

SD-8516 PPU

This is a short reference to the graphics capabilities of the XY-85 arcade board, an expansion board sold together with the SD-8516.

The PPU is a proprietary 32-bit central processing unit (CPU) developed for the XY-85 arcade board. It was designed to deliver high-performance framebuffer access and blit hundreds of sprites per frame, as well as provide high quality 16-bit sample playback at up to 48khz.

Introduction

The following shows the speed tests and design decisions that went into the PPU.

Primitives

PPIXEL (plot_pixel)

Method	Pixels per second (WASM)
BASIC PIXEL command	2,100
INT 18h plot pixel	26,000
INT 18h plot pixel (no bounds check)	30,000
PPU via INT 0x18	90,000
PPU via INT 0x03 (direct)	660,000
PPIXEL (unrolled 1,000 times)	1,300,000

The numbers above only show that the plot rate is bound by the CPU. At one instruction per cycle, 1.28 MIPS gets up to 1.28 PIPS (pixels per second). However, once you start adding in commands that load data, process color and so on, the number can drop. A more realistic number might be closer to 300,000 pixels per second at 1 MIPS. Good enough for a bitmapped font, good enough for a couple of sprites, good enough for the early console era (Intellivision, Atari 2600).

How useful is PPIXEL if we want to push the limits? It would not be your go-to choice for anything past the late 70s era. Asteroids (1979) arcade machine is a great example. It ran on a 6502 at 1.5mhz but required a special 'digital vector generator' chip to do the heavy lifting. The 6502 simply couldn't keep up with the refresh rate even with a simple game like asteroids.

Notably, the Apple II and VIC-20 had no PPU and relied on the 6502 for all graphics. Therefore, at 0.5 to 1 MIPS, using PPIXEL will closely approximate up to that era.

PLINE

The conclusion over PPIXEL is that it is bound by the speed of the CPU. When that isn't enough you would want a command like PLINE. The analogy here is the Atari Digital Vector Generator chip used in Asteroids (1979) and many other games.

These figures are for screen clears using LINE in a Y=0 to 199 loop.

Method	Pixels per Second
BASIC LINE command	22,000
INT 18h draw line	26,000
BASIC using PPU via INT 0x18	156,000
BASIC using PPU direct call	165,000
PPU via INT 0x18	15,000,000
PPU via INT 0x03 (direct)	55,000,000
PLINE (PPU via opcode)	77,000,000

As it turns out the line drawing algorithm, even though it is in assembly, is the limiting factor. The BASIC interpreter might execute 50 to 100 lines of assembly to get to INT 18h, but INT 18h is executing over 13,000 lines of assembly to draw a single horizontal line from 0,0 to 319,0. Thus replacing INT \$18 with a PLINE opcode increased speed 7.5x to 165,000 pps fill rate. This implies 5-10 16×16 sprites with a smart draw algorithm. Of course, for BASIC, you have DRAWCHAR, and I suspect PBLIT and a series of SPRITE commands for BASIC will be the real breakthrough we need for our BASIC. But it's nice to know PLINE works well in BASIC. The numbers above represent 510 lines per second. With this much speed it is possible to write an ELITE clone in BASIC. That is going to be the benchmark.

The big win comes from the direct call in assembly. The speedup is equivalent to dropping five instructions; two INT calls, two RTI, and a LDA for the inner INT \$3 call.

Fast tiles and sprites in BASIC with PLINE

If you have a smart drawing routine that reads contiguous pixels, then clusters of pixels can draw in ~1 cycle. So instead of having to call PPIXEL four times for the top row of a sprite, if the pixels are next to each other they can be detected as such as drawn via PLINE. While this might not be practical on-the-fly, it is interesting to consider a packed image format that would allow this to operate quickly; i.e. store the sprite data itself as a series of line draws. In a 16×16 sprite it is conceivable you could use about half the number of PLINE calls as you would use PPIXEL. The difference is that you would need a special format for storing the image data. This idea fits BASIC's "DATA" statements very well as it would be in a compressed format. The idea is you would store images in a kind of bytecode, and then the BASIC BLIT routine would read that format to quickly draw a sprite to screen. Of course, there is (will be) a PPU BLIT soon, so no one would use PLINE for this - but it's possible to do so.

PRECT and PFRECT

```
AH=$03 draw_rect
```

```
AH=$04 fill_rect
```

Tested and working. 160,000 rps and up in a normal loop.

PCIRCLE and PFCIRCLE

```
AH=$05 draw_circle
```

```
AH=$06 fill_circle
```

Draws circles. Tested and working. Circles draw depending on their size:

Radius	Draw speed	Example usage
10-20	150,000/sec	Games
80-100	18,000/sec	Art/Games
large	4500/sec	Art

For any meaningful use case, this is probably good enough. At 100,000+ circles a second at radius 30 and under, you could write any kind of game with this circle.

PCLEAR

AH=\$07 clear-to-color

Clears screen to color in cl. Tested and working.

Sprites

Sprites are arguably the reason for a PPU, and why it's called a PPU and not a 2d accelerator.

- INT 18h LOAD and DRAW for 4bpp and 8bpp: Tested and working

The INT 18h DRAW function can draw a 16×16 sprite in 1.3ms. This is very slow.

```
spritebench_loop:
    ; Clear screen
    LDA $0100                ; CMD_CLEAR
    LDCL $00
    INT $03

    LDELM $A000
    LDFLD $020000
    CALL @draw_sprite_data

    INC X
    CMP X, #303
    JC @done

    LDAH $52                ; set VSTEP mode (step once)
    INT 0x18

spin_wait_loop:
    LDAH $53
    INT 0x18
    CMP AL, 1
    JNZ @spin_wait_loop

    JMP @spritebench_loop
```

If you take out the spin-wait loop, the clear screen and the VSTEP instruction, this code executes 303 draws in 1.3ms per draw. That's painfully slow. Why is it so slow? The draw_sprite assembly routine goes through about 1,800 assembly instructions to draw a single sprite! We cannot MEMCOPY if we want pixel transparency in the framebuffer. And, even if we could, it would at best double our throughput on the fast path (for x & 1 == 0).

The conclusion is, it works, but 1.3ms per draw is essentially unusable. Even a ColecoVision or a NES had more sprite power than the SD-8516 – *but not without a PPU!* The PPU provides hardware accelerated sprites, and that's just what we need here.

Wiring up the PPU

The first test was to create the sprite data manually. This is the exact same code we used for the first test above, now available as AH=\$30, INT \$18:

```
; Load sprite/tile data
LDELM @tile_player
LDFLD $A000          ; load it into some free area
LDAH $30             ; This is just the import_sprite_4bpp from below.
INT $18
RET
```

```
tile_player:
    .bytes #16, #16
    .bytes "                "
    .bytes "        666      "
    .bytes "    66666        "
    .bytes "        666      7 "
    .bytes "            6      7 "
    .bytes "    FF88Fbb6      7 "
    .bytes "    F8FFFbb 6 7 "
    .bytes "    FF8FFb    777 "
    .bytes "    FFF8Fb      7 "
    .bytes "        F8F4        "
    .bytes "        F444        "
    .bytes "        44 44        "
    .bytes "        44 44        "
    .bytes "        66 66        "
    .bytes "    666    666      "
    .bytes "                "
```

Next, we used the PPU to load the sprite:

```
; Step 2: Load the converted data into PPU tile slot 0
LDB #0                ; slot 0
LDELM $A000           ; sprite data
LDX [ELM, +]          ; load tile width
```

```
LDY [ELM, +]      ; load tile height
LDCL #0           ; set transparent color = 0
LDCH #4           ; store data as 4bpp
LDA $0110         ; CMD_LOAD_TILE
INT $03
RET
```

The calling convention will be discussed in documentation later, but you can glean it from the comments above; ELM is a pointer to the data. The header, already read into X and Y. If you didn't do this you can point ELM at the data and do:

```
LDX [ELM, +]
LDY [ELM, +]
```

At any rate, after wiring up the PPU to the routine, we tried this test:

```
LDY #0
draw_yloop:
  LDX #0
draw_loop:
  ; Step 3: Draw the tile from slot 0 at (50, 50)
  LDB #0           ; slot 0
  LDA $0112         ; CMD_DRAW_TILE
  INT $03

  INC X
  CMP X, #304
  JNC @draw_loop

  INC Y
  CMP Y, #185
  JNZ @draw_yloop
```

This test attempts to draw a sprite to every valid screen location; from 0,0 to 303,183 – a total of 55,936 times. Can you guess how fast it was? The routine completed in 0.45. That's right, calibre 0.45 – 0.45 microseconds that is. Yes, that's right, it's so fast I had to repeat the test so many times because one row (~303 blits) was completing in less than a millisecond. This is very fast, and very good! At this speed, we could draw 3600 sprites per frame. But this doesn't take into account clearing the screen and syncing the frame. Let's try a test; Can we draw 32 tiles per frame, at 60fps?

Syncing the Frames

It was precisely at this time that I discovered a bug in the video code. You see, the batch executes at 241 times per second, and the video renderer executed at 60 frames per second. But due to some jitterbugs, there was an average delay introduced before the value was able to be read. After some bugfixing I was able to remove this delay. But I had to do it using super secret magic bugspray. This one was hard. I fixed it but I do not know entirely why the fix works; I only know “that's the place that

needed fixing” and after quite some poking it seems to run correctly. That's the story of getting VSTEP to work correctly in assembly.

It has something to do with refresh rate. I had to just let it use the monitor's refresh rate. So if you're on 120hz for example, you get 120hz in the browser and in the SD-8516. it also means you need to know the refresh rate if you are timing your game by frames.

Blit test

Once I could sync to frame, I tried to draw one sprite per frame for five seconds. It worked. After some testing I found we could draw over 2,000 sprites *per frame* at 60fps. Too much more than that and it starts to skip frames. Still, I couldn't have expected better results:

- Up to 2048 sprites *per frame* at 60fps
- Up to 4096 sprites *per frame* at 45fps
- Up to 5600 sprites *per frame* at 30fps

Now, if you reserve 50% of your game for logic, that's 1024 sprites per frame at 60fps. The SNES could do 128 (but only 32 per scanline). This result places us firmly in the super-high end early 90s arcade board territory; Sega Y board (1988) was the first board to crack the 2000 barrier, while even later boards like the SNK Neo Geo (1990) were hardware limited to 381 sprites. It was boards like this that enabled the superscalar arcade games of the 90s. Having a microcomputer with this kind of graphics powerhouse would have been the dream of every microcomputer aficionado in the 80s/90s.

And don't knock 30fps. There is also some value to 30fps. Games like Teenage Mutant Ninja Turtles (NES, 1989), Ghosts 'n Goblins (NES, 1986) and Contra Force (NES, 1992) ran internally at 30fps. Even SNES games like Return of Double Dragon, or N64/PS1 games (ex. Super Mario 64) would run at 30fps. Other famous 30fps games include Ocarina of Time (N64, 1998), Soul Reaver (PS1, 1999), Resident Evil, Tomb Raider and GoldenEye 007. These were great, legendary games; Sometimes 30fps is ok. 45fps is definitely OK.

And, for what it's worth, both Star Fox (SNES, 1993) and the Intellivision (1980!) ran at 20fps internally.

No, I couldn't be happier with this result! 2000 sprites per frame! This is great!

To put this in context, the Neo Geo's 381 sprites/frame was a defining feature of its arcade hardware in 1990; games like Metal Slug and King of Fighters built their visual identity around it. Bust-A-Move. Magical Drop 3. Buttery smooth quick animation, faster than the eye could see.

The kinds of games that ran on systems between SNES and SNK Neo Geo arcade quality boards are all famous well known titles; OutRun, Shinobi and Altered Beast ran on Sega System 16; Capcom CPS-1 ran Street Fighter II, Final Fight, and Ghosts 'n Goblins; CPS-2 headlined Street Fighter Alpha and Marvel vs. Capcom. All of these boards could pull 200-800 sprites per frame. Namco System 2 and Taito F3 also, were both able to handle hundreds of sprites, and headlined games like Tekken, Assault (1988), Splatterhouse, and Darius Gaiden, Bubble Symphony, and RayForce.

Conclusion

A decent tile and sprite engine is the foundation of an 80s/90s console PPU and of a high end arcade board. Extensive testing must be done before I can come back and add anything to this. But, there are a few little things that may prove useful, i.e. flip transforms. As it stands, the PPU is considered ready for testing in the main system.

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