How to Jailbreak iOS 16

A technical deep dive into the Dopamine jailbreak

Lars Fröder / @opa334dev

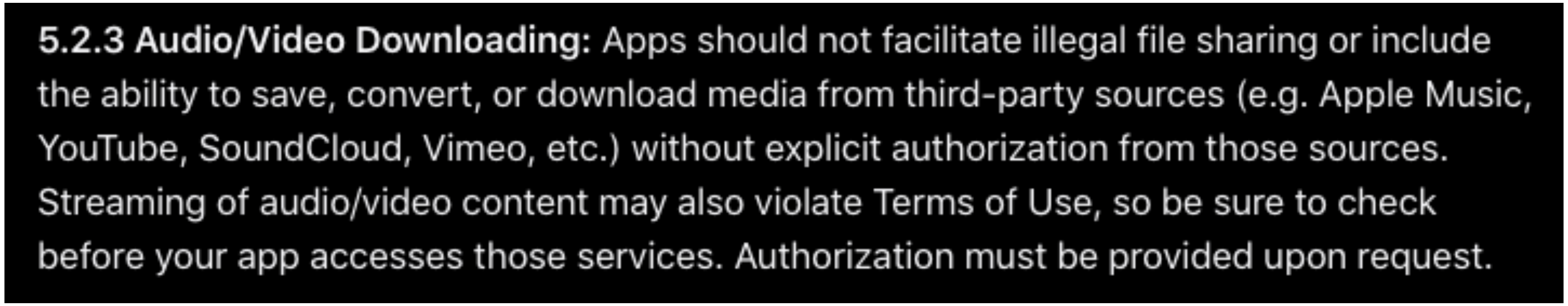
Whoami

- Researcher from Germany
- GitHub @opa334, Twitter @opa334dev
- Employed at Cellebrite Labs (We‘re hiring!)
- Software developer (Since 2017)
- Jailbreak developer (Since 2022)
    - Released TrollStore in 2022
    - Released Dopamine 1.x (iOS 15.0 - 15.4.1) in 2023
    - Released Dopamine 2.x (iOS 15.0 - 16.5) in 2024
- Recently completed my Bachelor of Science

Why Jailbreak?

- More control over a device that is your property (Crazy right?)
- Run apps not permitted by Apple’s arbitrary App Store rules
- Root access
- Proper shell environment
- System extensions / tweaks
- Better debugging capabilities (Useful for security researchers)
  - lldb
  - frida

How I became a Jailbreaker



5.2.3 Audio/Video Downloading: Apps should not facilitate illegal file sharing or include the ability to save, convert, or download media from third-party sources (e.g. Apple Music, YouTube, SoundCloud, Vimeo, etc.) without explicit authorization from those sources. Streaming of audio/video content may also violate Terms of Use, so be sure to check before your app accesses those services. Authorization must be provided upon request.

How I became a Jailbreak Developer

- iOS 15.0 released in October 2021
- No jailbreak for a long time
- First iOS 15.0 - 15.1.1 jailbreak (XinaA15) released in November 2022
    - iOS 16 was already out by two months
- Fugu15 Exploit Chain released in October 2022, but no one used it in a proper jailbreak
- “If no one else does it…”

Basics

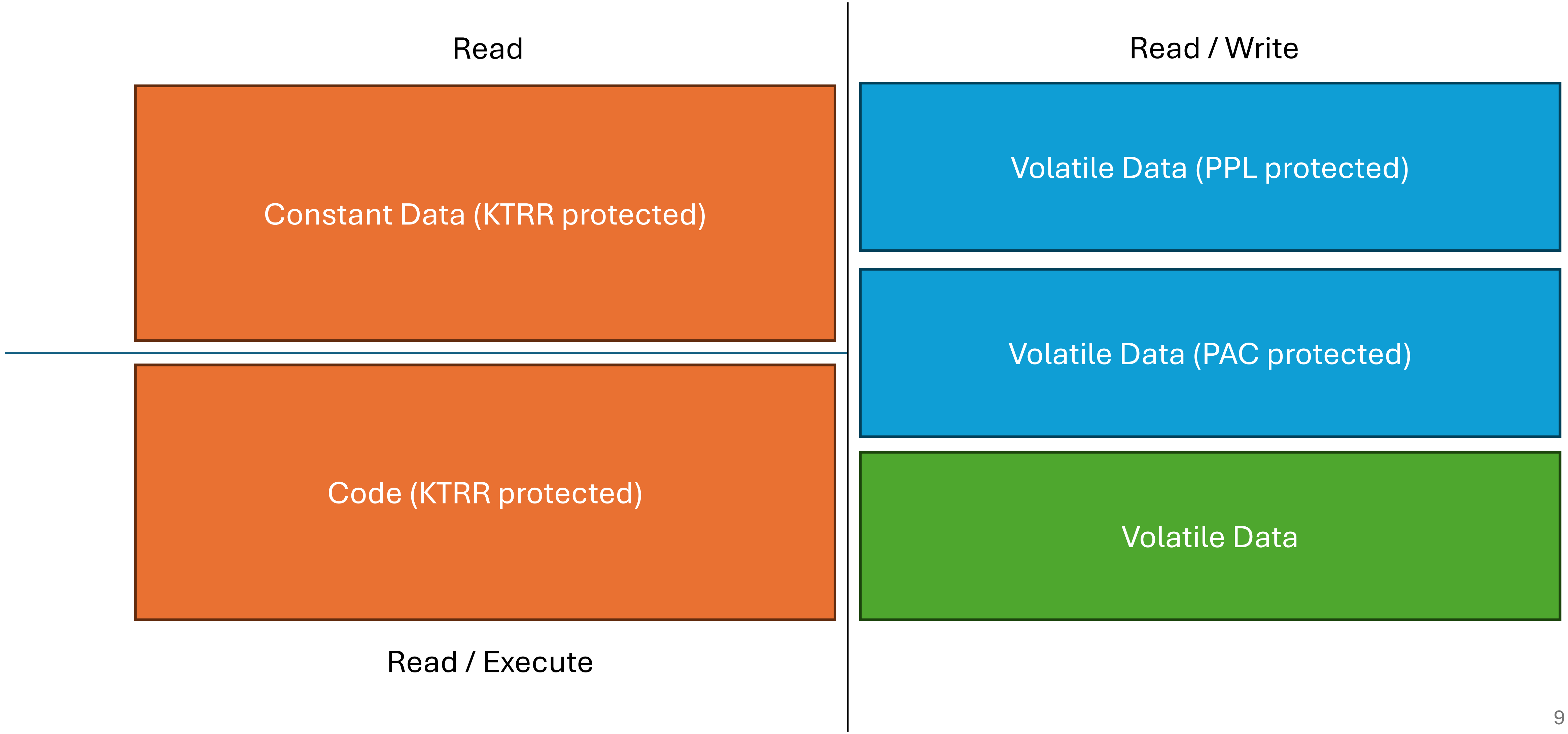
Goals of a Jailbreak

- Bypass Code Signature Enforcement
  - Allow unsigned binaries to run
- Install a Bootstrap that provides a shell environment and a package manager (dpkg)
- Install a package manager GUI app (Sileo / Zebra, formally Cydia)
- Enable tweak injection

Challenges of a Modern Jailbreak (iOS 15+)

- Post Exploit Mitigations
  - Kernel Text Read-only Region (KTRR)
  - Kernel Page Protection Layer (PPL)
  - Kernel Pointer Authentication (PAC / Control Flow Integrity)
- Signed System Volume (SSV)
  - Root file system is cryptographically signed…
- Improved Codesigning Enforcement
  - Protected by PPL now

Kernel Memory (KTRR + PAC + PPL)


Read
Read / Write
Constant Data (KTRR protected)
Volatile Data (PPL protected)
Volatile Data (PAC protected)
Code (KTRR protected)
Volatile Data
Read / Execute

Old Flow (Dopamine 1.x, iOS 15.0 - 15.4.1)

- Dopamine 1.x utilized the Fugu15 exploit chain
- Run kernel exploit to get Kernel R/W (oobPCI: CVE-2022-26763)
- Construct arbitrary mapping primitive
- Use that to trigger PAC bypass (badRecovery: CVE-2022-26765)
- Use primitives gained through PAC bypass to invoke PPL routines
- Trigger PPL bypass through that (tlbFail: CVE-2022-26764)

New Flow (Dopamine 2.x, iOS 15.0 - 16.5)

- Gain Kernel R/W using kernel exploit (kfd landa, CVE-2023-41974)
- Construct physical mapping primitive
- Use that to write to DMA registers involved in Operation Triangulation PPL bypass (CVE-2023-38606)

- No PAC bypass = no kcall primitive???
- No (big) problem, none of the relevant structures for jailbreaking are not PAC protected on iOS 15.2+ ☺
  - Dopamine 1.x on 15.2+ only uses kcall to allocate page tables

Exploitation & Primitives

Chaining multiple bugs, Constructing primitives, Primitive handoff

<=16.5(.1) PPL Bypass (CVE-2023-38606)

- For details, check out Operation Triangulation talk (https://youtu.be/1f6YyH62jFE)
- Unlike the Fugu15 PPL bypass, this one does not require invoking PPL routines
- Therefore, no PAC bypass is needed to exploit it
- As the DMA region is not mapped inside the kernel virtual address space, we do need a physical mapping primitive though
- Not functional 16.5.1 on A15 and A16 due to chip specific DMA register not being writable (AMCC panic)

Physical Mapping Primitive (IOSurface)

- Originally published by Linus Henze as part of Fugu15_Rootful
- Still works on iOS 16!
- Create IOSurface object from app
- Find object in Kernel memory
  - Decrement reference count
  - Modify the physical address it represents
  - NULL out some attributes
- Call IOSurfaceGetMachPort on the IOSurface
  - Makes the Kernel map the physical address to our process

Physical Mapping Primitive (IOSurface)

- Allows mapping arbitrary non PPL protected Kernel pages to userland
- Using this, we can map the pages containing the DMA registers involved in the PPL bypass
- Afterwards, these pages can be used to perform writes to PPL protected pages using the bug
- Next up: Get fully stable PPL R/W by injecting page table entries

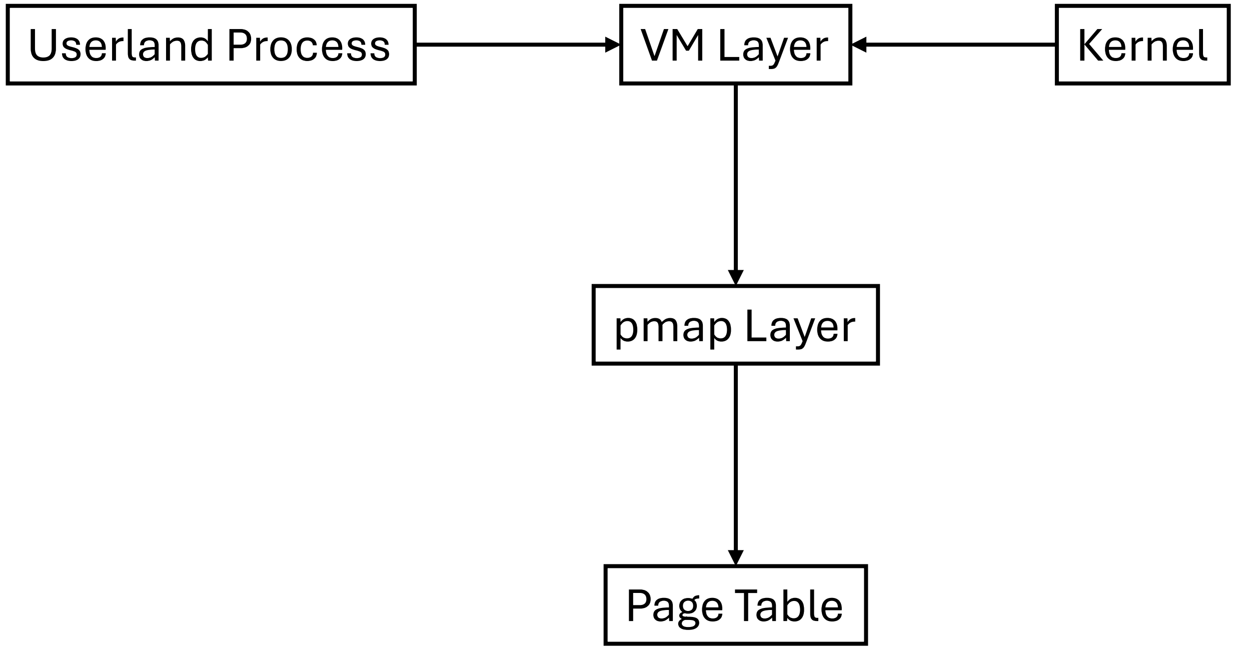
PPL R/W Handoff

- Integral component of modern jailbreaks
- Pass physical read / write primitives (including PPL protected pages) to another process
- In practice, we will archive this by modifying the page table

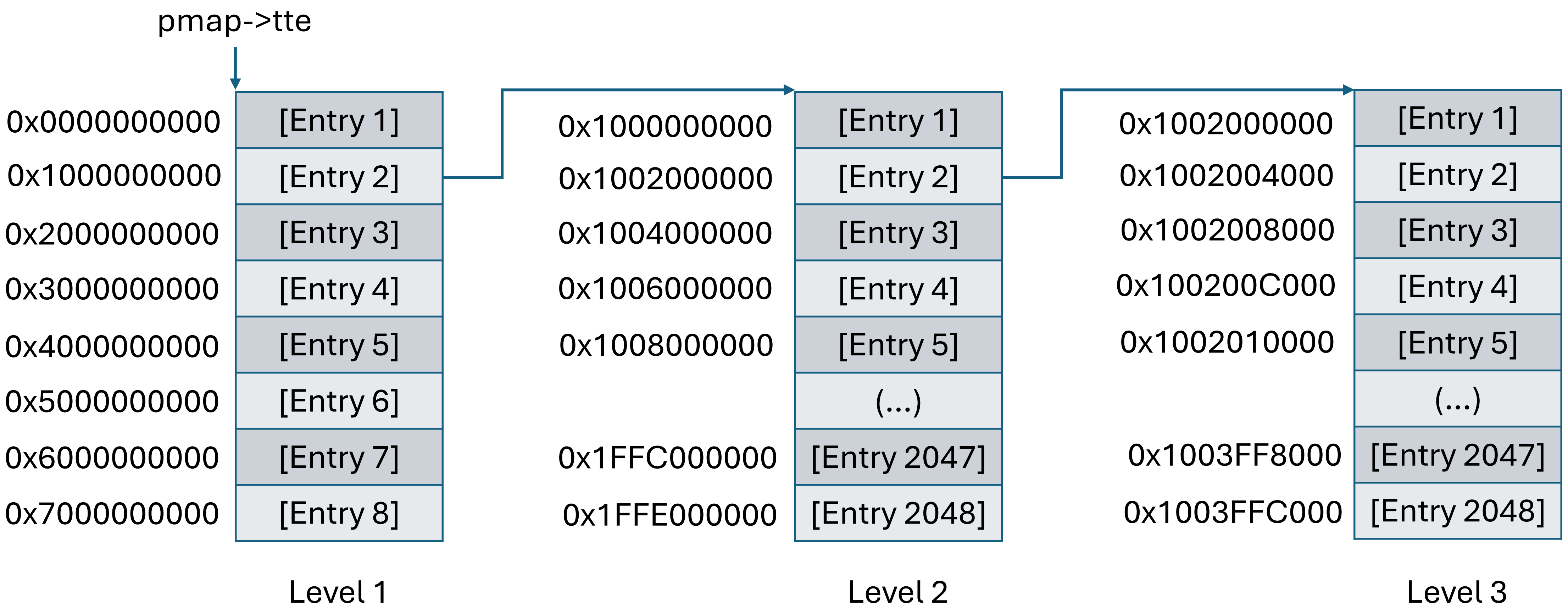
PPL R/W Handoff

- App exploits PPL bug to get initial primitive, then spawns jailbreak server and passes primitives to it
- Jailbreak server then preserves the primitives and uses them to provide jailbreak features to other processes
- During initial jailbreak, use PPL bypass to handoff PPL R/W to our own process

Memory Management on *OS



Page Tables



pmap->tte
0x0000000000
[Entry 1]
0x1000000000
[Entry 2]
0x2000000000
[Entry 3]
0x3000000000
[Entry 4]
0x4000000000
[Entry 5]
0x5000000000
[Entry 6]
0x6000000000
[Entry 7]
0x7000000000
[Entry 8]
Level 1
0x1000000000
[Entry 1]
0x1002000000
[Entry 2]
0x1004000000
[Entry 3]
0x1006000000
[Entry 4]
0x1008000000
[Entry 5]
(...)
0x1FFC000000
[Entry 2047]
0x1FFE000000
[Entry 2048]
Level 2
0x1002000000
[Entry 1]
0x1002004000
[Entry 2]
0x1002008000
[Entry 3]
0x100200C000
[Entry 4]
0x1002010000
[Entry 5]
(...)
0x1003FF8000
[Entry 2047]
0x1003FFC000
[Entry 2048]
Level 3

pmap Layer

- Provides routines to interact with physical pages
  - Every process owns a vm_map object
  - Every vm_map object owns a pmap object
- On arm64e: Implemented in PPL mode, all data structures are protected
- Backed by actual page table used by the MMU of the specific process (pmap->ttep is TTBR0 at runtime)
- Every mapping is registered in the pmap layer and then reflected in the backed page table
- Allocates and deallocates page tables as needed

pmap Layer

- Every physical page has a descriptor (pt_entry / pt_desc)
- pv_head_table: pv_entry_t[], one entry for every existent physical page (gPhysBase -> gPhysBase + gPhysSize)
- Every page has a type, indicating what it is used for
  - PVH_TYPE_NULL: Not mapped
  - PVH_TYPE_PVEP: Page mapped in multiple pmaps
  - PVH_TYPE_PTEP: Page mapped in one pmap
  - PVH_TYPE_PTDP: Page used as Page Table
- More attributes, depending on the type

VM Layer

- Interacts with pmap layer to provide virtual memory to userspace processes
- Every mapping represents one vm_entry being added to the tasks map attribute
- VM Layer handles memory faults and maps in the backing memory as needed

VM Layer + pmap Layer: Example

Userland

```
void *page = malloc(0x4000);

*(uint32_t *)page = 0x4141;
```

Kernel

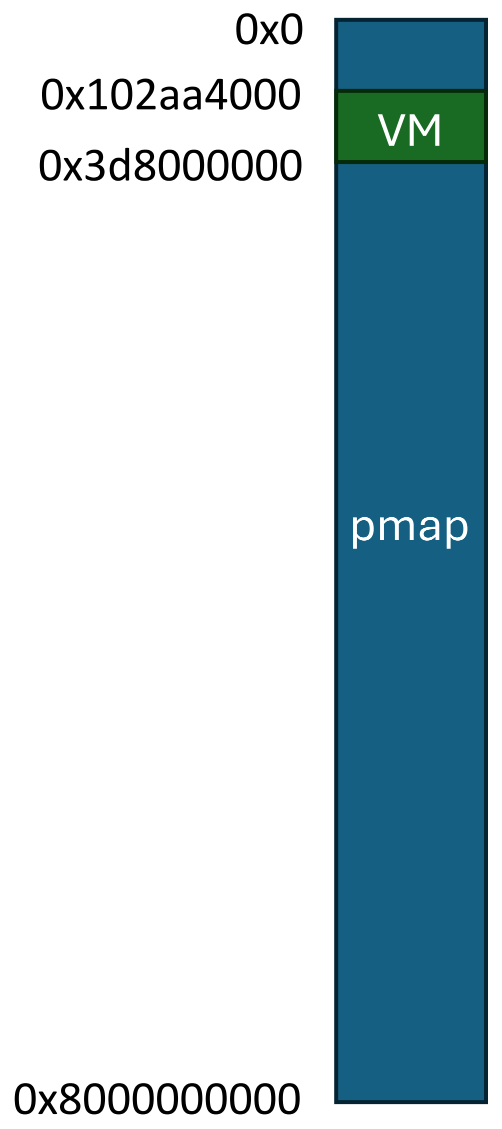
```
vm_allocate
↳ vm_map_enter

handle_user_abort
↳ vm_fault
   ↳ pmap_enter_options
```

Injecting Page Table Entries

- To map arbitrary kernel pages into our process, we need to be able to allocate level 2 and level 3 page tables
- If we don’t do this, the system will panic on process exit, because it can’t clean up page tables that haven’t been properly allocated
- Avoid mapping to addresses that are managed by the VM layer
  - Our injected page table entries are neither added to the VM layer, nor the pmap layer
  - If the system attempts to map something else on top of our mapping, that will either destroy our mapping or crash the system

VM Layer Coverage

- VM layer covers only a small chunk of memory (0x102aa4000 to 0x3d8000000 on my iPhone 13 Pro on 15.1.1) of the actual page table
- Other addresses are always unused
- When the jailbreak maps a kernel page, it needs to do so in unused area to avoid colliding with regular allocations



Allocate Page Table (Legacy, with Kcall)

- pmap_enter_options(pmap, <lvl2_addr>, 0x13370000)
  - Map the (garbage) physical address 0x13370000 to the place address which we want to allocate a page table in our process
- pmap->nested = true
- pmap_remove_options(pmap, <lvl2_addr>)
  - The garbage 0x13370000 entry is removed but the allocation will stay, because we set nested
- pmap->nested = false
- Now we can insert arbitrary entries into the level 2 table

Allocate Page Table (No Kcall)

- Every page table has an associated pt_desc / ptd_info
- A reference to this exists in the pv_entry structure of the page that contains the page table allocation

```
typedef struct pt_desc {
        queue_chain_t pt_page;
        struct pmap *pmap;
        vm_offset_t va[PT_INDEX_MAX];
        ptd_info_t *ptd_info;
} pt_desc_t;
```

```
typedef struct {
        unsigned short refcnt;
        unsigned short wiredcnt;
} ptd_info_t;
```

Allocate Page Table (No Kcall)

- posix_memalign(&lvl2_addr, L2_BLOCK_SIZE, L2_BLOCK_SIZE)
    - Allocate the entire span of an L2 page table (0x2000000 bytes)
    - Faulting in one page in it will allocate the page table
    - We now have full control over this page table and can deallocate it at will
- Find pt_desc of page table
- Artificially bump pt_desc->ptd_info->refcnt using PPLRW
- free(lvl2_addr)
- Decrease reference count
- Page table is now still allocated and associated with process

Allocate Page Table (No Kcall)

- The allocated page table will be inside the memory that‘s covered by the VM layer
- We need to move it elsewhere to avoid collisions
- We also want to be able to give it to other processes
    - pt_desc->pmap = <target pmap>
    - pt_desc->va[0] = <target pmap va start>
- Setting these will prevent the system from panicing when the process exits
- Insert the allocated page table into the target pmap’s ttep
- Can be used as both level 2 and level 3 page table

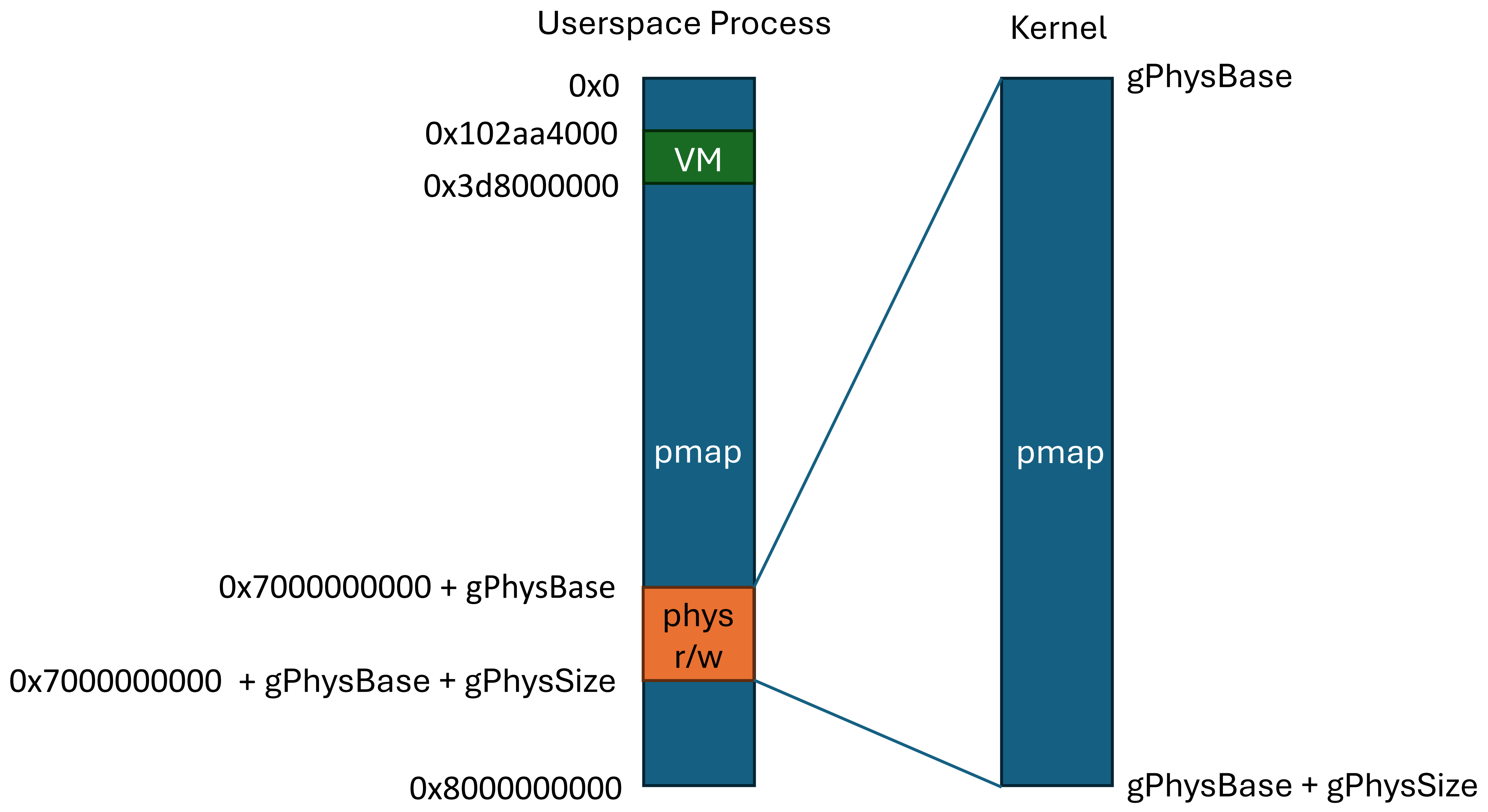
```
typedef struct pt_desc {
		queue_chain_t pt_page;
		struct pmap *pmap;
		vm_offset_t va[PT_INDEX_MAX];
		ptd_info_t *ptd_info;
} pt_desc_t;
```

```
typedef struct {
		unsigned short refcnt;
		unsigned short wiredcnt;
} ptd_info_t;
```

Full Kernel Mapping

- Read gPhysStart, gPhysSize to determine what pages need to be mapped
- Write logic that maps PA to VA by allocating page tables as needed
- Call said logic to map all pages between (gPhysStart) and (gPhysStart + gPhysSize) to between (gPhysStart + 0x7000000000) and (gPhysStart + gPhysSize + 0x7000000000)
- Phys R/W can now be done by simply adding 0x7000000000 to the physical pointer and dereferencing it!
- Fastest possible way of doing Kernel R/W

Full Kernel Mapping

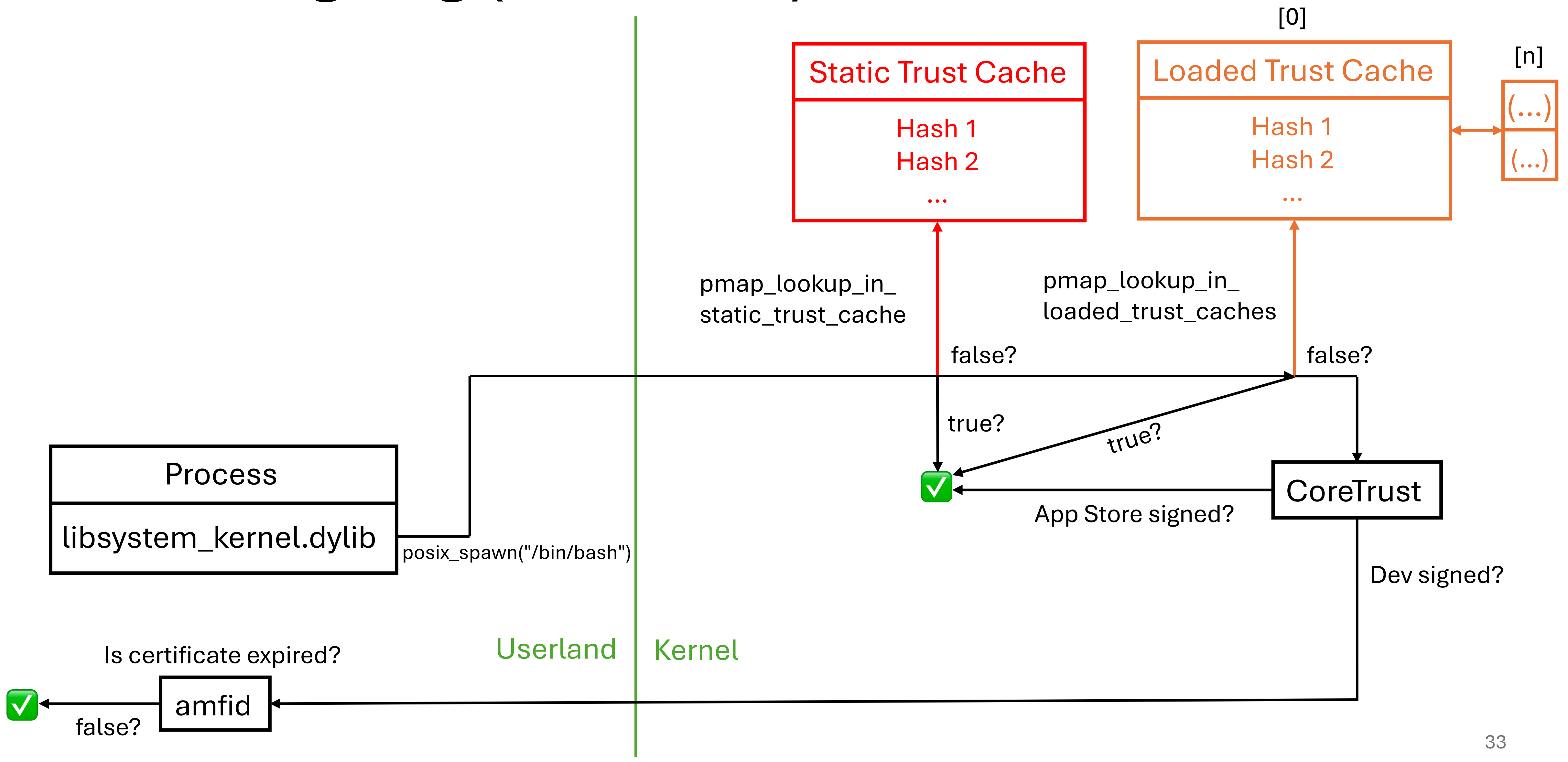


Building a Jailbreak Environment

We have primitives and handoff techniques now, so all that‘s left is for us to utilize them!

KTRR PPL

Code Signing (iOS >=15)



Bypassing Code Signing

- Using PPL R/W, we can inject arbitrary CDHashes into a dynamic Trust Cache
- We first bundle a few binaries with the jailbreak and add them to trust cache
- This allows us to run code with arbitrary entitlements
- But in the end, we would like to modify the system to the point where *ANY* binary can run
- We need to automate adding the CDHash to Trust Cache for any binary that is attempted to be spawned and any library that is attempted to be loaded

Bypassing Code Signing

- All binaries are spawned via calling posix_spawn (and a few other functions) from userland
    - launchd: Parent process of the entire userland
- Hook posix_spawn inside every process, add binary to Trust Cache, then call original implementation
- We can use a launchd task port to load a library into it (By creating a thread that calls dlopen)
- In this library we can hook posix_spawn
- But how do we extend this hook to the entire system?

Jailbreak Server (inside launchd)

- Inside launchd, hook XPC message handler to add additional logic to it
- After the app has ran the exploit chain and injected the library into launchd, the library will use XPC to communicate with the app to transfer PPL R/W to itself
- Once obtained, launchd can now provide the rest of the system with APIs to interact with the Kernel using PPL R/W
- For example, it can expose a call to add an executable to Trust Cache

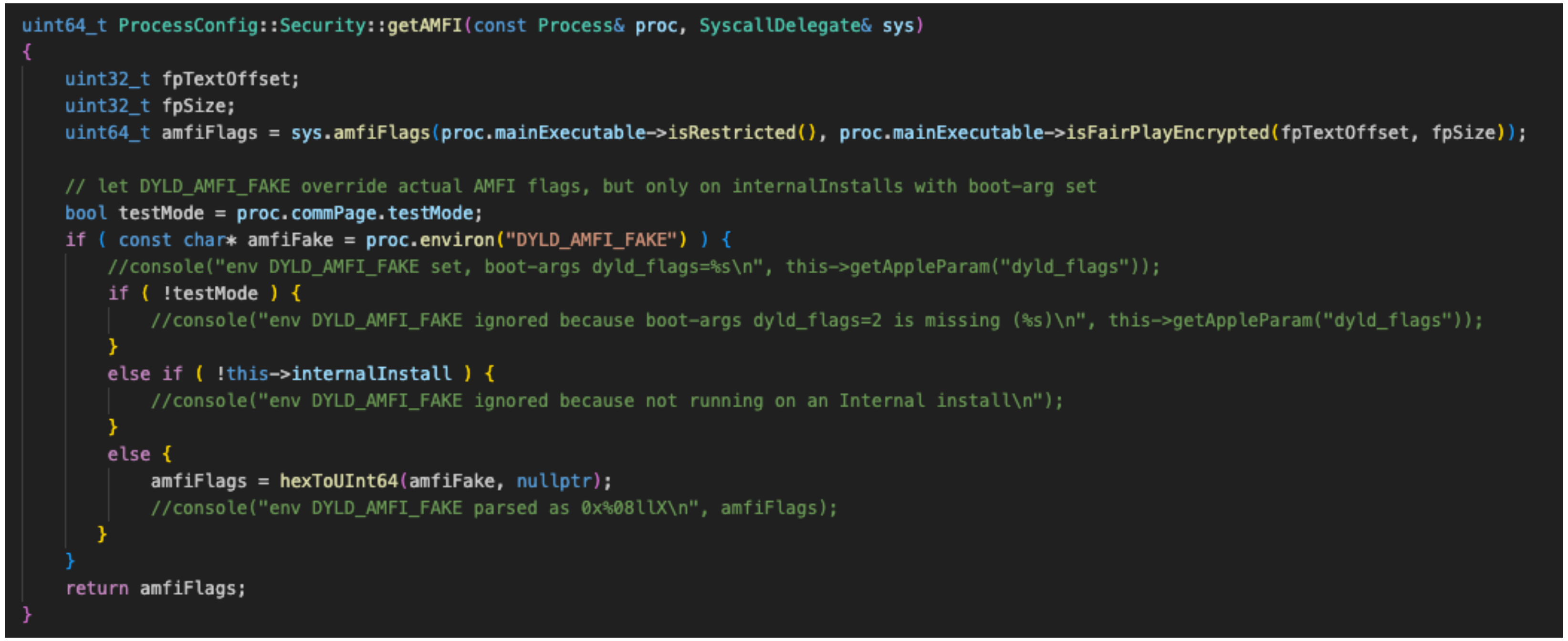
System Wide Hook

- Idea: One library injects system wide and hooks relevant functions inside every single process
- If we hook posix_spawn, we can add custom environment variables to any processes spawned
- Using this, we can add DYLD_INSERT_LIBRARIES to reinsert the system hook library
- Unfortunately, dyld will ignore this environment variable under normal circumstances

Dyld: AMFI Flags

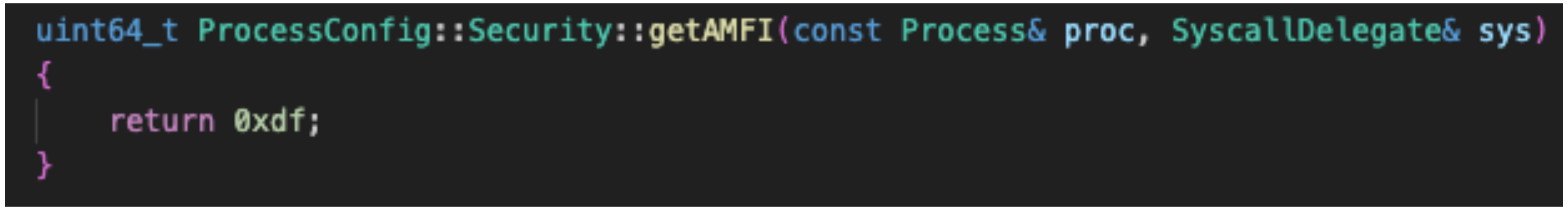
- Dyld calls out to Kernel to get “AMFI flags” for the process it runs in
- These flags dictate which environment variables are allowed
- DYLD_INSERT_LIBRARIES is only allowed if the process has the get-task-allow entitlement
- Normally, only stuff compiled for debugging has this
- If we want to use this environment variable, we need to find a way to bypass this requirement

dyld Patch



```
uint64_t ProcessConfig::Security::getAMFI(const Process& proc, SyscallDelegate& sys)
{
    uint32_t fpTextOffset;
    uint32_t fpSize;
    uint64_t amfiFlags = sys.amfiFlags(proc.mainExecutable->isRestricted(), proc.mainExecutable->isFairPlayEncrypted(fpTextOffset, fpSize));

    // let DYLD_AMFI_FAKE override actual AMFI flags, but only on internalInstalls with boot-arg set
    bool testMode = proc.commPage.testMode;
    if ( const char* amfiFake = proc.environ("DYLD_AMFI_FAKE") ) {
        //console("env DYLD_AMFI_FAKE set, boot-args dyld_flags=%s\n", this->getAppleParam("dyld_flags"));
        if ( !testMode ) {
            //console("env DYLD_AMFI_FAKE ignored because boot-args dyld_flags=2 is missing (%s)\n", this->getAppleParam("dyld_flags"));
        }
        else if ( !this->internalInstall ) {
            //console("env DYLD_AMFI_FAKE ignored because not running on an Internal install\n");
        }
        else {
            amfiFlags = hexToUInt64(amfiFake, nullptr);
            //console("env DYLD_AMFI_FAKE parsed as 0x%08llX\n", amfiFlags);
        }
    }
    return amfiFlags;
}
```

↓



```
uint64_t ProcessConfig::Security::getAMFI(const Process& proc, SyscallDelegate& sys)
{
    return 0xdf;
}
```

iOS 16: “In-Cache dyld”

- In iOS 16, Apple introduced “In-Cache dyld”
- dyld now resides inside the dyld_shared_cache
- This is bad for us!
  - The dyld_shared_cache is very big so patching it would be very storage intensive
  - No one has really figured out how to properly patch it, lots of mysteries
- Luckily, the “In-Cache dyld” is only used if the LC_UUID of the dyld binary matches with what the Kernel expects
- As we are already patching dyld, we can simply change the LC_UUID and our modified dyld will be used once again!

dyld Patch

- Now that we have a statically patched dyld, we need to find a way to make the system use it
- dyld normally resides inside /usr/lib
- Idea
  - Copy contents of /usr/lib to writable location
  - Replace dyld file in there
  - Mount writable location on top of /usr/lib
- That way, the Kernel will map in our patched dyld into every newly started process

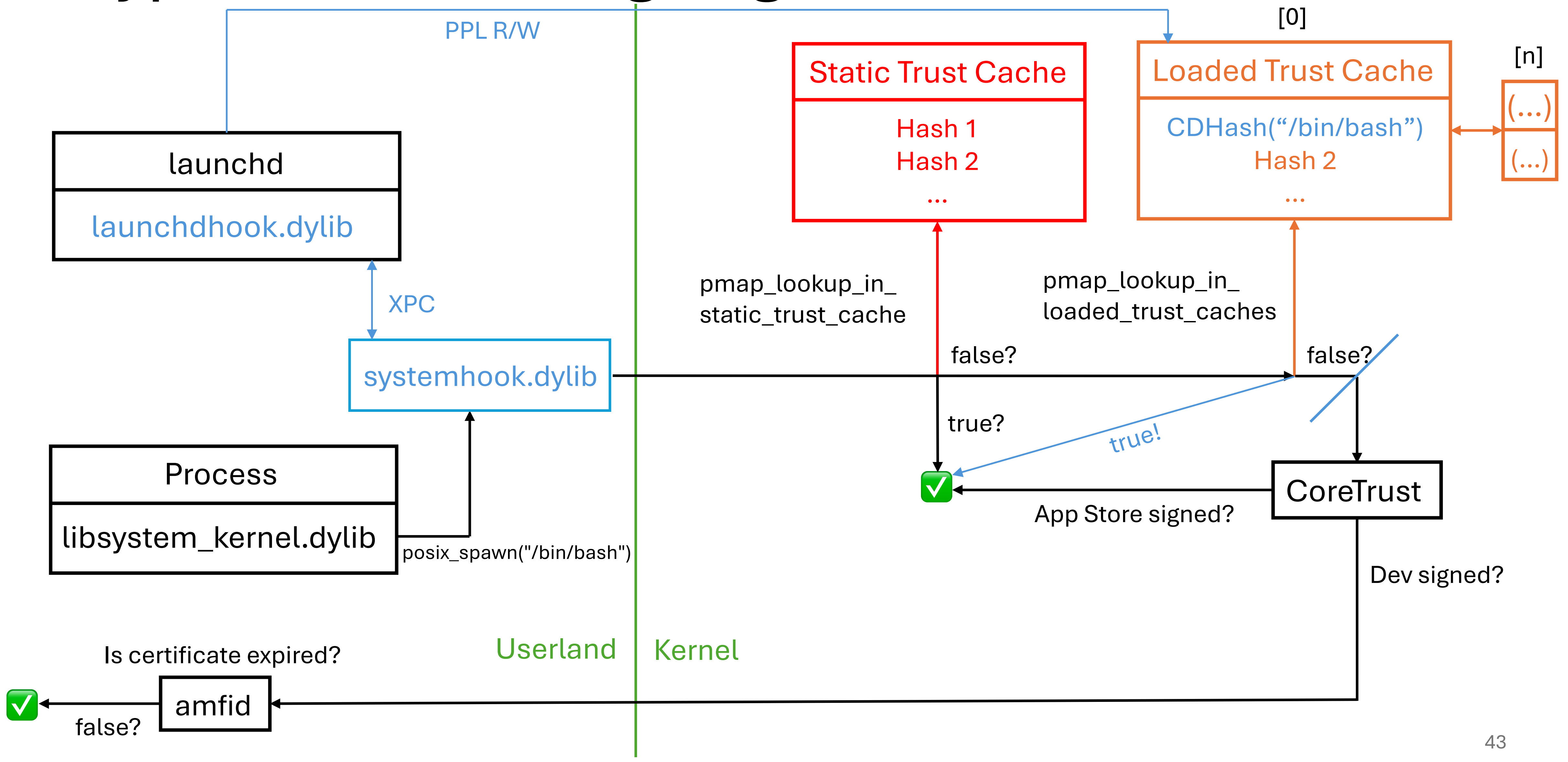
dyld: Bind Mount

- Bind mounts allow mounting a directory on top of another directory
- Idea: Bind mount /var/jb/basebin/.fakelib on top of /usr/lib
- Mounting on top of /usr/lib is prohibited by sandbox
- We need to temporarily borrow the kernel ucred to bypass that

- Once applied, our patched dyld is now active and DYLD_INSERT_LIBRARIES works system wide!

Jailbreak KTRR PPL

Bypassed Code Signing



iOS 16+: Developer Mode

- In iOS 16, various entitlements are locked behind developer mode
  - E.g. task_for_pid-allow
- Stock flow to enable developer mode is complicated
  - Attempt to sideload an app
  - Enable toggle in settings
  - Reboot device, afterwards there will be a confirmation alert
- At runtime, the developer mode is stored in ppl_developer_mode_storage global bool
- Variable is PPL protected, using PPL R/W we can enable developer mode in a non persistent way by writing to it

iOS 16+: Protobox

- New sandbox feature introduced in iOS 16
- Amongst other things, provides syscall whitelists for system processes
- Apple uses these for more and more processes to make attackers lives harder
- If a process attempts to use a non whitelisted syscall, it will crash
- Problem: Some tweaks inject into system processes and depend on such syscalls

Codesigning Implementations

Name	Devices	iOS
CSM	arm64	*
PMAP_CS	arm64e	15+
TXM	A15+	17+

PMAP_CS: Page Protection

- Map unsigned code as executable?
  - Prevented by check in pmap_cs_associate

- Run unsigned code that‘s already mapped executable?
  - Prevented by check in pmap_cs_enforce

- Allowed if wx_allowed bit is set on pmap object
- We can set this bit using PPL R/W, which allows us to disable page protection for the process

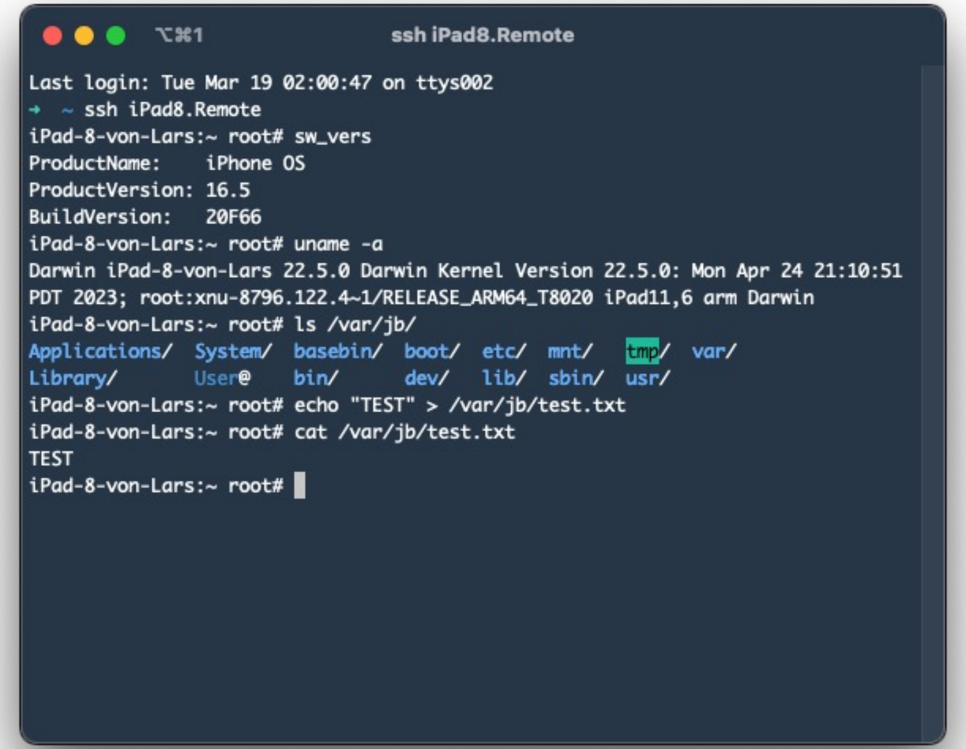
Jailbreak Server: Process check in

- The system wide hook, in it‘s library constructor, will send a “check in” message to the jailbreak server
- The jailbreak server then applies various modifications to the process
    - Disable Protobox by setting syscall mask to all 1’s
    - Disable page validation as shown in previous slide
    - Return sandbox extensions to access /var/jb to caller process
    - If process main executable has setuid bit set, apply it

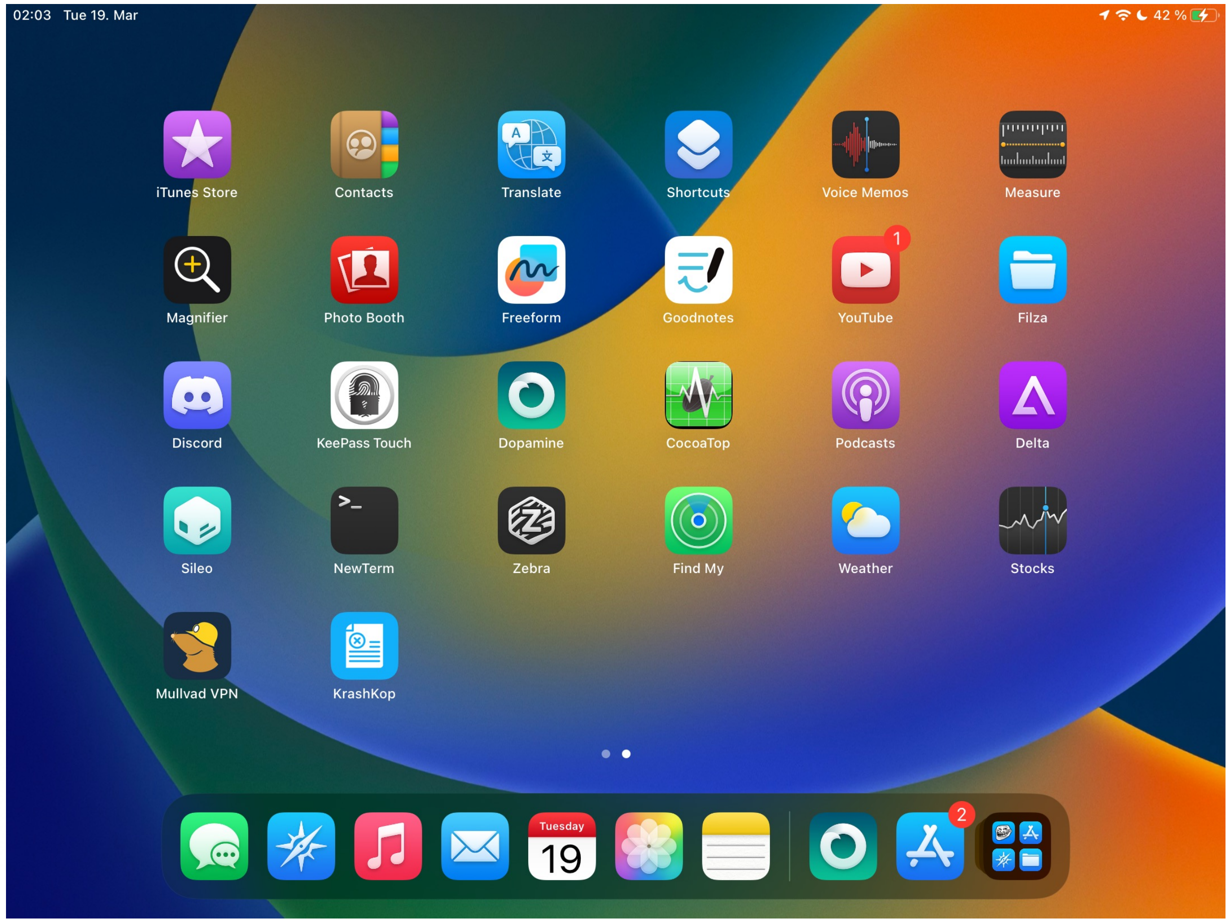
Tweak Injection

- All major security features have been bypassed and we already have system wide tweak injection
- dlopen “/var/jb/usr/lib/TweakLoader.dylib” if it exists
  - Provided by tweak injection library, such as Ellekit
- That then parses tweak plists inside /var/jb/Library/MobileSubstrate/DynamicLibraries and loads libraries that filter the process
- Those libraries can then modify the process at will

Jailbreak Complete



```
Last login: Tue Mar 19 02:00:47 on ttys002
➜  ~ ssh iPad8.Remote
iPad-8-von-Lars:~ root# sw_vers
ProductName:    iPhone OS
ProductVersion: 16.5
BuildVersion:   20F66
iPad-8-von-Lars:~ root# uname -a
Darwin iPad-8-von-Lars 22.5.0 Darwin Kernel Version 22.5.0: Mon Apr 24 21:10:51
PDT 2023; root:xnu-8796.122.4~1/RELEASE_ARM64_T8020 iPad11,6 arm Darwin
iPad-8-von-Lars:~ root# ls /var/jb/
Applications/  System/  basebin/  boot/  etc/  mnt/  tmp/  var/
Library/       User@    bin/      dev/   lib/  sbin/  usr/
iPad-8-von-Lars:~ root# echo "TEST" > /var/jb/test.txt
iPad-8-von-Lars:~ root# cat /var/jb/test.txt
TEST
iPad-8-von-Lars:~ root# █
```



The End

Questions?