprite then a portion of the bottom of the sprite will still be on screen when the refresh happens, and if you are drawing a sprite, then only a portion of the top of the sprite will have been drawn when the refresh happens.





Now it's true that by the time the next refresh comes around the sprite will have been completely erased or drawn – and that will be just one sixtieth of a second later. So you might be thinking – how would anyone ever notice the defect in that short space of time? But what actually happens is that sprite erasing/drawing gets interrupted so often that it causes a very noticeable jitter, which can spoil the user's experience of games and other applications quite considerably. The solution, as we've seen, is to wait until a screen refresh has just finished and then draw or erase the sprite. After a screen refresh, about 1313 cycles (a few more if timers are inactive) will occur before the next screen refresh begins. In the worst case scenario, the sprite display routine requires 954 machine cycles to complete its work, so we can be sure that erasing or drawing will be finished before the screen is refreshed again.

A contemporary interpreter must support this instruction. However, the strategy adopted is going to depend on the graphics hardware of the target platform. It's likely that a contemporary interpreter's sprite drawing routine will be a lot simpler than this one as most programmers now will be able to work with display hardware that is significantly more sophisticated than that supplied with the COSMAC VIP.

This entry was posted in Chip-8, Retro Computing, Uncategorized and tagged chip-8, COSMAC VIP, interpreter, interrupts, memory, programming, RCA 1802. Bookmark the permalink.

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