GAME BOY EMULATION

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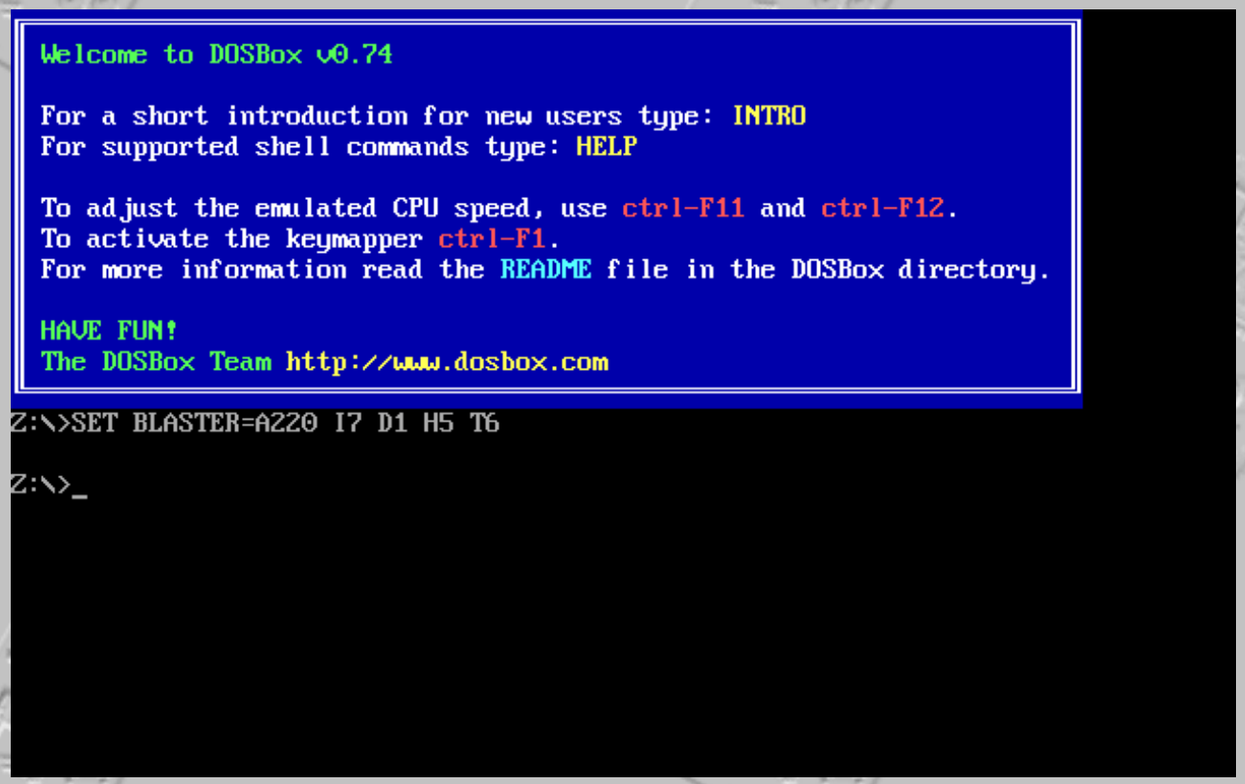
EMULATION OVERVIEW

“hardware or software that enables one computer system (called the host) to behave like another computer system (called the guest)”



GAME BOY ARCHITECTURE

- Split up software components
- Simulate parts, test individually, "wire" together

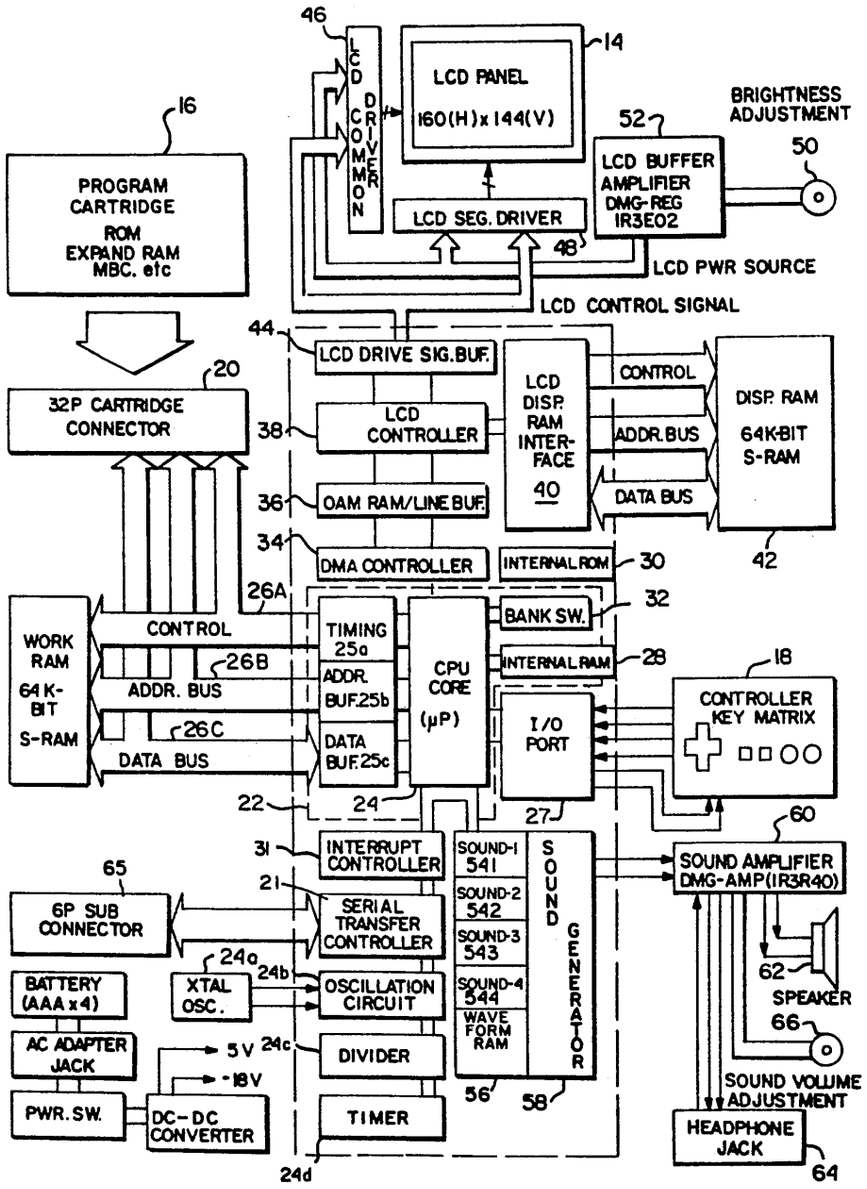
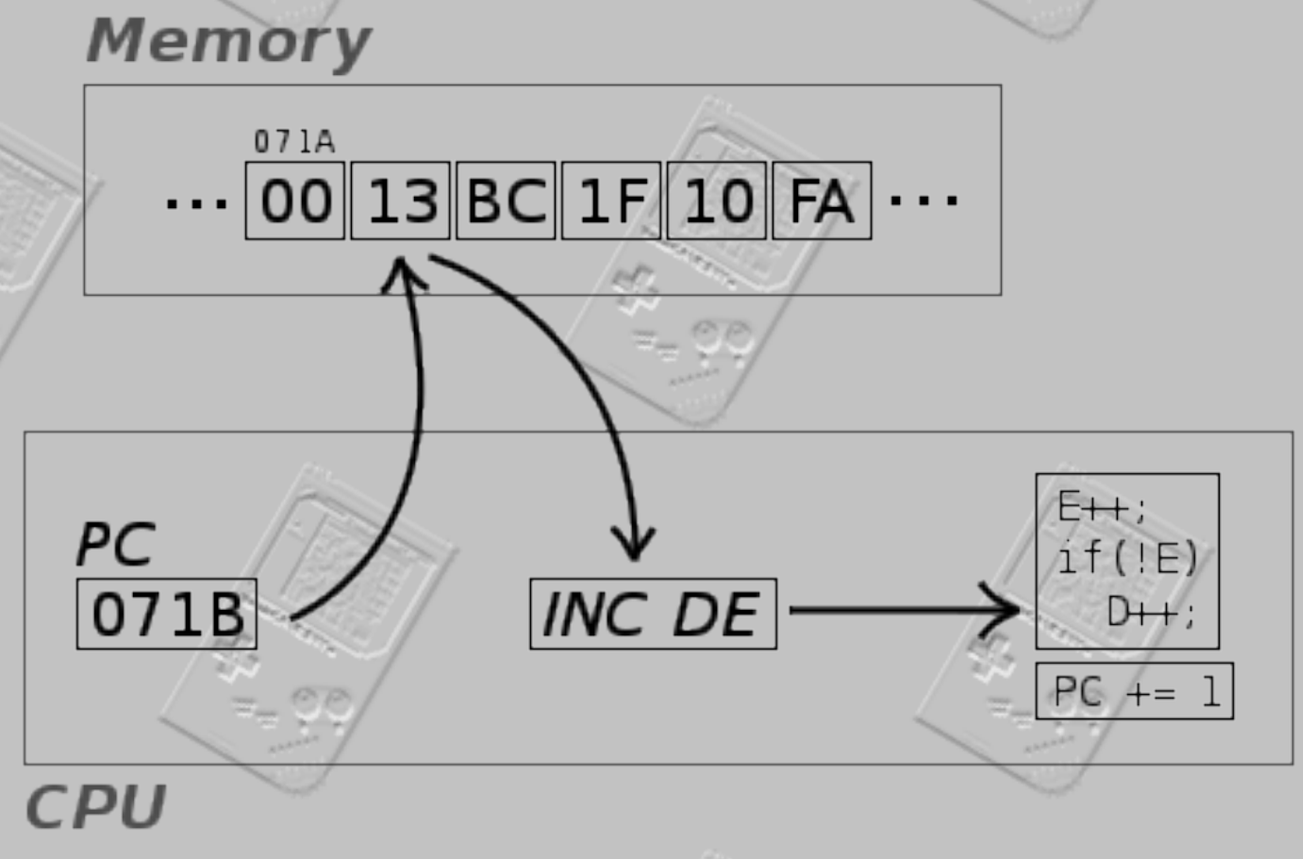


FIG. 4

WHAT'S A ROM?

"I've been downloading them 100% legally for years!"

```
00000100:□00c3□5001□ceed□6666□cc0d□000b□0373□0083□□..P...ff.....s..□
00000110:□000c□000d□0008□111f□8889□000e□dccc□6ee6□□................n.□
00000120:□dddd□d999□bbbb□6763□6e0e□eccc□dddc□999f□□......gcn.......□
00000130:□bbb9□333e□5445□5452□4953□0000□0000□0000□□..3>TETRIS......□
00000140:□0000□0000□0000□0000□0000□0001□000b□89b5□□................
```



SHARP LR35902

- Frankenstein Zilog Z80 / Intel 8080

- 8 8-bit registers, 2 16-bit

- Whopping 4.19MHz clock speed

- 245 non-prefix instructions, 255 CB-prefixed

CPU IMPLEMENTATION

- CPU
- registers
- instructions
- CB-prefixed instructions
- executors

REGISTERS

```
type Registers struct {
    a byte // Accumulator
    // Flags
    // ZNHC 0000
    // Z = zero, N = subtract, H = half carry, C = carry
    f byte

    b byte
    c byte

    d byte
    e byte

    h byte
    l byte

    sp []byte // Stack pointer
    PC []byte // Program counter
}
```

Also contains methods to modify flags

INSTRUCTIONS

```
type Instruction struct {
    Mnemonic string
    // Number of T cycles instruction takes to execute
    // Divide by 4 to get number of M cycles
    TCycles uint16
    NumOperands uint16
    Executor    func() int // Executes appropriate function
}
```

```
0x00: Instruction{"NOP", 4, 1, func() int { return 0 }},
0x01: Instruction{"LD BC,i16", 12, 3, func() int { gbcpu.LDrrnn(&gbcpu.Regs.b, &gbcpu.Regs.c); return 0 }},
0x02: Instruction{"LD (BC),A", 8, 1, func() int { gbcpu.LDaar(&gbcpu.Regs.b, &gbcpu.Regs.c, &gbcpu.Regs.a); return 0 }},
0x03: Instruction{"INC BC", 8, 1, func() int { gbcpu.INCrr(&gbcpu.Regs.b, &gbcpu.Regs.c); return 0 }},
0x04: Instruction{"INC B", 4, 1, func() int { gbcpu.INCr(&gbcpu.Regs.b); return 0 }},
```

EXECUTORS

```
// XORr -> e.g. XOR B
// Bitwise XOR of reg into A
// Flags: Z000
func (gbcpu *GBCPU) XORr(reg *byte) {
    gbcpu.Regs.a ^= *reg

    // Check for zero
    if gbcpu.Regs.a == 0x00 {
        gbcpu.Regs.setZero()
    } else {
        gbcpu.Regs.clearZero()
    }

    // Set flags
    gbcpu.Regs.clearSubtract()
    gbcpu.Regs.clearHalfCarry()
    gbcpu.Regs.clearCarry()
}
```

```
// LDSPnn -> e.g. LD SP,i16
// Loads 16 bit value from next 2 bytes into SP
// Flags: none
func (gbcpu *GBCPU) LDSPnn() {
    operands := gbcpu.getOperands(2)
    gbcpu.Regs.sp = operands
}
```

```
// CALLaa -> e.g. CALL $028B
// Pushes the addr at PC+3 to the stack
// Jumps to the address specified by next 2 bytes
func (gbcpu *GBCPU) CALLaa() {
    operands := gbcpu.getOperands(2)
    nextInstr := gbcpu.sliceToInt(gbcpu.Regs.PC) + 3
    nextInstrBytes := make([]byte, 2)
    binary.LittleEndian.PutUint16(nextInstrBytes, nextInstr)
    gbcpu.pushByteToStack(nextInstrBytes[1])
    gbcpu.pushByteToStack(nextInstrBytes[0])
    gbcpu.Regs.PC = operands

    gbcpu.Jumped = true
}
```

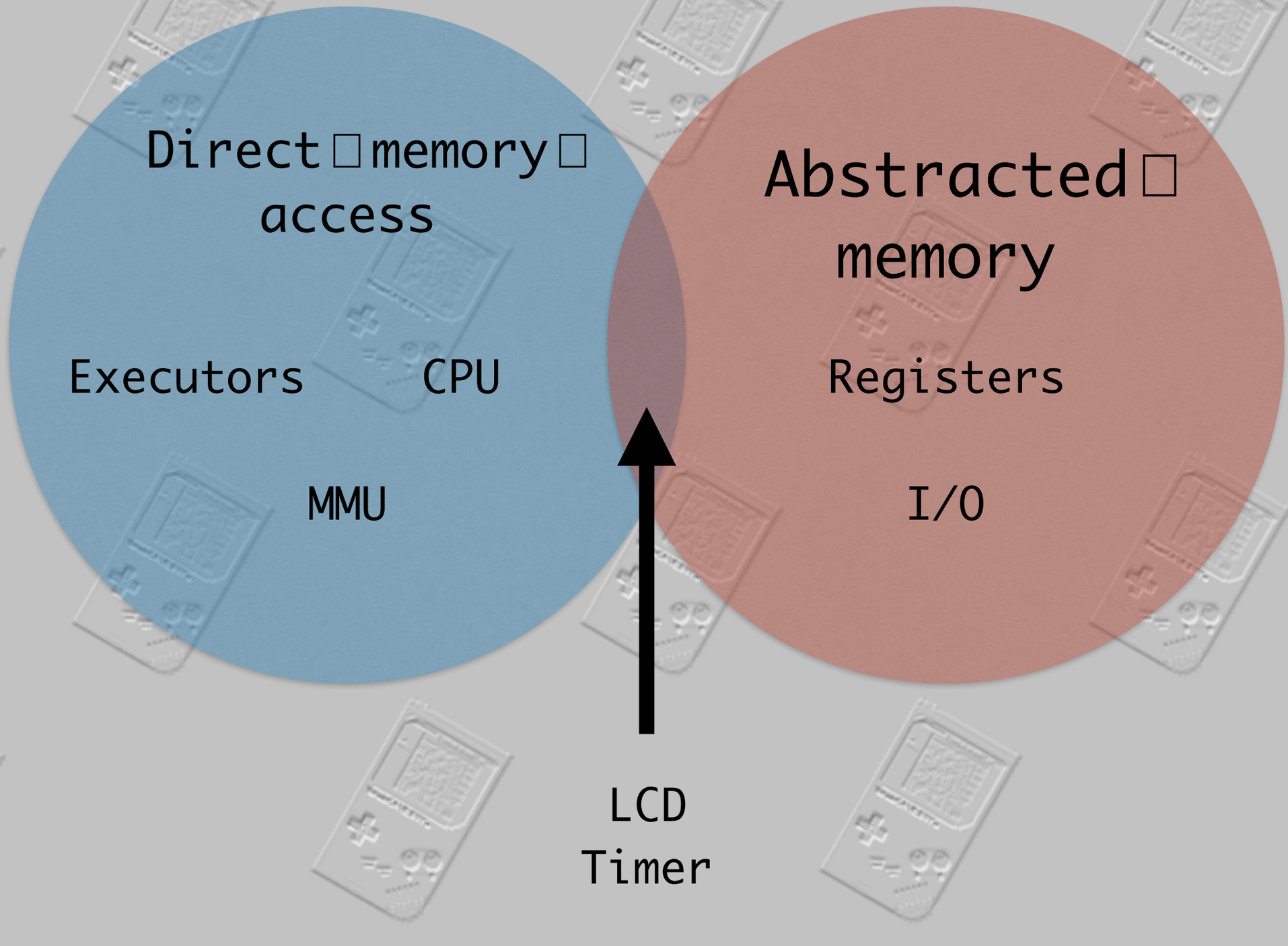
MEMORY

- Straightforward representation as a flat byte array
- Load ROM into correct location, begin fetch-decode-dispatch loop
- Can ignore all memory dealing with video & I/O

GameBoy Memory Areas

$FFFF	Interrupt Enable Flag
$FF80-$FFFE	Zero Page - 127 bytes
$FF00-$FF7F	Hardware I/O Registers
$FEA0-$FEFF	Unusable Memory
$FE00-$FE9F	OAM - Object Attribute Memory
$E000-$FDFF	Echo RAM - Reserved, Do Not Use
$D000-$DFFF	Internal RAM - Bank 1-7 (switchable - CGB only)
$C000-$CFFF	Internal RAM - Bank 0 (fixed)
$A000-$BFFF	Cartridge RAM (If Available)
$9C00-$9FFF	BG Map Data 2
$9800-$9BFF	BG Map Data 1
$8000-$97FF	Character RAM
$4000-$7FFF	Cartridge ROM - Switchable Banks 1-xx
$0150-$3FFF	Cartridge ROM - Bank 0 (fixed)
$0100-$014F	Cartridge Header Area
$0000-$00FF	Restart and Interrupt Vectors

REPRESENTATION

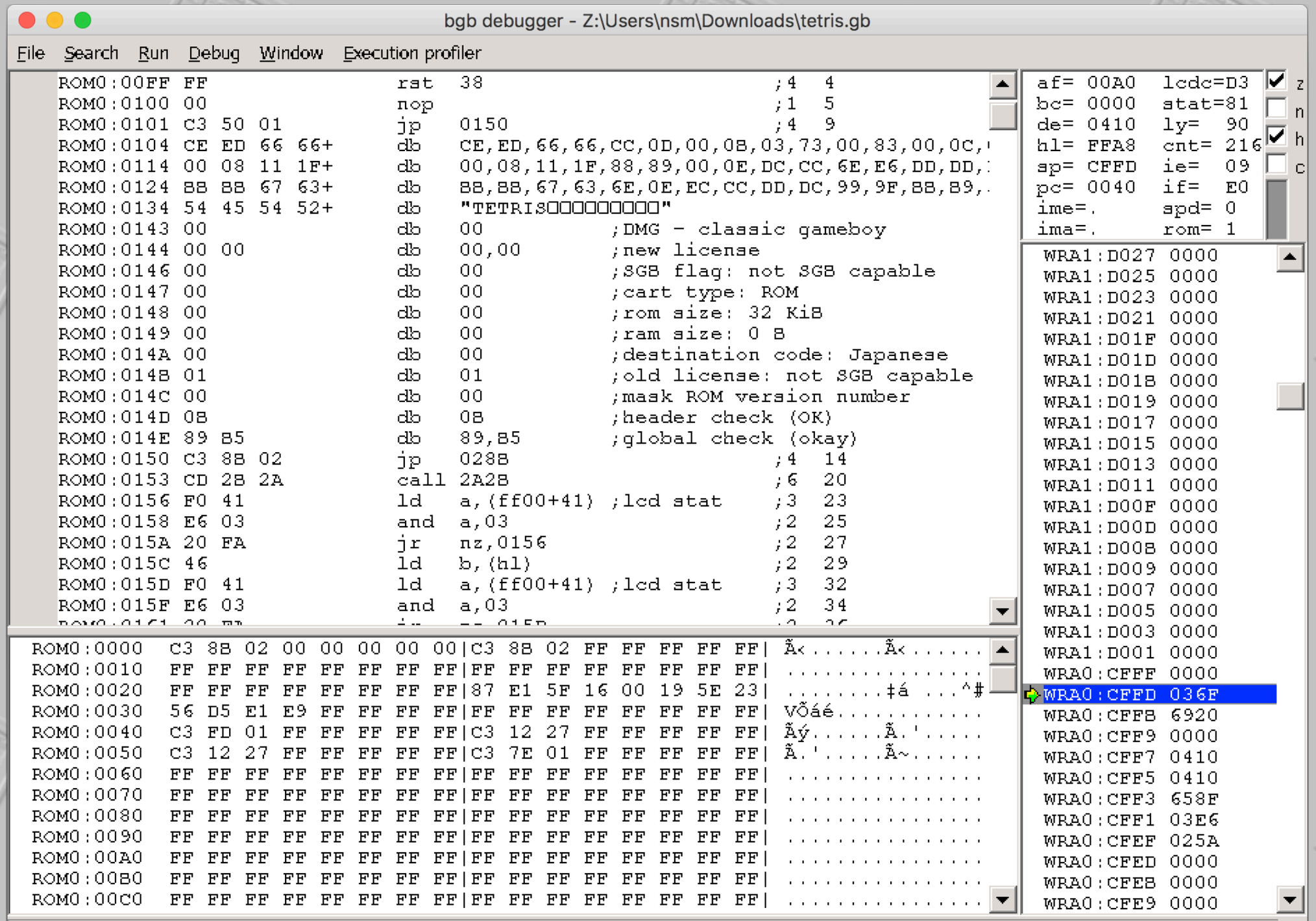


BENEFITS

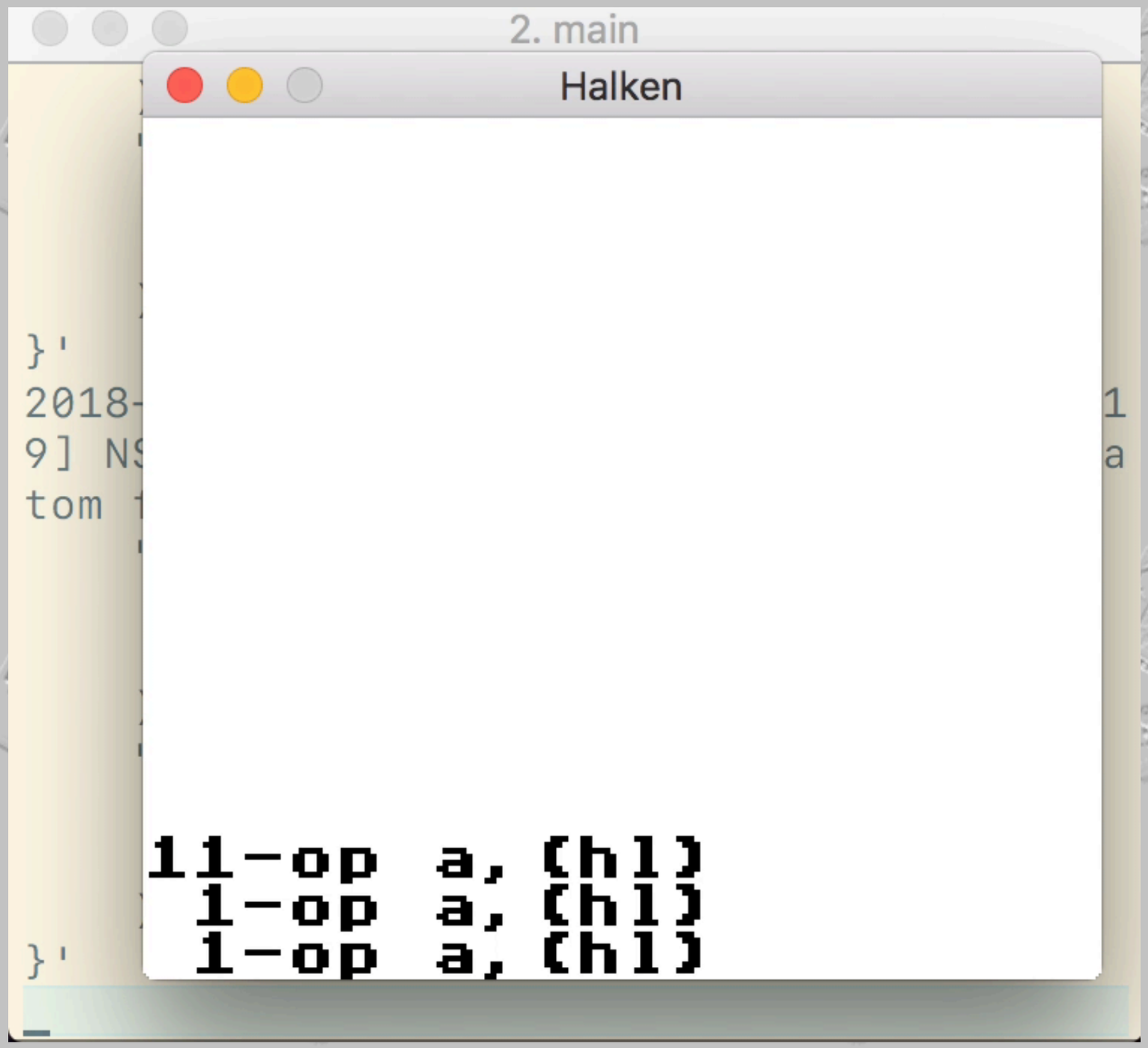
```
wb: function(addr,val) {
  switch(addr&0xF000)
  {
    // ROM bank 0
    // MBC1: Turn external RAM on
    case 0x0000: case 0x1000:
      switch(MMU._carttype)
      {
        case 1:
          MMU._mbc[1].ramon = ((val&0xF)==0xA)?1:0;
          break;
      }
    break;

  // MBC1: ROM bank switch
  case 0x2000: case 0x3000:
    switch(MMU._carttype)
    {
      case 1:
        MMU._mbc[1].rombank &= 0x60;
        val &= 0x1F;
        if(!val) val=1;
        MMU._mbc[1].rombank |= val;
        MMU._romoffs = MMU._mbc[1].rombank * 0x4000;
        break;
    }
    break;
```

```
func (gbmmu *GBMMU) WriteData(addr uint16, data byte) {
    if addr == 0xFF00 {
        GbIO.SetCol(data)
    } else if addr == 0xFF0F {
        // TODO What do writes here really do? Ignored or bit set?
        // gbmmu.Memory[0xFF0F] |= (1 << 0)
    } else if addr == 0xFF41 {
        // TODO Same as above
    } else if addr >= 0x0000 && addr <= 0x150 {
        // Don't allow writes to invalid locations
    } else if addr == 0xFF46 {
        spriteAddr := int(data) * 256
        for i := range gbmmu.Memory[0xFE00:0xFEA0] {
            gbmmu.Memory[0xFE00+i] = gbmmu.Memory[spriteAddr+i]
        }
    } else if addr == 0xFF07 {
        gbmmu.Memory[addr] += data
    } else {
        gbmmu.Memory[addr] = data
    }
}
```

PAINFUL DEBUGGING



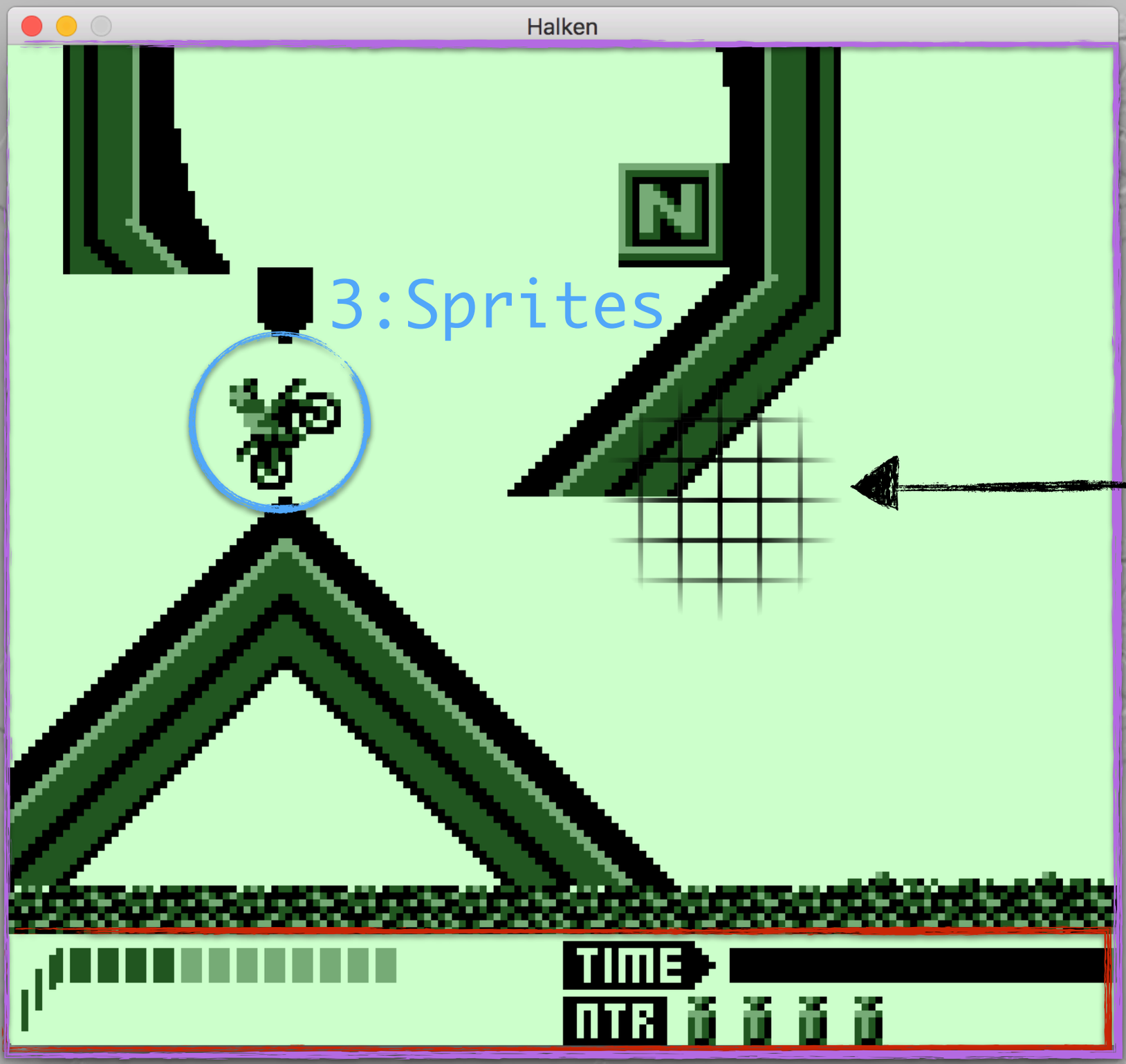
NICE DEBUGGING



THE LCD

- **160x144** pixels
- **20x18** tiles, each **8x8** pixels
- **256x256** “background”
- **40** sprites at once
- **4** colors, shades of gray

GRAPHICS "LAYERS"



TILE MAPS

=

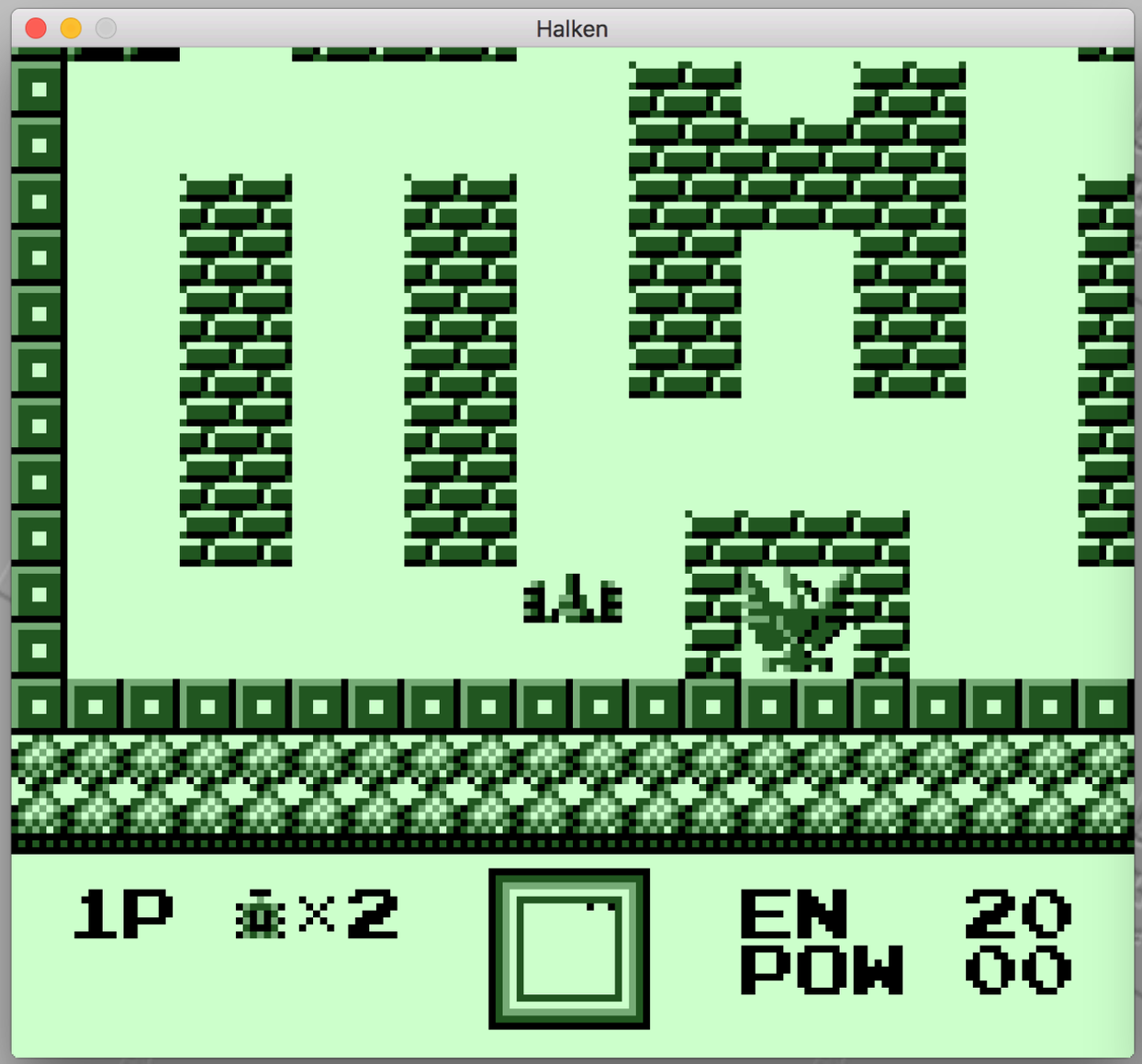
```
8E,8E,8E,8E,8E,8E,8E,8E,8E,8E,8E,8E,8E,8E,8E,8E,8E,8E
8E,8E,8E,8E,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
5A,5B,5B,5B,5B,5B,5B,5B,5B,5B,5B,5B,5B,5B,5B,5B,5B,5B
5B,5B,5B,5C,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
5D,80,81,82,83,90,91,92,81,82,83,90,6C,6D,6E,6F
70,71,72,5E,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
5D,84,85,86,87,93,94,95,85,86,87,93,73,74,75,76
77,78,2F,5E,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
5D,2F,88,89,2F,96,97,98,88,89,2F,96,79,7A,7B,7C
7D,7E,2F,5E,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
5D,2F,8A,8B,2F,8E,8F,6B,8A,8B,2F,8E,7F,66,67,68
69,6A,2F,5E,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
5F,60,60,60,60,60,60,60,60,60,60,60,60,60,60,60,60,60
60,60,60,61,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
8E,3C,3C,3C,3C,3C,3C,3C,3C,3C,3C,3C,3C,3C,3D,3E
3C,3C,3C,8E,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
8E,8C,8C,62,63,8C,8C,3A,8C,8C,8C,8C,8C,3A,42,43
3B,8C,8C,8E,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
8E,3A,8C,64,65,8C,8C,8C,8C,3B,8C,8C,8C,8C,44,45
8C,8C,8C,8E,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
8E,8C,8C,8C,8C,8C,8C,8C,8C,8C,8C,8C,8C,8C,46,47,48
49,3F,40,8E,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
8E,8C,8C,8C,8C,3A,8C,8C,8C,8C,53,54,8C,4A,4B,4C
4D,42,43,8E,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
8E,8C,8C,8C,8C,8C,8C,8C,8C,54,55,56,57,4E,4F,50
51,52,45,8E,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
41,41,41,41,41,41,41,41,41,41,41,41,41,41,41,41
41,41,41,41,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
2F,2F,59,19,15,0A,22,0E,1B,2F,2F,2F,99,19,15,0A
22,0E,1B,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
2F,2F,9A,9A,9A,9A,9A,9A,9A,2F,2F,2F,9A,9A,9A,9A
9A,9A,9A,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
2F,2F,2F,2F,33,30,31,32,31,2F,34,35,36,37,38,39
2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F,2F
```

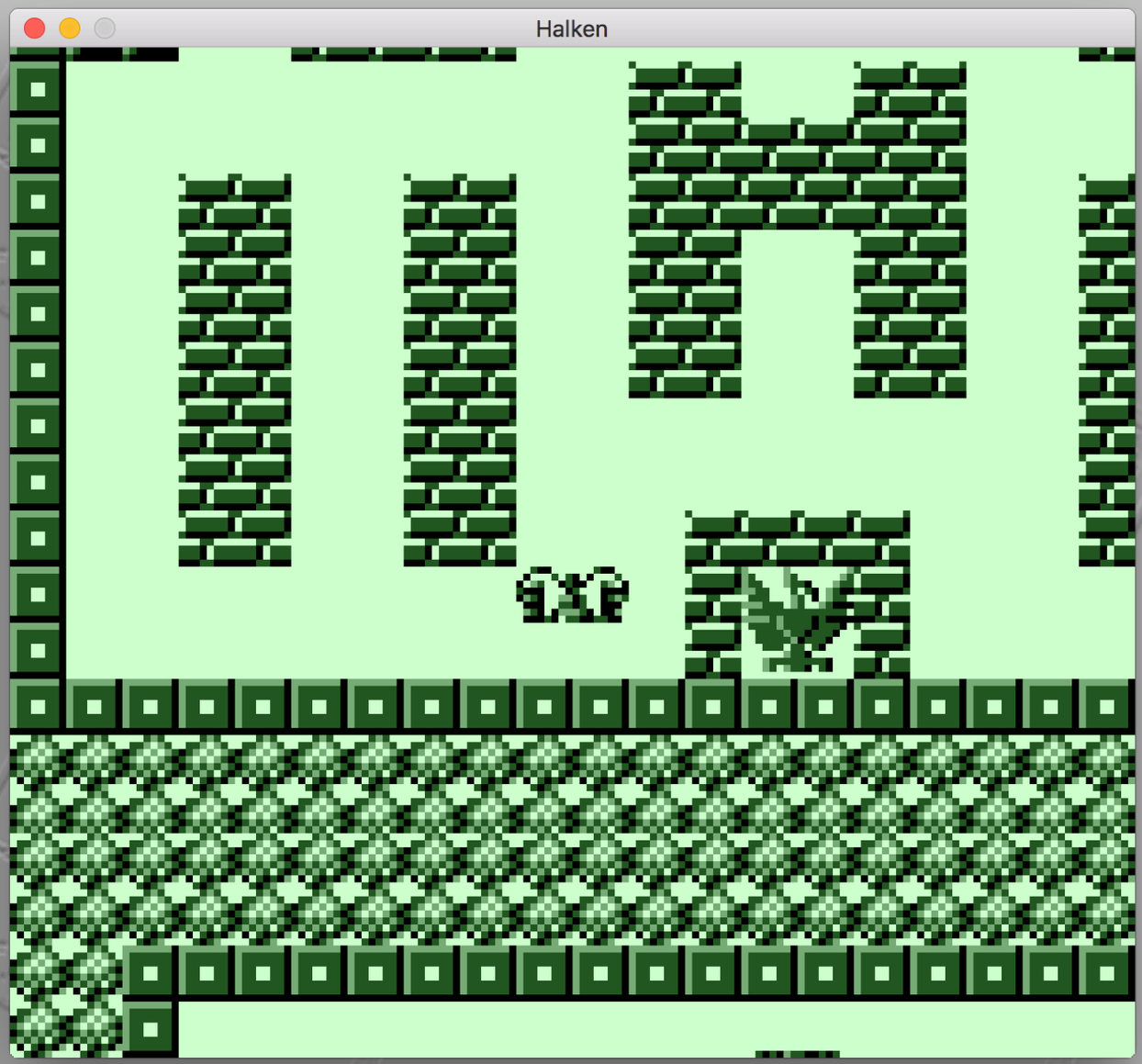
TILE RENDERING

```
Tile:                                  Image:

.33333..                    .33333.. -> 01111100 -> 7Ch
22...22.                                01111100 -> 7Ch
11...11.                    22...22. -> 00000000 -> 00h
2222222. <-- digits represent           11000110 -> C6h
33...33.     color numbers  11...11. -> 11000110 -> C6h
22...22.                                00000000 -> 00h
11...11.                    2222222. -> 00000000 -> 00h
........                                11111110 -> FEh
                            33...33. -> 11000110 -> C6h
                                        11000110 -> C6h
                            22...22. -> 00000000 -> 00h
                                        11000110 -> C6h
                            11...11. -> 11000110 -> C6h
                                        00000000 -> 00h
                            ........ -> 00000000 -> 00h
                                        00000000 -> 00h
```

ASCII from: https://fms.komkon.org/GameBoy/Tech/Software.html

WINDOW





Win.□X□offset->$FE4B,□Win.□Y□offset->$FE4A

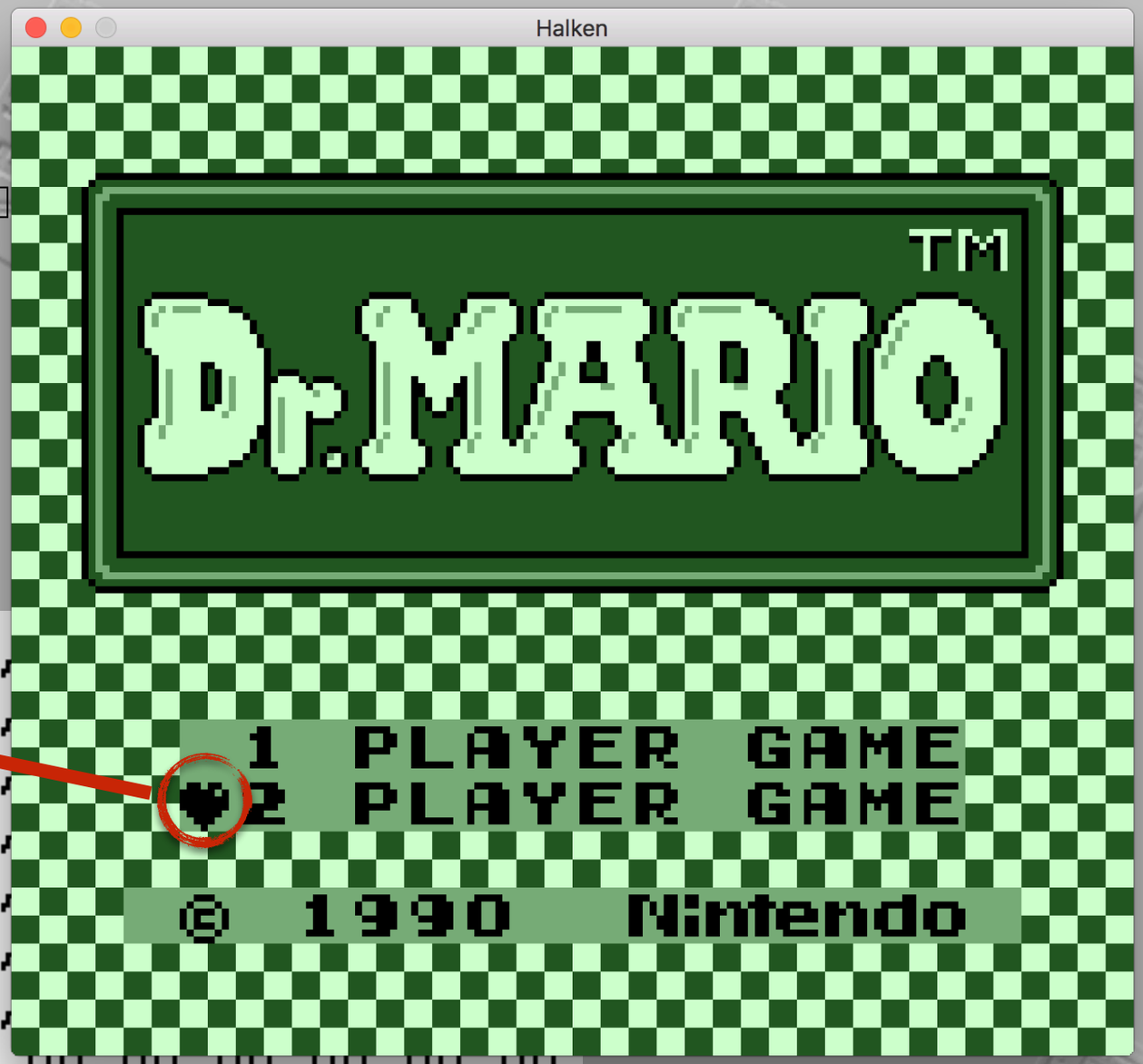
SPRITES

Attributes

```
0->Palette□#□(CGB)□□
1->Palette□#□(CGB)□
2->Palette□#□(CGB)□
3->VRAM□bank□(CGB)□
4->Palette□#□(DMG)□
5->X□flip□
6->Y□flip□
7->Above□BG
```

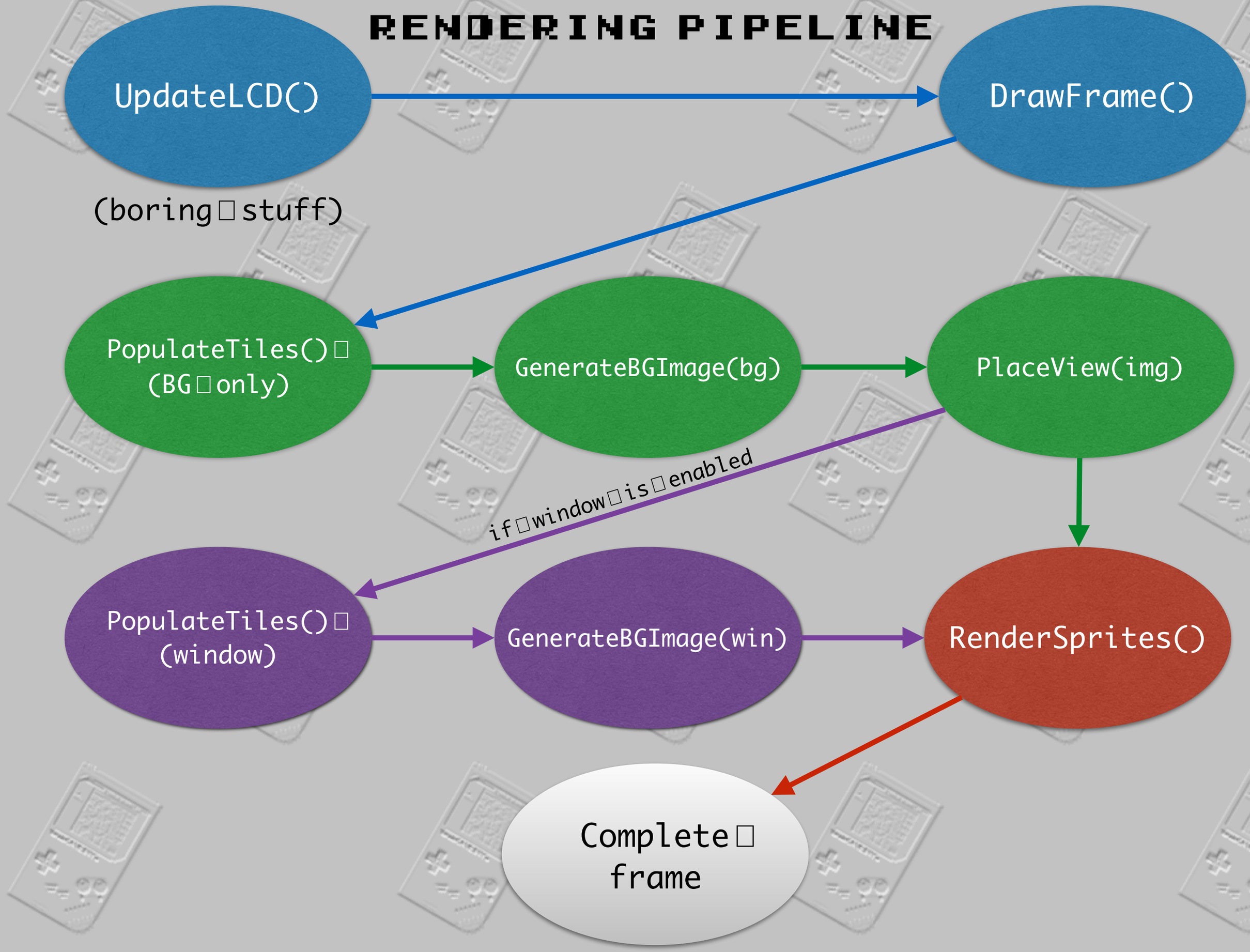
ID X Y

```
78,20,9B,00 00,00,00,00,00,
00,00,00,00,00,00,00,00,00,
00,00,00,00,00,00,00,00,00,
00,00,00,00,00,00,00,00,00,
00,00,00,00,00,00,00,00,00,
00,00,00,00,00,00,00,00,00,
00,00,00,00,00,00,00,00,00,
00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
```



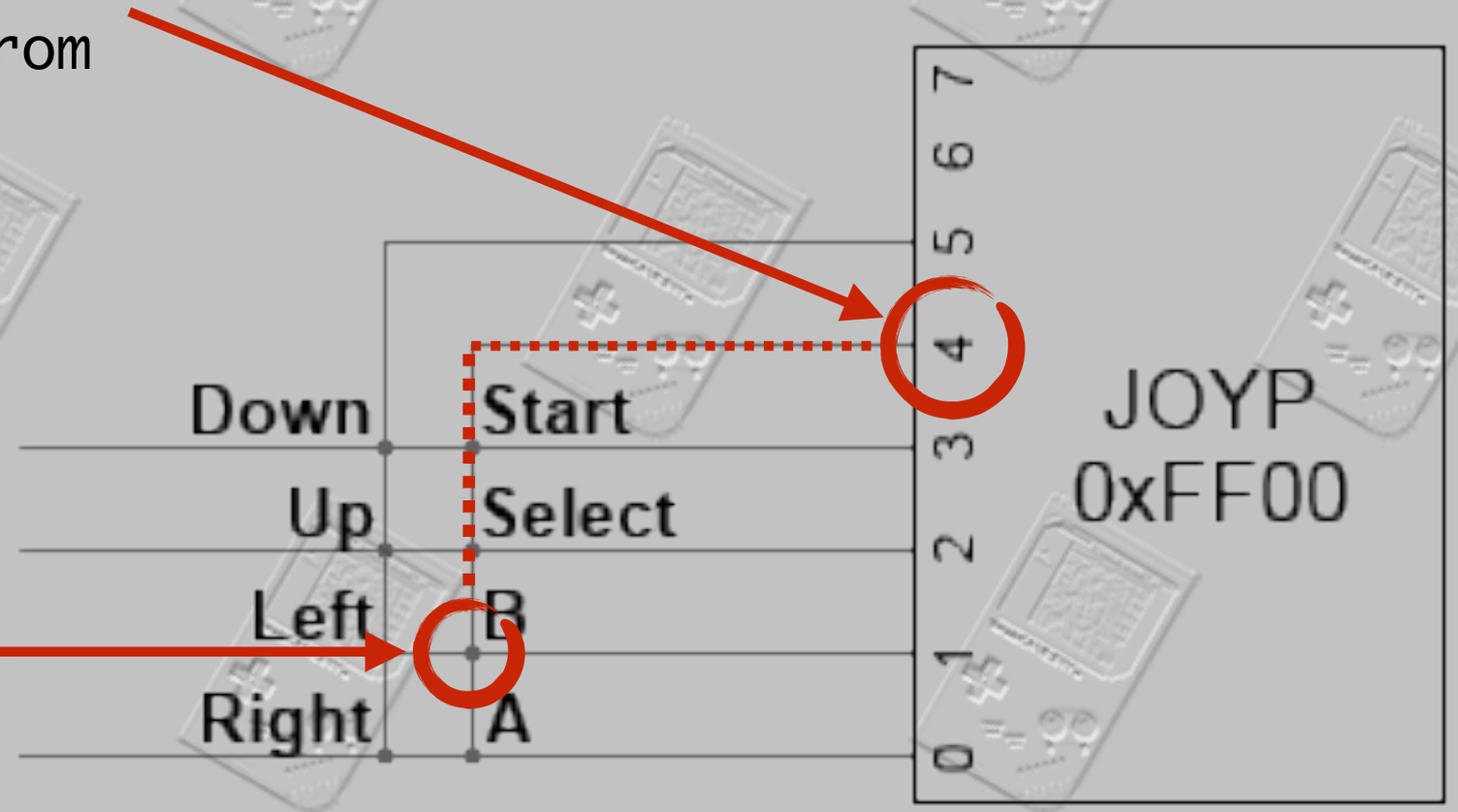
Sprite□OAM:□$FE00-$FEA0

RENDERING PIPELINE



INPUTS

Hardware selects which column it wants input from



Last button pressed
updated 60 times
per second

cols = [0x0F, 0x0F]
Values altered by reading inputs
Selected column = index 0 or 1
Return value

Image: http://imrannazar.com/GameBoy-Emulation-in-JavaScript:-Input

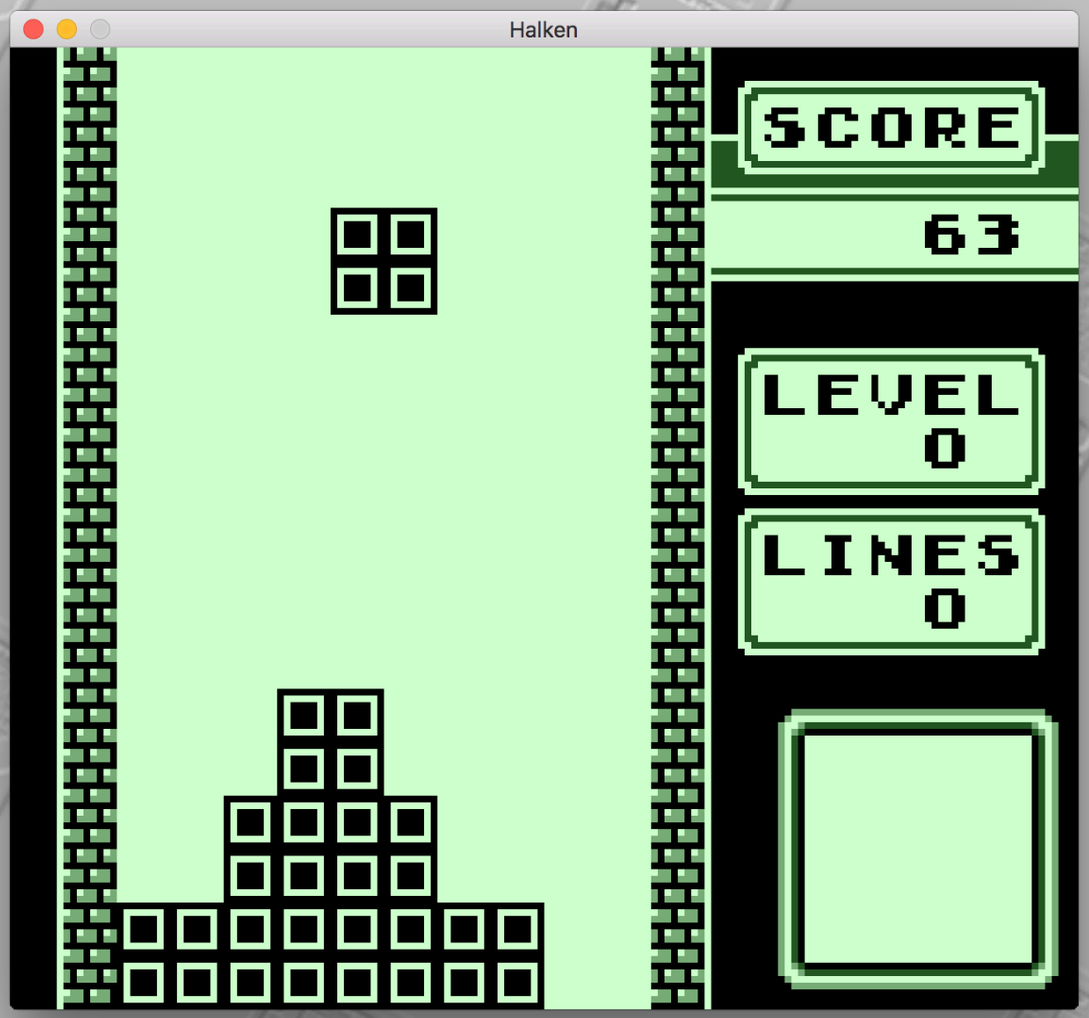
TIMER

- $FF04 = divider, acts as PRNG

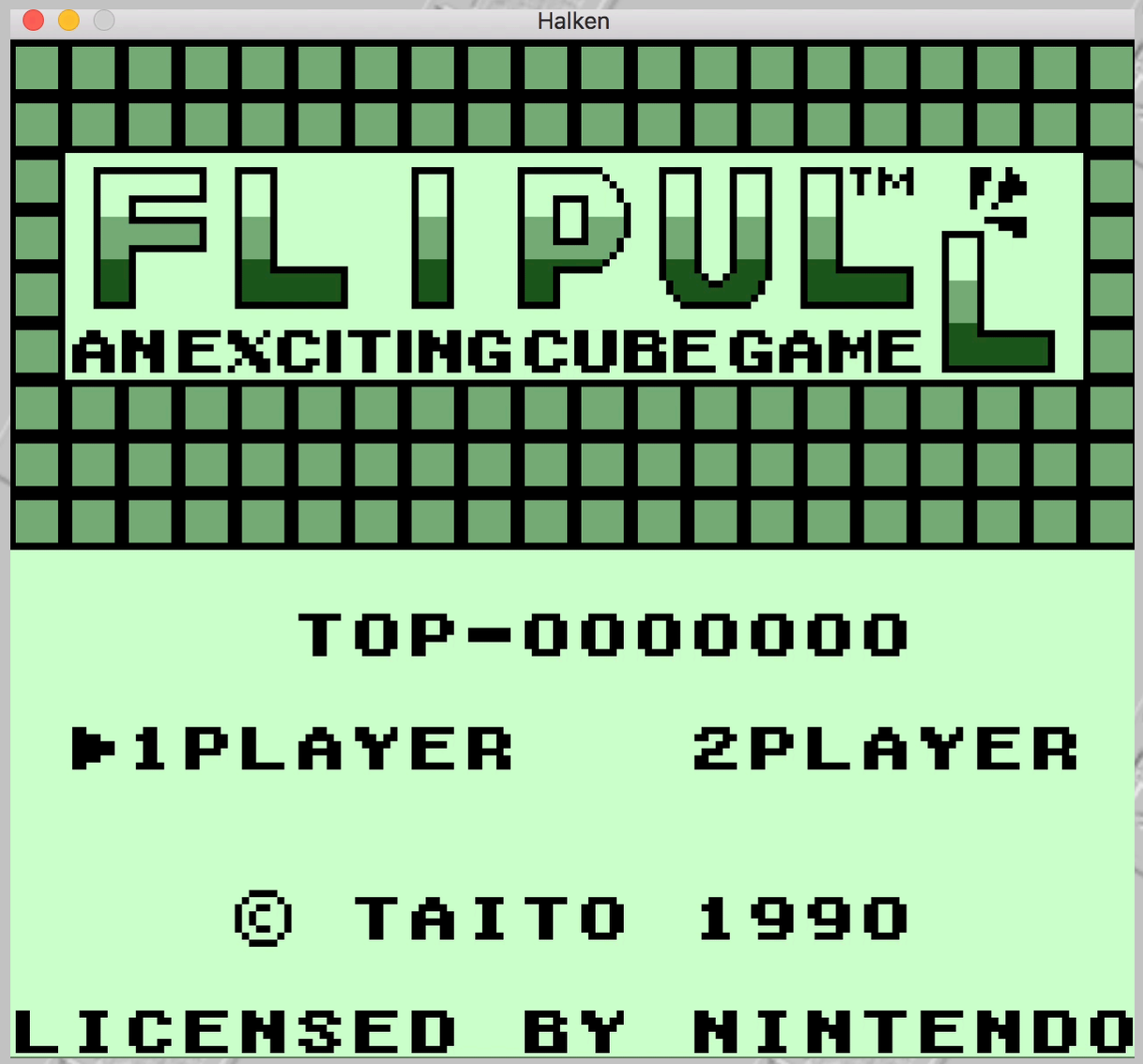
- $FF05 = counter, triggers timer interrupt when overflows

- $FF06 = modulo, when counter overflows, resets. Used to generate PRNG in divider

- $FF07 = control, bits 0 & 1 set speed, bit 2 sets timer on/off



WHAT'S DONE



- CPU
- Memory
- (most) Graphics
- (most) Interrupts
- Timer
- I/O

WHAT'S NOT

- Sound
- LCD STAT interrupt not entirely correct
- Sprites only use 1 color palette
- 8x16 sprites aren't implemented, get cut off
- ROM banking

WHAT I LEARNED

- a lot
- Excellent exercise in lower-level programming, computer organization/architecture
- Some software projects take a LONG time to write
- Testing is extremely helpful, especially when someone else wrote the tests
- Hardware restrictions lead to creative programming