KIKENDO ENTERTAINMENT SYSTEM

CREATING A NES EMULATOR*

GAMES INCLUDED!

SUPER MARIO BROS.

DONKEY KONG

MARIO BROS.

Galaga

POPEYE

KiKendo®

Kike Alcor @SuperKeeks // Feb 2018

*: Audio sold separately

Motivation

- Curious about how old console games were made
- Emulators felt like black magic
- Refresh my HW knowledge (and C++!)
- Why the NES?

Objectives

- Get Super Mario Bros. running
  - Side quest: Implement Audio
- Try SDL 2
- Get used to Unit Testing
- Meet deadlines

The process

1. Read some NES documentation
   - nestech.txt
   - 6502 Programming guide
2. Choose technology
3. Start coding

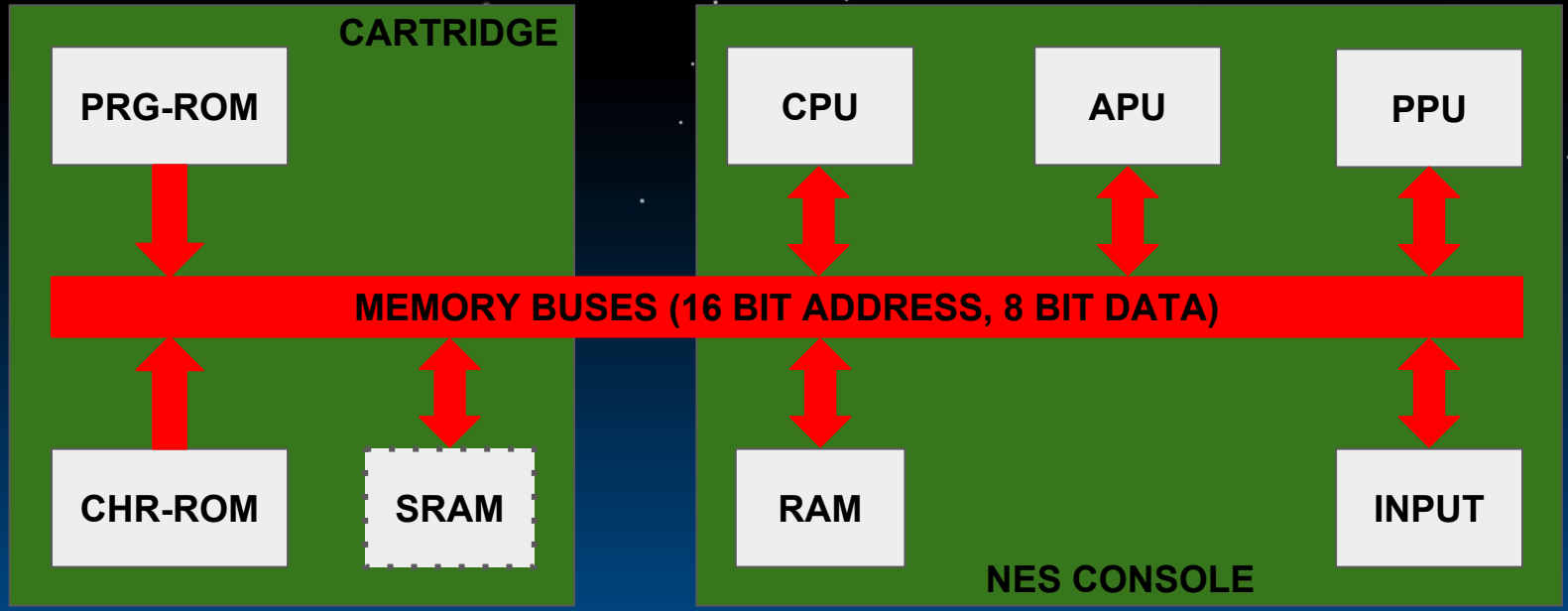
Technology & Tools

- C++ 11
- SDL 2 (Video, Input and Audio?)
- Visual Studio Community 2017
- Git (Bitbucket + Sourcetree)
- Trello

NES Specs

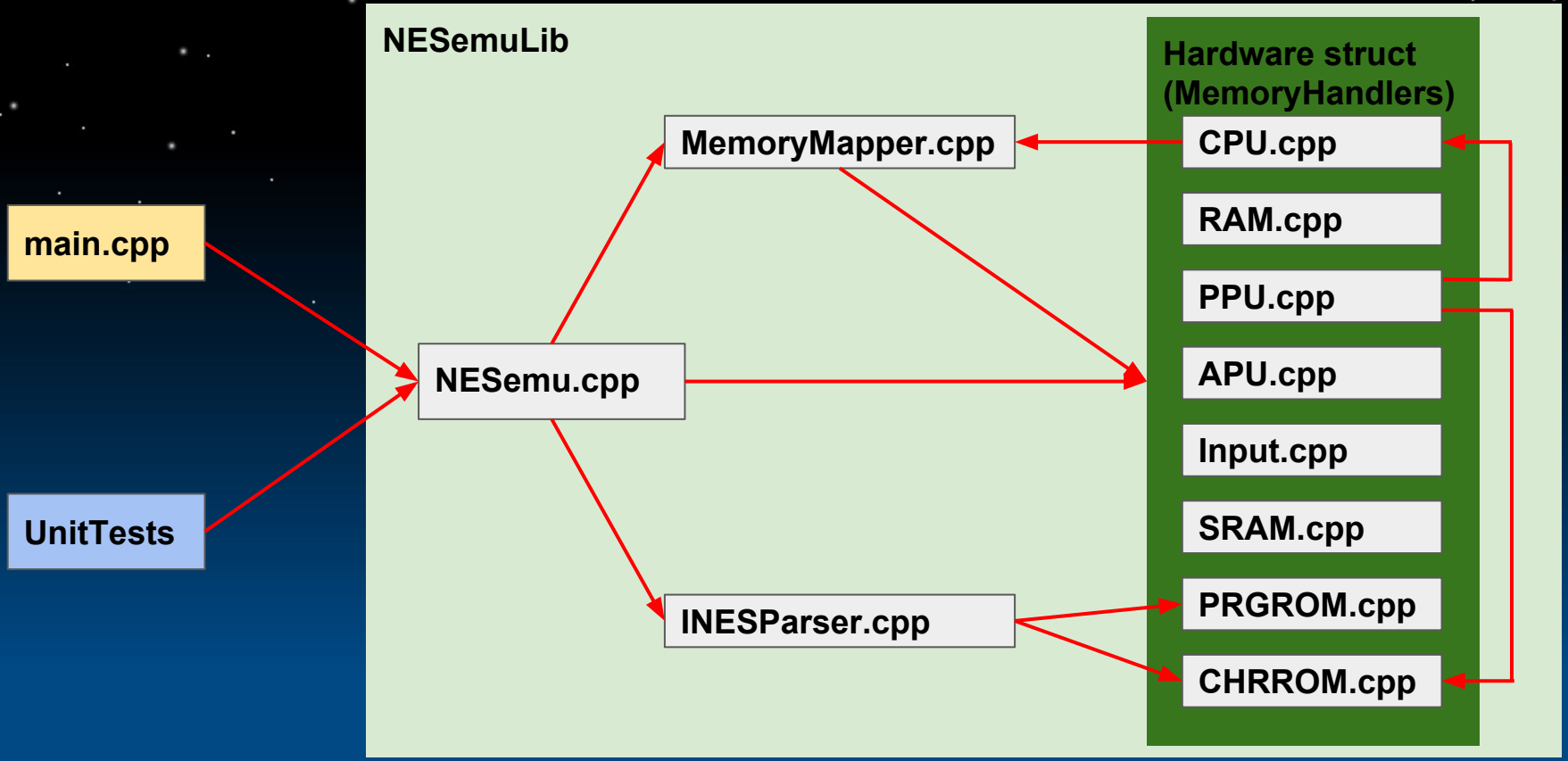
- 8 bit (8 bit registers / data, 16 bit address space)
- CPU: MOS 6502 @ 1.789 MHz (NTSC)
  - + pAPU (Pseudo-Audio Processing Unit)
- PPU (GPU): RICOH 2C02 @ 5.369 MHz (NTSC)
- RAM: 2 KB
- VRAM: 2 KB
- Palette: 54 Colours
- Resolution: 256x240 pixels

NES Architecture



Optional

Emulator architecture



main.cpp

```
InitVideo();
InitInput();
emu.Load("rom_name.nes");
while (!quit)
{
    UpdateInput();
    emu.Update(deltaTime);
    PresentFramebuffer();
}
DestroySDL();
```

NOTE:
All the SDL code in the project is here
(i.e. the emulator itself has no 3rd party code dependencies)

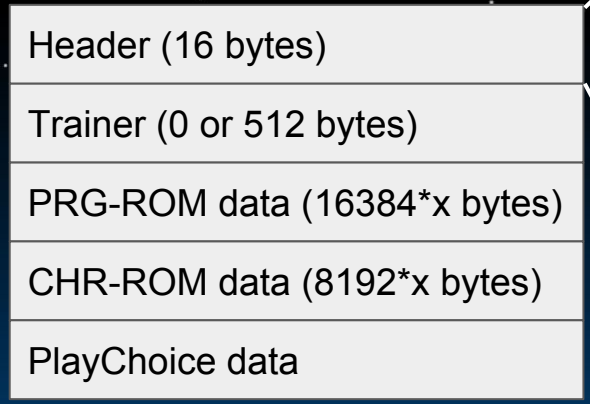
NESemu::Update(double delta)

```
double masterDelta = kMasterClockSpeed * delta;
int ppuDelta = round(masterDelta / 4);

for (int i = 0; i < ppuDelta; ++i)
{
    if (i % 3 == 0)
    {
        cpu.Tick();
    }

    ppu.Tick();
}
```

kMasterClockSpeed = 21.477272 MHz = 21477272 Hz

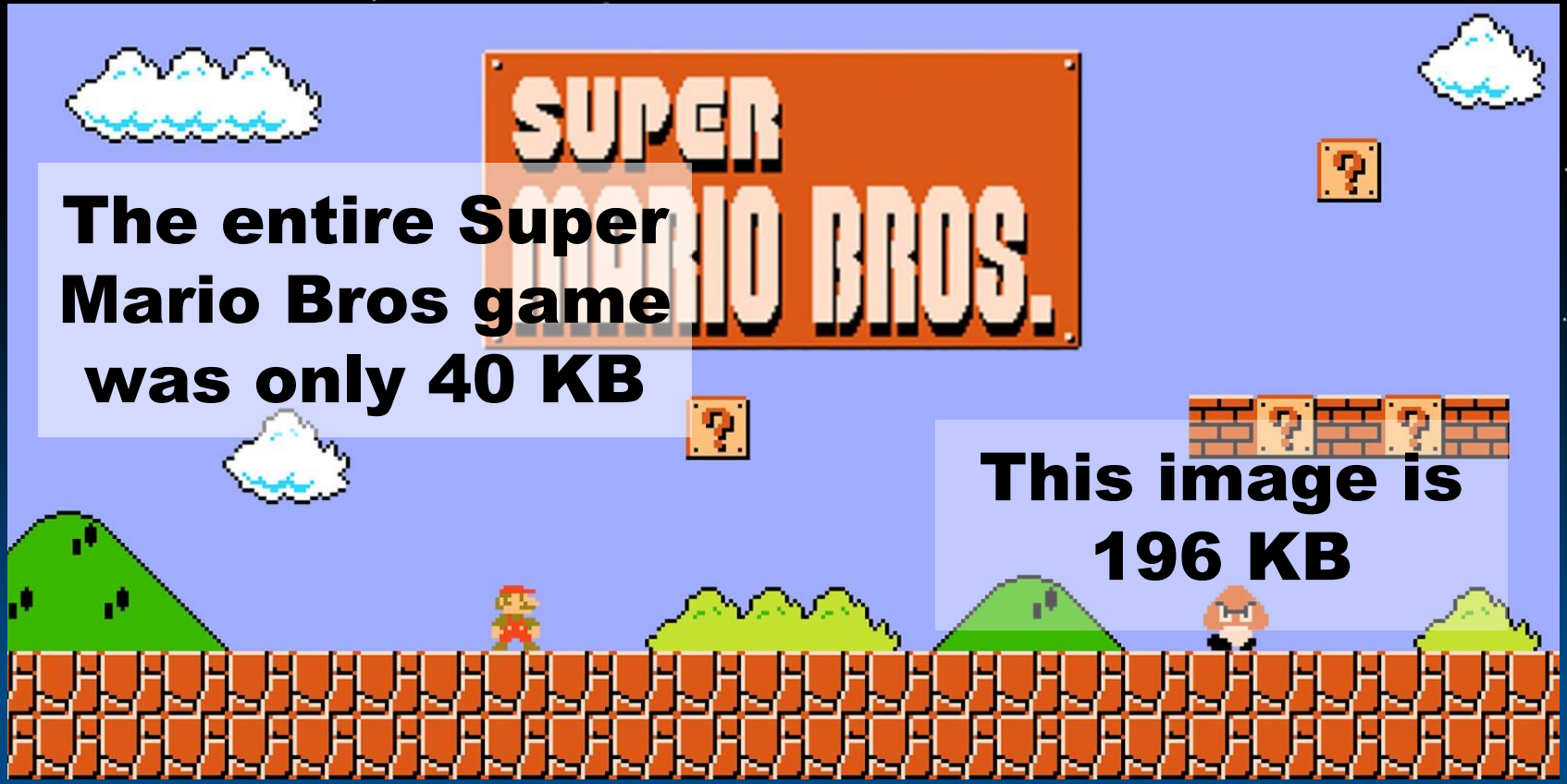
PPU Clock: kMaster / 4
CPU Clock: kMaster / 12

.nes (iNES) parser



0	‘N’
1	‘E’
2	‘S’
3	EOF
4	PRG-ROM page count (16 KB)
5	CHR-ROM page count (8 KB)
6	Flags (Mirroring, SRAM...)
7	Flags
8	PRG-RAM page count (8 KB)
9	Flags
10	Flags (unofficial)
11	0
12	0
13	0
14	0
15	0

.nes (iNES) parser



CPU Memory map

0x0000 - 0x1FFF	RAM (2 KB) + Mirrors
0x2000 - 0x3FFF, 0x4014	PPU (8 registers + Mirrors)
0x4000 - 0x4013, 0x4015, 0x4017 (W)	APU
0x4016, 0x4017 (R)	Input
0x6000 - 0x7FFF	SRAM
0x8000 - 0xFFFF	PRG-ROM

RAM, SRAM, PRG-ROM, CHR-ROM

```
uint8_t _ram[2048];

uint8_t _sram[8192];

uint8_t _prgRom[16384 * 2];

uint8_t _chrRom[8192 * 4];
```

Input

Reads of 0x4016 (P1) and 0x4017 (P2) return state of buttons in this order:

A, B, Select, Start, Up, Down, Left, Right

Possible values are:

- **0x40 (Button Released)**
- **0x41 (Button Pressed)**

Input

To read input again, write 0, then 1 to 0x4016.

NOTE: These writes are the reason why 0x4X values are returned when reading input (high bits are retained in the bus)

CPU: Registers

- Accumulator (A)
- X
- Y
- Status/Flags
  - Carry, Zero, InterruptDisable, Decimal (N/A), Break, Unused, Overflow, Sign
- Program Counter (16 bit)
- Stack Pointer

CPU: Assembly intro/review

_ram[0x1234] = 2 + 11;

```
CLC           // Clear carry Flag
LDA #$02      // Loads 2 into accum.
ADC #$11      // Adds 11 to accum.
STA $1234     // Stores result into 0x1234
```

0x0B

CPU: Addressing modes

Immediate

```
LDA #$44          _a = 0x44;
```

Zero Page

```
LDA $44           _a = Read(0x44);
```

Zero Page X & Zero Page Y

```
LDA $44,X         _a = Read(0x44 + _x);
```

Absolute

```
LDA $1234         _a = Read(0x1234);
```

Absolute X & Absolute Y

```
LDA $1234,X       _a = Read(Read(0x1234) + _x);
```

CPU: Addressing modes

Indirect X:

```
LDA ($44,X)    int temp = Read(0x44) + _x;
               int final = Read(temp) + Read(temp + 1) << 8;
               _a = ReadMem(final);
```

Indirect Y:

```
LDA ($44),Y   int addr = Read(0x44) + Read(0x44 + 1) << 8 + _y;
              _a = Read(addr);
```

CPU: Assembly intro/review

CPU: CLC

```
int CPU::CLC(AddressingMode mode)
{
    SetFlag(Flag::Carry, false);
    return 2;
}
```

CPU: LDA

```
int CPU::LDA(AddressingMode mode)
{
    int cycles = 1;
    const uint8_t value = GetValueWithMode(mode, cycles);
    SetAccumulator(value);

    return cycles;
}
```

CPU: ADC

```
int CPU::ADC(AddressingMode mode)
{
    int cycles = 1;
    const uint8_t value = GetValueWithMode(mode, cycles);
    const bool isValueNegative = IsValueNegative(value);
    const bool wasAccumulatorNegative = IsValueNegative(_accumulator);
    uint16_t result16 = _accumulator + value + (GetFlag(Flag::Carry) ? 1 : 0);
    SetAccumulator((uint8_t)result16);
    const bool isResultNegative = IsValueNegative(_accumulator);

    SetFlag(Flag::Overflow, (isValueNegative == wasAccumulatorNegative) &&
        (isValueNegative != isResultNegative));
    SetFlag(Flag::Carry, result16 != _accumulator);

    return cycles;
}
```

CPU: STA

```
int CPU::STA(AddressingMode mode)
{
    int cycles = 1;
    SetValueWithMode(mode, _accumulator, cycles);

    return cycles;
}
```

CPU: Opcodes

STA SBC CPY RTS

TAX CPX

56 INSTRUCTIONS

151 OPCODES

BPL PLP BIT BCS

TYA BEQ CLV

ROL ROR LDX

STY STX PLA RTI

CPU: Timing

```
void CPU::Tick()
{
    --_ticksUntilNextInstruction;
    if (_ticksUntilNextInstruction <= 0)
    {
        _ticksUntilNextInstruction = ExecuteNextInstruction() - 1;
    }
}
```

CPU: ExecuteNextInstruction()

```cpp
int CPU::ExecuteNextInstruction()
{
    // Fetch next opcode
    const uint8_t opcode = _memoryMapper->ReadMem(++_programCounter);

    switch (opcode)
    {
        // LDA
        case 0xA9: PrintOpcodeInfo(opcode, "LDA", AddressingMode::Immediate); return LDA(AddressingMode::Immediate);
        case 0xA5: PrintOpcodeInfo(opcode, "LDA", AddressingMode::ZeroPage); return LDA(AddressingMode::ZeroPage);
        case 0xB5: PrintOpcodeInfo(opcode, "LDA", AddressingMode::ZeroPageX); return LDA(AddressingMode::ZeroPageX);
        case 0xAD: PrintOpcodeInfo(opcode, "LDA", AddressingMode::Absolute); return LDA(AddressingMode::Absolute);
        case 0xBD: PrintOpcodeInfo(opcode, "LDA", AddressingMode::AbsoluteX); return LDA(AddressingMode::AbsoluteX);
        case 0xB9: PrintOpcodeInfo(opcode, "LDA", AddressingMode::AbsoluteY); return LDA(AddressingMode::AbsoluteY);
        case 0xA1: PrintOpcodeInfo(opcode, "LDA", AddressingMode::IndirectX); return LDA(AddressingMode::IndirectX);
        case 0xB1: PrintOpcodeInfo(opcode, "LDA", AddressingMode::IndirectY); return LDA(AddressingMode::IndirectY);

        // LDX
        case 0xA2: PrintOpcodeInfo(opcode, "LDX", AddressingMode::Immediate); return LDX(AddressingMode::Immediate);
        case 0xA6: PrintOpcodeInfo(opcode, "LDX", AddressingMode::ZeroPage); return LDX(AddressingMode::ZeroPage);
```

CPU: Unit Tests

```
TEST_METHOD(DEXINX)
{
    NESemu emu;
    CPU& cpu = *emu.GetCPU();
    uint8_t rom[PRGROM::kMaxPRGROMSize];
    rom[CPU::kResetVectorAddressL - PRGROM::kStartAddress] = 0;
    rom[CPU::kResetVectorAddressH - PRGROM::kStartAddress] = PRGROM::kStartAddress >> 8;
    int cycles;
    int codeIndex = 0;

    rom[codeIndex++] = 0xA2; // LDX Immediate
    rom[codeIndex++] = 0x00; // Value to load
    rom[codeIndex++] = 0xE8; // INX
    rom[codeIndex++] = 0xCA; // DEX
    rom[codeIndex++] = 0xCA; // DEX
    rom[codeIndex++] = 0xE8; // INX

    emu.Load(rom, PRGROM::kMaxPRGROMSize);
```

```
    cpu.ExecuteNextInstruction();
    Assert::AreEqual((uint8_t)0x00, cpu.GetX());
    cycles = cpu.ExecuteNextInstruction();
    Assert::AreEqual((uint8_t)0x01, cpu.GetX());
    Assert::AreEqual(false, cpu.GetFlag(CPU::Flag::Sign));
    Assert::AreEqual(false, cpu.GetFlag(CPU::Flag::Zero));
    Assert::AreEqual(2, cycles);
    cycles = cpu.ExecuteNextInstruction();
    Assert::AreEqual((uint8_t)0x00, cpu.GetX());
    Assert::AreEqual(false, cpu.GetFlag(CPU::Flag::Sign));
    Assert::AreEqual(true, cpu.GetFlag(CPU::Flag::Zero));
    Assert::AreEqual(2, cycles);
    cycles = cpu.ExecuteNextInstruction();
    Assert::AreEqual((uint8_t)0xFF, cpu.GetX());
    Assert::AreEqual(true, cpu.GetFlag(CPU::Flag::Sign));
    Assert::AreEqual(false, cpu.GetFlag(CPU::Flag::Zero));
    Assert::AreEqual(2, cycles);
    cycles = cpu.ExecuteNextInstruction();
    Assert::AreEqual((uint8_t)0x00, cpu.GetX());
    Assert::AreEqual(false, cpu.GetFlag(CPU::Flag::Sign));
    Assert::AreEqual(true, cpu.GetFlag(CPU::Flag::Zero));
    Assert::AreEqual(2, cycles);
}
```

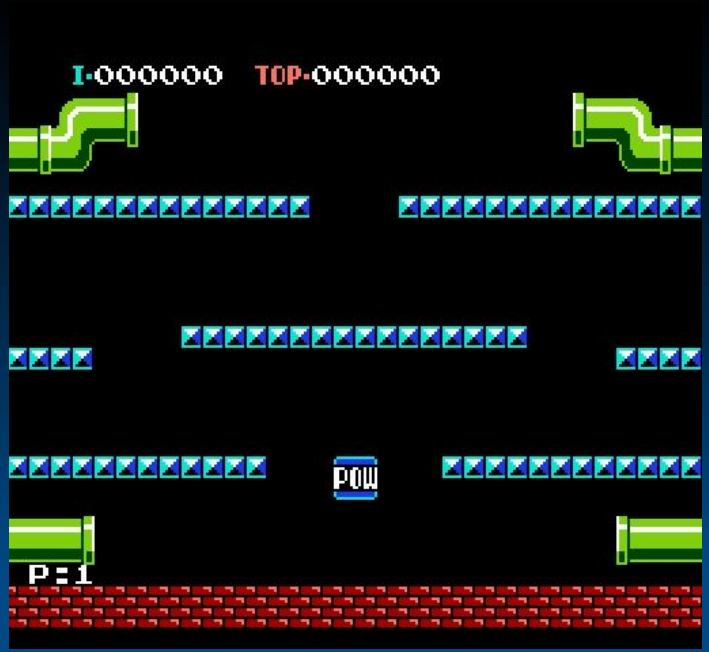
PPU: Intro

2 types of renderable objects:

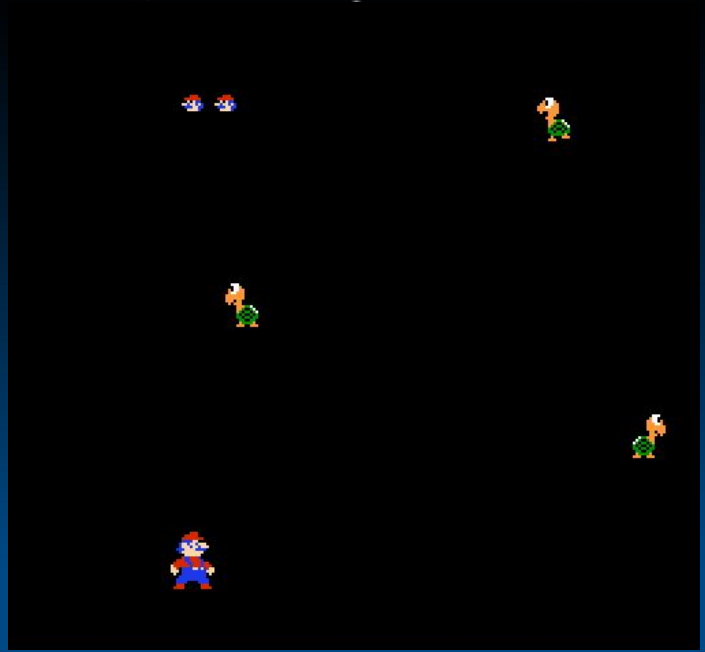
- Background: Mostly static objects, scrollable. Stored in nametables.
- Sprites: Moving objects (player, enemies, projectiles...), but unaffected by scroll. Stored in OAM. Can be above or behind the background.

PPU: Background vs Sprites

Background



Sprites



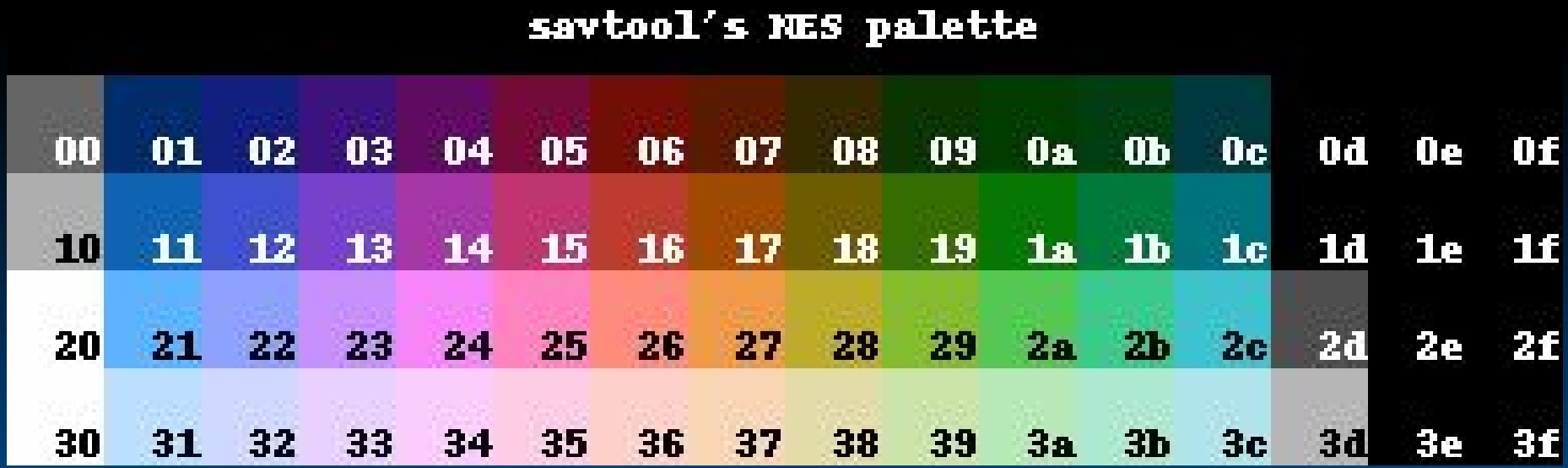
PPU: Registers & Data

- **Control (W): Various PPU config values: interrupt enable, sprite height (8/16), bkg/sprite pattern table...**
- **Mask (W): More config values affecting colour and visibility of sprites and background.**
- **Status (R): Various flags indicating current PPU status: VBlank, sprite 0 Hit, sprite overflow...**

PPU: Registers & Data

- PPU Address (W): For setting VRAM address.
- PPU Data (R/W): VRAM data read/write.
- OAM Address (W): Used for initialising OAM address.
- OAM Data (R/W): Sprite data read/write. Each write increments the address.
- Scroll (W): 2 writes: 1 for X, 1 for Y.
- OAM DMA (W): Fast RAM->OAM transfer.

PPU: Palettes



PPU: Palettes

The output colours aren't accessed directly but by palettes:

- **Universal background colour**
- **4 Background palettes (3 colours each)**
- **4 Sprite palettes (3 colours each)**

Address	Purpose
$3F00	Universal background color
$3F01-$3F03	Background palette 0
$3F05-$3F07	Background palette 1
$3F09-$3F0B	Background palette 2
$3F0D-$3F0F	Background palette 3
$3F11-$3F13	Sprite palette 0
$3F15-$3F17	Sprite palette 1
$3F19-$3F1B	Sprite palette 2
$3F1D-$3F1F	Sprite palette 3

PPU: Nametables

Nametables: Arrays that contain indices of patterns (tiles)

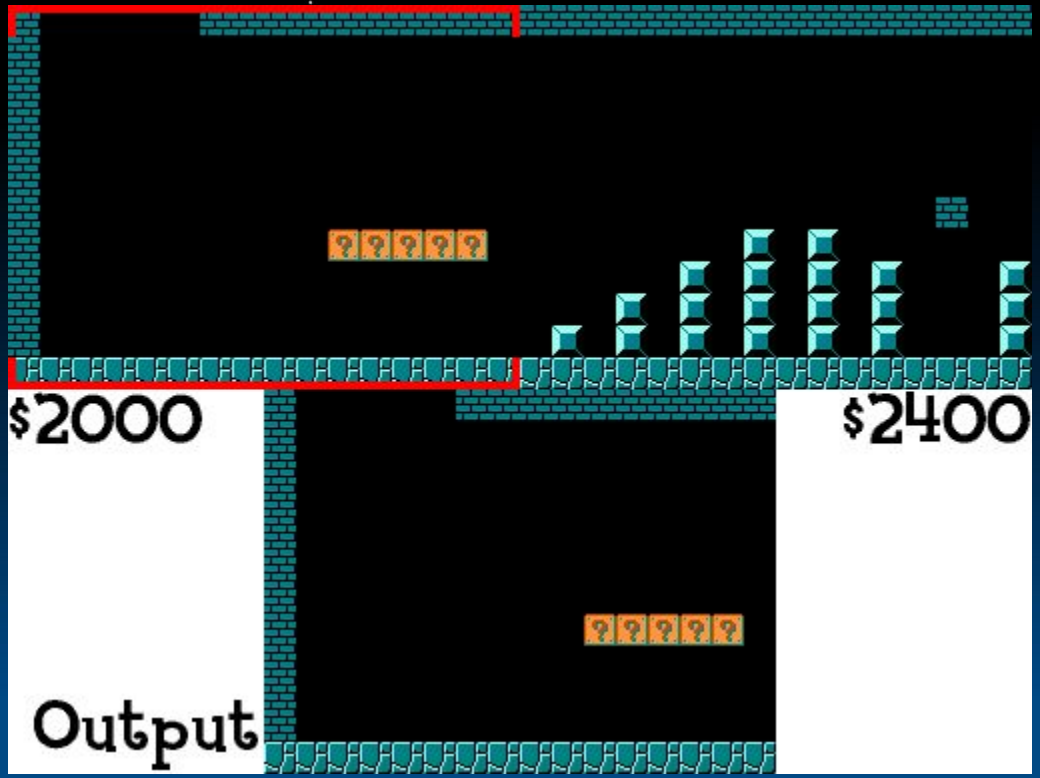
Each nametable contains 30x32 tiles (256x240 pixels = 1 fullscreen)

0x2000	0x2400
0x2800	0x2C00

Each nametable is 1 KB, however there are only 2 KB of VRAM! Solution: mirroring:

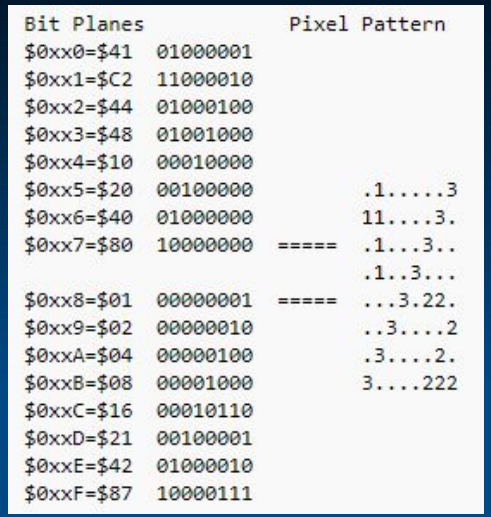
- **Vertical mirroring: 0x2000 equals 0x2800 and 0x2400 equals 0x2C00**
- **Horizontal mirroring: 0x2000 equals 0x2400 and 0x2800 equals 0x2C00**

PPU: Scrolling



PPU: Pattern/Tile tables

Pattern table: Area of data (part of CHR-ROM) that defines tiles (each tile = 16 bytes) Each pixel is represented by a 2 bit value (4 colours, 1 being transparent) made up of 2 planes.



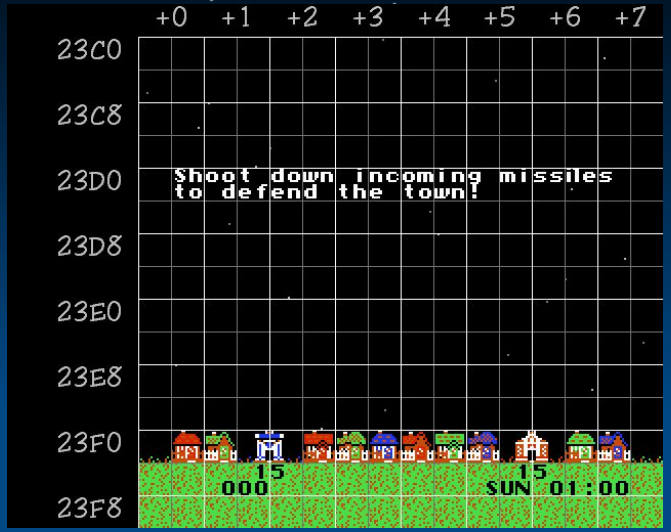
PPU: Pattern/Tile tables

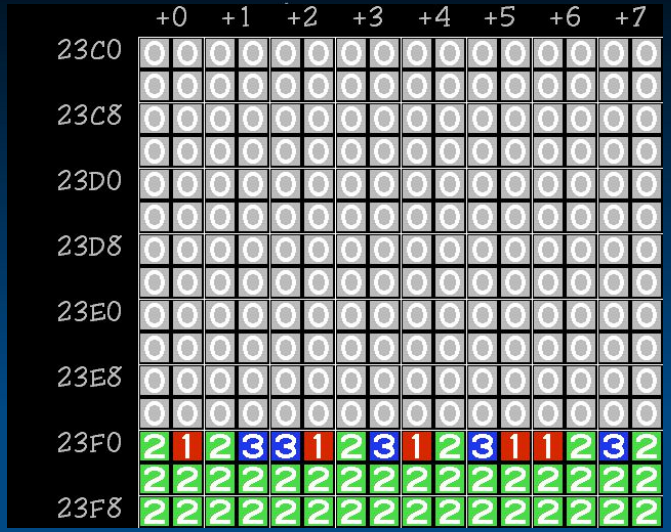
```
Bit Planes                Pixel Pattern
$0xx0=$41  01000001
$0xx1=$C2  11000010
$0xx2=$44  01000100
$0xx3=$48  01001000
$0xx4=$10  00010000
$0xx5=$20  00100000          .1.....3
$0xx6=$40  01000000          11....3.
$0xx7=$80  10000000  =====   .1...3..
                             .1..3...
$0xx8=$01  00000001  =====   ...3.22.
$0xx9=$02  00000010          ..3....2
$0xxA=$04  00000100          .3....2.
$0xxB=$08  00001000          3....222
$0xxC=$16  00010110
$0xxD=$21  00100001
$0xxE=$42  01000010
$0xxF=$87  10000111
```

PPU: Attribute tables

Attribute table: 64-byte array at the end of each nametable that controls which palette is assigned to each part of the background.

Each byte controls a 4x4 tile area. Each 2 bits of this byte controls a 2x2 tile sub-area.





PPU: CalculateBkgColourAt()

1. Calculate pattern index (Base nametable + tile position within nametable)
2. Get pattern value (2 bits) -> Index within palette.
   If 0, return transparent colour
3. Get attribute value, select area bits (2 bits) -> Palette number.
4. Final colour index = Palette number + Index within palette.

PPU: Sprites

- Up to 64 sprites (OAM)
  - Each sprite is made of 4 bytes:
    - 0: Y position
    - 1: Pattern index
    - 2: Attributes (2 palette bits, priority vs background, horizontal flip, vertical flip)
    - 3: X position
- Up to 8 sprites per scanline (Secondary OAM)

PPU: Sprite evaluation

- For each scanline: find (up to 8) sprites in scanline, copy to secondary OAM
- For each pixel within scanline
  - Find first sprite that overlaps pixel within secondary OAM
  - Evaluate colour for pixel (apply flipping if necessary)
    - If colour = transparent, check next sprite
    - If colour != transparent, return colour index

PPU: RenderPixel()

```
void PPU::RenderPixel(int x, int y)
{
    SpriteLayer spriteLayer;
    const uint8_t spritePixelColour = CalculateSpriteColourAt(x, y, spriteLayer);
    const uint8_t bkgPixelColour = CalculateBkgColourAt(x, y);

    if (spritePixelColour != kTransparentPixelColour &&
        (spriteLayer == SpriteLayer::Front || bkgPixelColour == kTransparentPixelColour))
    {
        SetPixelInFrameBuffer(x, y, spritePixelColour);
    }
    else if (bkgPixelColour != kTransparentPixelColour)
    {
        SetPixelInFrameBuffer(x, y, bkgPixelColour);
    }
    else
    {
        SetPixelInFrameBuffer(x, y, ReadPPUMem(kUniversalBkgColourAddress));
    }
}
```

TODO

- Implement more memory mappers to support more games (i.e. SMB 3)
- APU

Lessons learned + advice

- CPU Unit Testing has been invaluable, almost a must.
- Asserts have also been super useful for checking my assumptions were right.
- Most important part to get right is probably memory mapping. All communication between components depends on it.

Lessons learned + advice

- Buts require A LOT of patience given you didn’t code the game.
- Start with simpler/older games like Mario Bros. Don’t start with *Super* Mario Bros, as it’s more challenging.
- Writing a NES emulator requires discipline and patience, but it’s not difficult.
- Again, be PATIENT, DON’T RUSH

Resources

Best NES wiki and forums:

nesdev.com

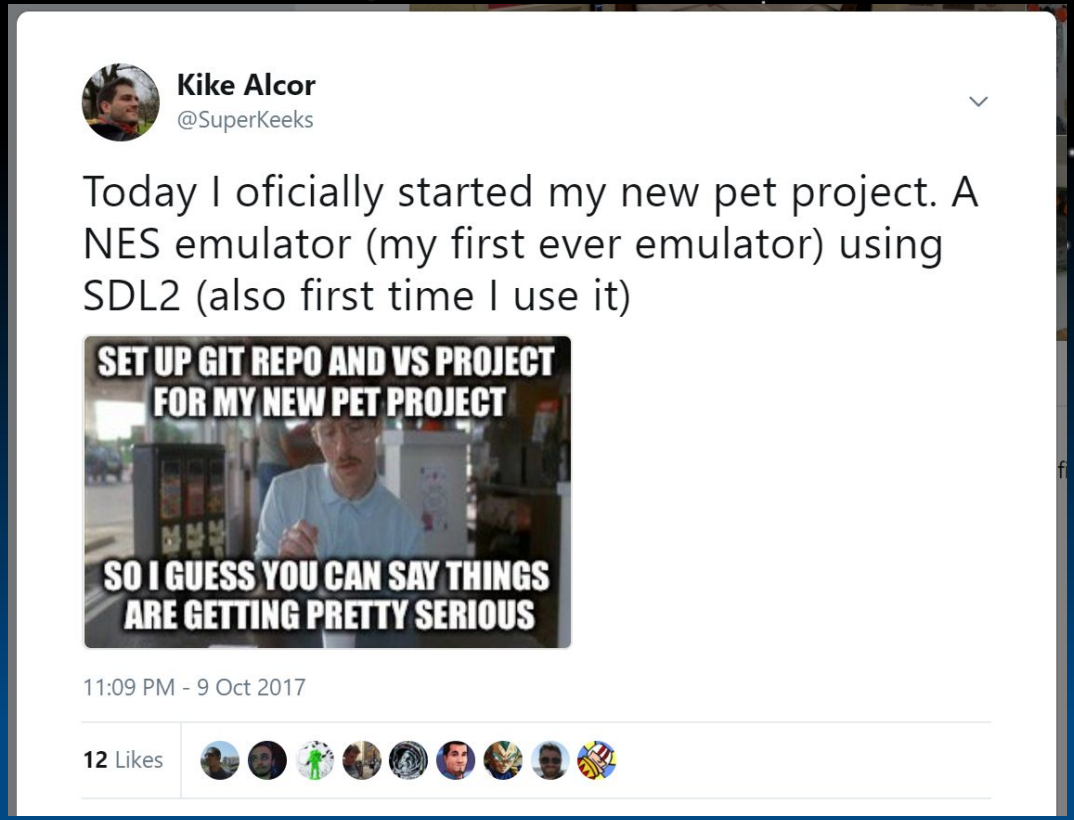
6502 opcode info:

6502.org/tutorials/6502opcodes.html

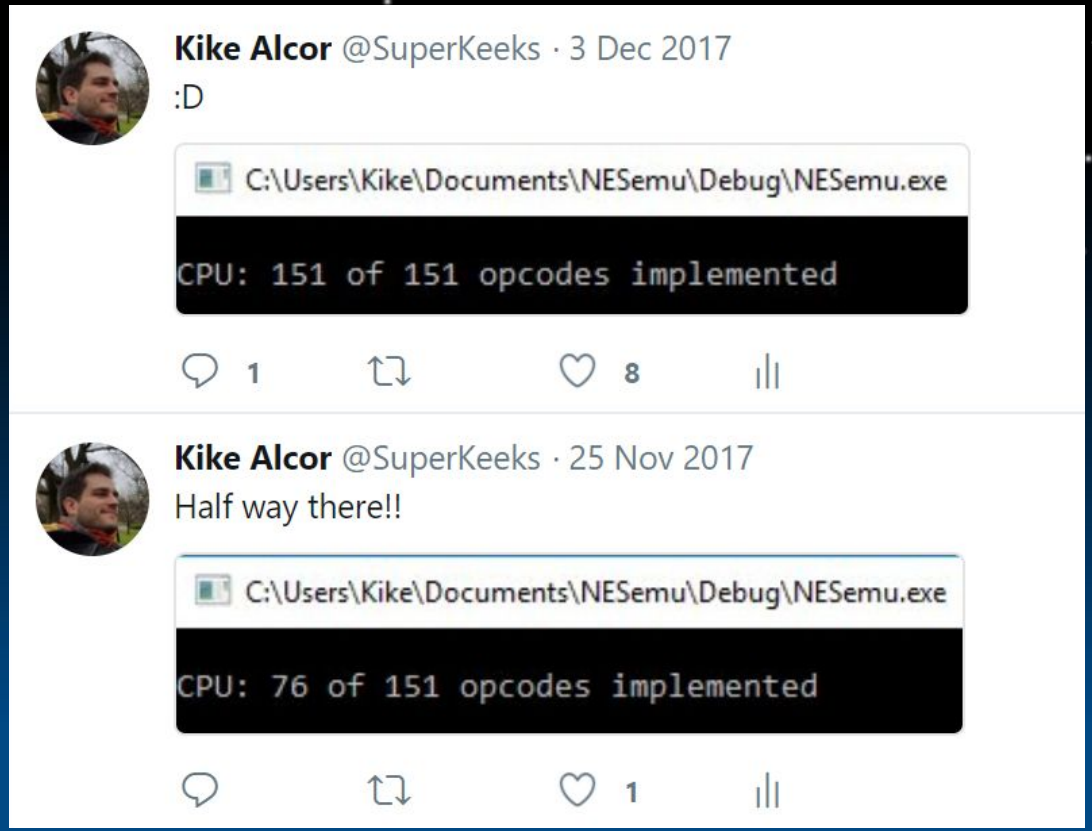
My NES emu repo:

bitbucket.org/gamezer0/nesemu

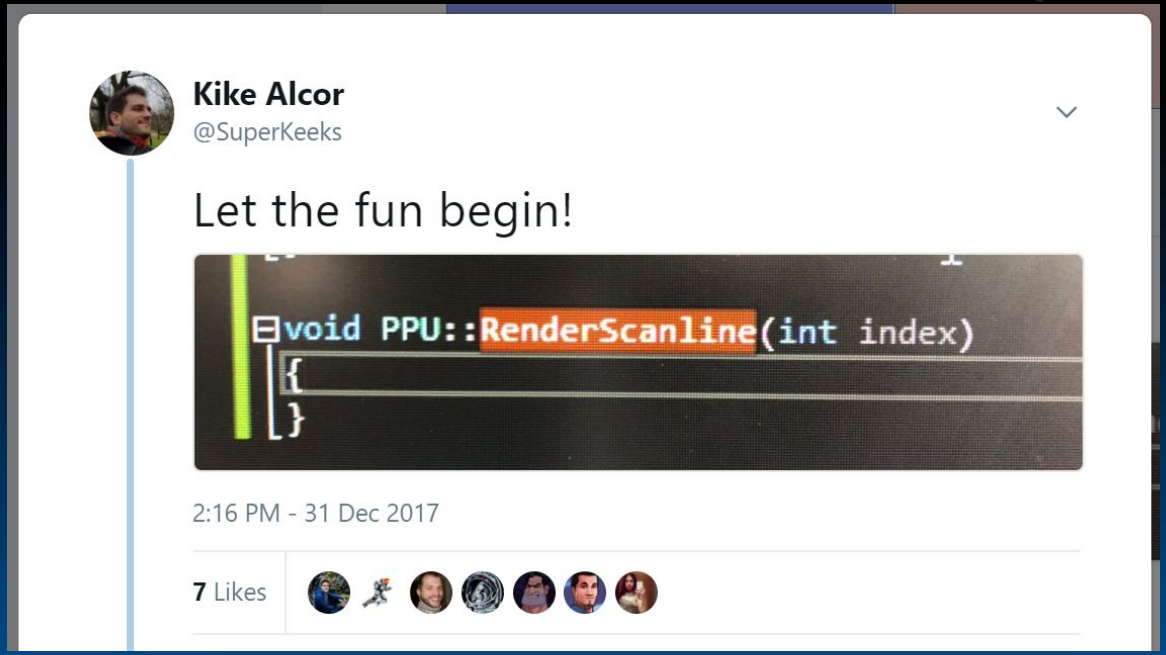
Project timeline



Project timeline



Project timeline



Project timeline

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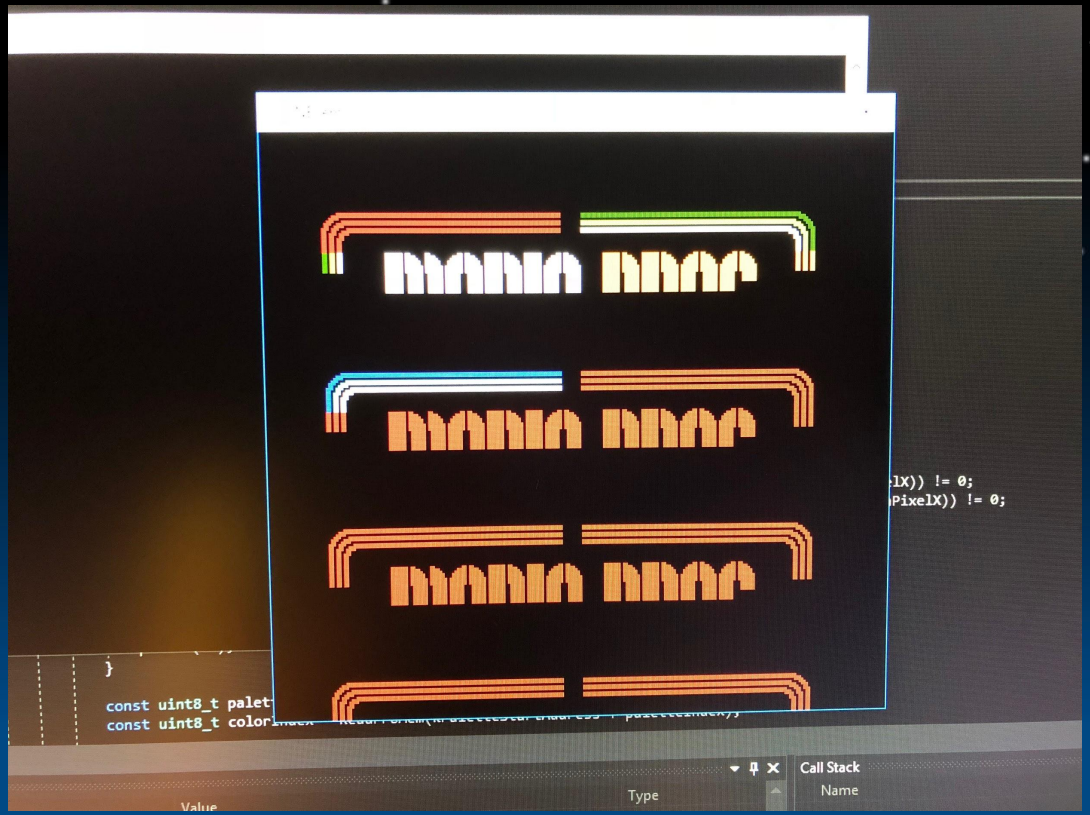

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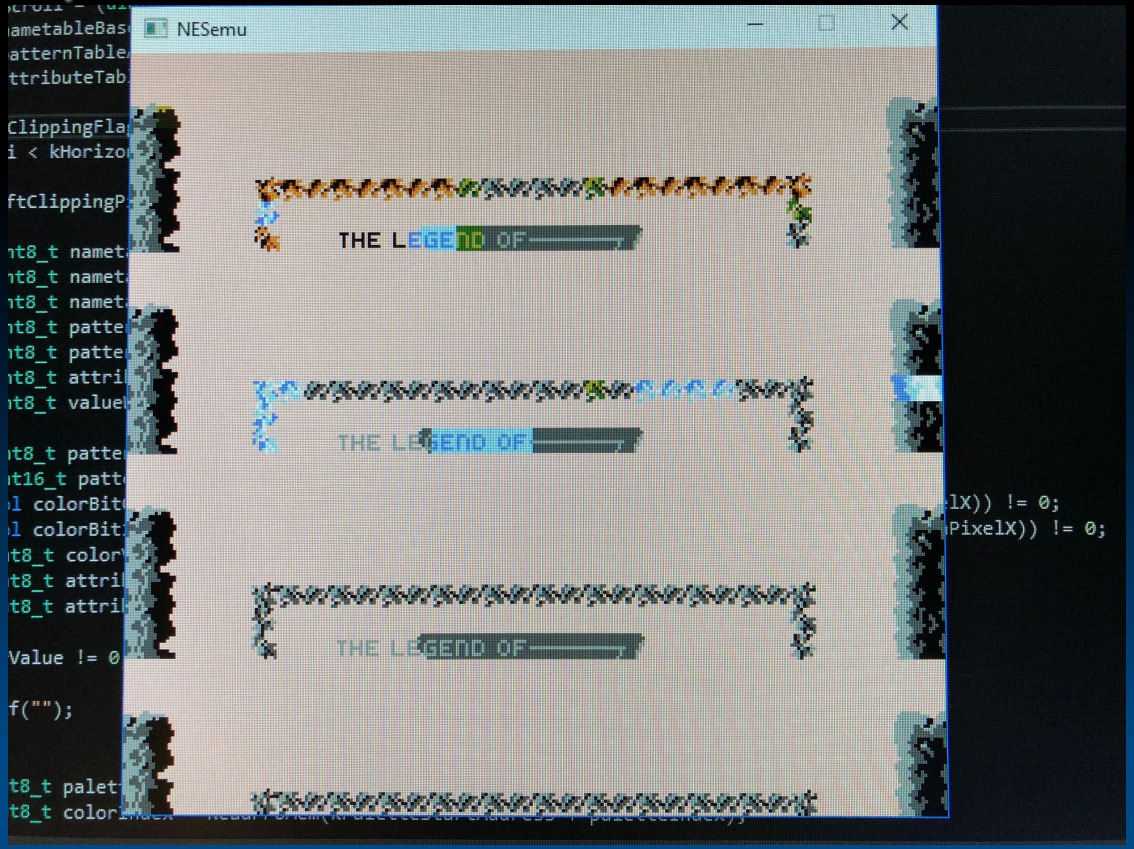

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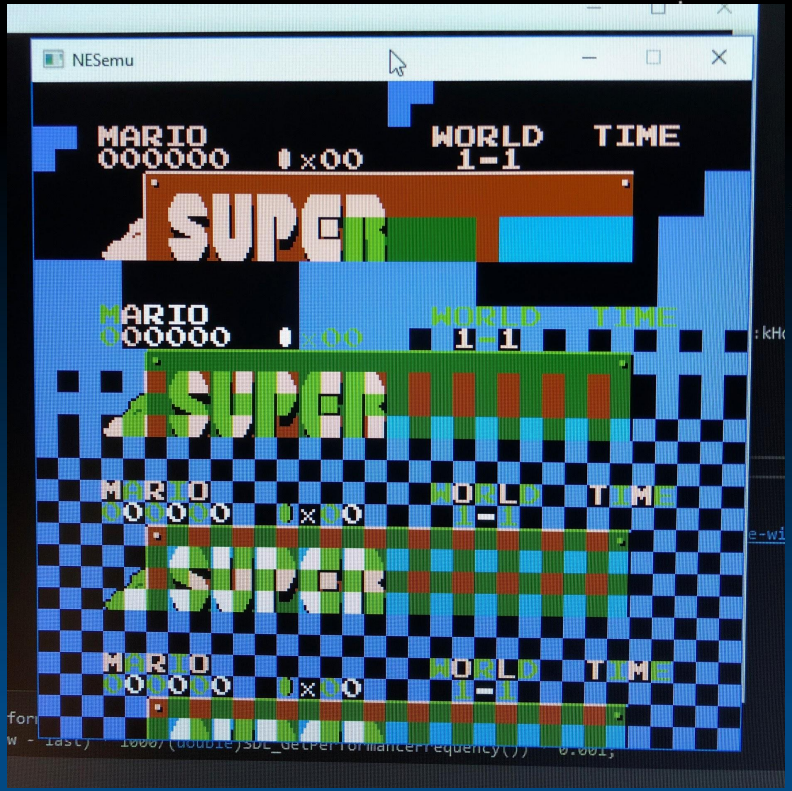

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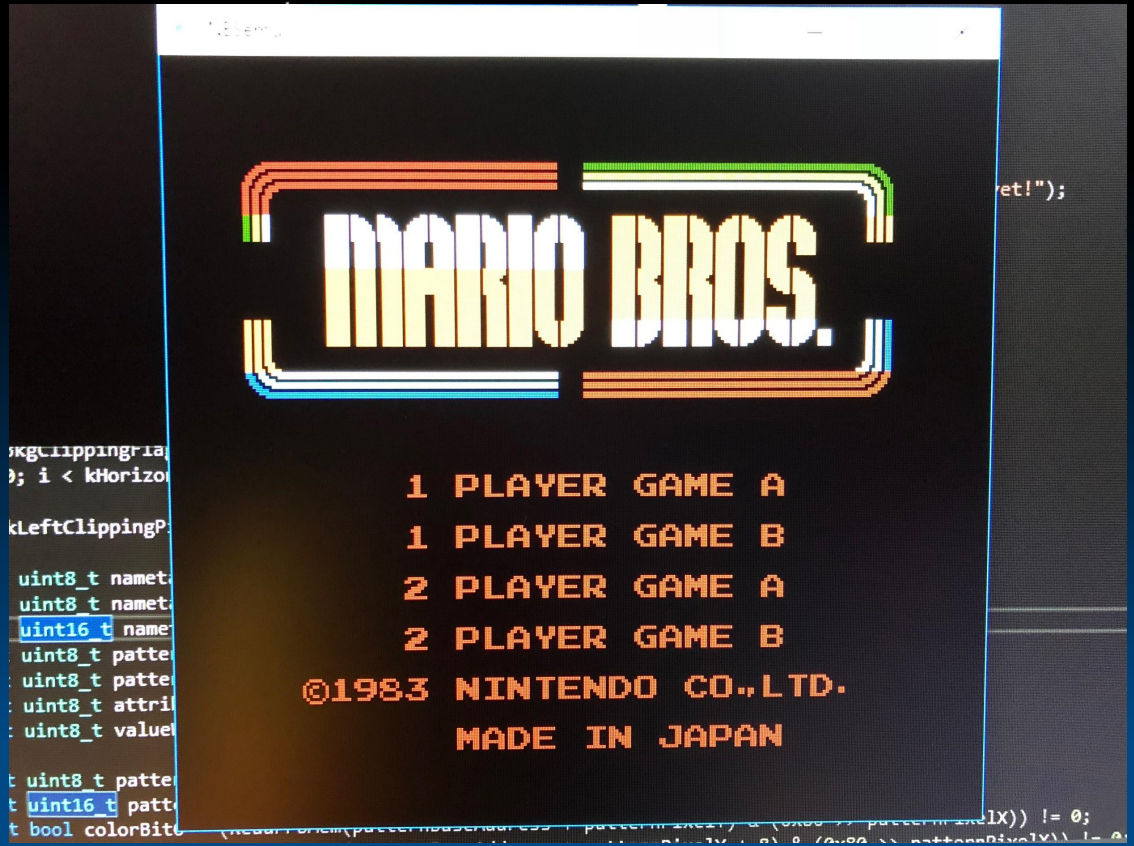

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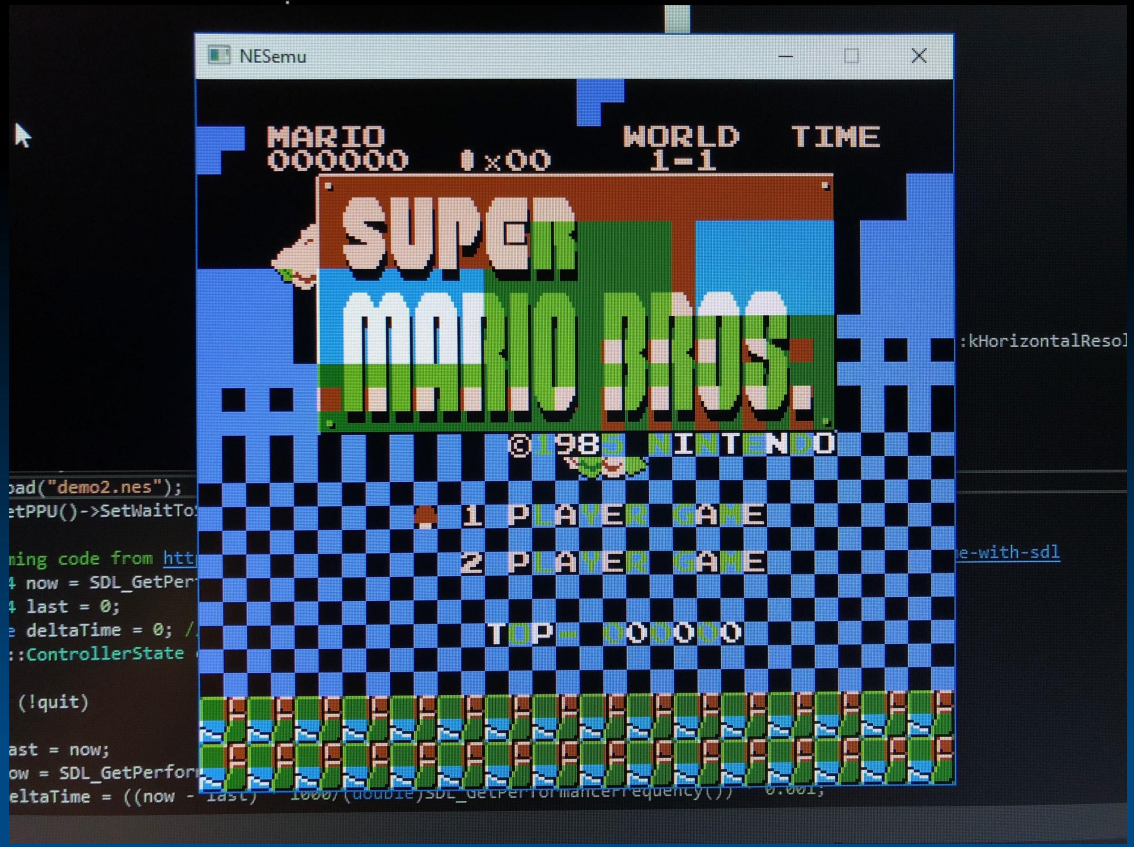

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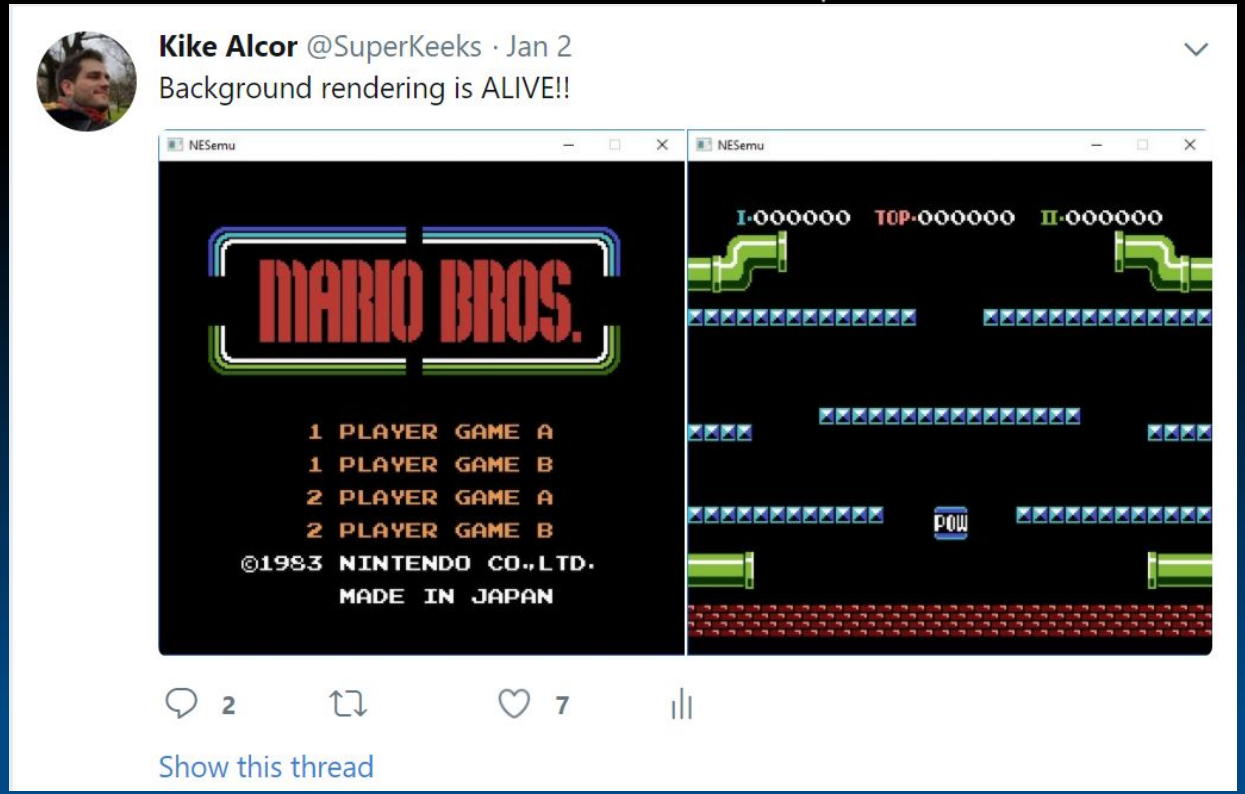
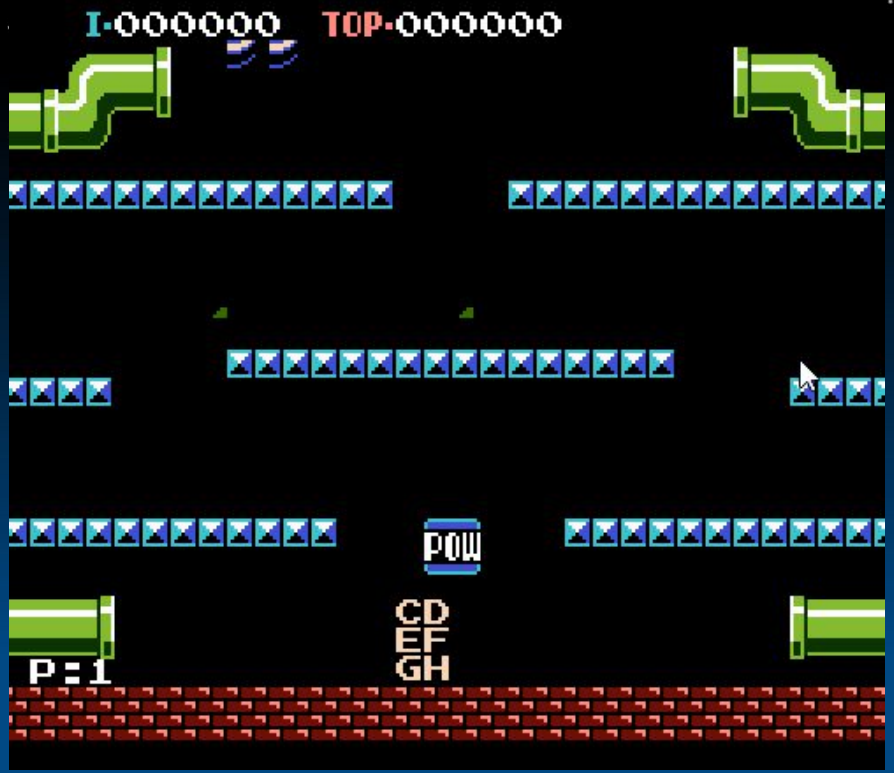


Project timeline

Project timeline

Project timeline



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MISSION ACCOMPLISHED!!!

THANKS!

 @SuperKeeks

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