Hacking from iOS 8 to iOS 9

TEAM PANGU

RUXCON 2015 / POC 2015

Agenda

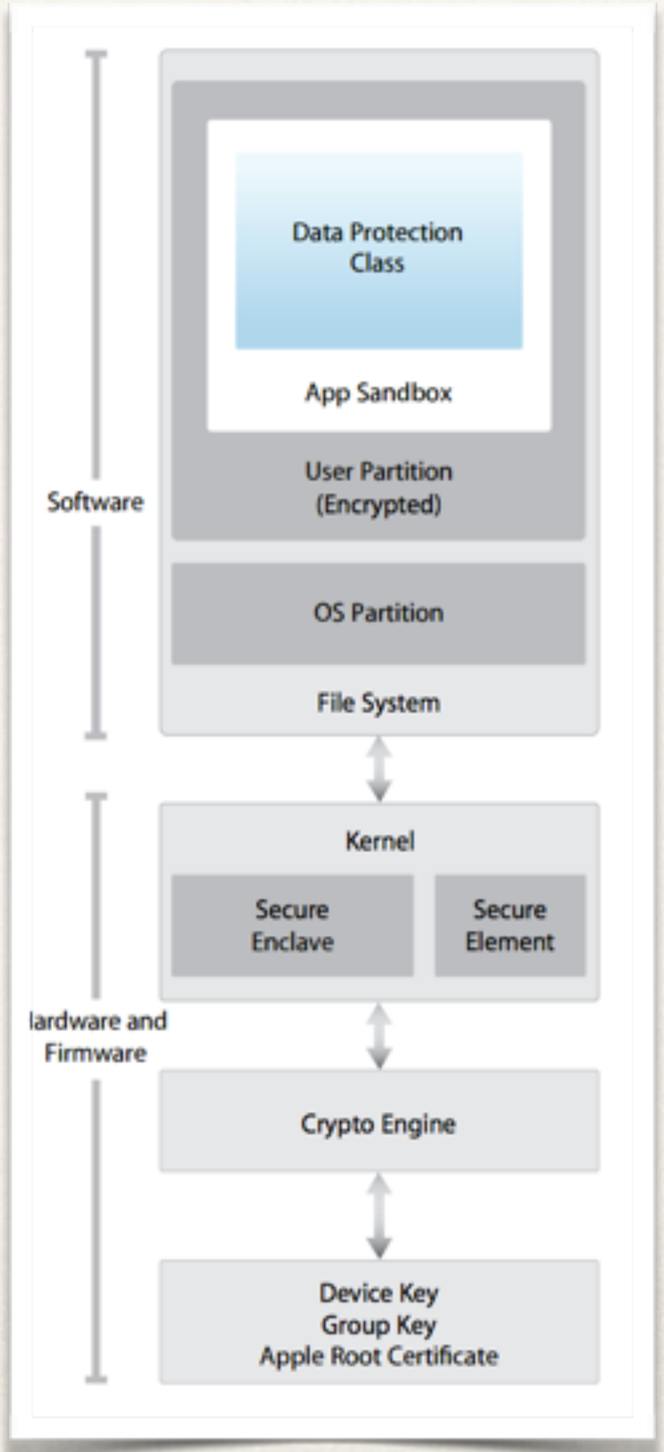
- iOS Security Overview
- Security Changes from iOS 8 to iOS 9
- Kernel Vulnerability Exploited in Pangu 9
- Kernel Exploit Chain
- Public Release vs. Bounty Hunting
- Conclusion

Who We Are

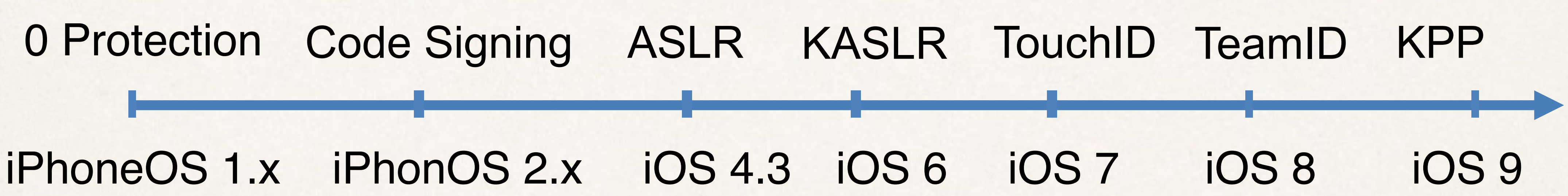
- Team Pangu is known for releasing jailbreak tools for iOS 7.1, iOS 8, and iOS 9
- We have broad security research interests
- Our research was present at BlackHat, CanSecWest, POC, RuxCon, etc.
- We also co-organize a mobile security conference named MOSEC (mosec.org) with POC

iOS Security Overview

- Apple usually releases a white paper to introduce iOS security architecture
  - Isolations
  - Restricted Sandbox
  - Mandatary Code Signing
  - Exploit Mitigation (ASLR, DEP)
  - Data Protection
  - Hypervisor



Timeline of Major Security Features



Many security features are undocumented

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Improved Team ID Validation

- Team ID was introduced in iOS 8
  - Prevent platform binaries from loading third-party code
- iOS 9 enforces that a process either is a platform binary or has a team identifier

```
prog_teamID = csproc_get_teamid_16(v11);
prog_platform = csproc_get_platform_binary_16();
v23 = prog_teamID == 0;
if ( !prog_teamID )
  v23 = prog_platform == 0;
if ( v23 )
{
  v17 = "[deny-mmap] main process has no team identifier in its signature";
  goto LABEL_17;
}
```

DYLD Environment Variables

- DYLD environment variables affect the dynamic linker dyld in many ways
  - Output debug info (e.g., through DYLD_PRINT_*)
  - Dylib injection (e.g., through DYLD_INSERT_LIBRARIES)
- iOS 8.3 starts to ignore DYLD environment variables unless the main executable has certain entitlements

Released Source Code of dyld

```
    sExecPath = apple[0];
    bool ignoreEnvironmentVariables = false;
    if ( sExecPath[0] != '/' ) {
        // have relative path, use  wd to make absolute
        char cwdbuff[MAXPATHLEN];
        if ( getcwd(cwdbuff, MAXPATHL  N) != NULL ) {
            // maybe use static buffe
            char* s = new char[strlen
            strcpy(s, cwdbuff);
            strcat(s, "/");
            strcat(s, sExecPath);
            sExecPath = s;
        }
    }
    // Remember short name of process for later logging
    sExecShortName = ::strrchr(sExecPath, '/');
    if ( sExecShortName != NULL )
        ++sExecShortName;
    else
        sExecShortName = sExecPath;
    sProcessIsRestricted = processRestricted(mainExecutableMH);
    if ( sProcessIsRestricted ) {
#if SUPPORT_LC_DYLD_ENVIRONMENT
        checkLoadCommandEnvironmentVariable
#if SUPPORT_VERSIONED_PATHS
        checkVersionedPaths();
#endif
#endif
        pruneEnvironmentVariables(en  , &apple);
        // set again because env   nd apple may have changed or moved
        setContext(mainExecuta  eMH, argc, argv, envp, apple);
    }
    else
        checkEnvironmentVariables(envp, ignoreEnvironmentVariables);
```

By default, ignoreEnvironmentVariables is false

checkEnvironmentVariables will not ignore DYLD environment variables

dyld on iOS 8.3

- ignoreEnvironmentVariables is set True according to v108

```
ignoreEnvironmentVariables = 0;
v26 = &v115;
LOBYTE(dyld::sProcessIsRestricted) = 0;
v129 = -1;
if ( (v108 & 0x1004) == 4096 )
  ignoreEnvironmentVariables = 1;
dyld::checkEnvironmentVariables(envp, ignoreEnvironmentVariables);
```

- Where is v108 from?

dyld on iOS 8.3

- v108 indicates the code signing status of the program
  - CSOPS is used to query the code signing attributes

```
if ( csops(0, 0, &csStatus, (void *)4) )
{
  v129 = -1;
  dyld::throwf((dyld *)"failed to get code signing flags", (const char *)0xFFFFFFFF);
}
v15 = (char *)dword_1FE26464;
v108 = *(_DWORD *)&csStatus;
```

dyld on iOS 8.3

- v108 & 0x1004 == 4096
- 0x0004 means that the program has get-task-allow entitlement

```
/* code signing attributes of a process */
#define   CS_VALID        0x0000001 /* dynamically valid */
#define CS_ADHOC          0x0000002 /* ad hoc signed */
#define CS_GET_TASK_ALLOW 0x0000004 /* has get-task-allow entitlement */
#define CS_INSTALLER      0x0000008 /* has installer entitlement */

#define   CS_HARD              0x0000100 /* don't load invalid pages */
#define   CS_KILL              0x0000200 /* kill process if it becomes invalid */
#define CS_CHECK_EXPIRATION    0x0000400 /* force expiration checking */
#define CS_RESTRICT       0x0000800 /* tell dyld to treat restricted */
#define CS_ENFORCEMENT         0x0001000 /* require enforcement */
#define CS_REQUIRE_LV          0x0002000 /* require library validation */
#define CS_ENTITLEMENTS_VALIDATED   0x0004000
```

- In other words, DYLD environment variables only work for binaries that have the get-task-allow entitlement

DYLD Environment Variables

- Consequence:
  - neagent is the only program on iOS that is allowed to load third party signed libraries (ignoring the TeamID validation because of the com.apple.private.skip-library-validation entitlement)
  - The trick to force neagent load an enterprise license signed library through the DYLD_INSERT_LIBRARIES no longer works

enable-dylibs-to-override-cache

- The present of this file was used to force loading of dynamic libraries from filesystem instead of the shared cache
- It was widely used by previous jailbreak tools to override the libmis library
- dyld in iOS 8.3 starts to ignore this flag

enable-dylibs-to-override-cache

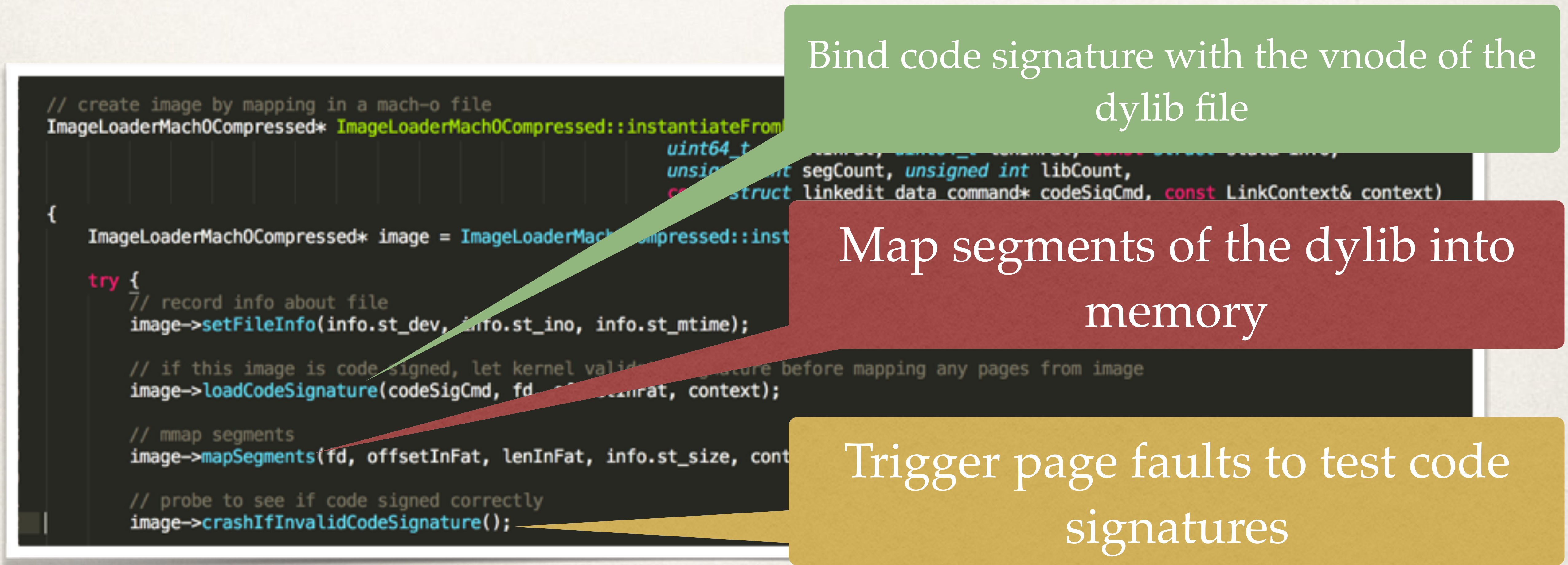
- The kernel disallows to check the present of the flag

```
if ( vFFFF4084 & 1 )
{
  v96 = dyld::my_stat(
          (dyld *)"/System/Library/Caches/com.apple.dyld/enable-dylibs-to-override-cache",
          (struct stat *)v127,
          (stat *)v82);
  v97 = 0;
  if ( !v96 )
  {
    v98 = 0;
    if ( v134 < 0x400 )
      v98 = 1;
    if ( (signed int)v135    0 )
      v97 = 1;
    if ( !v135 )
      v97 = v98;
  }
  LOBYTE(dyld::sDylibsOverrideCa   ) = v97;
}
```

This value is read from 0xFFFF4084, an address in the kernel and read only in userspace

Reduced TOCTOU Time Window in iOS 9

- dyld is responsible for loading dynamic libraries and probing to test if the libraries are signed correctly



Reduced TOCTOU Time Window in iOS 9

- dyld is responsible for loading dynamic libraries and probing to test if the libraries are signed correctly

```
// create image by mapping in a mach-o file
ImageLoaderMachOCompressed* ImageLoaderMachOCompressed::instantiateFrom
                                                        uint64_t of
                                                        unsigned in
                                                        const struc
{
    ImageLoaderMachOCompressed* image = ImageLoaderMachOCompressed::ins

    try {
        // record info about file
        image->setFileInfo(info.st_dev, info.st_ino, info.st_mtime);

        // if this image is code signed, let kernel vali                nature before mapping any pages from image
        image->loadCodeSignature(codeSigCmd, fd,          InFat, context);

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

        // probe to see if code signed correctly
        image->crashIfInvalidCodeSignature();
```

Many segment overlapping tricks were used in the past to bypass the subsequent code signing checks

Reduced TOCTOU Time Window in iOS 9

- dyld on iOS 9 now validates the mach-o header (first pages) before mapping segments into the memory

```
ImageLoader::setFileInfo(v46, v24, v23, v25);
v48 = 2;
ImageLoaderMachO::loadCodeSignature((int)v46, a12, v45, a5, a6, a14);
v48 = 3;
v37 = v43;
v38 = a5;
v39 = a6;
v40 = a14;
ImageLoaderMachO::validateFirstPages(v46, a12, v45, v42);
v26 = *(_QWORD *)(a9 + 60);
v48 = 4;
v37 = a7;
v38 = a8;
*(_QWORD *)&v39 = v26;
v41 = a14;
ImageLoaderMachO::mapSegments(v46, v45, a5, a6);
v48 = 5;
ImageLoaderMachOCompressed::registerEncryption(v46, a13, a14);
v48 = 6;
ImageLoaderMachO::crashIfInvalidCodeSignature(v46);
```

Changes in Loading Launchd Daemons

- xpcd_cache.dylib is used to store plist files of launchd daemons
  - All plist files are encoded in the dylib and thus protected by signatures
- Before iOS 9, by using a fake xpcd_cache.dylib (e.g., masking the __xpcd_cache segment as readonly), jailbreak tools can easily customize the launchd daemons

Changes in Loading Launchd Daemons

- For example, launchd on iOS 8.4 loads the bplist in following way. Masking the __xpcd_cache segment readonly does not cause any problem

```
if ( lstat("/System/Library/Caches/com.apple.xpcd/xpcd_cache.dylib", &v27) )
{
  v26 = 0;
  v3 = dlopen("/System/Library/Caches/com.apple.xpcd/xpcd_cache.dylib", 2);
  if ( v3 )
  {
    v4 = dlsym(v3, "__xpcd_cache");
    if ( v4 )
    {
      if ( dladdr(v4, &v25) )
      {
        v5 = getsectiondata(v25.dli_fbase, "__TEXT", "__xpcd_cache", &v26);
        if ( v5 )
          v7 = xpc_create_from_plist(v5, v26, v6);
        else
          v7 = xpc_dictionary_create(0, 0, 0);
        dword_36C54 = v7;
      }
    }
  }
}
```

Changes in Loading Launchd Daemons

- Launchd on iOS 9 will first invoke a trivial API in xpcd_cache.dylib to ensure the present of executable permission

```
if ( lstat("/System/Library/Caches/com.apple.xpcd/xpcd_cache.dylib", &v29) )
{
  v28 = 0;
  v3 = dlopen("/System/Library/Caches/com.apple.xpcd/xpcd_cache.dylib", 2);
  if ( v3 )
  {
    v4 = dlsym(v3, "__xpcd_cache");
    v5 = v4;
    if ( v4 )
    {
      if ( ((int (__cdecl *)(void *, int *, int))v4)(v4, v1, v2) != 1 )
      {
ABEL_38:
        v26 = _os_assert_log(0, 0);
        _os_crash(v26);
        __debugbreak();
      }
      if ( dladdr(v5, &v27) )
      {
        v6 = getsectiondata(v27.dli_fbase, "__TEXT", "__xpcd_cache", &v28);
        if ( v6 )
          v8 = xpc_create_from_plist(v6, v28, v7);
        else
          v8 = xpc_dictionary_create(0, 0, 0);
```

Changes in Loading Launchd Daemons

- Launchd on iOS 9 only loads platform binaries
- Launchd uses csops to query the status of code signing attributes of the process

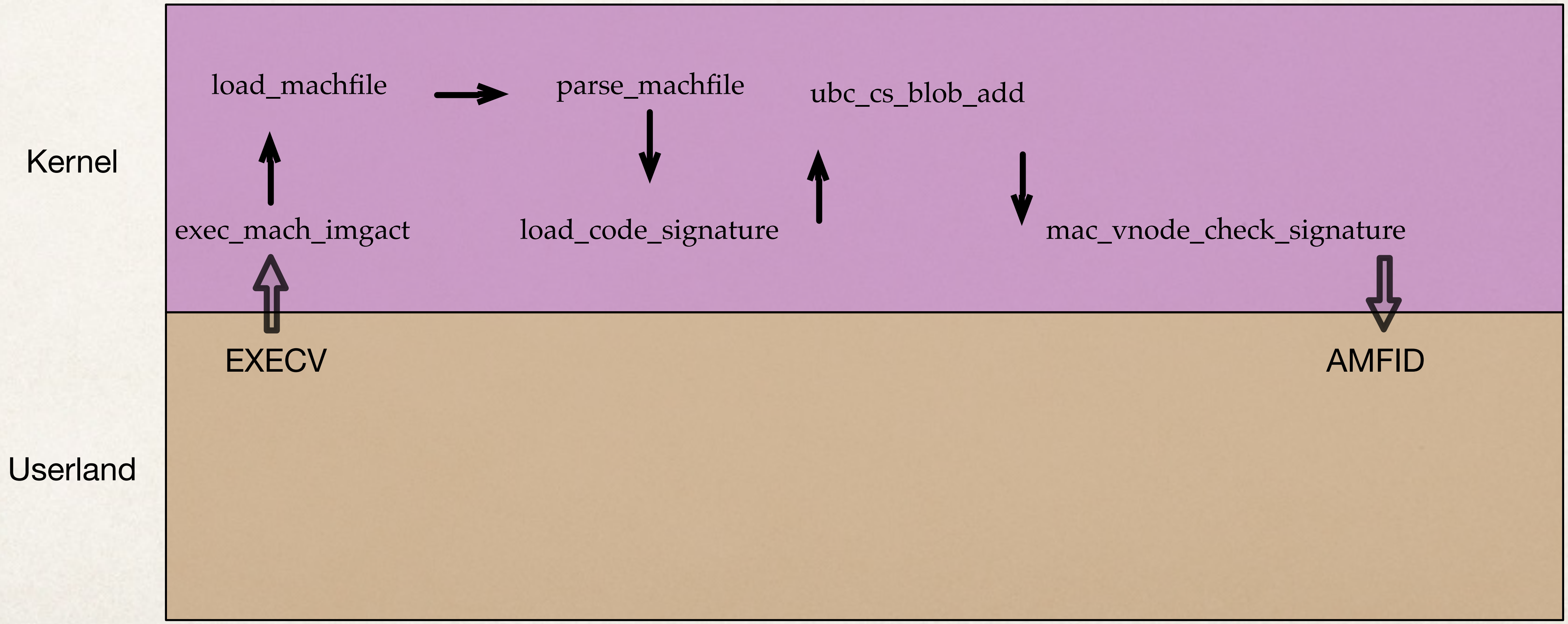
Changes in loading launchd daemons

- Non-platform binary cannot be launched

```
  if ( csops(v26, 0, &v45, 4) )
  {
    result = (int *)*__error();
    if ( result != (int *)3 )
    {
      if ( *__error() )
      {
        v30 = _os_assumes_log();
        _os_avoid_tail_call(v30);
      }
      goto LABEL_83;
    }
  }
  else
  {
    result = v45;
    if ( !((unsigned int)v45 & 0x4000000) )
    {
EL_83:
      sub_223C4((int)"unexpected exec of non-platform binary");
      goto LABEL_84;
    }
  }
```

Changes in Loading Main Executable

- The iOS kernel is responsible for parsing and loading the main executable while creating a new process



Changes in Loading Main Executable

- Before iOS 8.3, the kernel does not directly validate the signature of the Mach-O header of the main executable
  - Kernel only ensures that the main executable has a correct code signature segment (i.e., the segment is signed correctly)
- Instead, the kernel leaves the validation to dyld
  - dyld will access the Mach-O header of the main executable and thus trigger page faults, leading to final SHA1 comparison

A Persistent Vector for Code signing Bypass before iOS 8.3

- Modify the Mach-O header of a platform binary
  - Change the LC_LOAD_DYLINKER of main executable to trick the kernel to load our fake dyld
  - Modify LC_UNIXTHREAD of our fake dyld which enables us to control all register values and point the PC value to a ROP gadget

Changes in Loading Main Executable

- In iOS 8.3, the kernel proactively compares the SHA1 of the Mach-O header with the SHA1 in corresponding cs_blob

```
if (got_code_signatures) {
    unsigned tainted = CS_VALIDATE_TAINTED;
    boolean_t valid = FALSE;
    struct cs_blob *blobs;
    vm_size_t off = 0;


    if (cs_debug > 10)
        printf("validating initial pages of %s\n", vp->v_name);
    blobs = ubc_get_cs_blobs(vp);

    while (off < size && ret == LOAD_SUCCESS) {
         tainted = CS_VALIDATE_TAINTED;

         valid = cs_validate_page(blobs,
                      NULL,
                      file_offset + off,
                      addr + off,
                      &tainted);
         if (!valid || (tainted & CS_VALIDATE_TAINTED)) {
             if (cs_debug)
                 printf("CODE SIGNING: %s[%d]: invalid initial page at offset %lld validated:%d tainted:%d csflags:0x%x\n",
                     vp->v_name, p->p_pid, (long long)(file_offset + off), valid, tainted, result->csflags);
             if (cs_enforcement(NULL) ||
             (result->csflags & (CS_HARD|CS_KILL|CS_ENFORCEMENT))) {
                 ret = LOAD_FAILURE;
             }
             result->csflags &= ~CS_VALID;
         }
         off += PAGE_SIZE;
    } ?  end while off<size&&ret==LOAD_S... ?
} ?  end if got_code_signatures ?
```

More Changes in Loading Main Executable

- Actually in iOS 9, Apple adds more check for picking up an already registered cs_blob

```
if ( v53->csb_cpu_type == v183 )
{
  if ( v53->csb_base_offset == file_offset )
  {
    if ( v53->csb_mem_size == *(_DWORD *)(v205 + v48) )
    {
      lck_mtx_lock(v224);
      if ( v224 )
      {
        if ( *(_WORD *)(v224 + 68) == 1 )
        {
          v55 = *(_DWORD *)(v224 + 76);
          if ( v55 )
          {
            if ( *(_DWORD *)(v55 + 28) == dword_8040AFF4 )
            {
              lck_mtx_unlock(v224);
              goto LABEL_126;      // success
            }
          }
        }
      }
```

Kernel Patch Protection (KPP)

- Apple introduced KPP in iOS 9 for 64bit devices
- Implementation details are unclear
    - It's believed that it is related to the Secure Enclave Processor (SEP), an alternative of TrustZone on iOS devices
    - Unfortunately, the SEP firmware is encrypted

KPP Observations

- KPP randomly checks the integrity of RX pages of the kernel-cache and page table
  - Persistent code patch is not feasible, because it would trigger random kernel panic
- Panic when RX page is modified

panic(cpu 1 caller 0xffffff80098fde28): SError esr: 0xbf575401 far: 0xffffff8009898000

- Panic when Page table is modified

panic(cpu 0 caller 0xffffff80214fde28): SError esr: 0xbf575407 far: 0xffffff8021498000

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Use-after-free in IOHIDResourceUserClient

- We found it by auditing IOHIDFamily source code
- The bug was also independently discovered by other researchers
  - @qwertyoruiop, Cererdlong, etc
- The interesting thing is this bug also affects Mac OS, but is only triggerable with root on Mac OS
  - We almost missed the bug
  - Thanks @qwertyoruiop for pointing out that it is triggerable with mobile on iOS

Use-after-free in IOHIDResourceUserClient

- _device is allocated in method 0
  - createDevice -> createAndStartDevice

```
//------------------------------------------------------------------------------
// IOHIDResourceDeviceUserClient::createAndStartDevice
//------------------------------------------------------------------------------
IOReturn IOHIDResourceDeviceUserClient::createAndStartDevice()
{
    IOReturn    result;
    OSNumber *  number = NULL;

    number = OSDynamicCast(OSNumber, _properties->getObject(kIOHIDRequestTimeoutKey));
    if ( number )
        _maxClientTimeoutUS = number->unsigned32BitValue();

    // If after all the unwrapping we have a dictionary, let's create the device
    _device = IOHIDUserDevice::withProperties(_properties);
    require_action(_device, exit, result=kIOReturnNoResources);
```

Use-after-free in IOHIDResourceUserClient

- _device is released in method 1
  - terminateDevice -> OSSafeRelease

```
//------------------------------------------------------------------
// IOHIDResourceDeviceUserClient::terminateDevice
//------------------------------------------------------------------
IOReturn IOHIDResourceDeviceUserClient::terminateDevice()
{
    if (_device) {
        _device->terminate();
    }
    OSSafeRelease(_device);

    return kIOReturnSuccess;
}
```

Use-after-free in IOHIDResourceUserClient

- OSSafeRelease is NOT safe
    - #define OSSafeRelease(inst) do { if (inst) (inst)->release(); } while (0)
- It does not nullify the pointer after releasing it!

Use-after-free in IOHIDResourceUserClient

- _device is used again in many functions
    - E.g. method 2 takes 1 input scalar and an input struct, also the the return value is directly passed to user space
        - IOHIDResourceDeviceUserClient::_handleReport

```
if ( arguments->scalarInput[0] )
    AbsoluteTime_to_scalar(&timestamp) = arguments->scalarInput[0];
else
    clock_get_uptime( &timestamp );

if ( !arguments->asyncWakePort ) {
    ret = _device->handleReportWithTime(timestamp, report);
    report->release();
} else {
```

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Context of the UAF

- 32bit
  - The UAF object is in the kalloc.192 zone
  - Both R1 and R2 are under control when the UAF is triggered

```
LDR.W           R0, [R4,#0x80] ; R0=_device
LDR             R1, [SP,#0x60+var_40]
LDR             R2, [SP,#0x60+var_3C] ; R1,R2=scalar[0]
LDR             R3, [R0]
LDR.W           R6, [R3,#0x3B4] ; vtable+0x3B4
MOVS            R3, #0
STR             R3, [SP,#0x60+var_60]
STR             R3, [SP,#0x60+var_5C]
MOV             R3, R5
BLX             R6      ; trigger
```

Context of the UAF

- 64bit
  - The UAF object is in the kalloc.256 zone
  - Only X1 is under control when the UAF is triggered

```
LDR     X0, [X19,#0xE8] ; X0=_device
LDR     X8, [X0]
LDR     X8, [X8,#0x630] ; vtable+0x630
LDR     X1, [SP,#0x28] ; X1=scalar[0]
MOV     W3, #0
MOV     W4, #0
MOV     W5, #0
ADD     X6, SP, #0x10
MOV     X2, X20
BLR     X8      ; trigger
```

Transfer UAF to Type Confusion

- The UAF object zone can be easily filled with variety IOUserClient objects via calling IOServiceOpen
- Check vtable offsets of all possible IOUserClient classes to see what functions we may call
  - OSMetaClass::serialize(OSSerialize *)
  - OSMetaClass::getMetaClass(void)
  - OSMetaClass::release(void)
  - OSMetaClassBase::isEqualTo(OSMetaClassBase const*)

Exploit Type Confusion to Leak Kernel Slide

- OSMetaClass::getMetaClass(void)
  - Return a static object inside kernel -> leak kernel base
  - 32bit return value is enough for arm64 also
    - High 32bit value is always 0xffffff80

```
__ZNK11OSMetaClass12getMetaClassEv
MOV                 R0, #(unk_8045FF20 - 0x8030BD34)
ADD                 R0, PC ; unk_8045FF20
ADDS                R0, #0x30
BX                  LR
```

```
__ZNK11OSMetaClass12getMetaClassEv
ADRP                X8, #unk_FFFFFF800BDA0040@PAGE
ADD                 X8, X8, #unk_FFFFFF800BDA0040@PAGEOFF
ADD                 X0, X8, #0x340
RET
```

Exploit Type Confusion to Leak Heap Address

- OSMetaClass::release(void)
  - R0/X0=self pointer -> leak low 32bit of the object address
  - Not enough for arm64
    - High 32bit value is 0xffffff80 or 0xffffff81

```
__ZNK11OSMetaClass7releaseEv
BX                     LR
```

```
__ZNK11OSMetaClass7releaseEv
RET
```

Exploit Type Confusion to Leak Heap Address for ARM64

- OSMetaClassBase::isEqualTo(OSMetaClassBase const*)
  - X1 is under control
    - Calling the function twice can decide the high 32bit value of the heap address

```
__ZNK15OSMetaClassBase9isEqualToEPKS_
CMP             X0, X1
CSET            W0, EQ
RET
```

Heap Spray with OSData

- What we have now - Kernel base / object address
- io_service_open_extended -> OSUnserializeXML -> spray OSData with controlled size and content
  - Set [object address] = vtable = object address - call offset + 8
    - When triggering the bug, function pointer at [object address +8] will be picked up
  - Set [object address+8] = gadget to call

The Read Gadget

- 32bit
  - LDR R0, [R1]; BX LR;
- 64bit
  - LDR X0, [X1,#0x20]; RET;

The Write Gadget

- 32bit - R1 and R2 are under control
  - STR R1, [R2]; BX LR;
- 64bit - X1 and contents of X0 are controlled
  - LDR X8, [X0,#0x60]; STR X1, [X8,#8]; RET;

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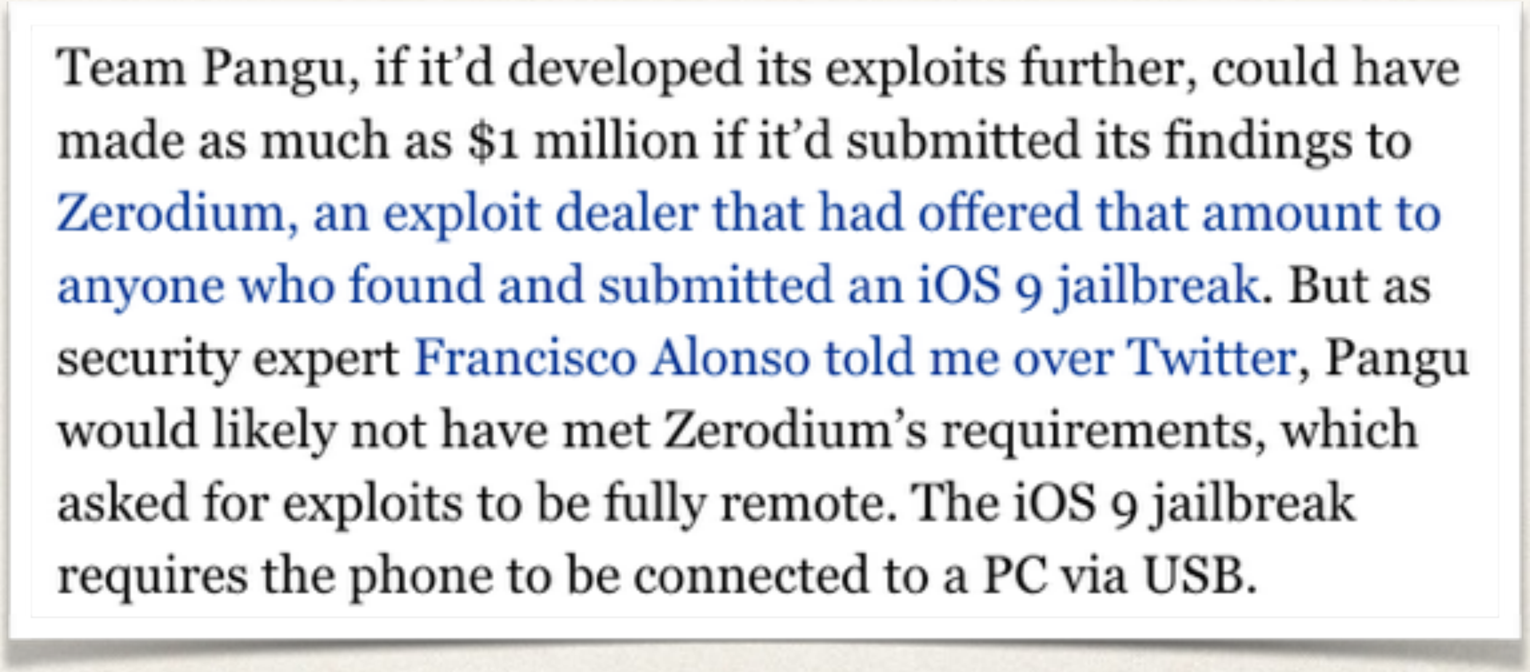
Pangu 9 Released

- Pangu 9 for iOS 9 was released at Oct 14, 2015
- Also we noticed that some people discussed whether Pangu 9 met the Zerodium bounty requirements



Pangu 9 vs. Bounty Requirement

- We never consider the bounty
- We release the jailbreak tool for
  - Full control of iOS devices for end users
  - Security research and jailbroken iOS development
- We think Mobile Safari is NOT a good landing point for jailbreak tools
  - It's too dangerous if the exploits are abused, which violates our purpose of releasing a jailbreak tool
  - It will also shorten the lifetime of a jailbreak tool, because Apple will (very likely) release a fix asap

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Conclusion

- Apple puts more efforts on improving the whole security mechanisms rather than fixing individual bugs
- A lot of security features in iOS were undocumented, which make jailbreaking more and more difficult
- KPP introduced in iOS 9 makes people believe that there may be no jailbreak anymore, what we did proves that hackers will always find their way in

Thanks for Your Attention

Q&A