Analysis of iOS 9.3.3 Jailbreak
&
Security Enhancements of iOS 10

Team Pangu

Agenda

- CVE-2016-4654
- Exploit Strategy
- iOS 10 Security Enhancements
- iPhone 7 New Protection
- Conclusion

Timeline of the Kernel Bug

- We showed Jailbreak for iOS 10 beta1 on MOSEC 2016
- The bug was fixed in iOS 10 beta2
- We released Jailbreak for 9.2-9.3.3 on 24th July
  - Exploited the kernel bug from an installed App
- Apple published 9.3.4 to fix it on 4th Aug Morning
  - https://support.apple.com/en-us/HT207026
- We gave a talk at Blackhat 2016 on the same day

CVE-2016-4654

- Any App can exploit this bug to attack kernel
- It's a heap overflow bug in IOMobileFrameBuffer
  - Length of the overflow is controlled
  - Data of the overflow is partially controlled
- Full discussion of this, and other past exploits can be found in "*OS Internals" volume III, by Jonathan Levin

CVE-2016-4654

- “IOMobileFramebuffer::swap_submit(IOMFBSwap *)”
  - IOMFBSwap is input from user-land
  - v33 comes from v31
  - v31 comes from swap+216+4*v15
  - No size check of v33 in the loop
  - Overflow of v34

```
v28 = swap + 4 * v15;
v30 = request + 4 * v15;
*(_DWORD *)(v30 + 176) = *(_DWORD *)(v28 + 176) & 7;
*(_QWORD *)(request + 304) = *(_QWORD *)swap;
*(_QWORD *)(request + 312) = *(_QWORD *)(swap + 8);
*(_QWORD *)(request + 320) = *(_QWORD *)(swap + 16);
v31 = *(_DWORD *)(v28 + 216);
*(_DWORD *)(v30 + 380) = v31;
if ( v31 )
{
  v32 = 0;
  v33 = (unsigned int *)(v30 + 380);
  v34 = (_OWORD *)(request + (v15 << 6) + 392);
  v35 = (__int128 *)v16;
  do
  {
    v36 = *v35;
    ++v35;
    *v34 = v36;
    ++v34;
    ++v32;
  }
  while ( v32 < *v33 );
}
```

Basics of IOMobileFrameBuffer

- It is a kernel extension for managing the screen frame buffer
- It is controlled by the user-land framework IOMobileFramebuffer.framework
- Output from ioreg for iPhone 6
  - AppleMobileADBE0 <class IORegistryEntry:IOService:IOMobileFramebuffer:AppleDisplayPipe:AppleH7DisplayPipe:AppleCLCD:AppleMobileADBE0, id 0x1000001de, registered, matched, active, busy 0 (4 ms), retain 9>
- Open IOMobileFramebufferUserClient via IOServiceOpen
  - IOServiceMatching with “AppleCLCD”

Basics of IOMobileFrameBuffer

- Locate the sMethods table used by externalMethod

```
sMethods        IOExternalMethodDispatch <sub_FFFFFF801B145D88, 3, 0, 0, 0>
                                         ; DATA XREF: __text:FFFFFF801B144350↑o
                                         ; IOMobileFrameBufferUserClient_start+2C↑o
                IOExternalMethodDispatch <sub_FFFFFF801B145DA8, 0, 0, 0, 0>
                IOExternalMethodDispatch <sub_FFFFFF801B145DA8, 0, 0, 0, 0>
                IOExternalMethodDispatch <sub_FFFFFF801B145DCC, 2, 0, 1, 0>
                IOExternalMethodDispatch <IOMobileFrameBufferUserClient__swap_begin, \
                                          0, 0, 1, 0>
                IOExternalMethodDispatch <IOMobileFrameBufferUserClient__swap_submit, \
                                          0, 0xFFFFFFFF, 0, 0>
                IOExternalMethodDispatch <sub_FFFFFF801B145EAC, 3, 0, 0, 0>
```

- selector=5 with input structure is calling swap_submit
  - It finally goes to IOMobileFramebuffer::swap_submit to trigger the overflow
- selector=4 with one output scalar is calling swap_begin
  - It creates an IOMFBSwapIORequest object which is required for calling swap_submit
  - It returns the request id in the output scalar

swap_submit

- The input structure is passed to swap_submit as IOMFBSwap data
  - Size of structure must be 544 for 9.3.x or 424 for 9.2.x
- It firstly gets the IOMFBSwapIORequest object by id stored in swap+24
- Then it fills the request object according to our input swap in a loop with index from 0 to 2
  - It will try to find IOSurface by id stored in swap+28/32/36 and save the pointers in request+32/36/40 object
  - Heap overflow occurs when filling request+392 with swap+228
    - No size check of count stored in swap+216/220/224
- Before exit it will check if the swap is ok, if not it will release IOMFBSwapIORequest and IOSurface objects

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Control the Overflow

- The overflow size is quite easy to control from input+216
- IOMFBSwapIORequest size is 872 in kalloc.1024
  - We can overwrite content of next kalloc.1024 object
- The overflow occurs while copying from input+228 to request+392
  - Remember there is size verification of input so we can't control the overflow data directly
  - Actually the input data is in a mach message handled by MIG and it's also in kalloc.1024 zone
  - It's possible to control the uninitialized memory content by heap fengshui

Next Step ?

- Do heap fengshui in kalloc.1024
  - [IOMFBSwapIORequest]+[victim object]
- We can overwrite data of the victim object
- Need to bypass KASLR
- How to choose the victim object?

Exploit Strategy A

- Find an object in kalloc.1024 and it stores its size at the beginning
- Overwrite the size of the object to a bigger one
- Free into wrong zone -> read/write of next kalloc.1024 kernel object
  - Doesn’t work on iOS 10 (we will discuss it later)
  - Not so stable because of only 4 objects are in one page for kalloc.1024
  - Should work for both 32bit and 64bit devices

Exploit Strategy B

- Target iOS 10 beta + 64bit devices
  - SMAP actually doesn't exist, kernel mode can access user-land data
- Choose IOMFBSwapIORequest as the victim object
  - All requests are linked, request+16 stores next request pointer
  - request+0 stores vtable pointer
  - request+328 stores the request id
  - Overwrite the next pointer to a user-land address to hijack the whole request list
    - We can read/write our controlled fake IOMFBSwapIORequest

Leak Kernel Address

- We call swap_submit again with our fake request id and a valid IOSurface id
  - We can get the IOSurface pointer at request+32
- Get property of “IOMFB Debug Info” will give us more detailed informations
  - It will retrieve information of all swap requests
    - Also it will try to get data of IOSurface

Leak Kernel Address

- It will read 4 bytes at IOSurface+12 as “src_buffer_id”

```
setDictionaryNumber(dict, (__int64)"src_buffer_Id", *(unsigned int *)(iosurface + 12), 32LL);
if ( *(_DWORD *)(iosurface + 176) )
{
  v9 = (*(__int64 (__fastcall **)(__int64, _QWORD))(*(_QWORD *)iosurface + 224LL))(iosurface, 0LL);
  v10 = "src_stride";
  v11 = v9;
}
else
{
  v11 = *(unsigned int *)(iosurface + 152);
  v10 = "src_stride";
}
```

- We can set request+32 from IOSurface to IOSurface-12
  - Get the lower 4 bytes of IOSurface vtable
- Set it to IOSurface-8 again to get the higher 4 bytes of IOSurface vtable
- We can now calculate the kernel base address

Kernel Code Execution

- Remember if the swap data is not correct, it will call IOMFBSwapIORequest::release before exit

```
CBZ             X0, loc_FFFFFF801B14C1DC
LDR             X8, [X0] ; X0=IOMFBSwapIORequest
LDR             X8, [X8,#0x28]
BLR             X8
B               loc_FFFFFF801B14C1DC
```

- And we could totally control the vtable of the fake request in user-land memory
  - X0 and X8 are under control

Arbitrary Kernel Reading

- Gadgets for reading

```
LDR             X8, [X0]
LDR             X2, [X8,#0xA8]
LDR             X1, [X0,#0x40] ; Control X1
BR              X2
```

```
LDR             X9, [X1,#0x78]
LDR             W9, [X9,#0x18] ; read 4 bytes
STR             W9, [X0,#0x50]
MOV             X0, X8
RET
```

Arbitrary Kernel Writing

- Gadgets for writing

```
LDR             X8, [X0]
LDR             X2, [X8,#0xA8]
LDR             X1, [X0,#0x40] ; Control X1
BR              X2
```

```
LDR             X8, [X8,#0x688]
ADD             X8, X8, X0
STR             X8, [X1] ; write 8 bytes
RET
```

Fix the Bug

```
v32 = *( DWORD *)(v29 + 216);
if ( v32 > 4 )
  v32 = 4;
*((_DWORD *)v30 + v16 + 94) = v32;
if ( v32 )
{
  v33 = 0LL;
  v34 = v69;
  v35 = (unsigned int *)(v69 + 4 * v16 + 376);
  v36 = v17;
  do
  {
    *(_OWORD *)((char *)v30 + v36 + 160) = *(_OWORD *)((char *)v2 + v36);
    ++v33;
    v36 += 16LL;
    v30 = (_QWORD *)v34;
  }
  while ( v33 < *v35 );
  v30 = (_QWORD *)v34;
}
```

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Hardened JIT Mapping

- --X mapping is now supported
- Create two mappings of the physical JIT memory
  - One is --X
  - One is RW-
  - Keeps the location of RW- secret

Kernel Heap Management

- For iOS 9
- Not all zones has page meta data
- Free into wrong zone works well when target is none page list zone
  - Enough to bypass KASLR and get code execution

Kernel Heap Management

- For iOS 10
  - There are page meta data for all zones
  - Prevent freeing into wrong zone, check zfree code

```
struct zone_page_metadata *page_meta = get_zone_page_metadata((struct
zone_free_element *)addr, FALSE);
if (zone != PAGE_METADATA_GET_ZONE(page_meta)) {
    panic("Element %p from zone %s caught being freed to wrong zone %s\n",
addr, PAGE_METADATA_GET_ZONE(page_meta)->zone_name, zone->zone_name);
}
```

Kernel Heap Management

- New function kfree_addr will automatically get size according to address
- Overwrite size of object no longer works

```
vm_size_t
kfree_addr(
    void        *addr)
{
    vm_map_t        map;
    vm_size_t       size = 0;
    kern_return_t   ret;
    zone_t          z;

    size = zone_element_size(addr, &z);
    if (size) {
        zfree(z, addr);
        return size;
    }
```

Enhanced Sandbox

- Platform profile is more restricted
  - Profile size is 0x10DE for 9.3 and 0x1849 for iOS 10
  - More operations are checked of iOS 10
    - file-map-executable
    - system-kext-query
    - process-exec-interpreter
    - process-exec*
    - file-write-create
    - …

KPP

- Change of the kernelcache memory layout
- Put all code and const together
- Put all RW data together
- Makes KPP more efficient
- __got is now under protection!

com.apple.driver.AppleD2333PMU:__got	FFFFFFF006FFEF00	FFFFFFF006FFF280
com.apple.driver.AppleD2333PMU:__mod_init_func	FFFFFFF006FFF280	FFFFFFF006FFF298
com.apple.driver.AppleD2333PMU:__mod_term_func	FFFFFFF006FFF298	FFFFFFF006FFF2B0
com.apple.driver.AppleD2333PMU:__const	FFFFFFF006FFF2B0	FFFFFFF0070009F0
com.apple.driver.AppleD2333PMU:GAP_hidden	FFFFFFF0070009F0	FFFFFFF007004000
__TEXT:HEADER	FFFFFFF007004000	FFFFFFF007007CE0
__TEXT:__const	FFFFFFF007007CE0	FFFFFFF00701F698
__TEXT:__cstring	FFFFFFF00701F698	FFFFFFF00705E9AA
__TEXT:__os_log	FFFFFFF00705E9AA	FFFFFFF00705FFFF
__DATA_CONST:__mod_init_func	FFFFFFF007060000	FFFFFFF007060210
__DATA_CONST:__mod_term_func	FFFFFFF007060210	FFFFFFF007060418
__DATA_CONST:__const	FFFFFFF007064000	FFFFFFF0070BFBE8
__TEXT_EXEC:__text	FFFFFFF0070C0000	FFFFFFF00753EC88
__KLD:__text	FFFFFFF007540000	FFFFFFF0075416DC
__KLD:__cstring	FFFFFFF0075416DC	FFFFFFF007541EA8
__KLD:__const	FFFFFFF007541EA8	FFFFFFF007541F10
__KLD:__mod_init_func	FFFFFFF007541F10	FFFFFFF007541F18
__KLD:__mod_term_func	FFFFFFF007541F18	FFFFFFF007541F20
__KLD:__bss	FFFFFFF007541F20	FFFFFFF007541F21
__LAST:__pinst	FFFFFFF007544000	FFFFFFF007544020
__LAST:__mod_init_func	FFFFFFF007544020	FFFFFFF007544028
__DATA:__data	FFFFFFF007548000	FFFFFFF007578CC8
__DATA:__sysctl_set	FFFFFFF007578CC8	FFFFFFF00757ADE0
__DATA:__bss	FFFFFFF00757B000	FFFFFFF0075F5828
__DATA:__common	FFFFFFF0075F6000	FFFFFFF0075F7130
com.apple.iokit.IONetworkingFamily:__data	FFFFFFF007658000	FFFFFFF0076580C8
com.apple.iokit.IONetworkingFamily:__common	FFFFFFF0076580C8	FFFFFFF007658430
com.apple.iokit.IONetworkingFamily:__bss	FFFFFFF007658430	FFFFFFF0076584B8
com.apple.iokit.IONetworkingFamily:GAP_hidden	FFFFFFF0076584B8	FFFFFFF0076584C0

KPP

- Time attacking is still practical
  - Patch/Restore in a short time window
- Kernel heap can be market as RWX
  - Kernel shell code works well
- BUT different story for iPhone 7 !

AMFI

- Fix a potential race in validateCodeDirectoryHashInDaemon
  - It's possible to replace the executable file to a valid one after kernel resolve the code signature and ask amfid to verify it
- Now amfid will also return the cdhash of the file it verified, the hash must match the one kernel already read

```
if ( isok == 1 )
{
  if ( (unsigned int)amfi_memcmp(cdhash, &return_cdhash, 20) )
  {
    amfi_IOLog("%s: Possible race detected. Rejecting.\n", v31, v51, v52, v53, v54, &v71);
    isok = 0;
    v70 = 0;
  }
```

AMFI

- Before iOS 10 amfid only checks return value of MISValidateSignature
  - Easy to bypass by hijacking it to some function just return 0
- Now it calls MISValidateSignatureAndCopyInfo instead and get cdhash to return to kernel

```
v24 = MISValidateSignatureAndCopyInfo(v19, v21, &v37);
if ( (_DWORD)v24 )
{
  memcpy(&v39, "<unknown>", 0x100uLL);
  v25 = (void *)MISCopyErrorStringForErrorCode(v24);
  if ( v25 )
  {
    CFStringGetCString(v25, &v39, 0x100uLL);
    CFRelease(v25);
  }
  if ( !*a8 )
    syslog(3, "%s not valid: 0x%x: %s", v15, v24, &v39);
  goto LABEL_19;
}
if ( v37 && (v27 = CFGetTypeID(v37), v27 == CFDictionaryGetTypeID()) )
{
  v28 = (void *)CFDictionaryGetValue(v37, *(_QWORD *)kMISValidationInfoCdHash_ptr);
  if ( v28 )
  {
    v30 = CFGetTypeID(v28);
    if ( v30 == CFDataGetTypeID() )
    {
      *a8 = 1;
      CFDataGetBytes(v28, 0LL, 20LL, cdhash);
```

Fix Lots of Unpublished Bugs

- Apple security team are hunting bugs
  - Two bugs of ours were fixed in iOS 10
    - One heap overflow and one UAF
- Researchers report bugs to Apple
  - task_t related issues
    - https://googleprojectzero.blogspot.jp/2016/10/taskt-considered-harmful.html
  - Multiple memory safety issues in mach_ports_register
    - https://bugs.chromium.org/p/project-zero/issues/detail?id=882
  - …
- Did your bugs get patched?

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Known Weakness

- It's actually easier to write kernel exploit for 64bit devices because of NO SMAP
- Current KPP architecture is not capable to prevent time attacking
- Kernel shellcode allows kernel level rootkit

KPP of Old Devices

- Kernel runs at EL1
- KPP monitor runs at EL3
- SMC(secure monitor call) causes an exception to EL3
- After kernel finish initialization, it calls SMC to tell KPP to init all checksums of protected memory

Switch to iPhone 7

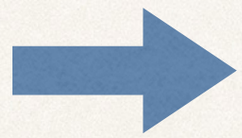
```
BL              _read_random
LDR             X8, [X20]
ORR             X8, X8, #1
STR             X8, [X20]
MOV             W8, #0xC
STR             W8, [SP,#0xE0+var_90]
MOV             W1, #1
MOV             W0, #1
ADD             X2, SP, #0xE0+var_88
ADD             X3, SP, #0xE0+var_90
BL              loc_FFFFFFF0070B3150
LDR             W8, [SP,#0xE0+var_88]
CMP             W8, #3
B.GT            loc_FFFFFFF0070D2D84
ADRP            X8, #byte_FFFFFFF00758D384@PAGE
STRB            W19, [X8,#byte_FFFFFFF00758D384@PAGEOFF]

D2D84                   ; CODE XREF: sub_FFFFFFF0070D0864+2
MOV             W0, #0x801
MOV             X1, #0
MOV             X2, #0
MOV             X3, #0
BL              smc_17
BL              loc_FFFFFFF007365130
STP             XZR,
STR             WZR,
STR             WZR,
STR             XZR,
STR             WZR,
ADRP            X23,
LDR             X20,
LDR             X8, [
MRS             X9, #
CMP             X8, X9
B.EQ            loc_FFFFFFF0070D2DE0
MOV             X0, X20

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

smc_17

                SMC             #0x11
                RET
; End of function smc_17
```



```
BL              _read_random
LDR             X8, [X19]
ORR             X8, X8, #1
STR             X8, [X19]
MOV             W8, #0xC
STR             W8, [SP,#0xE0+var_90]
MOV             W1, #1
MOV             W0, #1
ADD             X2, SP, #0xE0+var_88
ADD             X3, SP, #0xE0+var_90
BL              loc_FFFFFFF0070F06CC
LDR             W8, [SP,#0xE0+var_88]
CMP             W8, #3
B.GT            loc_FFFFFFF00711034C
ADRP            X8, #byte_FFFFFFF0075C9384@PAGE
STRB            W23, [X8,#byte_FFFFFFF0075C9384@PAGEOFF]

11034C                  ; CODE XREF: kernel_init+2624↓j
MOV             W0, #0
BL              _ml_set_interrupts_enabled
MOV             X20, X0
LDR             X8, [X22,#qword_FFFFFFF0075CF740@PAGEOFF]
LDR             WZR, [X8,#0x7EC]
MRS             X8, #4, c15, c2, #2
ADRP            X19, #dword_FFFFFFF007004000@PAGE
ADD             X19, X19, #dword_FFFFFFF007004000@PAGEOFF
ADR             X1, a__prelink_text ; "__PRELINK_TEXT"
NOP
ADD             X2, SP, #0xE0+var_88
MOV             X0, X19
BL              sub_FFFFFFF00749E65C
BL              sub_FFFFFFF0071C3CD0
MOV             X21, X0
ADR             X1, a__last ; "__LAST"
NOP
ADD             X2, SP, #0xE0+var_90
MOV             X0, X19
BL              sub_FFFFFFF00749E65C
BL              sub_FFFFFFF0071C3CD0
SUB             X8, X0, #1
LDR             W9, [X24,#0x98]
LSL             W9, W23, W9
NEG             W10, W9
SBFM            X10, X10, #0, #0x1F
AND             X26, X10, X8
LDR             X8, [X28,#0x80]
SUB             X8, X21, X8
LDR             X10, [X27,#0x88]
ADD             X0, X8, X10
LDR             W8, [SP,#0xE0+var_90]
SUB             W8, W8, W21
ADD             W8, W8, W26
ADD             W8, W9, W8
SUB             W1, W8, #1
BL              sub_FFFFFFF0070C230C
LDR             X8, [X22,#qword_FFFFFFF0075CF740@PAGEOFF]
STR             W23, [X8,#0x7EC]
ISB
MSR             #4, c15, c2, #3, X21
MSR             #4, c15, c2, #4, X26
MSR             #4, c15, c2, #2, X23
ISB
BL              sub_FFFFFFF0070CC730
MOV             X0, X20
BL              _ml_set_interrupts_enabled
```

KPP of iPhone 7

- Apparently there is no SMC
- The initialize code retrieves physical addresses of “__PRELINK_TEXT” and “__LAST” segments. It then store them in special system registers which requires minimum EL=EL2
- All code and const values are between “__PRELINK_TEXT” and “__LAST”
- This new protection is obviously implemented in hardware

KPP of iPhone 7

- It prevents writing to the protected physical memory
  - Can’t touch code memory
  - Time attacking doesn’t work anymore
- It prevents executing outside of the protected physical memory range
  - Can’t execute shellcode in kernel
  - ROP is still an option

SMAP on iPhone 7

- Also we notice there is kind of SMAP on iPhone 7
- Dereference valid user-land address will simply hang the CPU, never get return
- Dereference invalid user-land address still cause a panic

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Conclusion

- Apple keeps putting lots of efforts to make their products more secure
- It's more easier for Apple to bring security feature which is combined with hardware and software
- iOS kernel exploit is now harder and more valuable

Q&A