Simplifying iOS Research: Booting iOS on QEMU

@alephsecurity @JonathanAfek

github.com/alephsecurity
alephsecurity.com

Aleph, security research by HCL AppScan

How current iOS research is done

- Third party iOS emulator on a remote server
- Development fused iPhone
- Checkm8 demoted iPhone (@axi0mX)
- Off the shelf iPhone - jailbroken
- Off the shelf iPhone - no jailbreak

iPhone panic log


```
{"bug_type":"210","timestamp":"2019-01-31 00:00:31.72 +0100","os_version":"iPhone OS 11.4.1
    (15G77)","incident_id":"C8D49F0C-DBCD-4217-848A-4E3409C968D2"}
{
  "build" : "iPhone OS 11.4.1 (15G77)",
  "product" : "iPhone9,4",
  "kernel" : "Darwin Kernel Version 17.7.0: Mon Jun 11 19:06:26 PDT 2018; root:xnu-4570.70.24~3\/RELEASE_ARM64_T8010",
  "incident" : "C8D49F0C-DBCD-4217-848A-4E3409C968D2",
  "crashReporterKey" : "bbd821d8854956ba61dd35c63d4c25144a58ad9b",
  "date" : "2019-01-31 00:00:28.39 +0100",
  "panicString" : "panic(cpu 0 caller 0xffffffff01b3f8cac): Unaligned kernel data abort. (saved state:
      0xffffffe024a0b290)\n\t  x0: 0xffffffe006405507  x1:  0xffffffe0005fb471  x2:  0x0000000000000001  x3:
      0x0000000000000000\n\t  x4: 0x00000000ffffffff  x5:  0x0000000000000001  x6:  0x0000000000000000  x7:
      0xffffffff01ace5a1c\n\t  x8: 0xffffffe0005fb470  x9:  0x0000000000000001  x10: 0x00000000001071ae  x11:
      0x00000000001071ad\n\t  x12: 0x0000000000000000 x13: 0x0000000000000138  x14: 0x0000000000000000  x15:
      0x0000000000000000\n\t  x16: 0xffffffff01b70a014 x17: 0x0000000000000000  x18: 0xffffffff01b2e1000  x19:
      0xffffffe0064054ff\n\t  x20: 0x0000000000000003 x21: 0x0000000000000001  x22: 0xffffffff01b825000  x23:
      0xffffffff01b2f87e8\n\t  x24: 0x0000000000000a31 x25: 0xffffffe007474000  x26: 0xffffffe0005fb470  x27:
      0xffffffe0003a5c00\n\t  x28: 0x0000000000000000 fp:  0xffffffe024a0b640  lr:  0xffffffff01b2f87a0  sp:
      0xffffffe024a0b5e0\n\t  pc:  0xffffffff01b301c7c cpsr: 0xa0400304         esr: 0x96000021          far:
      0xffffffe006405507\n\nDebugger message: panic\nMemory ID: 0x1\nOS version: 15G77\nKernel version: Darwin Kernel
      Version 17.7.0: Mon Jun 11 19:06:26 PDT 2018; root:xnu-4570.70.24~3\/RELEASE_ARM64_T8010\nKernelCache UUID:
      C50E403D58F345EADBFECCF458171791\niBoot version: iBoot-4076.70.15\nsecure boot?: YES\nPaniclog version: 9\nKernel
      slide:     0x0000000014200000\nKernel text base: 0xffffffff01b204000\nEpoch Time:        sec       usec\n  Boot    :
      0x5c522a5b 0x0008dae2\n  Sleep   : 0x00000000 0x00000000\n  Wake    : 0x00000000 0x00000000\n  Calendar: 0x5c522c57
      0x00026e6e\n\nPanicked task 0xffffffe0003e1ce8: 27417 pages, 234 threads: pid 0: kernel_task\nPanicked thread:
      0xffffffe0005fb470, backtrace: 0xffffffe024a0aa90, tid: 401\n\t\t  lr: 0xffffffff01b3f96e8  fp:
      0xffffffe024a0abd0\n\t\t  lr: 0xffffffff01b2e15f4  fp: 0xffffffe024a0abe0\n\t\t  lr: 0xffffffff01b313a44  fp:
      0xffffffe024a0af50\n\t\t  lr: 0xffffffff01b313dd4  fp: 0xffffffe024a0afb0\n\t\t  lr: 0xffffffff01b313c00  fp:
      0xffffffe024a0afd0\n\t\t  lr: 0xffffffff01b3f8cac  fp: 0xffffffe024a0b130\n\t\t  lr: 0xffffffff01b3f9dfc  fp:
      0xffffffe024a0b270\n\t\t  lr: 0xffffffff01b2e15f4  fp: 0xffffffe024a0b280\n\t\t  lr: 0xffffffff01b301c7c  fp:
      0xffffffe024a0b640\n\t\t  lr: 0xffffffff01b2f87a0  fp: 0xffffffe024a0b690\n\t\t  lr: 0xffffffff01b2fffa0  fp:
      0xffffffe024a0b770\n\t\t  lr: 0xffffffff01b306be8  fp: 0xffffffe024a0b850\n\t\t  lr: 0xffffffff01b339988  fp:
      0xffffffe024a0b8e0\n\t\t  lr: 0xffffffff01b634b84  fp: 0xffffffe024a0b950\n\t\t  lr: 0xffffffff01b654448  fp:
      0xffffffe024a0b980\n\t\t  lr: 0xffffffff01b654124  fp: 0xffffffe024a0bab0\n\t\t  lr: 0xffffffff01b654e1c  fp:
      0xffffffe024a0bb30\n\t\t  lr: 0xffffffff01b652ea8  fp: 0xffffffe024a0bc90\n\t\t  lr: 0xffffffff01b2ec500  fp:
      0x0000000000000000\n\n",
  "panicFlags" : "0x2",
  "otherString" : "\n** Stackshot Succeeded ** Bytes Traced 202128 **\n",
  "memoryStatus" :
      {"compressorSize":0,"compressions":0,"decompressions":0,"busyBufferCount":0,"pageSize":16384,"memoryPressure":false
      ,"memoryPages":
      {"active":46523,"throttled":0,"fileBacked":69049,"wired":32283,"purgeable":1282,"inactive":14971,"free":48793
      ,"speculative":29929}},
```

Jonathan Afek

- Aleph Research group manager at HCL/AppScan
- 15 years of experience in security research and low level development including vulnerability research, Linux kernel, storage systems, WiFi systems and FW, security systems and more

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iOS on QEMU work done by @zhuowei (Worth Doing Badly)

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QEMU

From Wikipedia, the free encyclopedia

QEMU (short for **Quick EMUlator**)[2] is a free and open-source emulator that performs hardware virtualization.

Past Research - Worth Doing Badly (@zhuowei)

- Chosen version is iPhone X iOS 12 beta 4
- Extracted the kernel image and the device tree from the software update package
- Kernel (patched), device tree and the kernel boot arguments were loaded in memory
- iOS RAMDisk was loaded in memory
- UART serial support was achieved (output only)
- Kernel was booted
- Launchd was executed (no non-Apple executables executed)

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Past Research - Worth Doing Badly (@zhuowei)

```
BSD root: md0, major 2, minor 0
apfs_vfsop_mountroot:1468: apfs: mountroot called!
apfs_vfsop_mount:1231: unable to root from devvp <ptr> (root_device): 2
apfs_vfsop_mountroot:1472: apfs: mountroot failed, error: 2
hfs: mounted PeaceSeed16A5327f.arm64UpdateRamDisk on device b(2, 0)
: : Darwin Bootstrapper Version 6.0.0: Mon Jul  9 00:39:56 PDT 2018; root:libxpc_execu
boot-args = debug=0x8 kextlog=0xfff cpus=1 rd=md0
Thu Jan  1 00:00:05 1970 localhost com.apple.xpc.launchd[1] <Notice>: Restore environm
```

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Goals of our project

- Booting iOS on QEMU ~~with no kernel patches~~
- Supporting hardware (disk, display, touch, sound, multiple CPUs, Interrupt controllers, etc…)
- Supporting different iOS versions
- Conducting iOS security research
- Learning about iOS and QEMU internals

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Status of our project

- Booting ~~Secure Monitor~~ and the kernel ~~(unpatched)~~ on QEMU
- Executing user-mode apps over launchd
- Running an interactive bash shell on an iOS kernel on QEMU
- Running gdb scripts listing and switching (tasks, threads, zones)
- Allowing access to tfp0 from user mode
- Mounting full disk images with our own block device driver
- Running most of the iOS user mode services
- Connecting to an SSH server running on the iOS system
- Displaying a textual iOS framebuffer
- Supporting only on iOS 12.1 for iPhone 6s plus for now

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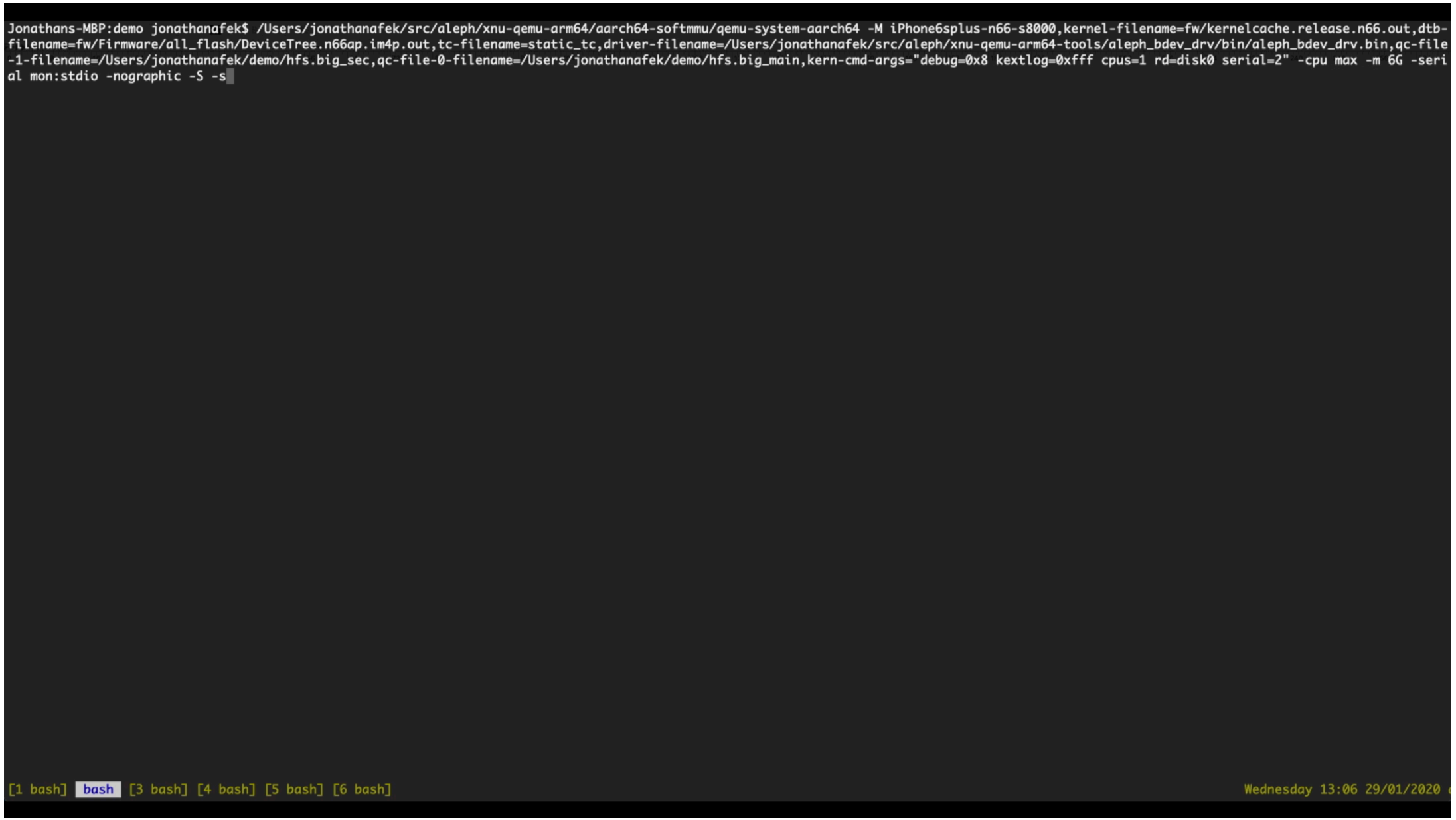
Jonathans-MBP:demo jonathanafek$ /Users/jonathanafek/src/aleph/xnu-qemu-arm64/aarch64-softmmu/qemu-system-aarch64 -M iPhone6splus-n66-s8000,kernel-filename=fw/kernelcache.release.n66.out,dtb-filename=fw/Firmware/all_flash/DeviceTree.n66ap.im4p.out,tc-filename=static_tc,driver-filename=/Users/jonathanafek/src/aleph/xnu-qemu-arm64-tools/aleph_bdev_drv/bin/aleph_bdev_drv.bin,qc-file-1-filename=/Users/jonathanafek/demo/hfs.big_sec,qc-file-0-filename=/Users/jonathanafek/demo/hfs.big_main,kern-cmd-args="debug=0x8 kextlog=0xfff cpus=1 rd=disk0 serial=2" -cpu max -m 6G -serial mon:stdio -nographic -S -s
[1 bash] bash [3 bash] [4 bash] [5 bash] [6 bash]
Wednesday 13:06 29/01/2020

```
(reverse-i-search)`ramf': /Users/jonathanafek/src/aleph/xnu-qemu-arm64/aarch64-softmmu/qemu-system-aarch64 -M iPhone6splus-n66-s8000,kernel-filename=fw/kernelcache.release.n66.out,dtb-filenam
e=fw/Firmware/all_flash/DeviceTree.n66ap.im4p.out,tc-filename=static_tc,driver-filename=/Users/jonathanafek/src/aleph/xnu-qemu-arm64-tools/aleph_bdev_drv/bin/aleph_bdev_drv.bin,qc-file-1-file
name=/Users/jonathanafek/demo/hfs.big_sec,qc-file-0-filename=/Users/jonathanafek/demo/hfs.big_main,xnu-ramfb=on,kern-cmd-args="debug=0x8 kextlog=0xfff cpus=1 rd=disk0 serial=2" -cpu max -m 6G
 -serial mon:stdio
```

Agenda

- Past public research on iOS on QEMU
- **iOS kernel boot process**
- Execution of non-Apple executables with Trust Cache
- Bash execution with launchd
- tfp0
- SSH connection
- Textual framebuffer
- Block device driver
- No secure monitor
- Launchd craziness
- Next steps

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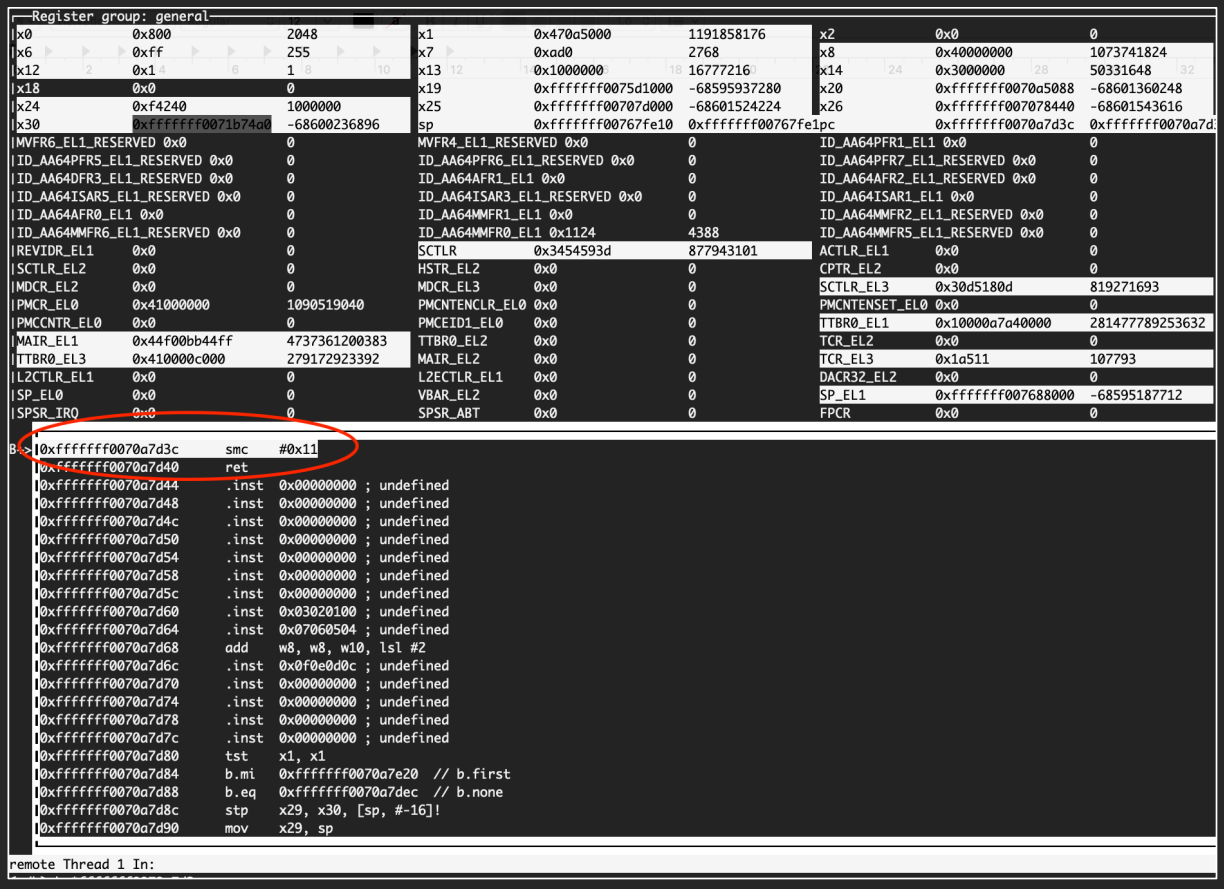
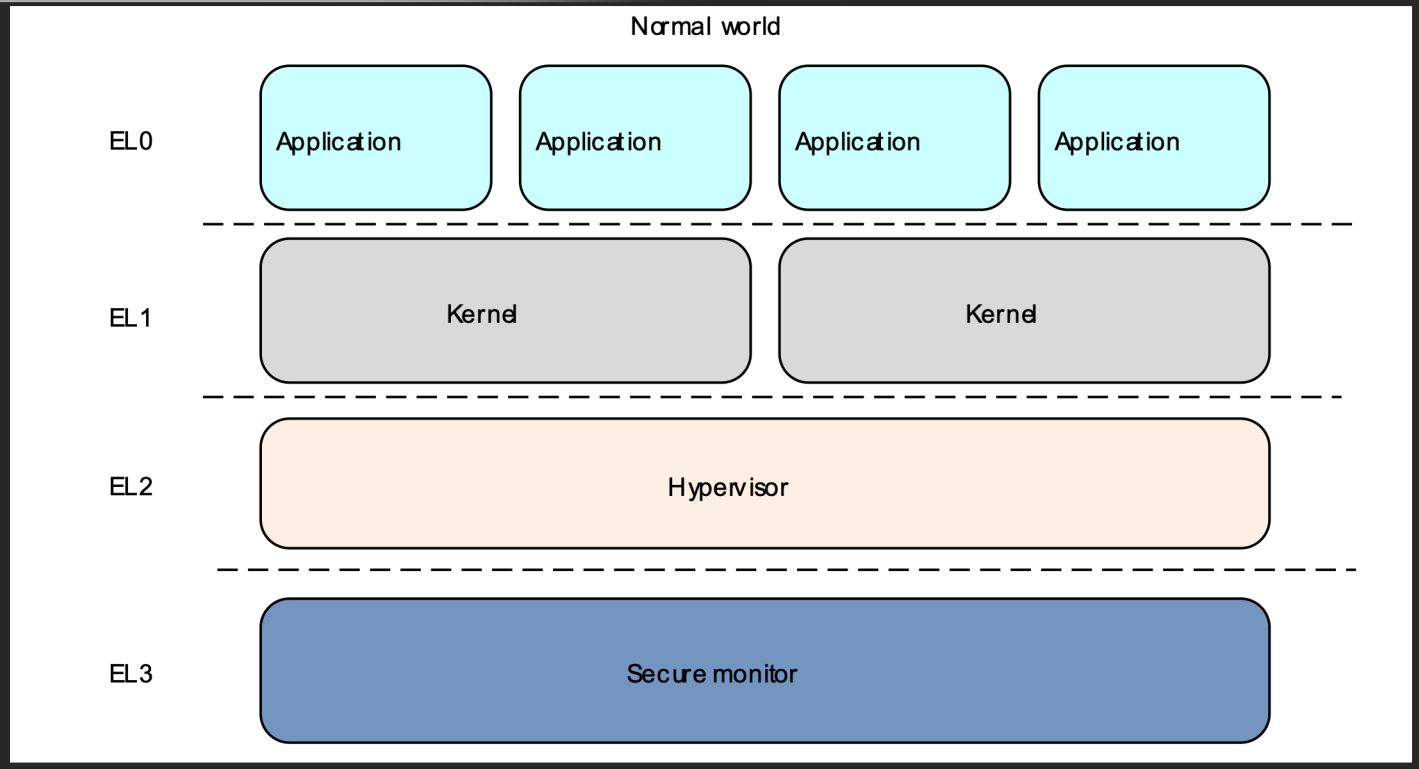
iOS kernel boot process

- Start booting the kernelcache code in EL1 as done by @zhuowei
- Crash on SMC instruction (Secure Monitor Call)



iOS kernel boot process



from https://developer.arm.com/docs/den0024/a/fundamentals-of-armv8

iOS kernel boot process

- Secure Monitor starts execution at boot in EL3
- It resides in a secure memory location inaccessible from EL1 (kernel code)
- It services SMC calls from the kernel (similar to how system calls from user apps to the kernel are serviced)
- It is responsible for KPP (Kernel Patch Protection) in our system

iOS kernel boot process

- Load the Secure Monitor image for iOS 12.1 for iPhone 6s plus in the secure memory
- Load the secure monitor boot arguments in the secure memory with the relevant values
- Start executing the secure monitor at its entry point in EL3
- The secure monitor finishes its boot sequence and jumps to the kernel at its entry point in EL1
- The kernel finishes its boot seq and uses the secure monitor to service its SMC calls

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And it works!

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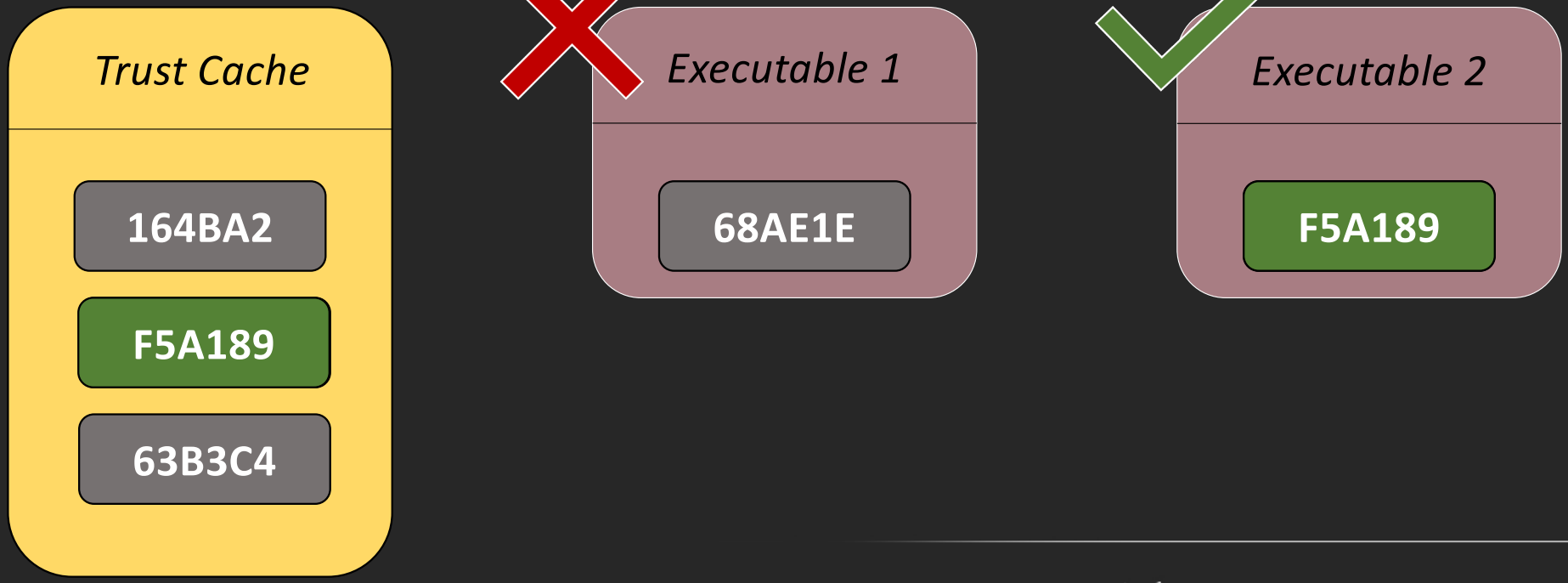
Trust Cache



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Trust Cache

- iOS has 3 different types of trust caches
  - A list of hardcoded hashes approved in the kernelcache
  - A dynamic trust cache that can be loaded at runtime from a file
  - A static trust cache in memory pointed from the device tree

Trust Cache

Device tree

From Wikipedia, the free encyclopedia

In computing, a **device tree** (also written **devicetree**) is a data structure describing the hardware components of a particular computer so that the operating system's kernel can use and manage those components, including the CPU or CPUs, the memory, the buses and the peripherals.

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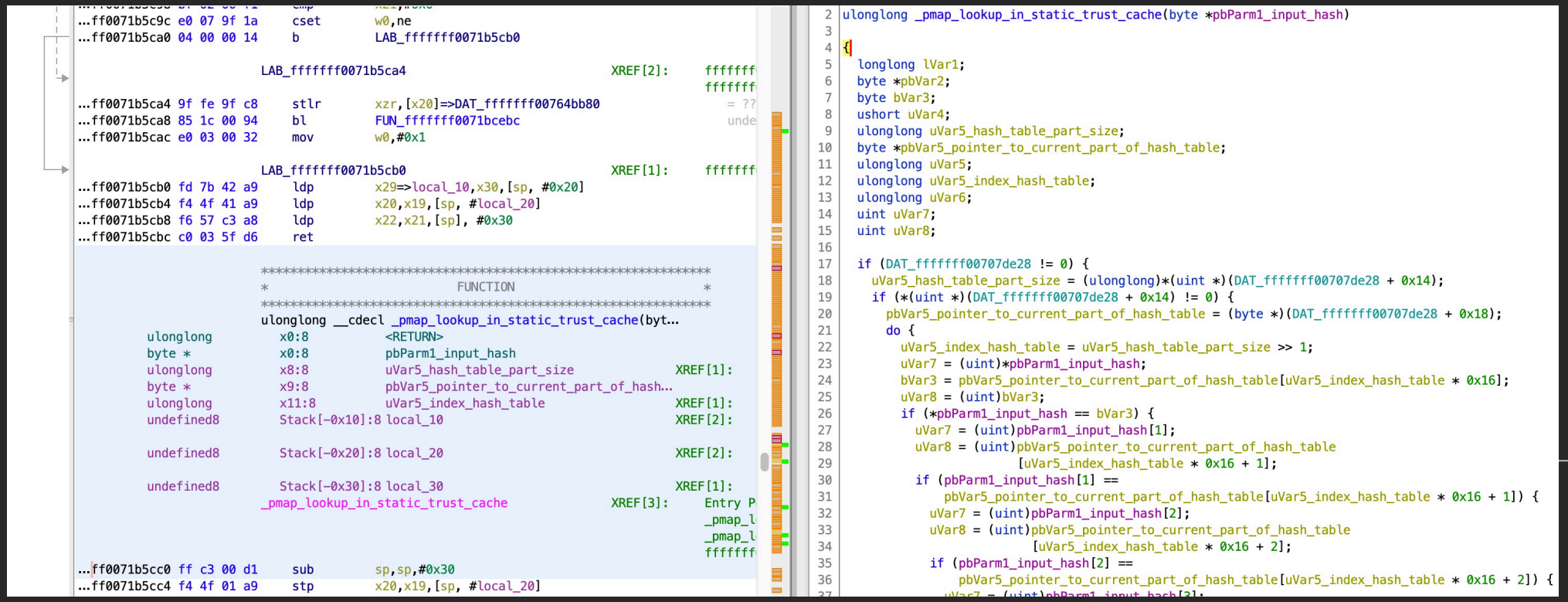
Trust Cache

- By reversing this code and other relevant code we were able to understand the input structure and construct our own static TC



```
...ff0071b5c9c e0 07 9f 1a     cset        w0,ne
...ff0071b5ca0 04 00 00 14     b           LAB_ffffff0071b5cb0

                        LAB_ffffff0071b5ca4                             XREF[2]:     ffffffff
...ff0071b5ca4 9f fe 9f c8     stlr        xzr,[x20]=>DAT_ffffff00764bb80                = ??
...ff0071b5ca8 85 1c 00 94     bl          FUN_ffffff0071bcebc                           unde
...ff0071b5cac e0 03 00 32     mov         w0,#0x1

                        LAB_ffffff0071b5cb0                             XREF[1]:     ffffffff
...ff0071b5cb0 fd 7b 42 a9     ldp         x29=>local_10,x30,[sp, #0x20]
...ff0071b5cb4 f4 4f 41 a9     ldp         x20,x19,[sp, #local_20]
...ff0071b5cb8 f6 57 c3 a8     ldp         x22,x21,[sp], #0x30
...ff0071b5cbc c0 03 5f d6     ret

                        *************************************************************
                        *                          FUNCTION                         *
                        *************************************************************
                        ulonglong __cdecl _pmap_lookup_in_static_trust_cache(byt...
          ulonglong           x0:8          <RETURN>
          byte *              x0:8          pbParm1_input_hash
          ulonglong           x8:8          uVar5_hash_table_part_size              XREF[1]:
          byte *              x9:8          pbVar5_pointer_to_current_part_of_hash...
          ulonglong           x11:8         uVar5_index_hash_table                  XREF[1]:
          undefined8          Stack[-0x10]:8 local_10                               XREF[2]:

          undefined8          Stack[-0x20]:8 local_20                               XREF[2]:

          undefined8          Stack[-0x30]:8 local_30                               XREF[1]:
                        _pmap_lookup_in_static_trust_cache              XREF[3]:     Entry P
                                                                                     _pmap_l
                                                                                     _pmap_l
                                                                                     ffffffff
...ff0071b5cc0 ff c3 00 d1     sub         sp,sp,#0x30
...ff0071b5cc4 f4 4f 01 a9     stp         x20,x19,[sp, #local_20]
```

```
ulonglong _pmap_lookup_in_static_trust_cache(byte *pbParm1_input_hash)

{
  longlong lVar1;
  byte *pbVar2;
  byte bVar3;
  ushort uVar4;
  ulonglong uVar5_hash_table_part_size;
  byte *pbVar5_pointer_to_current_part_of_hash_table;
  ulonglong uVar5;
  ulonglong uVar5_index_hash_table;
  ulonglong uVar6;
  uint uVar7;
  uint uVar8;

  if (DAT_ffffff00707de28 != 0) {
    uVar5_hash_table_part_size = (ulonglong)*(uint *)(DAT_ffffff00707de28 + 0x14);
    if (*(uint *)(DAT_ffffff00707de28 + 0x14) != 0) {
      pbVar5_pointer_to_current_part_of_hash_table = (byte *)(DAT_ffffff00707de28 + 0x18);
      do {
        uVar5_index_hash_table = uVar5_hash_table_part_size >> 1;
        uVar7 = (uint)*pbParm1_input_hash;
        bVar3 = pbVar5_pointer_to_current_part_of_hash_table[uVar5_index_hash_table * 0x16];
        uVar8 = (uint)bVar3;
        if (*pbParm1_input_hash == bVar3) {
          uVar7 = (uint)pbParm1_input_hash[1];
          uVar8 = (uint)pbVar5_pointer_to_current_part_of_hash_table
                        [uVar5_index_hash_table * 0x16 + 1];
          if (pbParm1_input_hash[1] ==
              pbVar5_pointer_to_current_part_of_hash_table[uVar5_index_hash_table * 0x16 + 1]) {
            uVar7 = (uint)pbParm1_input_hash[2];
            uVar8 = (uint)pbVar5_pointer_to_current_part_of_hash_table
                          [uVar5_index_hash_table * 0x16 + 2];
            if (pbParm1_input_hash[2] ==
                pbVar5_pointer_to_current_part_of_hash_table[uVar5_index_hash_table * 0x16 + 2]) {
```

Trust Cache

- Which Apple released the source code for

```
DTEntry memory_map;
MemoryMapFileInfo *trustCacheRange;
unsigned int trustCacheRangeSize;
int err;

err = DTLookupEntry(NULL, "chosen/memory-map", &memory_map);
assert(err == kSuccess);

err = DTGetProperty(memory_map, "TrustCache", (void**)&trustCacheRange
if (err == kSuccess) {
        assert(trustCacheRangeSize == sizeof(MemoryMapFileInfo));

        segEXTRADATA = phystokv(trustCacheRange->paddr);
        segSizeEXTRADATA = trustCacheRange->length;

        arm_vm_page_granular_RNX(segEXTRADATA, segSizeEXTRADATA, FALSE
}
```

And it works!

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Bash on Launchd

- Mount the RAMDisk image on OSX
- Remove all files in /System/Library/LaunchDaemons/
- Add a single file there for running bash (com.apple.bash.plist)
- Add the bash executable to the RAMDisk
- Add the bash executable hash to the Trust Cache
- Unmount the RAMDisk and run QEMU

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Bash on Launchd

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN" "http://www.appl
<plist version="1.0">
<dict>
        <key>EnablePressuredExit</key>
        <false/>
        <key>Label</key>
        <string>com.apple.bash</string>
        <key>POSIXSpawnType</key>
        <string>Interactive</string>
        <key>ProgramArguments</key>
        <array>
                <string>/iosbinpack64/bin/bash</string>
        </array>
        <key>RunAtLoad</key>
        <true/>
        <key>StandardErrorPath</key>
        <string>/dev/console</string>
        <key>StandardInPath</key>
        <string>/dev/console</string>
        <key>StandardOutPath</key>
        <string>/dev/console</string>
        <key>Umask</key>
        <integer>0</integer>
        <key>UserName</key>
        <string>root</string>
</dict>
</plist>
```

Bash on Launchd

- System tries to execute bash
- Logs show missing libraries required for bash

Any ideas?

Bash on Launchd

- The RAMDisk image comes without the dynamic loader cache on it, which is a file that holds most of the common runtime libs for iOS
- Copy this file into the RAMDisk at the correct path from the full disk images

Any ideas?

Bash on Launchd

- Debug /usr/lib/dyld (the dynamic loader) which is responsible for loading the dynamic loader cache

Bash on Launchd

```
// map in shared cache to shared region
int fd = openSharedCacheFile();
if ( fd != -1 ) {
        uint8_t firstPages[8192];
        if ( ::read(fd, firstPages, 8192) == 8192 ) {
                dyld_cache_header* header = (dyld_cache_header*)firstF
#if __x86_64__
                const char* magic = (sHaswell ? ARCH_CACHE_MAGIC_H : A
#else
                const char* magic = ARCH_CACHE_MAGIC;
#endif
                if ( strcmp(header->magic, magic) == 0 ) {
                        const dyld_cache_mapping_info* const fileMappi
                        const dyld_cache_mapping_info* const fileMappi
                        shared_file_mapping_np  mappings[header->mappi
                        unsigned int mappingCount = header->mappingCou
```

Bash on Launchd

- Stepping through the execution path with gdb showed the error was in here

```
if (_shared_region_map_and_slide_np(fd, mappingCount, mappings, codeSi
        // successfully mapped cache into shared region
        sSharedCache = (dyld_cache_header*)mappings[0].sfm_address;
        sSharedCacheSlide = cacheSlide;
        dyld::gProcessInfo->sharedCacheSlide = cacheSlide;
        //dyld::log("sSharedCache=%p sSharedCacheSlide=0x%08lX\n", sSh
        // if cache has a uuid, copy it
        if ( header->mappingOffset >= 0x68 ) {
                memcpy(dyld::gProcessInfo->sharedCacheUUID, header->uu
        }
}
else {

        throw "dyld shared cache could not be mapped";

        if ( gLinkContext.verboseMapping )
                dyld::log("dyld: shared cached file could not be mappe
}
```

Bash on Launchd

- Since we have a kernel debugger in gdb we can step into the system call in the kernel

```
int
shared_region_map_and_slide_np(
        struct proc                                 *p,
        struct shared_region_map_and_slide_np_args      *uap,
        __unused int                                    *retvalp)
{
        struct shared_file_mapping_np   *mappings;
        unsigned int                    mappings_count = uap->count;
        kern_return_t                   kr = KERN_SUCCESS;
        uint32_t                        slide = uap->slide;

#define SFM_MAX_STACK   8
        struct shared_file_mapping_np   stack_mappings[SFM_MAX_STACK]

        /* Is the process chrooted?? */
        if (p->p_fd->fd_rdir != NULL) {
                kr = EINVAL;
                goto done;
        }
```

Bash on Launchd

- Stepping through this function we see that the call to _shared_region_map_and_slide() is the part that fails

```
kr = _shared_region_map_and_slide(p, uap->fd, mappings_count, mapping
                                  slide,
                                  uap->slide_start, uap->slide_size);
if (kr != KERN_SUCCESS) {
        return kr;
}


return kr;
```

Bash on Launchd

- Stepping in that function reveals the error here

```
/* make sure vnode is owned by "root" */
VATTR_INIT(&va);
VATTR_WANTED(&va, va_uid);
error = vnode_getattr(vp, &va, vfs_context_current());
if (error) {
        SHARED_REGION_TRACE_ERROR(
                ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                 "vnode_getattr(%p) failed (error=%d)\n",
                 (void *)VM_KERNEL_ADDRPERM(current_thread()),
                 p->p_pid, p->p_comm,
                 (void *)VM_KERNEL_ADDRPERM(vp), vp->v_name,
                 (void *)VM_KERNEL_ADDRPERM(vp), error));
        goto done;
}
if (va.va_uid != 0) {
        SHARED_REGION_TRACE_ERROR(
                ("shared_region: %p [%d(%s)] map(%p:'%s'): "
                 "owned by uid=%d instead of 0\n",
                 (void *)VM_KERNEL_ADDRPERM(current_thread()),
                 p->p_pid, p->p_comm,
                 (void *)VM_KERNEL_ADDRPERM(vp),
                 vp->v_name, va.va_uid));
        error = EPERM;
        goto done;
}
```

Bash on Launchd

- The code validates that the cache file is owned by root
- Mount the RAMDisk image in a different way to allow permission editing
- Copy the cache file and chown to root

And it works!

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tfp0

- task_for_pid() is a mach trap (like a system call) that allows getting access to another task port on the same host from usermode
- For pid 0 this gives access to the kernel task port
- Access to this port gives full control over the other task (memory read/write, code execution, etc..)

tfp0

```
kern_return_t task_for_pid(struct task_for_pid_args *args)
{
    // ...

    /* Always check if pid == 0 */
    if (pid == 0) {
        (void ) copyout((char *)&t1, task_addr, sizeof(mach_port_name_t));
        AUDIT_MACH_SYSCALL_EXIT(KERN_FAILURE);
        return(KERN_FAILURE);
    }

    // ...
}
```

from https://github.com/Siguza/hsp4/blob/master/README.md

Aleph Research

tfp0

```
task_t convert_port_to_task_with_exec_token(ipc_port_t port, uint32_t *exec_token)
{
    // ...

    if (task == kernel_task && current_task() != kernel_task) {
        ip_unlock(port);
        return TASK_NULL;
    }

    // ...
}
```

from https://github.com/Siguza/hsp4/blob/master/README.md

Aleph Research

tfp0 (@s1guza)

```
vm_map_remap(
    kernel_map,
    &remap_addr,
    sizeof(task_t),
    0,
    VM_FLAGS_ANYWHERE | VM_FLAGS_RETURN_DATA_ADDR,
    zone_map,
    kernel_task,
    false,
    &dummy,
    &dummy,
    VM_INHERIT_NONE
);
// mach_vm_wire_external as of High Sierra
mach_vm_wire(&realhost, kernel_map, remap_addr, sizeof(task_t), VM_PROT_READ | VM_PROT_WRITE);
ipc_port_t port = ipc_port_alloc_special(ipc_space_kernel);
ipc_kobject_set(port, remap_addr, IKOT_TASK);
realhost.special[4] = ipc_port_make_send(port);
```

from https://github.com/Siguza/hsp4/blob/master/README.md

tfp0

- Allocate static virtual memory for the remapped kernel task
- QEMU “MMIO” to redirect reads/writes from/to our fake kernel task to the real kernel task

```
ktpp->remap.orig_pa = vtop_mmu(global_kernel_ptr,  ktpp->cs);$
ktpp->remap.pa = remap_task_paddr;$
ktpp->remap.orig_as = ktpp->as;$
ktpp->remap.size = KERNEL_TASK_ALLOC_SIZE;$

xnu_dev_remap_create(sysmem, &ktpp->remap, "kernel_task_remap_dev");
```

Aleph Research

tfp0

- Create a copy of the kernel task port pointing to the remapped kernel task

```
static void copy_kernel_task_port(hwaddr kernel_port_new_addr,$
                                  hwaddr kernel_task_new_addr,$
                                  hwaddr kernel_port_orig_addr,$
                                  AddressSpace *as)$
{$
    uint8_t port_buffer[KERNEL_PORT_SIZE_16B92];$
$
    //read out the kernel task port$
    address_space_rw(as, kernel_port_orig_addr, MEMTXATTRS_UNSPECIFIED,$
                     &port_buffer[0], KERNEL_PORT_SIZE_16B92, 0);$
$
    //ovr write the kernel task pointer with the new copy$
    *(uint64_t *)&port_buffer[KERNEL_TASK_OFFSET_16B92] = \$
        ptov_static(kernel_task_new_addr);$
$
    //write the new kernel task port to memory$
    address_space_rw(as, kernel_port_new_addr,$
                     MEMTXATTRS_UNSPECIFIED, &port_buffer[0],$
                     KERNEL_PORT_SIZE_16B92, 1);$
}$
```

tfp0

- Copy the port to host special port 4

```
address_space_rw(ktpp->as, vtop_mmu(special_port_4_vaddr, ktpp->cs),$
                 MEMTXATTRS_UNSPECIFIED, (uint8_t *)&fake_port_vaddr,$
                 sizeof(hwaddr), 1);$
```

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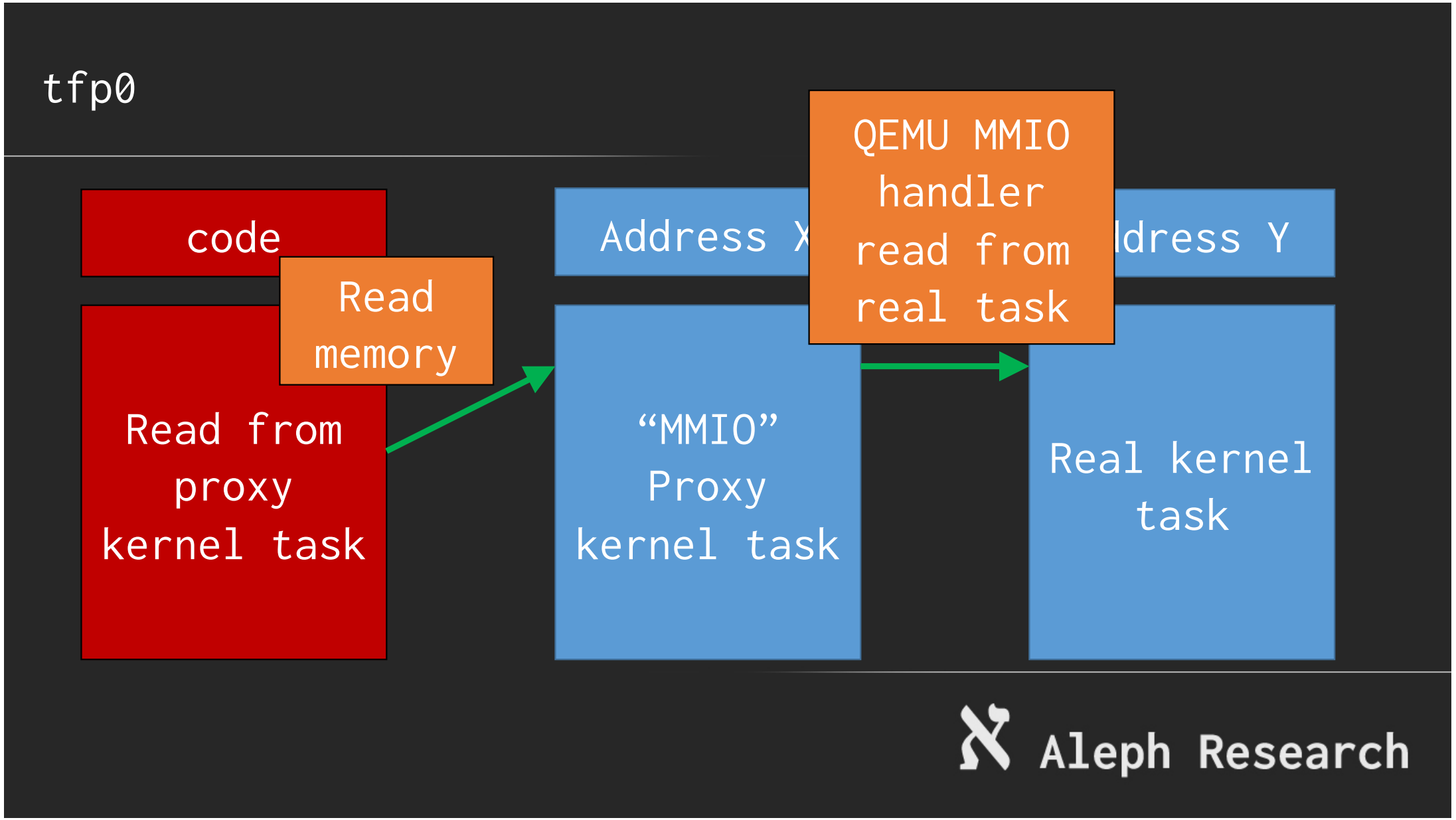
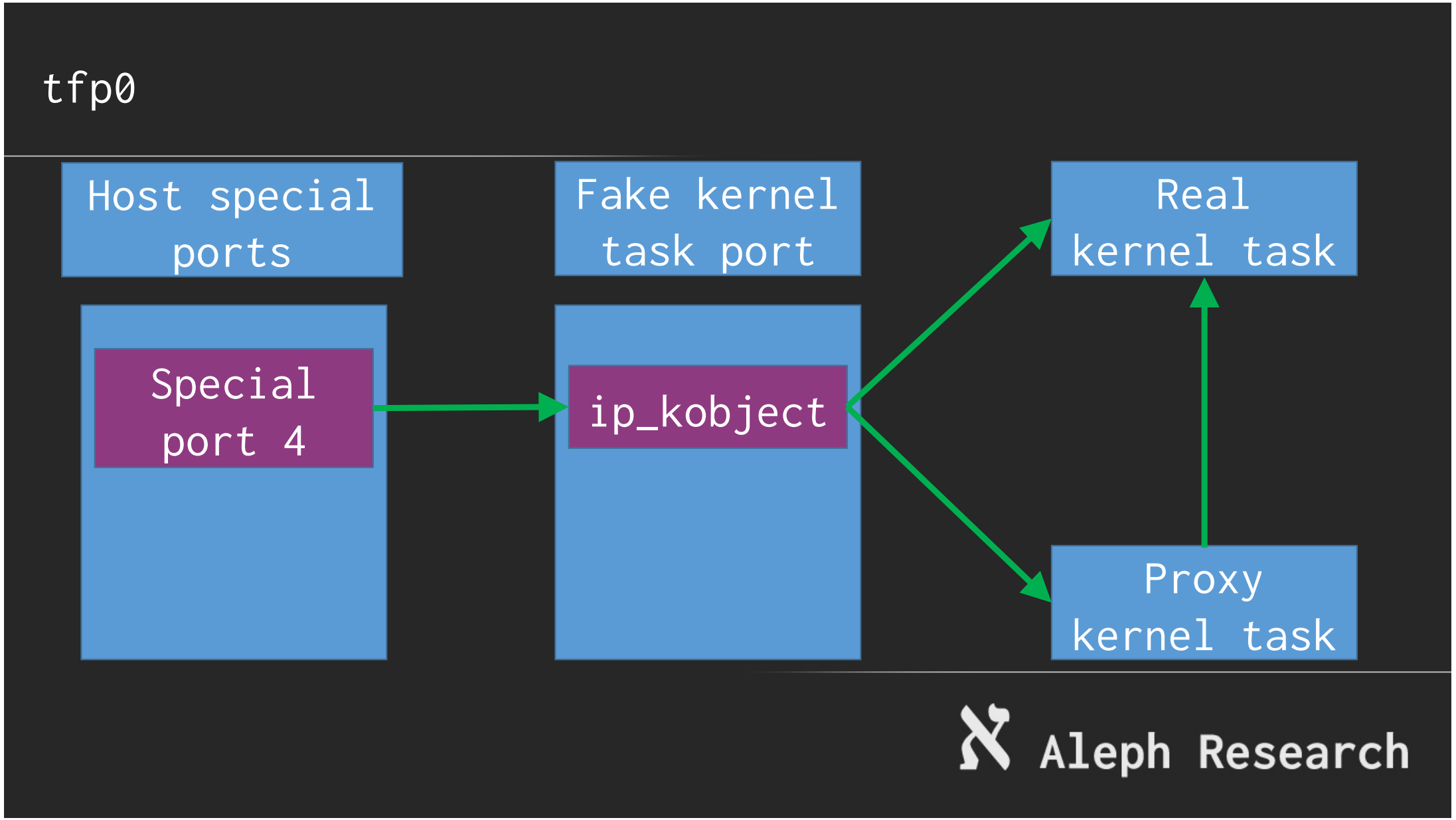

tfp0
code
Read memory
Read from proxy kernel task
Address X
“MMIO” Proxy kernel task
QEMU MMIO handler read from real task
dress Y
Real kernel task
Aleph Research


tfp0
Host special ports
Fake kernel task port
Real kernel task
Special port 4
ip_kobject
Proxy kernel task
Aleph Research

tfp0

And it works!

```
-bash-4.4# kmem 0xffffff005c5c000 256
[*] Reading 256 bytes from 0xffffff005c5c000
CF FA ED FE 0C 00 00 01  00 00 00 00 0B 00 00 00  |................|
03 00 00 00 78 00 00 00  02 00 00 00 00 00 00 00  |....x...........|
19 00 00 00 48 00 00 00  5F 5F 4C 49 4E 4B 45 44  |....H..__LINKED|
49 54 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |IT..............|
68 0A 00 00 00 00 00 00  00 10 00 00 00 00 00 00  |h...............|
68 0A 00 00 00 00 00 00  01 00 00 00 01 00 00 00  |h...............|
00 00 00 00 04 00 00 00  02 00 00 00 18 00 00 00  |................|
00 10 00 00 44 00 00 00  40 14 00 00 28 06 00 00  |....D...@...(...|
CF FA ED FE 0C 00 00 01  00 00 00 00 0B 00 00 00  |................|
03 00 00 00 78 00 00 00  02 00 00 00 00 00 00 00  |....x...........|
19 00 00 00 48 00 00 00  5F 5F 4C 49 4E 4B 45 44  |....H..__LINKED|
49 54 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |IT..............|
E4 96 00 00 00 00 00 00  00 10 00 00 00 00 00 00  |................|
E4 96 00 00 00 00 00 00  01 00 00 00 01 00 00 00  |................|
00 00 00 00 04 00 00 00  02 00 00 00 18 00 00 00  |................|
00 10 00 00 99 03 00 00  90 49 00 00 54 5D 00 00  |.........I..T]..|
```

Agenda

- Past public research on iOS on QEMU
- iOS kernel boot process
- Execution of non-Apple executables with Trust Cache
- Bash execution with launchd
- tfp0
- **SSH connection**
- Textual framebuffer
- Block device driver
- No secure monitor
- Launchd craziness
- Next steps

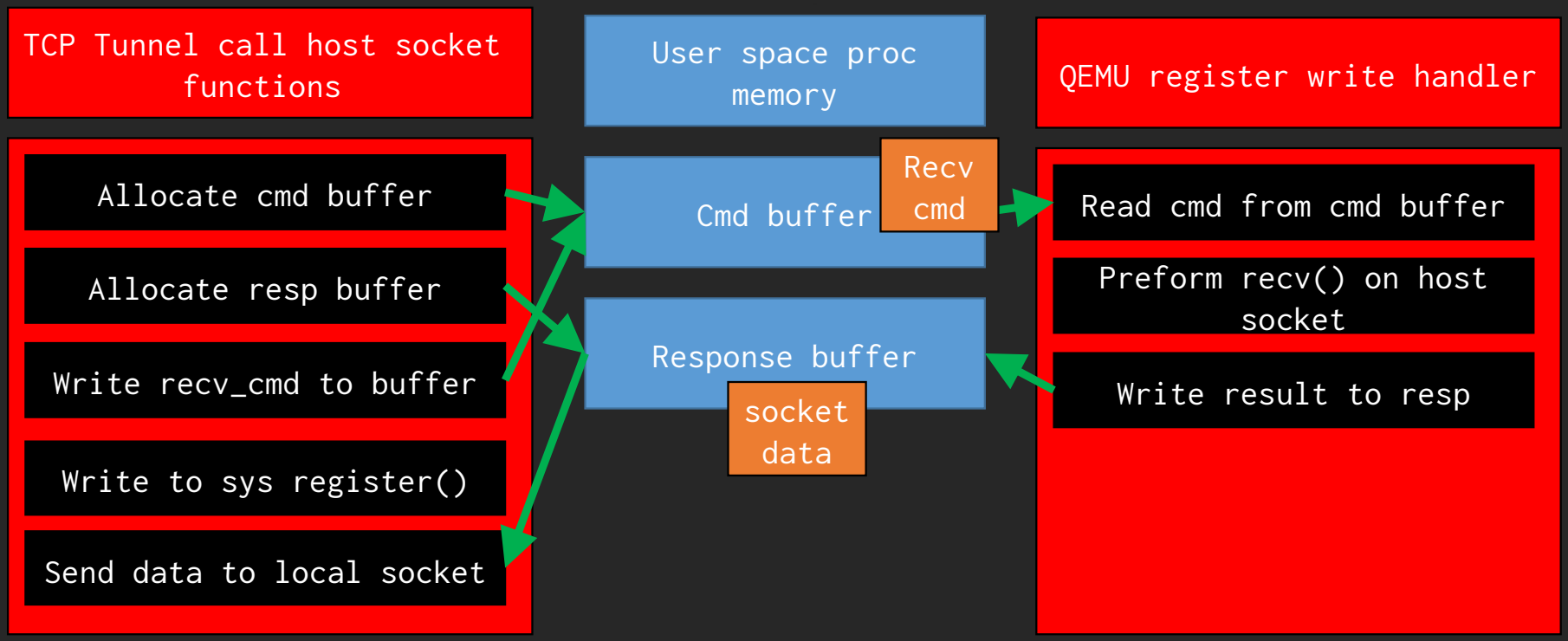
Aleph Research

TCP connections and SSH (@levaronsky)

- The “normal” way emulating the networking hardware
- The “normal” way with a driver and an emulated network controller for that driver
- Our way with communicating with the QEMU host from a usermode TCP tunnel proc using QEMU’s register write callbacks

Aleph Research

TCP connections and SSH



Aleph Research

TCP connections and SSH

- recv() from host socket and send() to guest socket and vice versa
- Very inefficient with a busy loop running endlessly without blocking at all when no traffic is available
- Works smoothly enough for now

```
Jonathans-MBP:~ jonathanafek$ ssh -p 2222 root@127.0.0.1
root@127.0.0.1's password:
[104] Dec 31 16:07:57 lastlog_perform_login: Couldn't stat /var/log/lastlog: No such file or directory
[104] Dec 31 16:07:57 lastlog_openseek: /var/log/lastlog is not a file or directory!
-bash-4.4# export PATH=$PATH:/iosbinpack64/usr/bin:/iosbinpack64/bin:/iosbinpack64/usr/sbin:/iosbinpack64/sbin
-bash-4.4# uname -a
Darwin localhost 18.2.0 Darwin Kernel Version 18.2.0: Tue Oct 16 21:02:23 PDT 2018; root:xnu-4903.222.5~1/RELEASE_ARM64_S8000 iPhone8,2
```

Aleph Research

Agenda

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Aleph Research

Textual framebuffer (@V3rochka)

- Setup a new ramfb device with our own display parameters on the QEMU host side

```
void xnu_define_ramfb_device(AddressSpace* as, hwaddr ramfb_pa){$
$
    DeviceState *fb_dev;$
    fb_dev = qdev_create(NULL, TYPE_XNU_RAMFB_DEVICE);$
    qdev_prop_set_uint64(fb_dev, "as", (hwaddr)as);$
    qdev_prop_set_uint64(fb_dev, "fb_pa", ramfb_pa);$
    qdev_prop_set_uint32(fb_dev, "fb_size", RAMFB_SIZE);$
    qdev_prop_set_uint32(fb_dev, "display_cfg.height", V_HEIGHT);$
    qdev_prop_set_uint32(fb_dev, "display_cfg.width", V_WIDTH);$
    qdev_prop_set_uint32(fb_dev, "display_cfg.linesize", V_LINESIZE);$
    qdev_init_nofail(fb_dev);$
}$
```

Aleph Research

Textual framebuffer

- Setup the iOS boot args to configure the textual framebuffer

```
void  xnu_get_video_bootargs(void *opaque, hwaddr ramfb_pa){$
$
    video_boot_args* v_bootargs = (video_boot_args*)opaque ;$
    v_bootargs->v_baseAddr = ramfb_pa;$
    v_bootargs->v_depth = V_DEPTH;$
    v_bootargs->v_display = V_DISPLAY;$
    v_bootargs->v_height = V_HEIGHT;$
    v_bootargs->v_width = V_WIDTH;$
    v_bootargs->v_rowBytes = V_LINESIZE;$
$
}$
```

```
#define V_DEPTH      16$
#define V_HEIGHT     800$
#define V_WIDTH      600$
#define V_DISPLAY    0$
#define V_LINESIZE   (V_WIDTH * 3)$
```

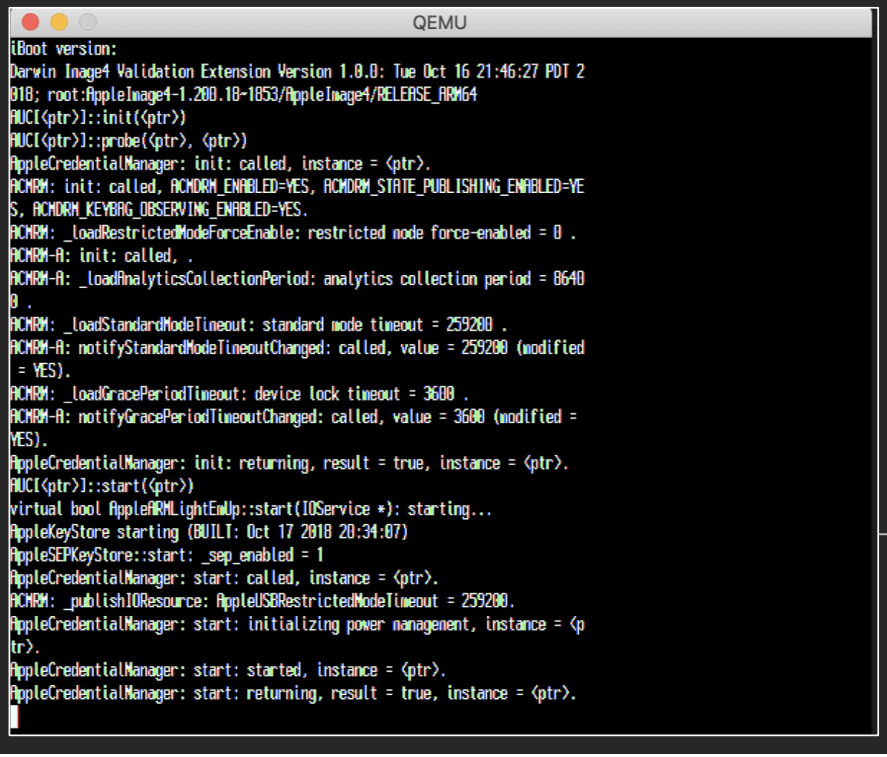
Aleph Research

Textual framebuffer

- Connect the QEMU ramfb device fb to the iOS framebuffer

Textual framebuffer

And it works!



Aleph Research

Agenda

- Past public research on iOS on QEMU
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Block Device Driver

- RAMDisk block devices do not support disks larger than 1.5 GB
- Full disk image is larger than 4GB
- Using the RAMDisk we only have 1 block device
- We want a BD for the root mount and another for the R/W data mount - same as a regular iOS system
- Write our own block device driver to load the 2 large block devices
- Patch the kernel and call our driver during kernel boot

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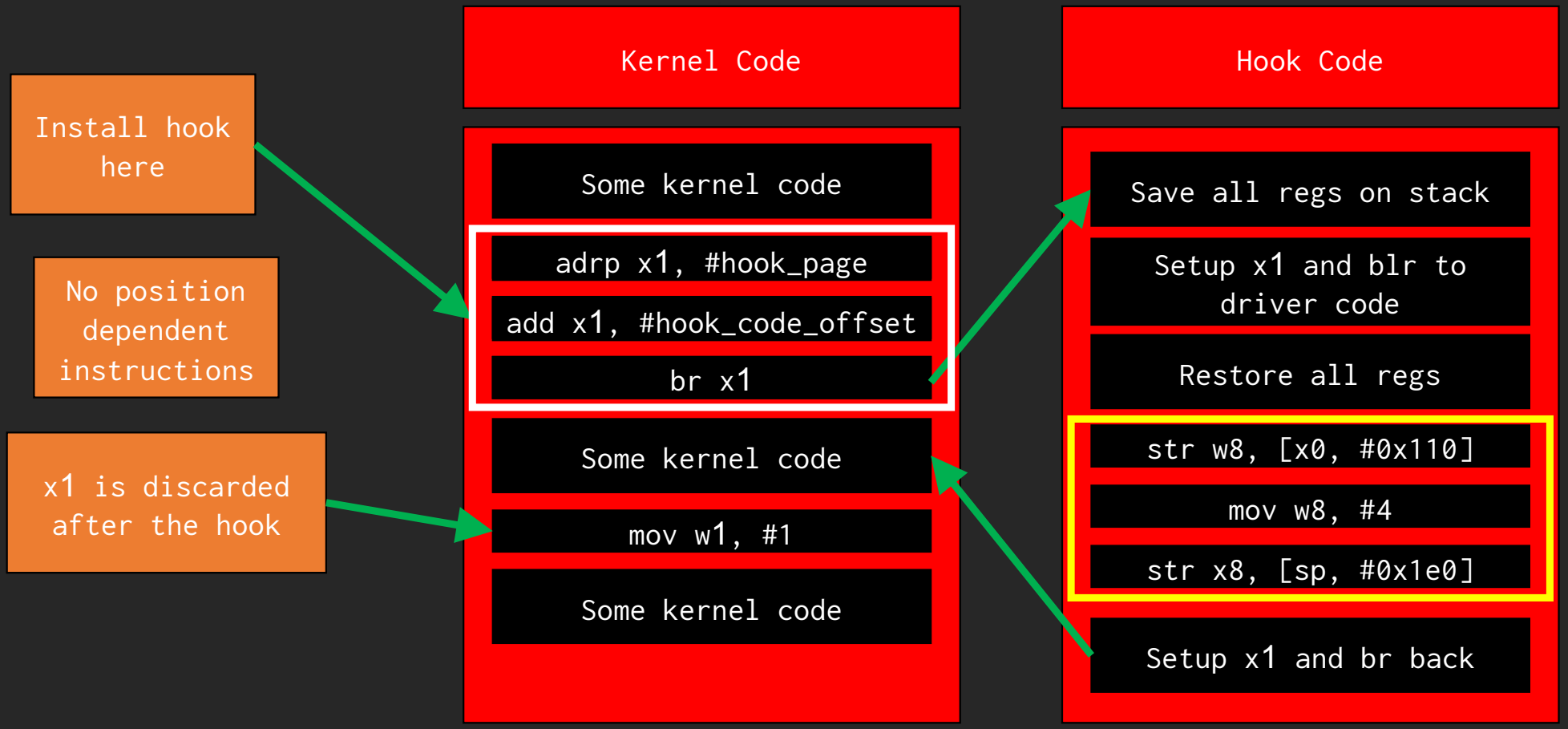
Block Device Driver - Hook

- Allocate kernel memory at a fixed location
- Trampoline hook code in assembly
- Flat binary compilation of c code for the driver
- Parse the page table and make all these pages RWX

Block Device Driver - Hook



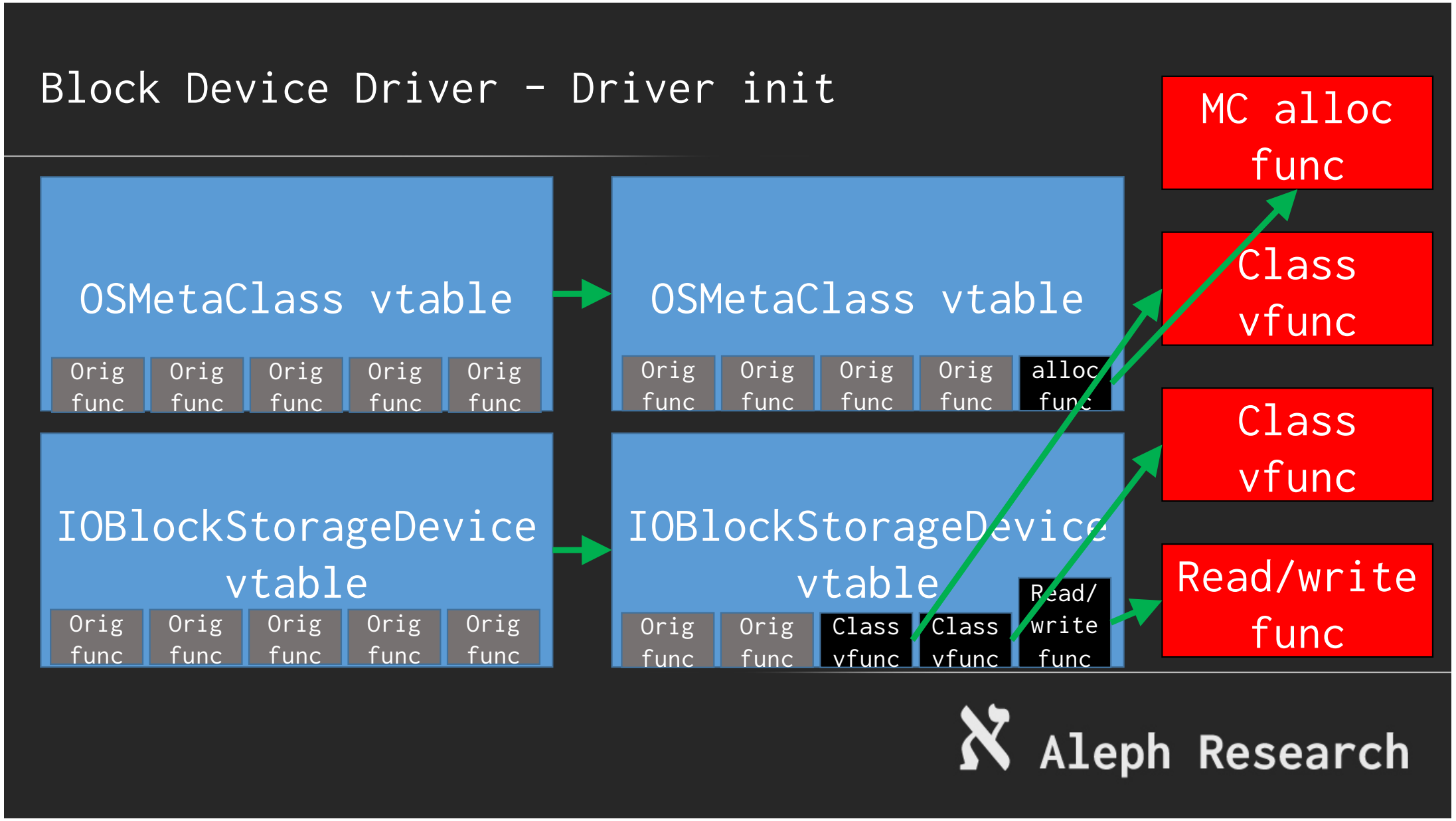
Block Device Driver - Driver init

- We do not have a kernel dev kit for iOS or a compatible cpp compiler
- Create our own driver inheriting from IOBlockStorageDevice with c code and build compatible cpp objects for the driver and its metaclass
- Create vtables for the new class and its OSMetaClass

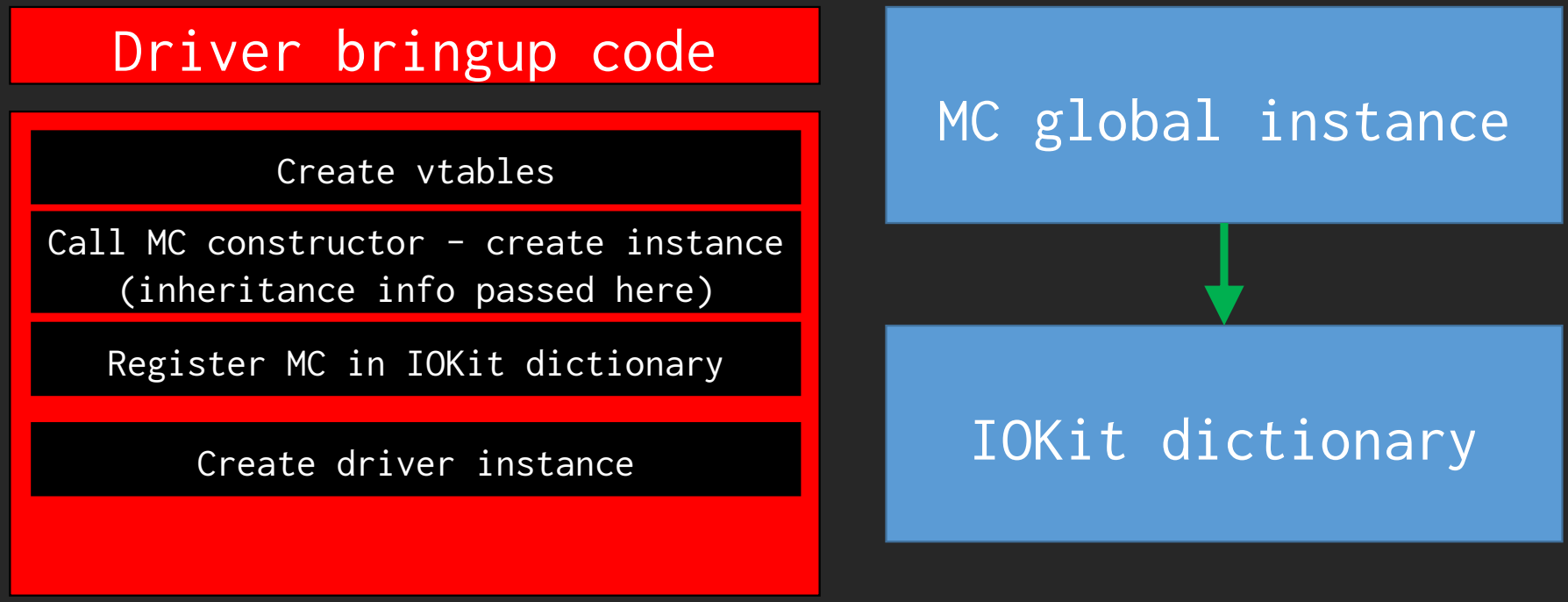
Block Device Driver - Driver init

- Call the OSMetaClass constructor and register the new class in the sAllClassesDict global classes dictionary
- Call OSMetaClass::allocClassWithName(“AlephStorageBlockDevice”) to create 2 instances of our class for the 2 block devices
- Attach them to a node in the IOKit registry and call ::registerService() on them to enable the new devices

Block Device Driver - Driver init



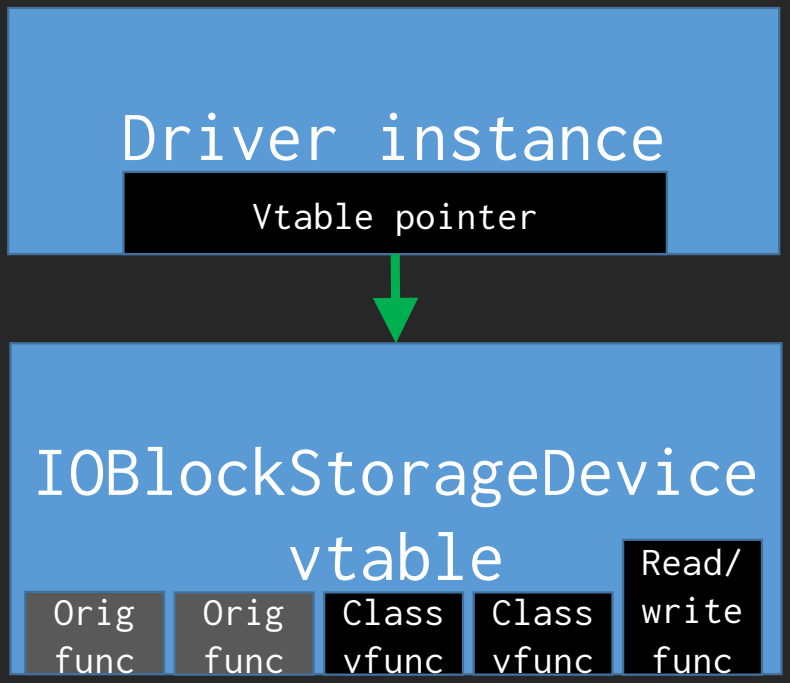
Block Device Driver - Driver init



Block Device Driver - Driver init

MC ::alloc() vfunc

- Allocate driver class instance
- Call super constructor
- Fix vtable pointer
- Call instanceConstructed() on MC inst



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Block Device Driver - Driver init

Driver bringup code

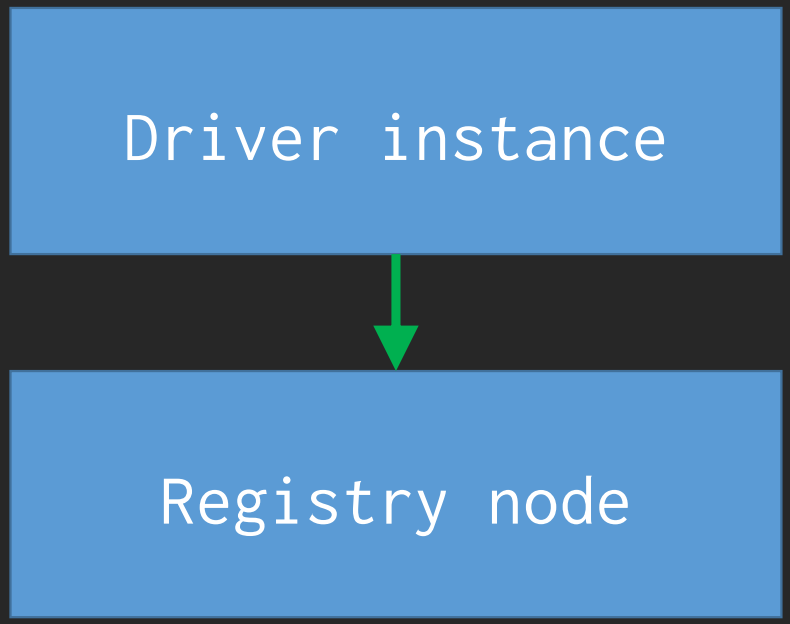
Find existing registry node

Attach driver to existing node

Call ::registerService() on inst

IOKit attaches drivers to inst

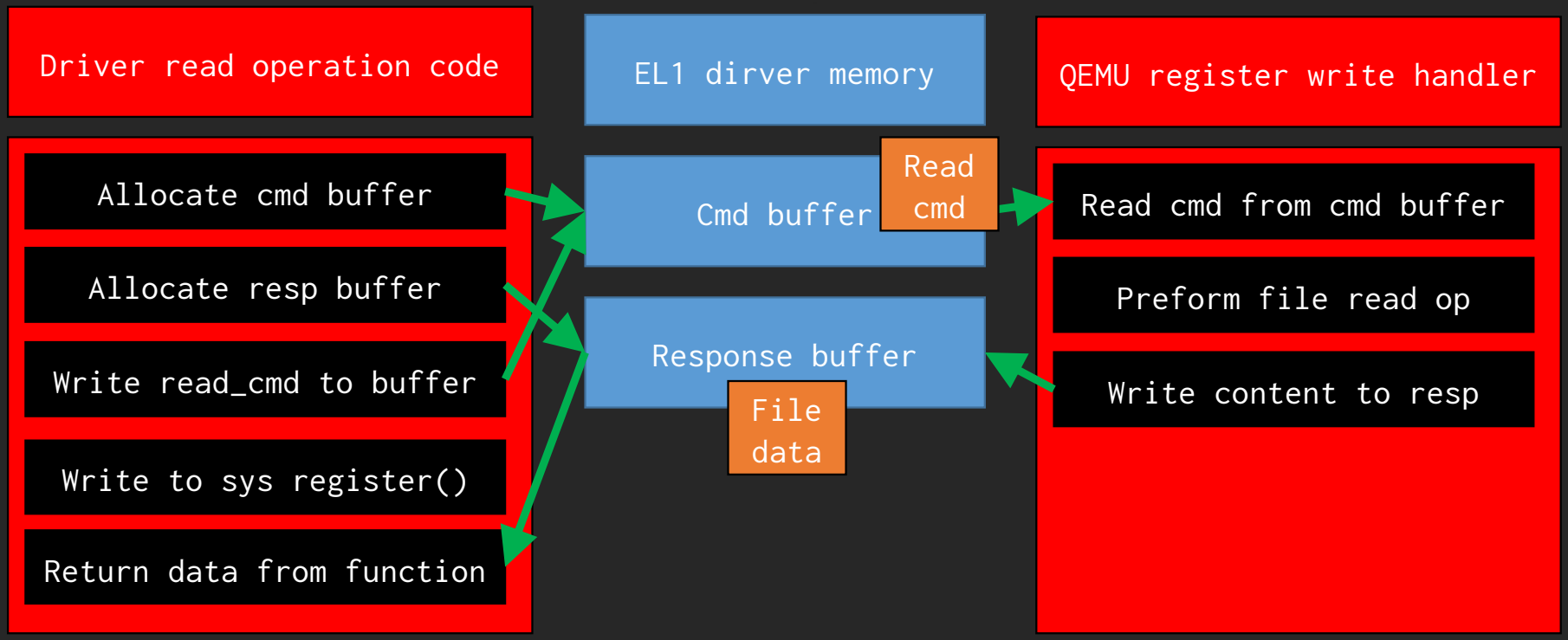
These drivers create a new BSD device



Block Device Driver - Driver read/write

- Implement the virtual functions to read/write from/to the new block devices
- Write to a system register and the QEMU callback reads/writes directly from/to memory buffers on the guest to transfer the data
- The block device data on the QEMU host is backed by files

Block Device Driver - Driver read/write



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```
    | | |
    | | +-o AlephStorageBlockDevice  <class IORegistryEntry:IOService:IOBlockStorageDevice:AlephStorageBlockDevice, id 0x1000001c7, registered, matched, active, busy 0 (633 ms), retain 7>
    | | | {
    | | |   "device-type" = "Generic"
    | | |   "IOMinimumSegmentAlignmentByteCount" = 0x4
    | | | }
    | | |
    | | +-o IOBlockStorageDriver  <class IORegistryEntry:IOService:IOStorage:IOBlockStorageDriver, id 0x1000001c8, registered, matched, active, busy 0 (613 ms), retain 8>
    | |   | {
    | |   |   "IOPropertyMatch" = {"device-type"="Generic"}
    | |   |   "IOProbeScore" = 0x0
    | |   |   "IOProviderClass" = "IOBlockStorageDevice"
    | |   |   "IOClass" = "IOBlockStorageDriver"
    | |   |   "CFBundleIdentifier" = "com.apple.iokit.IOStorageFamily"
    | |   |   "Statistics" = {"Operations (Write)"=0x0,"Latency Time (Write)"=0x0,"Bytes (Read)"=0x1a5f9000,"Errors (Write)"=0x0,"Total Time (Read)"=0x427c05e97,"Retries (Read)"=0x0,"Late
ations (Read)"=0x13cb,"Retries (Write)"=0x0}
    | |   |   "IOMatchCategory" = "IODefaultMatchCategory"
    | |   |   "IOGeneralInterest" = "IOCommand is not serializable"
    | |   | }
    | |   |
    | |   +-o 0Aleph 0AlephBDev Media  <class IORegistryEntry:IOService:IOStorage:IOMedia, id 0x1000001c9, registered, matched, active, busy 0 (613 ms), retain 9>
    | |     | {
    | |     |   "Removable" = No
    | |     |   "Content" = ""
    | |     |   "Whole" = Yes
    | |     |   "Leaf" = Yes
    | |     |   "BSD Name" = "disk0"
    | |     |   "Ejectable" = No
    | |     |   "Preferred Block Size" = 0x1000
    | |     |   "IOMediaIcon" = {"IOBundleResourceFile"="External.icns","CFBundleIdentifier"="com.apple.iokit.IOStorageFamily"}
    | |     |   "BSD Minor" = 0x0
    | |     |   "Writable" = Yes
    | |     |   "BSD Major" = 0x1
    | |     |   "Size" = 0x180000000
    | |     |   "Open" = Yes
    | |     |   "Content Hint" = ""
    | |     |   "BSD Unit" = 0x0
    | |     | }
    | |     |
    | |     +-o IOMediaBSDClient  <class IORegistryEntry:IOService:IOMediaBSDClient, id 0x1000001ca, registered, matched, active, busy 0 (3 ms), retain 7>
    | |         {
    | |           "IOClass" = "IOMediaBSDClient"
    | |           "IOMatchCategory" = "IOMediaBSDClient"
    | |           "IOProbeScore" = 0x7530
    | |           "IOProviderClass" = "IOMedia"
    | |           "IOResourceMatch" = "IOBSD"
    | |           "CFBundleIdentifier" = "com.apple.iokit.IOStorageFamily"
    | |         }
    | |
```

Block Device Driver

```
bash-4.4# mount -t hfs /dev/disk1 /mnt1

mount_hfs: Could not create property for re-key environment check: No such file or directory
hfs: mounted PeaceB16B92.arm64UpdateRamDisk on device disk1
bash-4.4#
bash-4.4# cd /mnt1/
bash-4.4# ls
.fseventsd              buddy                   log                     run
Keychains               containers              logs                    staged_system_apps
Managed Preferences     db                      mobile                  tmp
MobileAsset             dropbear                msgs                    vm
MobileDevice            empty                   networkd                wireless
MobileSoftwareUpdate    folders                 preferences
audit                   installd                root
bash-4.4#
```

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- Launchd craziness
- Next steps

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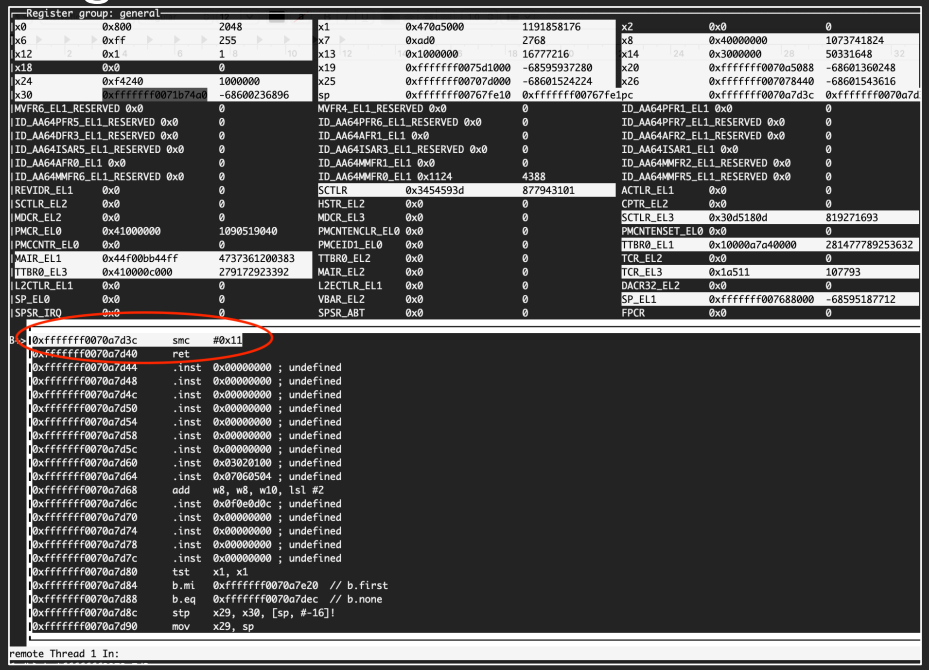
No Secure Monitor

- Move from not patching the kernel to patching it for driver loading
- Disable the Secure Monitor to disable KPP

No Secure Monitor

- Don’t load the Secure Monitor image
- Start executing the kernel at EL1 at its entry point
- NOP SMC instruction (Secure Monitor Call)



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No Secure Monitor

- Another way KPP kicks in is by trapping FP operations done in EL0 or in EL1 to EL3 (secure monitor)
- Intercept writes to CPACR_EL1 (in QEMU) so that it will always hold 0x30000
  - This means FPEN is 3 (don’t trap any FP execution at all)
- xerub.github.io/ios/kpp/2017/04/13/tick-tock.html (@xerub)

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Aleph Research

Launchd craziness

- Created 2 raw HFS block device disk images with the full disk images content from the software update package
- Started QEMU pointing the root mount to the new block devices
- Added launchd items to execute our bash shell, start the TCP tunnel, start the dropbear SSH server and other services
- Our services didn’t run but the original system services did run

Any ideas?

Launchd craziness

- Removed all launchd items
- Still no go - they execute the same as before
- Removed the directory
- Panic and nothing executes
- Boot with the content of the ramdisk we used before
- Panic with an error about a missing service cache

Launchd craziness

```
lVar2 = _dlopen("/System/Library/Caches/com.apple.xpcd/xpcd_cache.dylib",2);
if ((lVar2 != 0) &&
   (UNRECOVERED_JUMPTABLE = (code *)_dlsym(lVar2,"__xpcd_cache"),
   UNRECOVERED_JUMPTABLE != (code *)0x0)) {
  iVar1 = (*UNRECOVERED_JUMPTABLE)();
  if (iVar1 != 1) {
    __os_assert_log(0);
    __os_crash();
                    /* WARNING: Could not recover jumptable at 0x00010000a248. Too many branches */
                    /* WARNING: Treating indirect jump as call */
    UNRECOVERED_JUMPTABLE = (code *)SoftwareBreakpoint(1,0x10000a24c);
    (*UNRECOVERED_JUMPTABLE)();
    return;
  }
  iVar1 = _dladdr(UNRECOVERED_JUMPTABLE,auStack72);
  if (iVar1 != 0) {
    puVar3 = _getsectiondata(local_40,"__TEXT","__xpcd_cache",(ulong *)&local_28);
    if (puVar3 == (uint8_t *)0x0) {
      DAT_1000436b8 = _xpc_dictionary_create(0,0,0);
    }
    else {
      DAT_1000436b8 = _xpc_create_from_plist(puVar3,local_28);
    }
  }
}
if ((DAT_1000436b8 == 0) ||
   (puVar4 = (undefined *)_xpc_get_type(), puVar4 != __xpc_type_dictionary)) {
  if (DAT_100044479 == '\0') {
                    /* WARNING: Subroutine does not return */
    FUN_100028f84("No service cache");
  }
  DAT_1000436b8 = _xpc_dictionary_create(0,0,0);
}
DAT_100043670 = _xpc_dictionary_get_value(DAT_1000436b8,"LaunchDaemons");
if ((DAT_100043670 == 0) ||
   (puVar4 = (undefined *)_xpc_get_type(), puVar4 != __xpc_type_dictionary)) {
  if (DAT_100044479 == '\0') {
                    /* WARNING: Subroutine does not return */
    FUN_100028f84("No daemons in cache");
  }
```

Launchd craziness

- Launchd decides whether to use this cache or the filesystem based on the bootargs (if it thinks it is a ramdisk boot)
- Patch this code “finds” rd=md0 in the boot args

```
lVar5 = FUN_100029448("kern.bootargs",&local_48);
if (lVar5 == 0) {
  cVar10 = '\0';
}
else {
  pcVar6 = _strnstr(local_48,"rd=md0",(size_t)lVar5);
  cVar10 = (char)pcVar6 + '\x01';
}
_free(local_48);
DAT_100044479 = cVar10;
```

Aleph Research

Launchd craziness

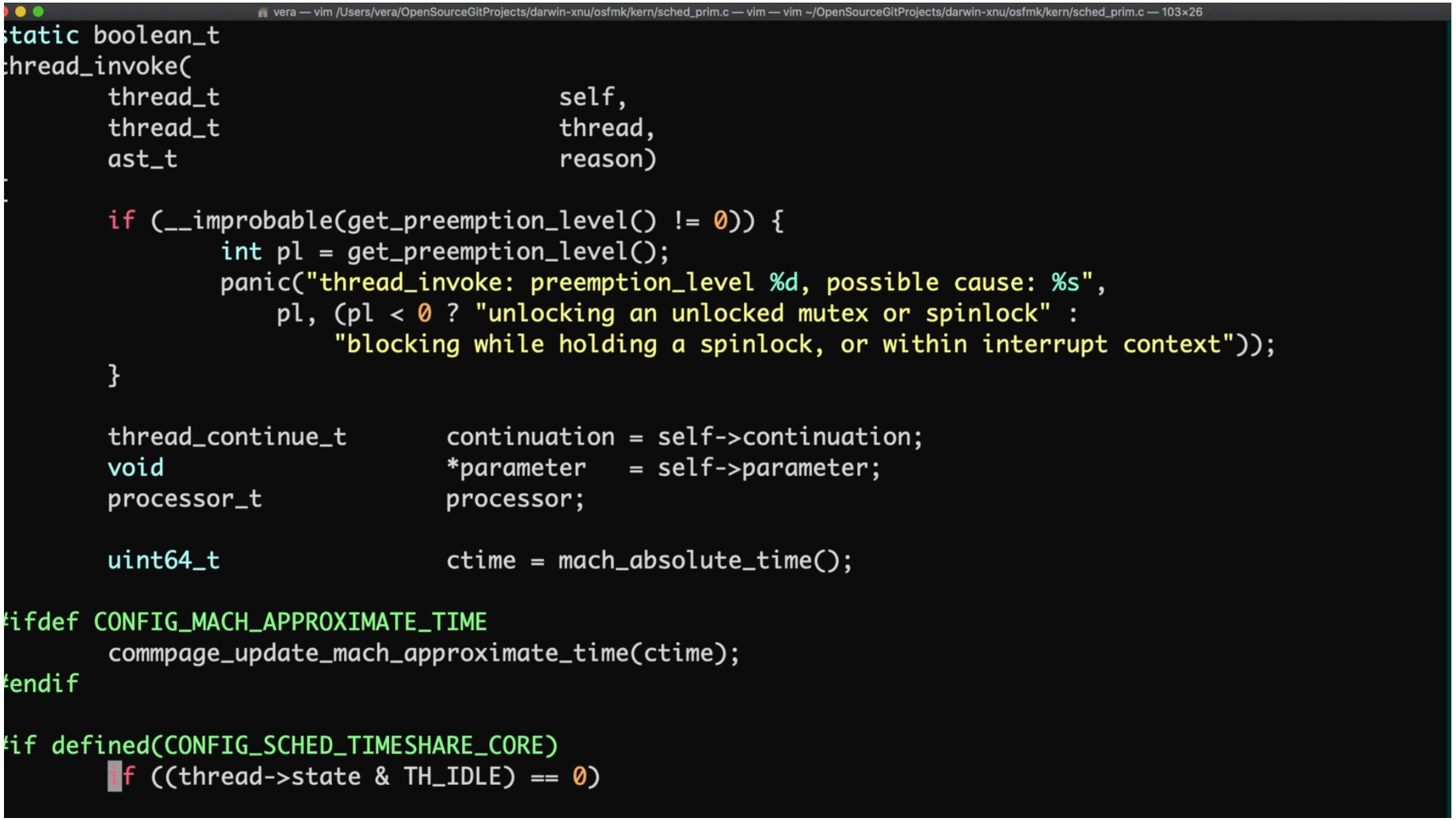
- Sign the patched binary
- Update the static trust cache
- Replace the launchd binary in the filesystem
- Remove the service cache dynamic lib file from the filesystem

Aleph Research

And it works!

Launchd craziness

```
* [0 ] | "kernel_task"                          | 0xffffffe0005f9c20
  [1 ] | "launchd"                              | 0xffffffe0005fa760
  [19] | "xpcproxy"                            | 0xffffffe000c305a0
  [27] | "xpcproxy"                            | 0xffffffe000c61680
  [39] | "xpcproxy"                            | 0xffffffe000c98b40
  [44] | "xpcproxy"                            | 0xffffffe000cbd680
  [52] | "xpcproxy"                            | 0xffffffe000cbc5a0
  [60] | "xpcproxy"                            | 0xffffffe000cfe1c0
  [62] | "xpcproxy"                            | 0xffffffe000cfed00
  [6 ] | "fseventsd"                           | 0xffffffe000cff2a0
  [7 ] | "bash"                                | 0xffffffe000cff840
  [16] | "configd"                             | 0xffffffe0005fb2a0
  [36] | "SpringBoard"                         | 0xffffffe000d4d680
  [21] | "tunnel"                              | 0xffffffe000d4cb40
  [23] | "wifid"                               | 0xffffffe000d4dc20
  [28] | "mobiletimerd"                        | 0xffffffe000d4e1c0
  [19] | "xpcproxy"                            | 0xffffffe000d4ed00
  [62] | "xpcproxy"                            | 0xffffffe000d4f2a0
  [45] | "locationd"                           | 0xffffffe000d4f840
  [42] | "dropbear"                            | 0xffffffe000d4c000
  [60] | "xpcproxy"                            | 0xffffffe000c33840
  [39] | "xpcproxy"                            | 0xffffffe000c310e0
  [55] | "AppleCredentialManagerDaemon"        | 0xffffffe000c332a0
  [43] | "timed"                               | 0xffffffe000c990e0
  [50] | "mobilewatchdog"                      | 0xffffffe000c99680
  [51] | "ptpd"                                | 0xffffffe0005f9680
  [52] | "xpcproxy"                            | 0xffffffe0005f8b40
  [58] | "mapspushd"                           | 0xffffffe000c62760
```


vera — vim /Users/vera/OpenSourceGitProjects/darwin-xnu/osfmk/kern/sched_prim.c — vim — vim ~/OpenSourceGitProjects/darwin-xnu/osfmk/kern/sched_prim.c — 103×26
static boolean_t
thread_invoke(
thread_t self,
thread_t thread,
ast_t reason)
if (__improbable(get_preemption_level() != 0)) {
int pl = get_preemption_level();
panic("thread_invoke: preemption_level %d, possible cause: %s",
pl, (pl < 0 ? "unlocking an unlocked mutex or spinlock" :
"blocking while holding a spinlock, or within interrupt context"));
}
thread_continue_t continuation = self->continuation;
void *parameter = self->parameter;
processor_t processor;
uint64_t ctime = mach_absolute_time();
#ifdef CONFIG_MACH_APPROXIMATE_TIME
commpage_update_mach_approximate_time(ctime);
#endif
#if defined(CONFIG_SCHED_TIMESHARE_CORE)
if ((thread->state & TH_IDLE) == 0)

Demo - Research a vulnerability - voucher_swap

- Research done by Brandon Azad
- iOS 12.1 jailbreak
- Trigger the vulnerability while debugging

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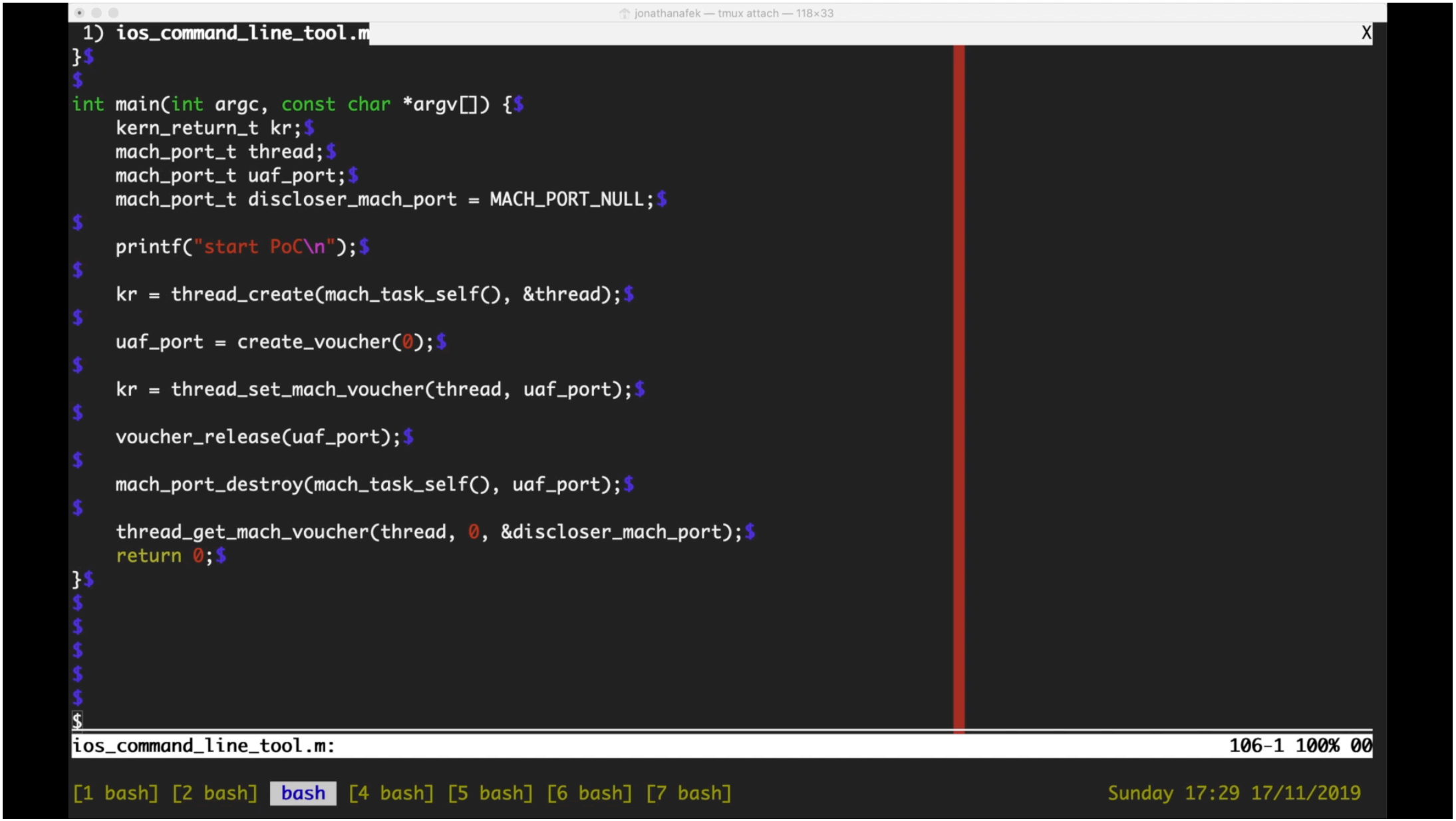
jonathanafek — tmux attach — 118×33
1) ios_command_line_tool.m
}$
$
int main(int argc, const char *argv[]) {$
kern_return_t kr;$
mach_port_t thread;$
mach_port_t uaf_port;$
mach_port_t discloser_mach_port = MACH_PORT_NULL;$
$
printf("start PoC\n");$
$
kr = thread_create(mach_task_self(), &thread);$
$
uaf_port = create_voucher(0);$
$
kr = thread_set_mach_voucher(thread, uaf_port);$
$
voucher_release(uaf_port);$
$
mach_port_destroy(mach_task_self(), uaf_port);$
$
thread_get_mach_voucher(thread, 0, &discloser_mach_port);$
return 0;$
}$
ios_command_line_tool.m:
106-1 100% 00
[1 bash] [2 bash] bash [4 bash] [5 bash] [6 bash] [7 bash]
Sunday 17:29 17/11/2019

Agenda

- Past public research on iOS on QEMU
- iOS kernel boot process
- Execution of non-Apple executables with Trust Cache
- Bash execution with launchd
- tfp0
- SSH connection
- Textual framebuffer
- Block device driver
- No secure monitor
- Launchd craziness
- **Next steps**

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Next steps and challenges

- GUI and HID support
- SEP and keybagd (if required for regular functioning)
- Interrupt support for TCP tunnel performance improvements
- VPN connection testing over SSH
- Performance improvements
  - Virtualization instead of emulation (qemu-kvm)
  - More than 1 CPU
  - Understand what it means to use a real GPU for OpenGLES
- More iOS versions and iOS devices
- Work on symbolication with Jonathan Levin’s jtool/joker and otherwise for more versions
- Fast state recovery
- Security research and fast coverage-guided, structure-aware with state recovery fuzzing

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HLT

- Use the the project and contribute! https://github.com/alephsecurity
- Check out our blog: https://alephsecurity.com
- Follow us on twitter: @alephsecurity @JonathanAfek
- Questions?

HCL AppScan

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