An open-source Emulator of Legacy Apple Devices

A Dive into Reverse Engineering and Understanding the iPod Touch

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About Me

- Postdoctoral Researcher @ EPFL, Switzerland
- Researcher in distributed ML Systems
- Reverse engineering enthousiast
  - Mobile banking apps during PhD

Motivation

- Inspired by Jonathan Afek's blog post
  - "Running iOS in QEMU to an interactive bash shell"
- Fun challenge
- (long-term) hardware preservation

Where to start?

- Which device to emulate?
- Modern embedded devices are hard to emulate
  - Neural engines
  - FaceID/TouchID engines
  - Secure enclaves
  - Trust caches
- iPod Touch 1G looks like a promising starting point
  - Released in 2007, ARMv6 instruction set
  - Should be simple enough to emulate *

iPod Touch 1G

* Famous last words

Related Projects

- Very early attempt by @cmwdotme to emulate S5L8900
  - Evolved into Correlium
- iPhone 6s plus emulation by Johathan Afek
- iPhone 11 emulator by Trung Nguyen
- OpeniBoot

QEMU

- Open-source framework for hardware emulation
- Define peripherals and their expected behaviour
- Support for popular hardware and protocols
  - USB, NICs, SPI, I^2C, SDIO, …

- Poor documentation ☹

Debugging with GDB

build — gdb — 175×48

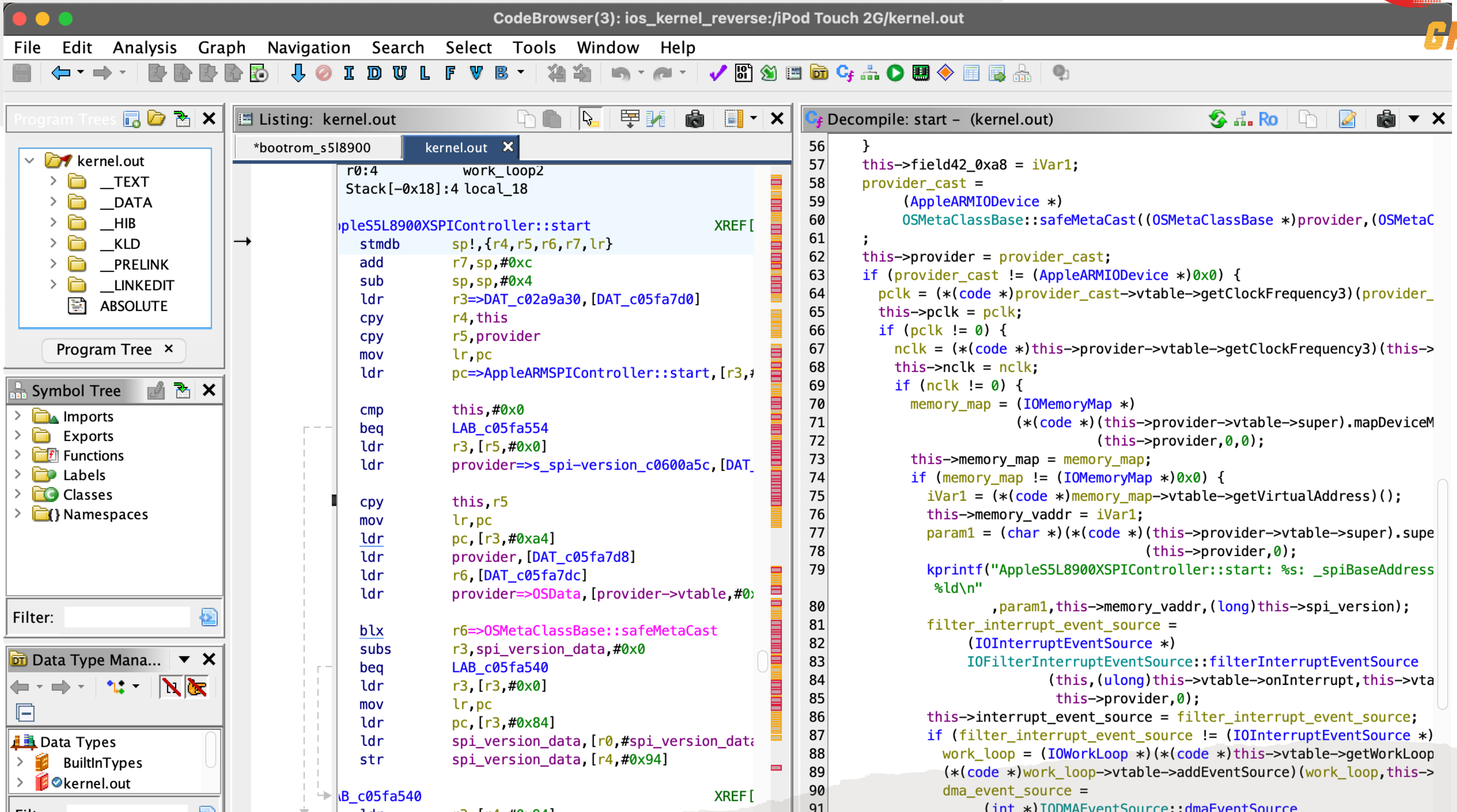
...evos/Documents/generate_nor_it2g/nor.bin -serial mon:stdio -cpu max -m 2G -d unimp -S -s   ~/Documents/qemu-it2g/build — gdb

```
Register group: general
r0             0x0            0              r1             0x0            0              r2             0x0            0
r3             0x0            0              r4             0x0            0              r5             0x0            0
r6             0x0            0              r7             0x0            0              r8             0x0            0
r9             0x0            0              r10            0x0            0              r11            0x0            0
r12            0x0            0              sp             0x0            0x0            lr             0x0            0
pc             0x40           0x40           cpsr           0x400001d3     1073742291     fpscr          0x0            0
fpsid          0x41034070     1090732144     fpexc          0x0            0              ID_MMFR1       0x40000000     1073741824
IFAR           0x0            0              ID_MMFR2       0x1260000      19267584       PMEVTYPER0     0x0            0
ID_MMFR3       0x2122211      34742801       VSESR_EL2      0x0            0              PMEVTYPER1     0x0            0
NSACR          0xc00          3072           DFAR           0x0            0              PMEVTYPER2     0x0            0
CBAR           0x0            0              ERRIDR_EL1     0x0            0              PMEVTYPER3     0x0            0
DBGBVR4_EL1    0x0            0              PMEVTYPER4     0x0            0              DBGBCR4_EL1    0x0            0
PMEVTYPER5     0x0            0              PMCCNTR        0x0            0              VDISR_EL2      0x0            0
RES_0_C0_C4_X  0x0            0              CNTP_CVAL      0x0            0              JIDR           0x0            0
```

```
  >0x40    mov     r0, pc
   0x44    ldr     r1, [pc, #708]  @ 0x310
   0x48    sub     r0, r0, r1
   0x4c    ldr     r1, [pc, #704]  @ 0x314
   0x50    cmp     r0, r1
   0x54    beq     0x78
   0x58    ldr     r1, [pc, #692]  @ 0x314
   0x5c    ldr     r2, [pc, #692]  @ 0x318
   0x60    ldr     r3, [r0], #4
   0x64    subs    r2, r2, #4
   0x68    str     r3, [r1], #4
   0x6c    bne     0x60
   0x70    ldr     r1, [pc, #668]  @ 0x314
   0x74    bx      r1
```

```
remote Thread 1.1 In:                                                                L??   PC: 0x40
(gdb) layout r
(gdb) target remote localhost:1234
Remote debugging using localhost:1234
warning: No executable has been specified and target does not support
determining executable automatically.  Try using the "file" command.
0x00000000 in ?? ()
(gdb) si
0x00000040 in ?? ()
(gdb)
```

Reverse Engineering with Ghidra

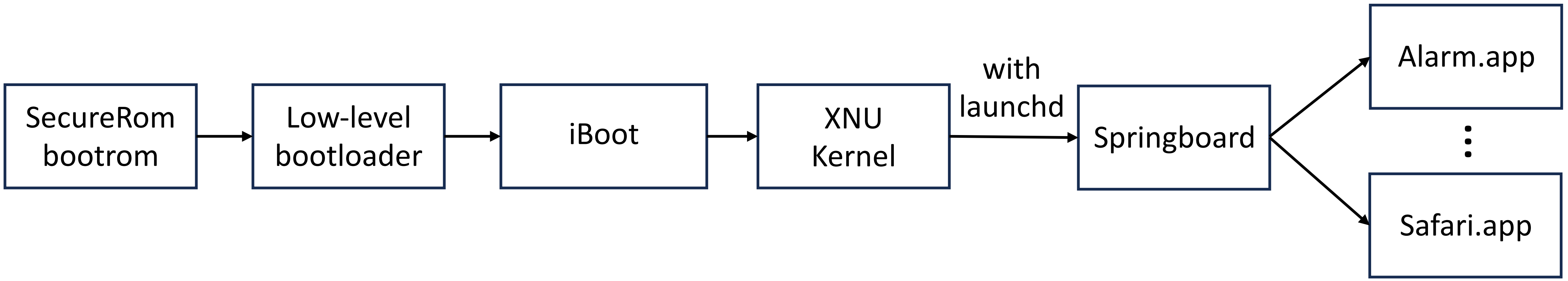


Philosophy

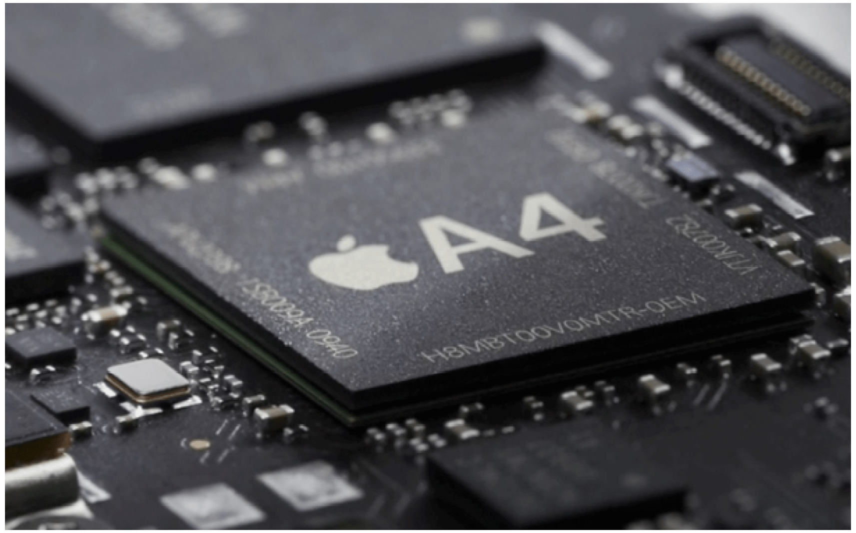
- Stay close to the real hardware
- Avoid relying on image patching if possible
- Hacks and workarounds might bite us later, better get it right early on

- As expected, emulator ended up with a bunch of hacks ☺

iPod Touch 1G/2G Boot Chain



Bootrom



- Very first code that executes on the device
  - Initializes some key peripherals
  - Loads LLB or puts the device into DFU (restoration) mode

- Jumps to unknown memory addresses
- Probably some proprietary encryption/decryption logic by Samsung
- No access to/dumps of the memory being jumped to ☹
  - Didn’t have a physical IT1G at that time

Low-level Bootloader (LLB)

- Initializes some peripherals and loads iBoot
- Same problem, jumps to unknown memory locations
- Let's skip the bootrom and LLB, and go straight to iBoot!

```
// load iBoot
file_data = NULL;
if (g_file_get_contents(nms->iboot_path, (char **)&file_data, &fsize, NULL)) {
    allocate_ram(sysmem, "iboot", IBOOT_BASE, 0x400000);
    address_space_rw(nsas, IBOOT_BASE, MEMTXATTRS_UNSPECIFIED, (uint8_t *)file_data, fsize, 1);
}
```

iBoot (main bootloader)

- Responsible for loading the kernel from NAND
- iBoot source code got leaked in 2018

Apple has confirmed that some of the source code for its iOS mobile operating system has been leaked online.

The boot-up source code used on its older iOS 9 operating platform was posted on code-sharing website Github.

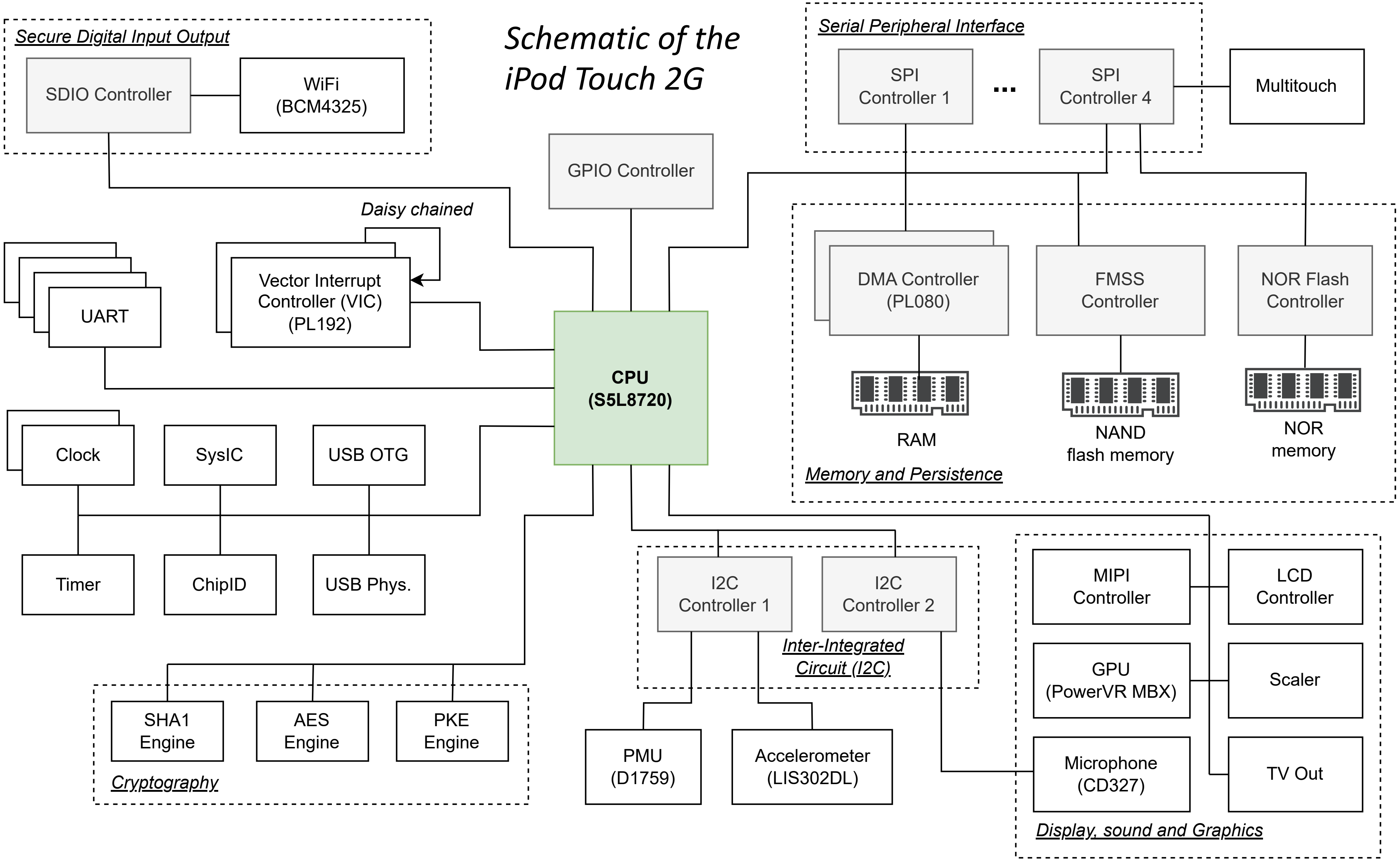
Apple typically keeps most of its iOS source code private and ordered Github to remove the content.

Device Tree

- Lists all peripherals and properties
- Included in the IPSW, populated by iBoot
- I used a public DT dump published on GitHub as reference

```
|
+-o aes@C00000  <class AppleARMIODevice, registered, matched, active, bus
| | {
| |   "IOInterruptControllers" = ("IOInterruptController00904AD0")
| |   "clock-ids" = <02000000>
| |   "IODeviceMemory" = (({"address"=952107008,"length"=4096}))
| |   "clock-gates" = <0a000000>
| |   "xxxxxxxx-disable_keys" = <"0_▯","Ksid">
| |   "AAPL,phandle" = <90b29000>
| |   "IOInterruptSpecifiers" = (<27000000>)
| |   "name" = <"aes">
| |   "device_type" = <"aes">
| |   "interrupts" = <27000000>
| |   "compatible" = <"aes,s5l8900x">
| |   "reg" = <0000c00000100000>
| |   "interrupt-parent" = <d04a9000>
| | }
| |
| +-o AppleS5L8900XAES  <class AppleS5L8900XAES, registered, matched, act
|     {
|       "IOProviderClass" = "AppleARMIODevice"
|       "IOProbeScore" = 0
|       "CFBundleIdentifier" = "com.apple.driver.AppleS5L8900XCrypto"
|       "IOMatchCategory" = "IODefaultMatchCategory"
|       "IOUserClientClass" = "IOAESAcceleratorUserClient"
|       "IONameMatched" = "aes,s5l8900x"
|       "IOClass" = "AppleS5L8900XAES"
|       "IONameMatch" = "aes,s5l8900x"
|       "IOPowerManagement" = {"CurrentPowerState"=1}
|     }
```

These devices are complicated!



Peripherals

- The kernel communicates with peripherals through memory-mapped I/O (MMIO)
- Each peripheral has a dedicated space in memory

```
// MMIO addresses
#define VROM_MEM_BASE   0x0
#define INSECURE_RAM_MEM_BASE 0x8000000
#define SECURE_RAM_MEM_BASE   0xB000000
#define FRAMEBUFFER_MEM_BASE  0xFB00000
#define IBOOT_MEM_BASE        0xFF00000
#define SRAM1_MEM_BASE        0x22020000
#define SHA1_MEM_BASE         0x38000000
#define DMAC0_MEM_BASE        0x38200000
#define USBOTG_MEM_BASE       0x38400000
#define DMAC1_0_MEM_BASE      0x38700000
#define DISPLAY_MEM_BASE      0x38900000
#define FMSS_MEM_BASE         0x38A00000
#define AES_MEM_BASE          0x38C00000
#define SDIO_MEM_BASE         0x38D00000
#define VIC0_MEM_BASE         0x38E00000
#define VIC1_MEM_BASE         0x38E01000
#define EDGEIC_MEM_BASE       0x38E02000
#define H264_MEM_BASE         0x38F00000
#define SCALER_CSC_MEM_BASE   0x39000000
#define TVOUT_MIXER2_MEM_BASE 0x39100000
#define TVOUT_MIXER1_MEM_BASE 0x39200000
#define TVOUT_SDO_MEM_BASE    0x39300000
#define SYSIC_MEM_BASE        0x39700000
#define DMAC1_1_MEM_BASE      0x39900000
#define MBX1_MEM_BASE         0x3B000000
#define MBX2_MEM_BASE         0x39400000
#define SPI0_MEM_BASE         0x3C300000
#define USBPHYS_MEM_BASE      0x3C400000
#define CLOCK0_MEM_BASE       0x3C500000
#define I2C0_MEM_BASE         0x3C600000
#define TIMER1_MEM_BASE       0x3C700000
#define I2C1_MEM_BASE         0x3C900000
#define UART0_MEM_BASE        0x3CC00000
#define SPI1_MEM_BASE         0x3CE00000
#define GPIO_MEM_BASE         0x3CF00000
#define PKE_MEM_BASE          0x3D000000
#define CHIPID_MEM_BASE       0x3D100000
#define SPI2_MEM_BASE         0x3D200000
#define UNKNOWN1_MEM_BASE     0x3D700000
#define MIPI_DSI_MEM_BASE     0x3D800000
```

Initializing Hardware with QEMU

```c
static void ipod_touch_sysic_class_init(ObjectClass *klass, void *data)
{

}

static const TypeInfo ipod_touch_sysic_type_info = {
    .name = TYPE_IPOD_TOUCH_SYSIC,
    .parent = TYPE_SYS_BUS_DEVICE,
    .instance_size = sizeof(IPodTouchSYSICState),
    .instance_init = ipod_touch_sysic_init,
    .class_init = ipod_touch_sysic_class_init,
};

static void ipod_touch_sysic_register_types(void)
{
    type_register_static(&ipod_touch_sysic_type_info);
}

type_init(ipod_touch_sysic_register_types)
```

Talking to Peripherals

```
static uint64_t ipod_touch_sysic_read(void *opaque, hwaddr addr, unsigned size)
{
    IPodTouchSYSICState *s = (IPodTouchSYSICState *) opaque;
    fprintf(stderr, "%s: offset = 0x%08x\n", __func__, addr);

    switch (addr) {
        case POWER_ONCTRL:
            return 42;
      default:
        break;
    }
    return 0;
}

static void ipod_touch_sysic_write(void *opaque, hwaddr addr, uint64_t val, unsigned size)
{
    IPodTouchSYSICState *s = (IPodTouchSYSICState *) opaque;
    fprintf(stderr, "%s: writing 0x%08x to 0x%08x\n", __func__, val, addr);

    switch (addr) {
        case POWER_ONCTRL:
            // do something
            break;
    }
}
```

More Complicated Hardware

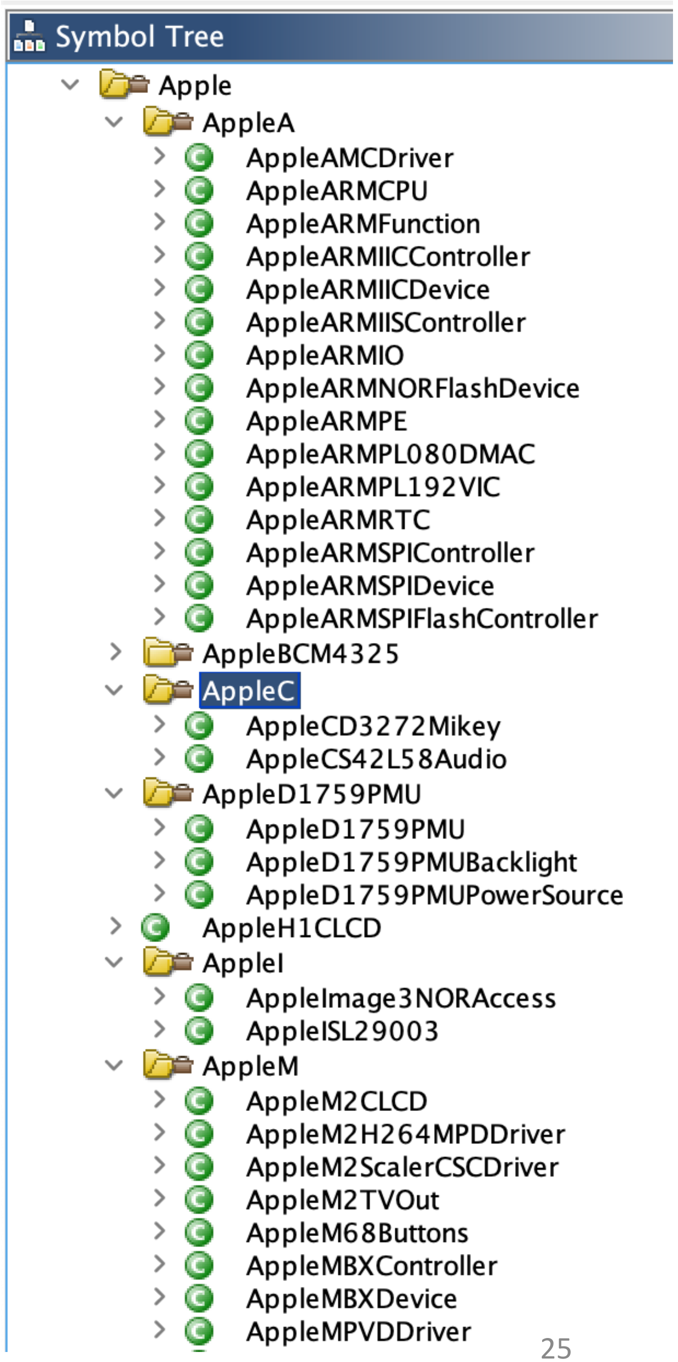
```
static uint64_t ipod_touch_spi_read(void *opaque, hwaddr addr, unsigned size)
{
    IPodTouchSPIState *s = IPOD_TOUCH_SPI(opaque);
    //printf("%s (base %d): read from location 0x%08x\n", __func__, s->base, addr);

    uint32_t r;
    bool run = false;

    r = s->regs[addr >> 2];
    switch (addr) {
        case R_RXDATA: {
            const uint8_t *buf = NULL;
            int word_size = apple_spi_word_size(s);
            uint32_t num = 0;
            if (fifo8_is_empty(&s->rx_fifo)) {
                hw_error("Rx buffer underflow\n");
                qemu_log_mask(LOG_GUEST_ERROR, "%s: rx underflow\n", __func__);
                r = 0;
                break;
            }
            buf = fifo8_pop_buf(&s->rx_fifo, word_size, &num);
            memcpy(&r, buf, num);

            if (fifo8_is_empty(&s->rx_fifo)) {
                run = true;
            }
            break;
        }
        case R_STATUS: {
```

Attaching Peripherals to the Machine

```c
dev = qdev_new("ipodtouch.sysic");
IPodTouchSYSICState *sysic_state = IPOD_TOUCH_SYSIC(dev);
nms->sysic = (IPodTouchSYSICState *) g_malloc0(sizeof(struct IPodTouchSYSICState));
memory_region_add_subregion(sysmem, SYSIC_MEM_BASE, &sysic_state->iomem);
busdev = SYS_BUS_DEVICE(dev);
for(int grp = 0; grp < GPIO_NUMINTGROUPS; grp++) {
    sysbus_connect_irq(busdev, grp, s5l8900_get_irq(nms, S5L8900_GPIO_IRQS[grp]));
}
```

XNU Kernel

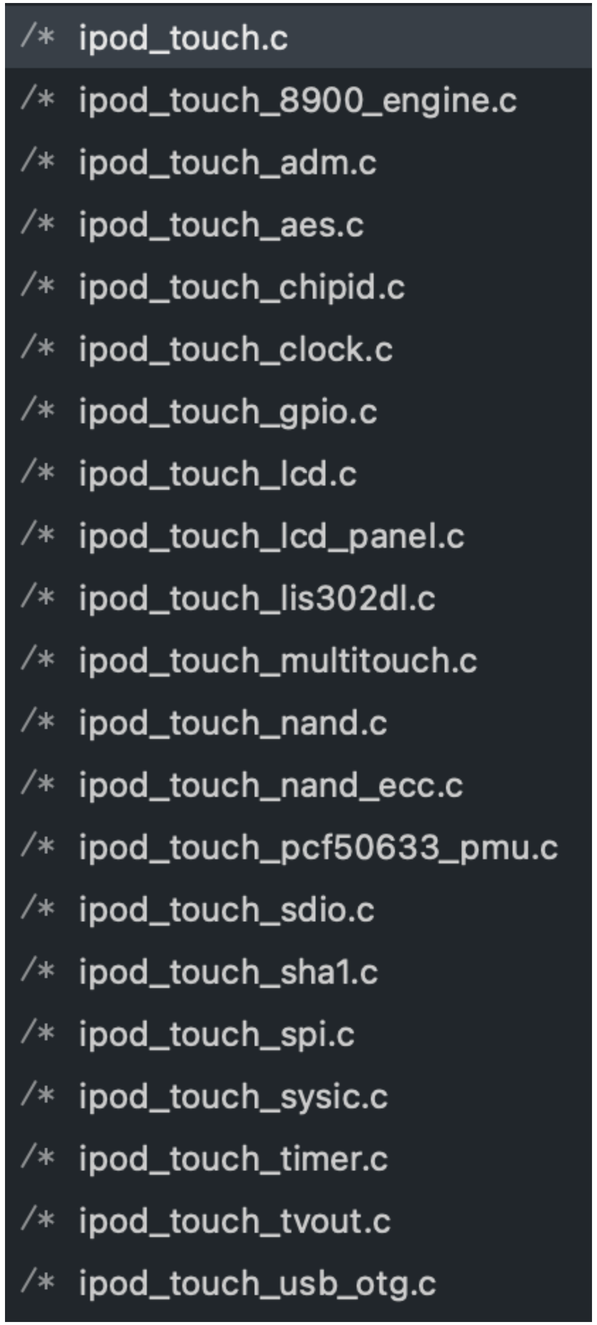
- First loads and starts all device drivers declared in the device tree
  - Uses IOKit
- Starting a driver usually involves resetting the peripheral
- After all drivers are loaded, it starts launchd



~20 peripherals later…

- Most key peripherals fully functional
  - Clock, timer, vector interrupt controller (VIC), DMA, crypto engines, …
- Only partial support for other peripherals
  - Just enough to make it past the initialization
  - TVOut, GPU, accelerometer, light sensor …
- Avoided GPU rendering with a flag

- Lots of work to do still, but we boot to userland! ☺

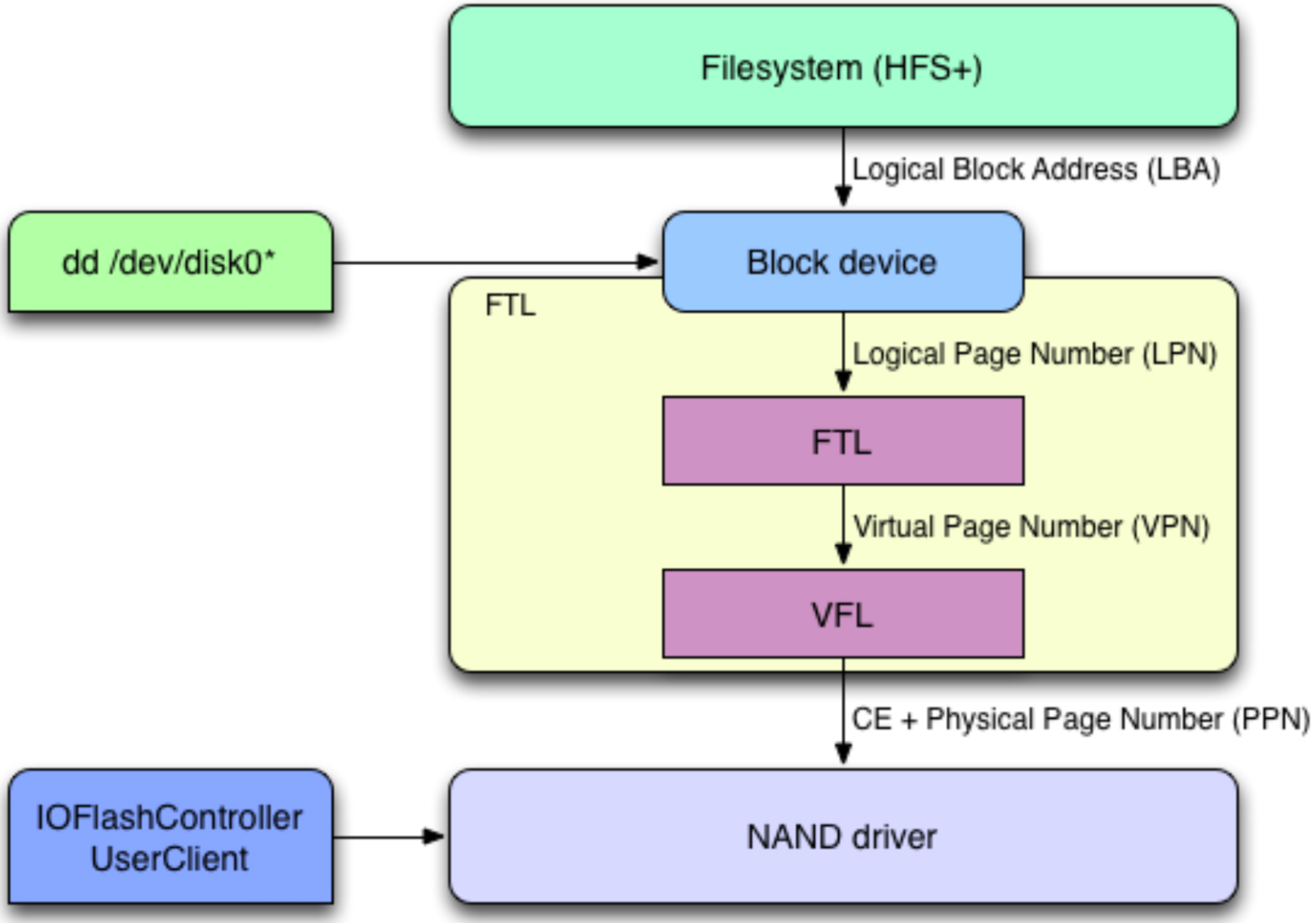


Persistence

- Two types of storage: NOR and NAND
- Key differences between iPod Touch 1G and 2G
- Emulator expects proper file system layouts
- Figuring out the layouts took most time (especially for NAND)

- Ended up with two scripts to generate the NOR and NAND images

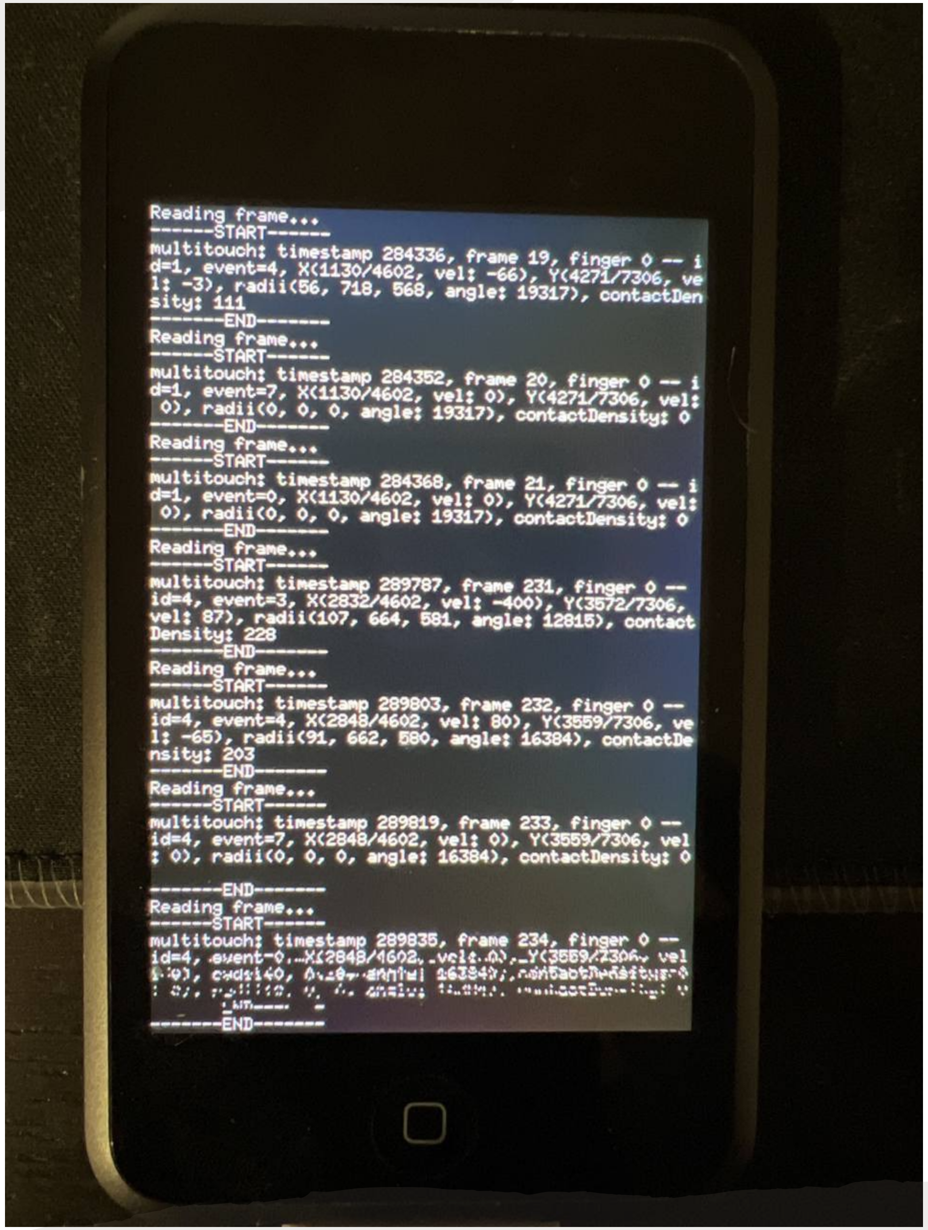
NAND



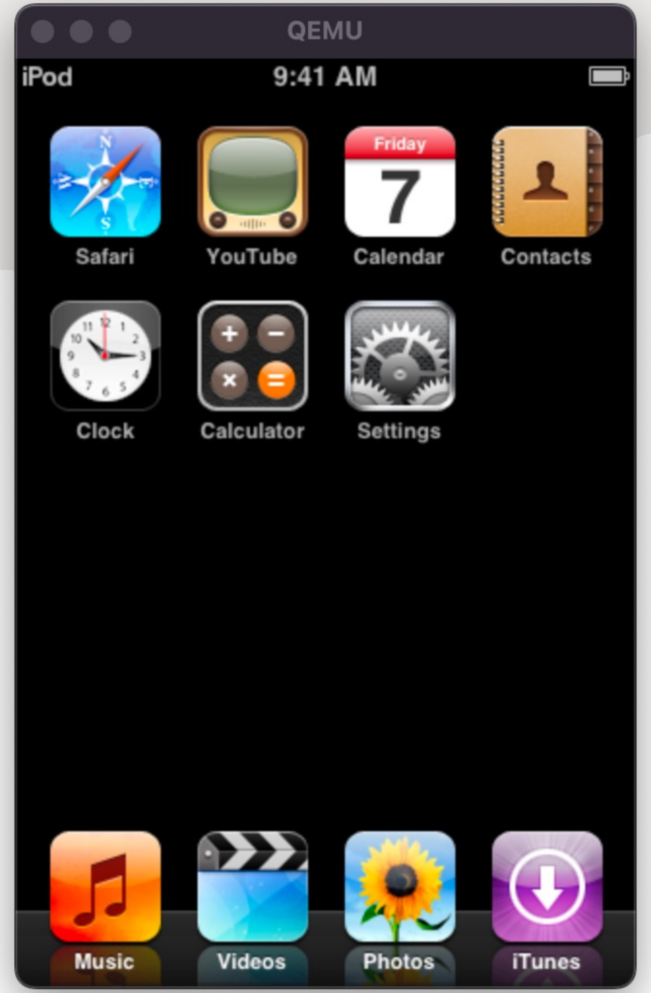
Source: Modern SSDs (Fall 2022), Jin-Soo Kim, Seoul National University

Multitouch

- Particularly challenging
    - Converting touch to coordinates is quite difficult
    - Complex initialization procedure
- Communicated with through SPI
- To get this working, I required the real device
- Installed OpeniBoot to read/analyze frames



Hello World!



iPod Touch 1G
iPhoneOS 1.0

iPod Touch 2G
iOS 2.1.1

QEMU-iOS

- An emulator for legacy Apple devices
- https://github.com/devos50/qemu-ios
- Support for iPod Touch 1G and 2G
- Current focus on iPod Touch 2G stability

- **Contributions are welcome!**

Thank you!

devos50

https://devos50.github.io
(some blog posts)