Use Ryuk to find bug in macOS and iOS kernel drivers

Xiaolong Bai and Min(Spark) Zheng
@ Alibaba Mobile Security

微博：@bxl1989 @zhengmin1989

Self Introduction

- Xiaolong Bai
  - Alibaba Security Engineer
  - Ph.D. graduated from Tsinghua University
  - Published papers on the top 4: S&P, Usenix Security, CCS, NDSS
  - Twitter, Weibo, Github: bxl1989

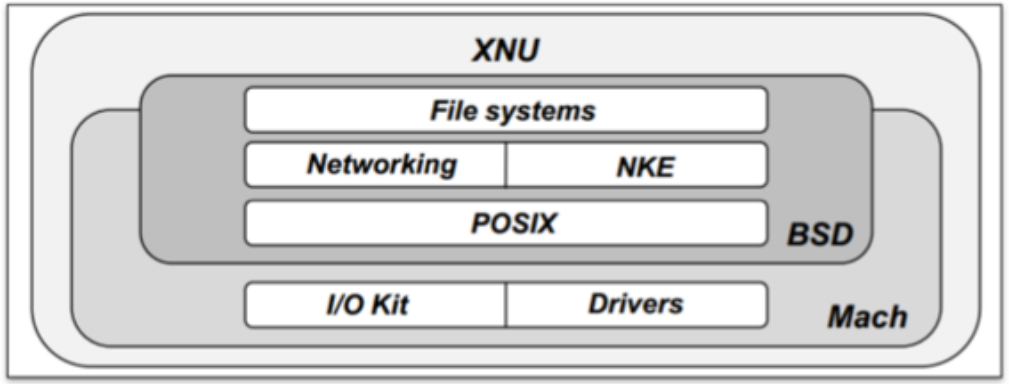
- Min (Spark) Zheng
  - Alibaba Security Expert
  - Ph.D. graduated from The CUHK
  - Twitter@SparkZheng Weibo@蒸米spark

Agenda

- Overview
  - Drivers in Kernel
  - Userland Perspective
- New Vulns in Drivers on macOS
  - Two new vulnerabilities
  - New exploitation strategies
  - Privilege escalation on the latest macOS
- Obstacles when analyzing Apple drivers
- Ryuk: a new tool to analyze Apple drivers
  - Design
  - Effects
  - Implementation
  - Benefits

Overview

- Every driver is a kernel extension (.kext) sharing the same space with the kernel
- System daemon *kextd* is responsible for loading and unloading drivers
- Location of driver binaries:
  - On macOS: /System/Library/Extensions
  - On iOS: integrated with kernel in kernelcache



Drivers in Kernel

- Programmed in C or C++
- Info.plist: configuration file in drivers for their property and usage

▼ IOKitPersonalities	Dictionary	(1 item)
▼ MyDriver	Dictionary	(6 items)
IOMatchCategory	String	com_onenaruto_FirstDriverTest
IOProviderClass	String	IOResources
IOKitDebug	Number	-1
IOClass	String	hello ← Class name of the driver
CFBundleIdentifier	String	$(PRODUCT_BUNDLE_IDENTIFIER)
IOUserClientClass	String	FirstDriverUserClient ← Class name to provide service to userspace
Copyright (human-readable)	String	Copyright © 2017年 bxl. All rights reserved.
▼ OSBundleLibraries	Dictionary	(3 items) ← Kernel libs used in the driver
com.apple.kpi.iokit	String	16.7
com.apple.kpi.libkern	String	16.7

Drivers in Kernel

- Kernel APIs (KPI): APIs can be used by drivers to live in kernel
  - /System/Library/Frameworks/Kernel.framework/Resources/SupportedKPIs-all-archs.txt (on macOS)
- Basic KPI Modules:
  - com.apple.kpi.iokit: For programming drivers, Apple provides an open-source framework called iokit, which includes basic driver classes
  - com.apple.kpi.libkern: a restricted c++ runtime lib in the kernel
    - excluded features—exceptions, multiple inheritance, templates
    - an enhanced runtime typing system: every class has an OSMetaClass object which describes the class's name, size, parent class, etc.

Drivers in Kernel

- A sample driver

Header File

```
#include <IOKit/IOService.h>
#ifndef FirstDriverTest_hpp
#define FirstDriverTest_hpp
class hello: public IOService {
    OSDeclareDefaultStructors(hello)
public:
    virtual bool init(OSDictionary *dictionary=0) override;
    virtual void free(void) override;
    virtual IOService *probe(IOService *provider, SInt32 *score) override;
    virtual bool start(IOService *provider) override;
    virtual void stop(IOService *provider) override;
};
#endif
```

Code File

```
#include <IOKit/IOLib.h>
#include "FirstDriverTest.hpp"
OSDefineMetaClassAndStructors(hello, IOService)
#define super IOService

bool hello::init(OSDictionary *dictonary) {
    return super::init(dictonary);
}

void hello::free(void){
    super::free();
}

IOService *hello::probe(IOService *provider, SInt32 *score){
    return super::probe(provider, score);
}

bool hello::start(IOService *provider){
    return super::start(provider);
}

void  hello::stop(IOService *provider){
    super::stop(provider);
}
```

Drivers in Kernel

- A sample driver

Header File

```
#include <IOKit/IOService.h>
#ifndef FirstDriverTest_hpp
#define FirstDriverTest_hpp
class hello: public IOService {
    OSDeclareDefaultStructors(hello)
public:
    virtual bool init(OSDictionary *dictionary=0) override;
    virtual void free(void) override;
    virtual IOService *probe(IOService *provider, SInt32 *score) override;
    virtual bool start(IOService *provider) override;
    virtual void stop(IOService *provider) override;
};
#endif
```

Class name of the driver

Parent of all drivers

Declare Con/Destructors

Callback methods of IOService

to be overriden by the driver

Code File

Auto Gen Con/Destructors

```
#include <IOKit/IOLib.h>
#include "FirstDriverTest.hpp"
OSDefineMetaClassAndStructors(hello, IOService)
#define super IOService

bool hello::init(OSDictionary *dictonary) {
    return super::init(dictonary);
}

void hello::free(void){
    super::free();
}

IOService *hello::probe(IOService *provider, SInt32 *score){
    return super::probe(provider, score);
}

bool hello::start(IOService *provider){
    return super::start(provider);
}

void  hello::stop(IOService *provider){
    super::stop(provider);
}
```

Drivers in Kernel

- In order to provide service to programs in userspace, drivers need to implement userclients
- Userclient: Kernel objects to provide service to programs in userspace
  - Create in two ways:

Info.plist

▼ IOKitPersonalities	Dictionary	(4 items)
▶ HID Game Controller Pointing Driver	Dictionary	(5 items)
▶ IOHIDEventServiceUserClient	Dictionary	(4 items)
▼ IOHIDResource	Dictionary	(6 items)
CFBundleIdentifier	String	com.apple.iokit.IOHIDFamily
IOClass	String	IOHIDResource
IOMatchCategory	String	IOHIDResource
IOProviderClass	String	IOResources
IOResourceMatch	String	IOBSD
IOUserClientClass	String	IOHIDResourceDeviceUserClient
▶ IOHIDSystem	Dictionary	(12 items)

Callback Method of Driver

```
IOReturn IOHIDEventService::newUserClient(
  task_t owningTask, void * securityID, UInt32 type,
  OSDictionary * properties, IOUserClient ** handler )
```

- A sample UserClient

```
OSDefineMetaClassAndStructors(FirstDriverUserClient, IOUserClient);
bool FirstDriverUserClient::initWithTask(task_t owningTask, void *securityToken, UInt32 type){
    return super::initWithTask(owningTask, securityToken, type);
}
bool FirstDriverUserClient::start(IOService* provider) {
    return super::start(provider);
}
void FirstDriverUserClient::free() {
    super::free();
}
IOReturn FirstDriverUserClient::externalMethod(
        uint32_t selector, IOExternalMethodArguments * arguments,
        IOExternalMethodDispatch * dispatch, OSObject * target, void * reference){
    ...
    return super::externalMethod(selector, arguments, dispatch, target, reference);
}
IOExternalMethod* FirstDriverUserClient::getTargetAndMethodForIndex(IOService** targetP, UInt32 index) {
    return super::getTargetAndMethodForIndex(targetP, index);
}
IOReturn FirstDriverUserClient::clientMemoryForType(
        UInt32 type, IOOptionBits * options, IOMemoryDescriptor ** memory ){
    return super::clientMemoryForType(type, options, memory);
}
IOReturn FirstDriverUserClient::clientClose( void ) {
    return super::clientClose();
}
IOReturn FirstDriverUserClient::clientDied( void ) {
    return super::clientDied();
}
```

→ Unique callbacks of UserClient

- IOUserClient provides services through several callback methods:
  - **externalMethod:** Provide methods that can be called in userspace
  - clientMemoryForType: Share memory with programs in userspace
  - registerNotificationPort: When userspace register to receive notification
  - clientClose: When userspace program close connection with the userclient
  - clientDied: When program in userspace connected to the userclient is dead
  - getTargetAndMethodForIndex: Similar to externalMethod, but old fashion
  - getAsyncTargetAndMethodForIndex: Similar to above, but async
  - getTargetAndTrapForIndex: Similar to externalMethod, but seldom used

- externalMethod: Callback to provide methods to userspace program
- IOReturn IOUserClient::externalMethod(uint32_t selector,
  IOExternalMethodArguments *arguments,
  IOExternalMethodDispatch *dispatch,
  OSObject *target, void *reference);
  - selector: to select method in userclient
  - arguments: arguments passed to the selected method
  - dispatch: a struct representing the method to be called
  - target: the target userclient for the method to be called on
  - reference: reference to send results back to userspace program

- Apple provides IOKit**.framework** for programs in user space to interact with kernel drivers
  - Though public, explicit invocation in iOS will be rejected by App Store
- Important APIs in IOKit.framework:
  - IOServiceGetMatchingService, IOServiceGetMatchingServices
  - IOServiceOpen, IOServiceClose
  - IOConnectCall…Method, IOConnectCallAsync…Method
  - IORegistryEntryCreateCFProperty, IORegistryEntrySetCFProperty
  - IOConnectMapMemory, IOConnectUnmapMemory
  - IOConnectSetNotificationPort

Userland Perspective

- The calling sequence to interact with a driver
  - IOServiceGetMatchingService → Get the service of the the target driver
    - IORegistryEntryCreateCFProperty → Get the driver's property
    - IORegistryEntrySetCFProperty → Set the driver's property
    - IOServiceOpen → Connect to the target driver
      - IOConnectCall…Method → Call the driver's method through the connection
      - IOConnectCallAsync…Method → Call method, asynchronously
      - IOConnectMapMemory → Get a memory mapped by the driver
      - IOConnectSetNotificationPort → Prepare to receive notification from driver
      - IOServiceClose → Close the connection

- Sample code of using service of IOKit driver

```
#include <IOKit/IOKitLib.h>
void main() {
    io_service_t service =
    IOServiceGetMatchingService(kIOMasterPortDefault,
                                IOServiceMatching("IOFireWireLocalNode"));
    kern_return_t kr;
    kr = IORegistryEntrySetCFProperty(deviceChild, CFSTR("hello"), CFSTR("hello"));
    io_connect_t port = (io_connect_t) 0;
    kr = IOServiceOpen(service, mach_task_self(), 0, &port);

    uint64_t input[3]; uint64_t inputCnt = 3;
    uint64_t output[16]; uint32_t outputCnt = 2;
    kr = IOConnectCallMethod((mach_port_t) port, /* Connection */
                             (uint32_t) 57,       /* Selector */ // kIsochChannel_Allocate
                             input, inputCnt,           /* input, inputCnt */
                             0,     /* inputStruct */
                             0,                /* inputStructCnt */
                             output, &outputCnt, NULL, NULL); /* Output stuff */
    IOServiceClose(port);
}
```

Get the service of IOFireWireLocalNode

Set property hello's value as hello

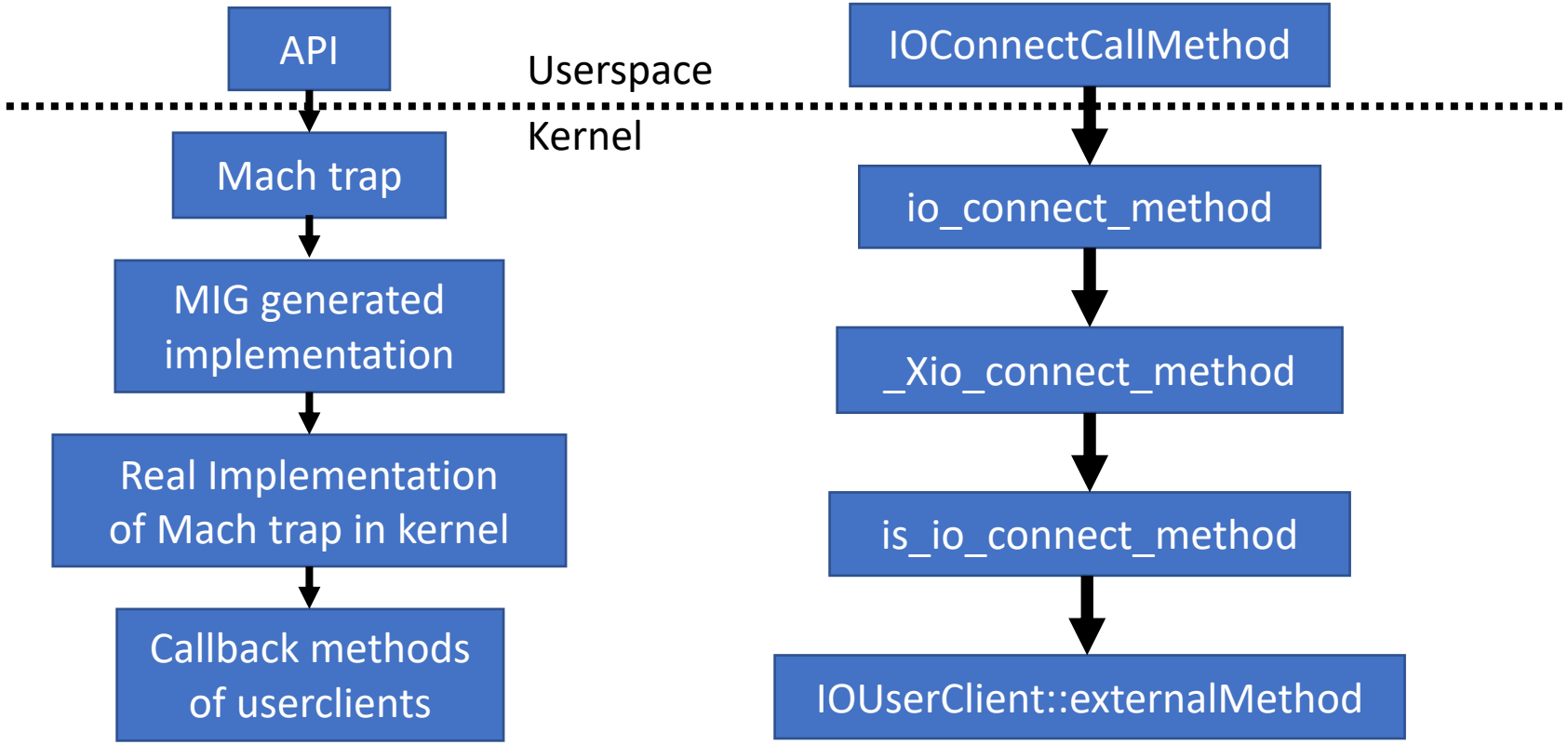
Connect to the target service, open IOFireWireUserClient

Call the driver's method, through the connection

Close connection with the target driver

Userland Perspective

- APIs in IOKit.framework are wrappers of Mach Traps (kinda syscall) , which are generated by Mach Interface Generator (MIG) and eventually call into callback methods implemented by userclients



Userland Perspective

- Despite of strict sandbox restriction, some userclients in IOKit drivers can still be accessed by sandboxed apps on iOS.
- Through experiments, we confirm these available userclients and their correponding IOKit device driver names on iOS 11
  - **IOHIDLibUserClient**: AppleSPUHIDDevice, AppleCSHTDCodecMikey
  - **IOMobileFramebufferUserClient**: AppleCLCD
  - **IOSurfaceAcceleratorClient**: AppleM2ScalerCSCDriver
  - **AppleJPEGDriverUserClient**: AppleJPEGDrive
  - **IOAccelDevice2**, **IOAccelSharedUserClient2**, **IOAccelCommandQueue2**: AGXAccelerator
  - **AppleKeyStoreUserClient**: AppleKeyStore
  - **IOSurfaceSendRight**, **IOSurfaceRootUserClient**: IOSurfaceRoot

New Vulns in Drivers on macOS – Current Secure Status

- Though within kernel, drivers are always blamed for poor quality, which make them frequently be used to exploit the kernel

- Vulns in drivers used in JailBreaks:
  - 11 (v0rtex | electra): IOSurfaceRoot (CVE-2017-13861)
  - 9 (pangu): IOMobileFrameBuffer (CVE-2016-4654)
  - 8 (TaiG): IOHIDFamily (CVE-2015-5774)
  - 7 (pangu): AppleKeyStore (CVE-2014-4407)

- With the help of Ryuk, we found and confirmed some new vulns on macOS

- Information Leakage due to uninitialized stack variable in IOFirewireFamily driver (CVE-2017-7119) – To defeat kaslr

```
case kIsochChannel_Allocate:
{
    IOFireWireUserClient * fw_uc = OSDynamicCast( IOFireWireUserClient, targetObject );
    if( fw_uc )
    {
        UserObjectHandle outChannelHandle;
        result = fw_uc->isochChannel_Create((bool)arguments->scalarInput[0],
                                            (UInt32)arguments->scalarInput[1],
                                            (IOFWSpeed)arguments->scalarInput[2],
                                            &outChannelHandle);

        arguments->scalarOutput[0] = (uint64_t) outChannelHandle;
    }
    else
    {
        result = kIOReturnBadArgument;
    }
    break;
}
```

- Information Leakage due to uninitialized stack variable in IOFirewireFamily driver (CVE-2017-7119) – To defeat kaslr

```
IOReturn
IOFireWireUserClient::isochChannel_Create (
    bool                    inDoIRM,
    UInt32                  inPacketSize,
    IOFWSpeed               inPrefSpeed,
    UserObjectHandle *  outChannelHandle )
{
    // this code the same as IOFireWireController::createIsochChannel
    // must update this code when controller changes. We do this because
    // we are making IOFWUserIsochChannel objects, not IOFWIsochChannel
    // objects

    IOReturn error = kIOReturnSuccess ;
    IOFWUserIsochChannel * channel = OSTypeAlloc( IOFWUserIsochChannel );
    if ( channel )
    {
        if ( channel->init( getOwner()->getController(), inDoIRM, inPacketSize, inPrefSpeed ) )
        {
            fExporter->addObject( channel,
                    (IOFWUserObjectExporter::CleanupFunction) & IOFWUserIsochChannel::s_exporterCleanup,
                    outChannelHandle ) ;
        }
```

- Information Leakage due to uninitialized stack variable in IOFirewireFamily driver (CVE-2017-7119) – To defeat kaslr

```
IOReturn
IOFWUserObjectExporter::addObject ( OSObject * obj, CleanupFunction cleanupFunction, IOFireWireLib::UserObjectHandle *
    outHandle )
{
    IOReturn error = kIOReturnSuccess ;
    lock () ;
    // if at capacity, expand pool
    if ( fObjectCount == fCapacity )
    {
        unsigned newCapacity = fCapacity + ( fCapacity >> 1 ) ;
        if ( newCapacity > 0xFFFE )
            newCapacity = 0xFFFE ;
        if ( newCapacity == fCapacity ) // can't grow!
        {
            DebugLog( "Can't grow object exporter\n" ) ;
            error = kIOReturnNoMemory ;
        }
    }
```

- Information Leakage due to uninitialized stack variable in IOFirewireFamily driver (CVE-2017-7119) – To defeat kaslr

```
* thread #1, stop reason = breakpoint 2.1
    frame #0: 0xffffff7f856947ac IOFireWireFamily`IOFireWireUserClie
nt::isochChannel_Create(this=0xffffff80177a2a00, inDoIRM=false, inPa
cketSize=0, inPrefSpeed=kFWSpeed100MBit, outChannelHandle=0xffffff91
340b3b48) at IOFireWireUserClient.cpp:4504 [opt]
(lldb) x/5g $r8
0xffffff91340b3b48: 0xffffff8004ebc0b6 0xffffff8016a8d000
0xffffff91340b3b58: 0xffffff80177a2a00 0x0000000000000039
0xffffff91340b3b68: 0xffffff80218791f4

(lldb) dis -a 0xffffff8004ebc0b6
kernel`IOEventSource::closeGate:
    0xffffff8004ebc0a0 <+0>:  pushq  %rbp
    0xffffff8004ebc0a1 <+1>:  movq   %rsp, %rbp
    0xffffff8004ebc0a4 <+4>:  pushq  %rbx
    0xffffff8004ebc0a5 <+5>:  pushq  %rax
    0xffffff8004ebc0a6 <+6>:  movq   %rdi, %rbx
    0xffffff8004ebc0a9 <+9>:  movq   0x30(%rbx), %rdi
    0xffffff8004ebc0ad <+13>: movq   (%rdi), %rax
    0xffffff8004ebc0b0 <+16>: callq  *0x180(%rax)
    0xffffff8004ebc0b6 <+22>: movq   0x40(%rbx), %rax
    0xffffff8004ebc0ba <+26>: movq   (%rax), %rbx
    0xffffff8004ebc0bd <+29>: testq  %rbx, %rbx
    0xffffff8004ebc0c0 <+32>: je     0xffffff8004ebc0d5
    0xffffff8004ebc0c2 <+34>: leaq   0x14cd57(%rip), %rdi
    0xffffff8004ebc0c9 <+41>: callq  0xffffff8004897880
    0xffffff8004ebc0ce <+46>: movq   %rax, 0x18(%rbx)
    0xffffff8004ebc0d2 <+50>: incl   0x28(%rbx)
    0xffffff8004ebc0d5 <+53>: addq   $0x8, %rsp
    0xffffff8004ebc0d9 <+57>: popq   %rbx
    0xffffff8004ebc0da <+58>: popq   %rbp
    0xffffff8004ebc0db <+59>: retq
```

```
FFFFFF80008BC0A0 ; __int64 __fastcall IOEventSource::closeGate(IOEventSo
FFFFFF80008BC0A0                 public __ZN13IOEventSource9closeGateEv
FFFFFF80008BC0A0 __ZN13IOEventSource9closeGateEv proc near
FFFFFF80008BC0A0                 push    rbp
FFFFFF80008BC0A1                 mov     rbp, rsp
FFFFFF80008BC0A4                 push    rbx
FFFFFF80008BC0A5                 push    rax
FFFFFF80008BC0A6                 mov     rbx, rdi
FFFFFF80008BC0A9                 mov     rdi, [rbx+30h]
FFFFFF80008BC0AD                 mov     rax, [rdi]
FFFFFF80008BC0B0                 call    qword ptr [rax+180h]
FFFFFF80008BC0B6                 mov     rax, [rbx+40h]
FFFFFF80008BC0BA                 mov     rbx, [rax]
FFFFFF80008BC0BD                 test    rbx, rbx
FFFFFF80008BC0C0                 jz      short loc_FFFFFF80008BC0D5
FFFFFF80008BC0C2                 lea     rdi, _pal_rtc_nanotime_info
FFFFFF80008BC0C9                 call    __rtc_nanotime_read
FFFFFF80008BC0CE                 mov     [rbx+18h], rax
FFFFFF80008BC0D2                 inc     dword ptr [rbx+28h]
FFFFFF80008BC0D5
FFFFFF80008BC0D5 loc_FFFFFF80008BC0D5:                   ; CODE XREF: IO
FFFFFF80008BC0D5                 add     rsp, 8
FFFFFF80008BC0D9                 pop     rbx
FFFFFF80008BC0DA                 pop     rbp
FFFFFF80008BC0DB                 retn
FFFFFF80008BC0DB __ZN13IOEventSource9closeGateEv endp
```

Kernel slide = 0x4ebc0b6-0x8bc0b6 = 0x4600000
Though outChannelHandle is only 32bit, but enough since the high 32bit is always 0xffffff80 here

New Vulns in Drivers on macOS – New Vuln 2

- CVE-2018-4135: UAF in IOFirewireFamily driver – To control PC
  - There is no locking or serialization when releasing and using a member variable
  - fMem is a member of class IOFWUserReadCommand

```
IOReturn
IOFWUserReadCommand::submit(
    CommandSubmitParams*    params,
    CommandSubmitResult*    outResult)
{
    IOReturn    error       = kIOReturnSuccess ;
    Boolean     syncFlag    = ( params->flags & kFWCommandInterfaceSyncExecute ) != 0 ;
    Boolean     copyFlag    = ( params->flags & kFireWireCommandUseCopy ) != 0;
    Boolean     absFlag     = ( params->flags & kFireWireCommandAbsolute ) != 0 ;
    bool        forceBlockFlag  = (params->flags & kFWCommandInterfaceForceBlockRequest) != 0;

    if ( params->staleFlags & kFireWireCommandStale_Buffer )
    {
        if ( fMem ) // whatever happens, we're going to need a new memory descriptor
        {
            fMem->complete() ;
            fMem->release() ;   <-- (a)
            fMem = NULL;
        }
        ...

    }

    if ( not error )
    {
        ...
            fCommand = fUserClient->getOwner()->createReadCommand( target_address,
                fMem, syncFlag ? NULL : & IOFWUserCommand::asyncReadWriteCommandCompletion,
                this, params->newFailOnReset ) ;      <-- (b)
        ...
    }
    ...
}
```

New Vulns in Drivers on macOS – New Vuln 2

- CVE-2018-4135: UAF in IOFirewireFamily driver – To control PC
  - Exploit: race two threads to call this function on the same userclient

```
IOReturn
IOFWUserReadCommand::submit(
    CommandSubmitParams*    params,
    CommandSubmitResult*    outResult)
{
    IOReturn    error       = kIOReturnSuccess ;
    Boolean     syncFlag    = ( params->flags & kFWCommandInterfaceSyncExecute ) != 0 ;
    Boolean     copyFlag    = ( params->flags & kFireWireCommandUseCopy ) != 0;
    Boolean     absFlag     = ( params->flags & kFireWireCommandAbsolute ) != 0 ;
    bool        forceBlockFlag  = (params->flags & kFWCommandInterfaceForceBlockRequest) != 0;

    if ( params->staleFlags & kFireWireCommandStale_Buffer )
    {
        if ( fMem ) // whatever happens, we're going to need a new memory descriptor
        {
            fMem->complete() ;
            fMem->release() ;   <-- (a)
            fMem = NULL;
        }
        ...

    }

    if ( not error )
    {
        ...
            fCommand = fUserClient->getOwner()->createReadCommand( target_address,
                fMem, syncFlag ? NULL : & IOFWUserCommand::asyncReadWriteCommandCompletion,
                this, params->newFailOnReset ) ;      <-- (b)
        ...
    }
    ...
}
```

New Vulns in Drivers on macOS – New Vuln 2

- CVE-2018-4135: UAF in IOFirewireFamily driver – To control PC
  - Exploit: race two threads to call this function on the same userclient

```
   0xffffff7f94c8be50 <+160>: testq  %r13, %r13
   0xffffff7f94c8be53 <+163>: je     0xffffff7f94c8be68
   0xffffff7f94c8be55 <+165>: movq   (%r13), %rax
   0xffffff7f94c8be59 <+169>: movq   %r13, %rdi
-> 0xffffff7f94c8be5c <+172>: callq  *0x1c8(%rax)

(lldb) re r
General Purpose Registers:
       rax = 0x4141414141414141
```

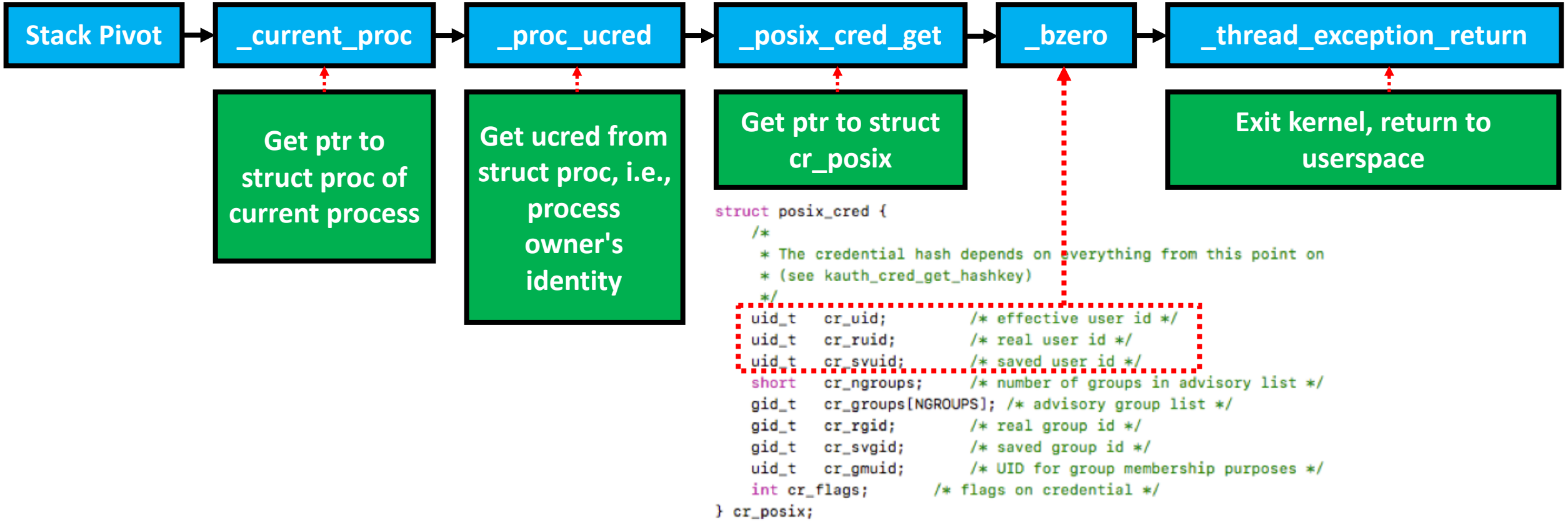
New Vulns in Drivers on macOS – New EXP strategies: Heap Spray

- A new heap spray strategy utilizing OSUnserializeXML on macOS
  - io_registry_entry_set_properties: set properties of device, eventually call is_io_registry_entry_set_properties in kernel

```
/* Routine io_registry_entry_set_properties */
kern_return_t is_io_registry_entry_set_properties(
    io_object_t registry_entry,
    io_buf_ptr_t properties,
    mach_msg_type_number_t propertiesCnt,
        kern_return_t * result) {
        ...
        obj = OSUnserializeXML( (const char *) data, propertiesCnt );
        ...
        res = entry->setProperties( obj );
}
```

  - Some drivers keep any properties set by userspace, e.g., IOHIDEventService
  - Pros: the sprayed data can be read; the head of sprayed data is controllable

- After controlling PC, we can gain privilege through ROP chain
- ROP chain (most employed from tpwn)



- After controlling PC, we can gain privilege through ROP chain
- Key step: Stack Pivot

In tpwn (on 10.10)

```
50                      push rax
0100                    add DWORD PTR [rax],eax
005b41                  add BYTE PTR [rbx+0x41],bl
5c                      pop rsp
415e                    pop r14
415f                    pop r15
5d                      pop rbp
c3                      ret
```

In rootsh (on 10.11)

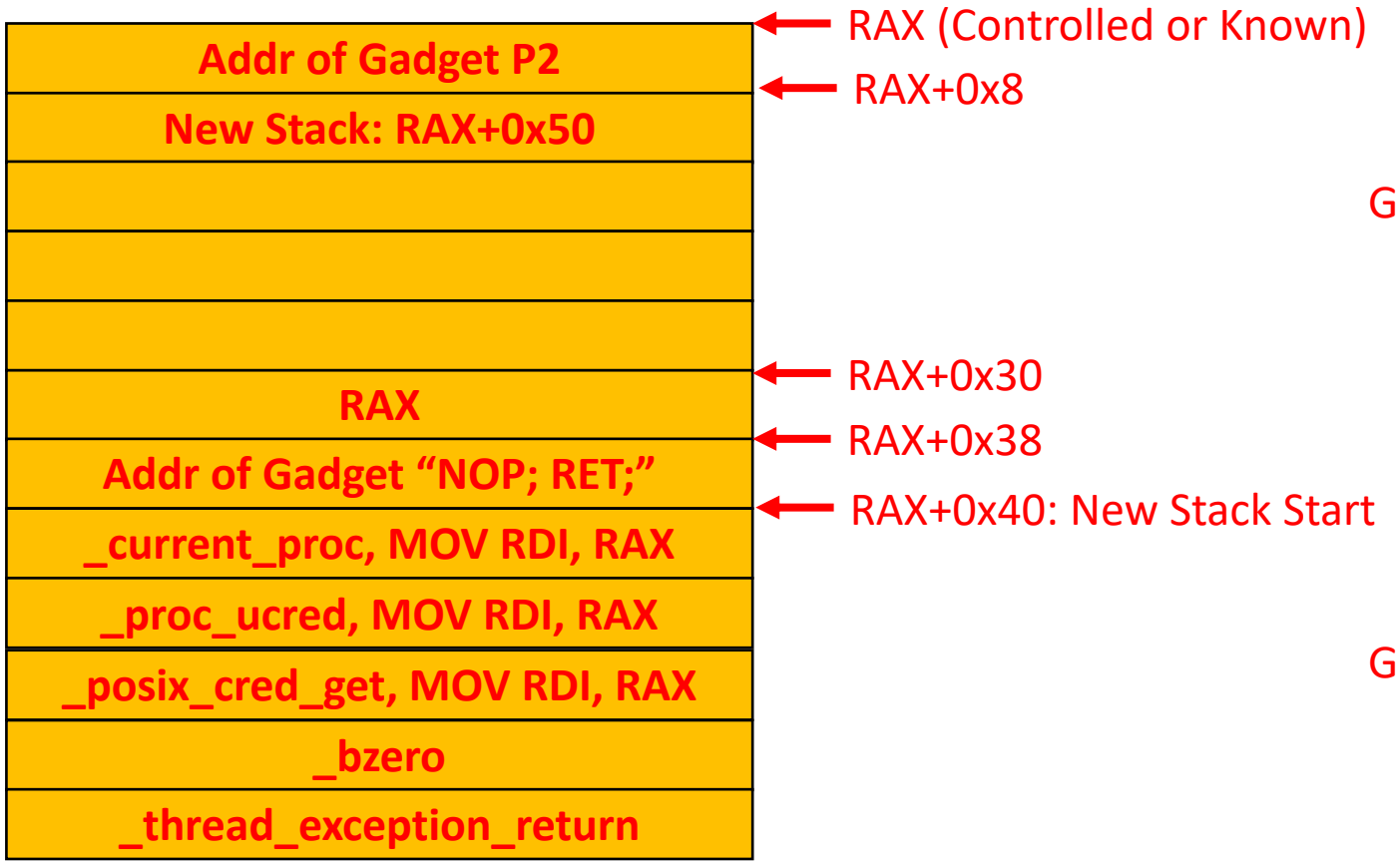
```
static const uint8_t xchg_esp_eax_pop_rsp_ins[] = {
        0x94,   /* xchg esp, eax */
        0x5c,   /* pop rsp       */
        0xc3,   /* ret           */
};
```

New

```
mov     rcx, [rax+30h]
mov     [rbp+var_50], rcx
call    qword ptr [rax]
```

```
mov     rsp, [rcx+8]
mov     rbx, [rcx]
mov     rbp, [rcx+10h]
mov     r12, [rcx+18h]
mov     r13, [rcx+20h]
mov     r14, [rcx+28h]
mov     r15, [rcx+30h]
jmp     qword ptr [rcx+38h]
```

- After controlling PC, we can gain privilege through ROP chain
- Key step: Stack Pivot



New

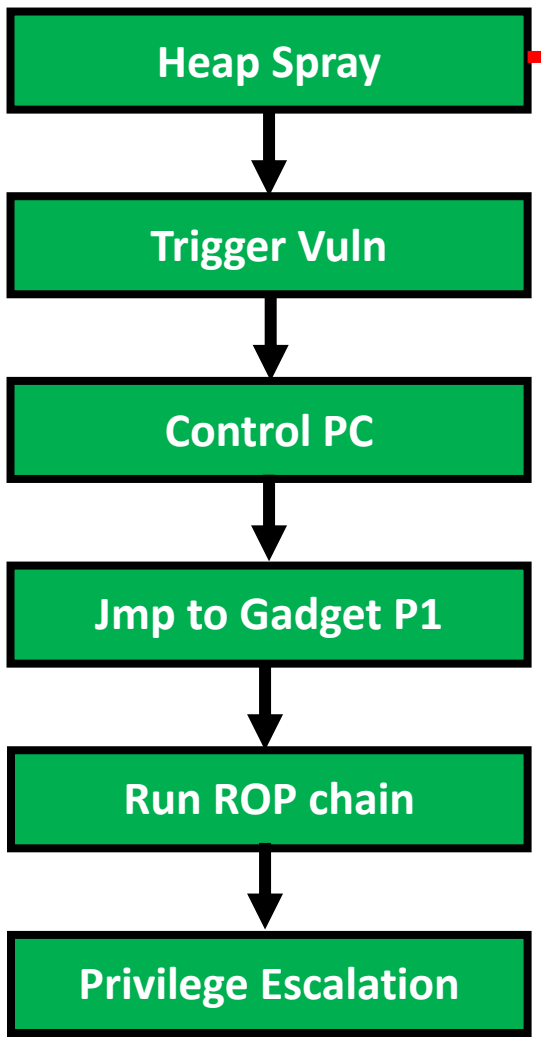
Gadget P1

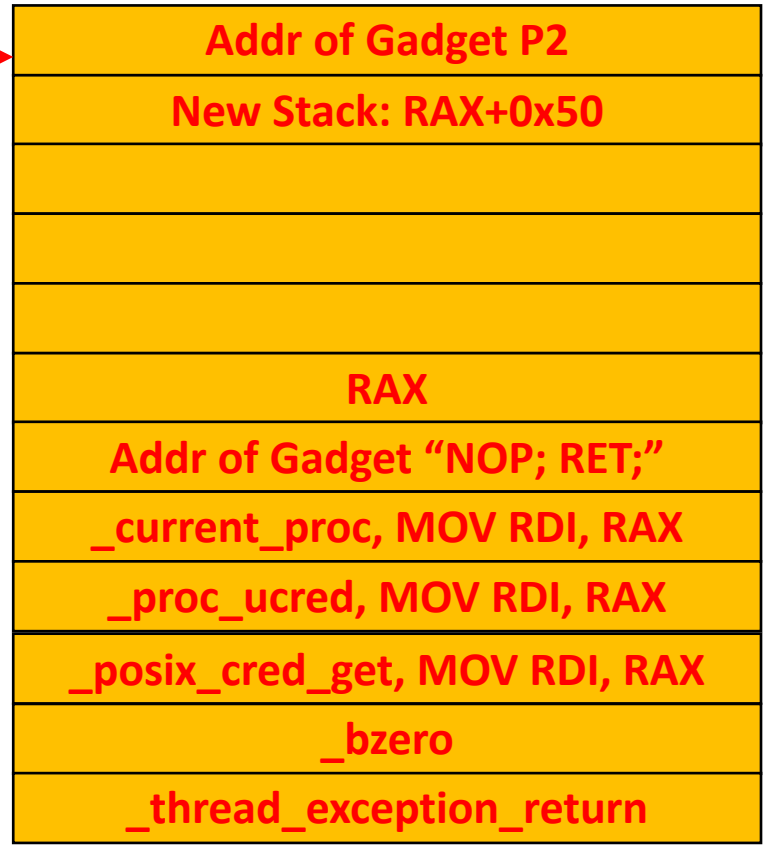
```
mov     rcx, [rax+30h]
mov     [rbp+var_50], rcx
call    qword ptr [rax]
```

Gadget P2

```
mov     rsp, [rcx+8]
mov     rbx, [rcx]
mov     rbp, [rcx+10h]
mov     r12, [rcx+18h]
mov     r13, [rcx+20h]
mov     r14, [rcx+28h]
mov     r15, [rcx+30h]
jmp     qword ptr [rcx+38h]
```

New Vulns in Drivers on macOS – Whole EXP Process





high space of heap
possessed by heap spray

New Vulns in Drivers on macOS – Privilege Escalation on 10.13.2

- Privilege escalation on the macOS

On macOS 10.13

```
sh-3.2# uname -a
Darwin bxldeMacBook-Air.local 17.0.0 Darwin Kernel Version 17.0.0: Thu Aug 24 21
:48:20 PDT 2017; root:xnu-4570.1.46~2/DEVELOPMENT_X86_64 x86_64
sh-3.2# whoami
root
sh-3.2#
```

On macOS 10.13.2

```
sh-3.2# uname -a
Darwin bxldeMacBook-Air.local 17.3.0 Darwin Kernel Version 17.3.0: Thu Nov  9 18:09:22 PST 2017; root:xnu-4570.31.3~1/DEVELOPMENT_X86_64 x86_64
sh-3.2# whoami
root
sh-3.2#
```

Bugs fixed on macOS 10.13.4

New Vulns in Drivers – Privilege Escalation on macOS 10.13.3


```
bxldeMacBook-Air:private bxl$
```

Analyze Apple Drivers: Obstacles

- But! Analyzing macOS and iOS kernel drivers is not easy!
  - Closed-source
  - Programmed in C++
  - Lack of Symbols (mainly for iOS)

- Let’s first look at how drivers’ binary code looks like in IDA pro

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – macOS
  - Readable

D	_kIOSurfaceClassName	000000000000C0F0	f	IOSurfaceRootUserClient::MetaClass::Met…	000000000000771C
D	_kIOSurfaceIsGlobal	000000000000C0F8	f	IOSurfaceRootUserClient::MetaClass::~M…	000000000000774E
D	_kIOSurfaceBytesPerRow	000000000000C100	f	IOSurfaceRootUserClient::IOSurfaceRoot…	0000000000007758
D	_kIOSurfaceBitsPerBlock	000000000000C108	f	IOSurfaceRootUserClient::IOSurfaceRoot…	0000000000007778
D	_kIOSurfaceBytesPerElement	000000000000C110	f	IOSurfaceRootUserClient::~IOSurfaceRoo…	0000000000007798
D	_kIOSurfaceWidth	000000000000C118	f	IOSurfaceRootUserClient::~IOSurfaceRoo…	00000000000077A2
D	_kIOSurfaceHeight	000000000000C120	f	IOSurfaceRootUserClient::~IOSurfaceRoo…	00000000000077AC
D	_kIOSurfaceElementWidth	000000000000C128	f	IOSurfaceRootUserClient::getMetaClass(v…	00000000000077CE
D	_kIOSurfaceElementHeight	000000000000C130	f	IOSurfaceRootUserClient::MetaClass::Met…	00000000000077DC
D	_kIOSurfaceOffset	000000000000C138	f	IOSurfaceRootUserClient::MetaClass::allo…	000000000000780E
D	_kIOSurfacePixelFormat	000000000000C140	f	IOSurfaceRootUserClient::IOSurfaceRoot…	000000000000784E
D	_kIOSurfaceAllocSize	000000000000C148	f	IOSurfaceRootUserClient::IOSurfaceRoot…	000000000000787E
D	_kIOSurfaceMemoryRegion	000000000000C150	f	IOSurfaceRootUserClient::init(IOSurfaceR…	00000000000078AE
D	_kIOSurfacePlaneInfo	000000000000C158	f	IOSurfaceRootUserClient::taskHasEntitle…	000000000000795C
D	_kIOSurfacePlaneOffset	000000000000C160	f	IOSurfaceRootUserClient::s_create_surfac…	00000000000079C0
D	_kIOSurfacePlaneWidth	000000000000C168	f	IOSurfaceRootUserClient::s_release_surfa…	0000000000007A64
D	_kIOSurfacePlaneHeight	000000000000C170	f	IOSurfaceRootUserClient::s_lock_surface(…	0000000000007A74
D	_kIOSurfacePlaneBitsPerBlock	000000000000C178	f	IOSurfaceRootUserClient::s_unlock_surfa…	0000000000007A90
D	_kIOSurfacePlaneBytesPerElement	000000000000C180	f	IOSurfaceRootUserClient::s_lookup_surfa…	0000000000007AAC

Many symbols are kept

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – macOS
  - Readable

```
__const:000000000000D720 ; `vtable for'IOSurfaceRootUserClient
__const:000000000000D720 __ZTV23IOSurfaceRootUserClient db    0
__const:000000000000D721                 db    0
__const:000000000000D722                 db    0
__const:000000000000D723                 db    0
__const:000000000000D724                 db    0
__const:000000000000D725                 db    0
__const:000000000000D726                 db    0
__const:000000000000D727                 db    0
__const:000000000000D728                 db    0
__const:000000000000D729                 db    0
__const:000000000000D72A                 db    0
__const:000000000000D72B                 db    0
__const:000000000000D72C                 db    0
__const:000000000000D72D                 db    0
__const:000000000000D72E                 db    0
__const:000000000000D72F                 db    0
__const:000000000000D730 off_D730        dq offset __ZN23IOSurfaceRootUserClientD1Ev
__const:000000000000D730                                 ; DATA XREF: IOSurfaceRootUserClient:
__const:000000000000D730                                 ; IOSurfaceRootUserClient::IOSurfaceR
__const:000000000000D730                                 ; IOSurfaceRootUserClient::~IOSurface
__const:000000000000D738                 dq offset __ZN23IOSurfaceRootUserClientD0Ev ; IOSurfaceRootUs
__const:000000000000D740                 dq offset __ZNK8OSObject7releaseEi ; OSObject::release(int)
__const:000000000000D748                 dq offset __ZNK8OSObject14getRetainCountEv ; OSObject::getRet
__const:000000000000D750                 dq offset __ZNK8OSObject6retainEv ; OSObject::retain(void)
__const:000000000000D758                 dq offset __ZNK8OSObject7releaseEv ; OSObject::release(void)
```

Event better, we have symbols of vtables and know where they are

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – macOS
  - Readable

```
__const:000000000000E190 ; IOSurfaceRootUserClient::init(IOSurfaceRoot *, task *, OSDictionary *)::methodI
__const:000000000000E190 __ZZN23IOSurfaceRootUserClient4initEP13IOSurfaceRootP4taskP12OSDictionaryE11methc
__const:000000000000E190                                         ; DATA XREF: IOSurfaceRootUserClient::ini
__const:000000000000E190                                         ; IOSurfaceRootUserClient::s_create_surfa
__const:000000000000E198                 db    0
__const:000000000000E199                 db    0
__const:000000000000E19A                 db    0
__const:000000000000E19B                 db    0
__const:000000000000E19C                 db 0FFh
__const:000000000000E19D                 db 0FFh
__const:000000000000E19E                 db 0FFh
__const:000000000000E19F                 db 0FFh
__const:000000000000E1A0                 db    0
__const:000000000000E1A1                 db    0
__const:000000000000E1A2                 db    0
__const:000000000000E1A3                 db    0
__const:000000000000E1A4                 db 0C8h ;
__const:000000000000E1A5                 db    3
__const:000000000000E1A6                 db    0
__const:000000000000E1A7                 db    0
__const:000000000000E1A8                 dq offset __ZN23IOSurfaceRootUserClient17s_release_surfaceEPS_PvI
__const:000000000000E1B0                 db    1
__const:000000000000E1B1                 db    0
__const:000000000000E1B2                 db    0
__const:000000000000E1B3                 db    0
__const:000000000000E1B4                 db    0
__const:000000000000E1B5                 db    0
```

Even sMethods of userclients have symbols

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – macOS
  - Readable

```
__text:000000000000795C ; __int64 __fastcall IOSurfaceRootUserClient::taskHasEntitlement(IOSurfaceRootU
__text:000000000000795C                 public __ZN23IOSurfaceRootUserClient18taskHasEntitlementEP4task
__text:000000000000795C __ZN23IOSurfaceRootUserClient18taskHasEntitlementEP4taskPKc proc near
__text:000000000000795C                                         ; CODE XREF: IOSurfaceRootUserClient::i
__text:000000000000795C                 push    rbp
__text:000000000000795D                 mov     rbp, rsp
__text:0000000000007960                 push    r14
__text:0000000000007962                 push    rbx
__text:0000000000007963                 call    _current_task
__text:0000000000007968                 lea     rsi, aCom_apple_priv ; "com.apple.private.iosurfaceinfo
__text:000000000000796F                 mov     rdi, rax        ; this
__text:0000000000007972                 call    __ZN12IOUserClient21copyClientEntitlementEP4taskPKc ; I
__text:0000000000007977                 mov     rbx, rax
__text:000000000000797A                 test    rbx, rbx
__text:000000000000797D                 jz      short loc_79A7
__text:000000000000797F                 mov     rax, cs:off_C048
__text:0000000000007986                 mov     rsi, [rax]
__text:0000000000007989                 mov     rdi, rbx
__text:000000000000798C                 call    __ZN15OSMetaClassBase12safeMetaCastEPKS_PK11OSMetaClass
__text:0000000000007991                 test    rax, rax
__text:0000000000007994                 jz      short loc_79AC
__text:0000000000007996                 mov     rcx, [rax]
__text:0000000000007999                 mov     rdi, rax
__text:000000000000799C                 call    qword ptr [rcx+118h]
__text:00000000000079A2                 mov     r14b, al
__text:00000000000079A5                 jmp     short loc_79AF
```

Functions have meaningful names (for both internal and externa).

These names can be demangled to know the argument types

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – macOS
  - Readable

```
char __fastcall IOSurfaceRootUserClient::taskHasEntitlement(IOSurfaceRootUserClient *this, task *a2,
{
  IOUserClient *v3; // rax@1
  const char *v4; // rdx@1
  __int64 v5; // rbx@1
  __int64 v6; // rsi@2
  __int64 v7; // rax@2
  char v8; // r14@3

  LODWORD(v3) = current_task(this, a2, a3);
  v5 = IOUserClient::copyClientEntitlement(v3, (task *)&"com.apple.private.iosurfaceinfo", v4);
  if ( v5 )
  {
    v6 = *off_C048;
    LODWORD(v7) = OSMetaClassBase::safeMetaCast(v5, *off_C048);
    if ( v7 )
      v8 = (*(int (__fastcall **)(__int64, __int64))(*(_QWORD *)v7 + 280LL))(v7, v6);
    else
      v8 = 0;
    (*(void (__fastcall **)(__int64))(*(_QWORD *)v5 + 40LL))(v5);
  }
  else
  {
    v8 = 0;
  }
  return v8;
}
```

Decompiled code is partially human-readable

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – macOS
  - Readable, **but not suitable for manual review and static analysis**

```
char __fastcall IOSurfaceRootUserClient::taskHasEntitlement(IOSurfaceRootUserClient *this, task *a2,
{
  IOUserClient *v3; // rax@1
  const char *v4; // rdx@1
  __int64 v5; // rbx@1
  __int64 v6; // rsi@2
  __int64 v7; // rax@2
  char v8; // r14@3

  LODWORD(v3) = current_task(this, a2, a3);
  v5 = IOUserClient::copyClientEntitlement(v3, (task *)&"com.apple.private.iosurfaceinfo", v4);
  if ( v5 )
  {
    v6 = *off_C048;
    LODWORD(v7) = OSMetaClassBase::safeMetaCast(v5, *off_C048);
    if ( v7 )
      v8 = (*(int (__fastcall **)(__int64, __int64))(*(_QWORD *)v7 + 280LL))(v7, v6);
    else
      v8 = 0;
    (*(void (__fastcall **)(__int64))(*(_QWORD *)v5 + 40LL))(v5);
  }
  else
  {
    v8 = 0;
  }
  return v8;
}
```

Types of object variables are unknown

Classes' vtable function pointers are used everywhere, IDA pro cannot recognize.

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – macOS
  - Readable, **but not suitable for manual review and static analysis**

```
__int64 __fastcall IOSurfaceRootUserClient::release_surface(IOSurfaceRootUserClient *this, __int64 a2)
{
  __int64 v2; // r14@2
  __int64 v3; // rax@5
  _QWORD *v4; // rcx@5
  __int64 result; // rax@7
  __int64 v6; // rbx@9

  IOLockLock(*((_QWORD *)this + 27));
  if ( *((_DWORD *)this + 74) > (unsigned int)a2
    && (v2 = *(_QWORD *)(*((_QWORD *)this + 36) + 8LL * (unsigned int)a2)) != 0 )
  {
    if ( *(_BYTE *)(v2 + 105) )
      --*((_DWORD *)this + 79);
    --*((_DWORD *)this + 80);
    v3 = *(_QWORD *)(v2 + 24);
    v4 = *(_QWORD **)(v2 + 32);
    if ( v3 )
    {
      *(_QWORD *)(v3 + 32) = v4;
      v4 = *(_QWORD **)(v2 + 32);
    }
    else
    {
      *((_QWORD *)this + 35) = v4;
    }
```

No structures for classes

Class sizes are unknown

Member variables cannot be recognized by IDA pro

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – iOS
  - **Messy! Nothing useful there! Unreadable, not to mention further**

sub_FFFFFFF00615A0BC	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A0BC
sub_FFFFFFF00615A19C	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A19C
sub_FFFFFFF00615A3D0	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A3D0
sub_FFFFFFF00615A498	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A498
sub_FFFFFFF00615A51C	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A51C
sub_FFFFFFF00615A52C	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A52C
sub_FFFFFFF00615A53C	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A53C
sub_FFFFFFF00615A574	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A574
sub_FFFFFFF00615A678	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A678
sub_FFFFFFF00615A730	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A730
sub_FFFFFFF00615A7E8	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A7E8
sub_FFFFFFF00615A820	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A820
sub_FFFFFFF00615A858	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615A858
sub_FFFFFFF00615AB20	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615AB20
sub_FFFFFFF00615AC00	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615AC00
sub_FFFFFFF00615AC0C	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615AC0C
sub_FFFFFFF00615AC34	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615AC34
sub_FFFFFFF00615AC3C	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615AC3C
sub_FFFFFFF00615AC44	com.apple.iokit.IONetworkingFamily:__text	FFFFFFF00615AC44

Functions do not have symbols

Function names are all meaningless "sub_"

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – iOS
  - **Messy! Nothing readable, not to mention further analysis**

```
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047A8                 DCQ unk_FFFFFFF0076DC0C8
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047B0                 DCQ unk_FFFFFFF0076DC248
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047B8 unk_FFFFFFF006E047B8 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047B8
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047B9                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047BA                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047BB                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047BC                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047BD                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047BE                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047BF                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047C0                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047C1                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047C2                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047C3                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047C4                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047C5                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047C6                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047C7                 DCB     0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047C8                 DCB  0x64 ; d
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047C9                 DCB  0x40 ; @
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047CA                 DCB  0x15
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047CB                 DCB     6
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047CC                 DCB  0xF0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047CD                 DCB  0xFF
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047CE                 DCB  0xFF
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047CF                 DCB  0xFF
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047D0                 DCB  0x68 ; h
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E047D1                 DCB  0x40 ; @
```

There is no symbol for vtables

No clue to know where vtables are

No entry can be found

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – iOS
  - **Messy! Nothing readable, not to mention further analysis**

```
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B524                STP             X20, X19, [SP,#-0x20]!
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B528                STP             X29, X30, [SP,#0x10]
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B52C                ADD             X29, SP, #0x10
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B530                MOV             X19, X0
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B534                LDR             W8, [X19,#0xD4]
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B538                ADD             W9, W8, #1
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B53C                STR             W9, [X19,#0xD4]
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B540                CBNZ            W8, loc_FFFFFFF00615B550
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B544                MOV             X0, X19
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B548                BL              sub_FFFFFFF006157638
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B54C                STR             W0, [X19,#0xD0]
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B550
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B550 loc_FFFFFFF00615B550                          ; CODE XREF: com
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B550                LDP             X29, X30, [SP,#0x10]
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B554                LDP             X20, X19, [SP],#0x20
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B558                RET
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B55C ; ---------------------------------------------------------------------------
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B55C                LDR             W8, [X0,#0xD4]
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B560                SUB             W8, W8, #1
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B564                STR             W8, [X0,#0xD4]
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B568                CBZ             W8, loc_FFFFFFF00615B570
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B56C                RET
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B570 ; ---------------------------------------------------------------------------
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B570
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B570 loc_FFFFFFF00615B570                          ; CODE XREF: com
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B570                LDR             W0, [X0,#0xD0]
com.apple.iokit.IONetworkingFamily:__text:FFFFFFF00615B574                B               loc_FFFFFFF006157670
```

Functions cannot be recognized by IDA pro

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – iOS
  - **Messy! Nothing readable, not to mention further analysis**

```
__int64 __fastcall sub_FFFFFFF00615A3D0(__int64 a1, __int64 a2, int a3)
{
  int v3; // w20
  __int64 v4; // x19
  __int64 v5; // x21
  __int64 result; // x0
  __int64 v7; // x0
  __int64 v8; // x21
  void (__fastcall *v9)(__int64, __int64); // x22
  __int64 v10; // x0
  signed __int64 v11; // x1

  v3 = a3;
  v4 = a2;
  v5 = (*(__int64 (**)(void))(*(_QWORD *)a1 + 1536LL))();
  result = sub_FFFFFFF006166F10(v4, off_FFFFFFF006E07190);
  if ( result )
  {
    if ( v5 )
    {
      v7 = (*(__int64 (__fastcall **)(__int64))(*(_QWORD *)v5 + 208LL))(v5);
      v8 = v7;
      if ( v7 )
      {
        (*(void (**)(void))(*(_QWORD *)v7 + 152LL))();
        v9 = *(void (__fastcall **)(__int64, __int64))(*(_QWORD *)v4 + 1488LL);
        v10 = (*(__int64 (__fastcall **)(__int64))(*(_QWORD *)v8 + 208LL))(v8);
```

Function names are meaningless

Vtable function pointers are not recognized

Variables and arguments do not have any type information

Analyze Apple Drivers: Obstacles

- How does a driver's binary look like in IDA pro – iOS
  - **Messy! Nothing readable, not to mention further analysis**

```
__int64 __fastcall sub_FFFFFFF00615A498(_BYTE *a1)
{
  _BYTE *v1; // x19
  __int64 result; // x0

  v1 = a1;
  if ( a1[196] )
    return 0LL;
  if ( !(*(unsigned int (**)(void))(*(_QWORD *)a1 + 1672LL))() )
    return 3758097084LL;
  v1[196] = 1;
  if ( !*((_QWORD *)v1 + 14) )
    return 0LL;
  result = (*(__int64 (__fastcall **)(_BYTE *, _BYTE *))(*(_QWORD *)v1 + 1648LL))(v1, v1);
  if ( (_DWORD)result )
  {
    (*(void (__fastcall **)(_BYTE *))(*(_QWORD *)v1 + 1152LL))(v1);
    return 0LL;
  }
  return result;
}
```

No structures for classes

Class sizes are unknown

Member variables cannot be recognized by IDA pro

Analyze Apple Drivers: A New Tool

- Ryuk: a new tool to recover symbols and solve object-oriented features in macOS and iOS drivers
  - Ryuk: character in the comics series *Death Note*, who loves eating apples.
  - Implemented as IDA pro python script

Ryuk: Design

- Features of Ryuk:
  - Class recognition and construction
  - Vtable recognition and construction
  - Recover function names
  - Resolve variable and argument types
  - UI support
  - …

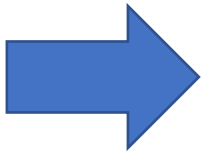
Ryuk: Effects

- Class Recognition and Construction

Size	Class Name
[00000090 BYTES. COLLAPSED STRUCT	IODMAEventSource. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000078 BYTES. COLLAPSED STRUCT	IOFilterInterruptEventSource. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000060 BYTES. COLLAPSED STRUCT	IOTimerEventSource. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000E8 BYTES. COLLAPSED STRUCT	IOBufferMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000078 BYTES. COLLAPSED STRUCT	IODMACommand. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000090 BYTES. COLLAPSED STRUCT	IOInterleavedMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000D0 BYTES. COLLAPSED STRUCT	IOMapper. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000030 BYTES. COLLAPSED STRUCT	IOMemoryCursor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000030 BYTES. COLLAPSED STRUCT	IONaturalMemoryCursor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000030 BYTES. COLLAPSED STRUCT	IOBigMemoryCursor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000030 BYTES. COLLAPSED STRUCT	IOLittleMemoryCursor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000060 BYTES. COLLAPSED STRUCT	IOMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000B0 BYTES. COLLAPSED STRUCT	IOGeneralMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000188 BYTES. COLLAPSED STRUCT	IOMemoryMap. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000070 BYTES. COLLAPSED STRUCT	IOMultiMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000030 BYTES. COLLAPSED STRUCT	IORangeAllocator. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000070 BYTES. COLLAPSED STRUCT	IOSubMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000E0 BYTES. COLLAPSED STRUCT	IOPlatformExpert. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000F0 BYTES. COLLAPSED STRUCT	IODTPlatformExpert. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000098 BYTES. COLLAPSED STRUCT	IOPlatformExpertDevice. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000090 BYTES. COLLAPSED STRUCT	IOPlatformDevice. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000E0 BYTES. COLLAPSED STRUCT	IOPanicPlatform. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000B8 BYTES. COLLAPSED STRUCT	IOCPU. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000B8 BYTES. COLLAPSED STRUCT	IOCPUInterruptController. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000118 BYTES. COLLAPSED STRUCT	IODTNVRAM. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000098 BYTES. COLLAPSED STRUCT	IODMAController. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000A0 BYTES. COLLAPSED STRUCT	IOInterruptController. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000C8 BYTES. COLLAPSED STRUCT	IOSharedInterruptController. PRESS CTRL-NUMPAD+ TO EXPAND]

- Vtable recognition and construction

```
FFFFFFF006F06178                DCB 0xA0
FFFFFFF006F06179                DCB 0xA1
FFFFFFF006F0617A                DCB 0x73 ; s
FFFFFFF006F0617B                DCB    7
FFFFFFF006F0617C                DCB 0xF0
FFFFFFF006F0617D                DCB 0xFF
FFFFFFF006F0617E                DCB 0xFF
FFFFFFF006F0617F                DCB 0xFF
FFFFFFF006F06180                DCB 0xF0
FFFFFFF006F06181                DCB 0xC0
FFFFFFF006F06182                DCB 0x6D ; m
FFFFFFF006F06183                DCB    7
FFFFFFF006F06184                DCB 0xF0
FFFFFFF006F06185                DCB 0xFF
FFFFFFF006F06186                DCB 0xFF
FFFFFFF006F06187                DCB 0xFF
FFFFFFF006F06188 unk_FFFFFFF006F06188 DCB    0
FFFFFFF006F06188
FFFFFFF006F06189                DCB    0
FFFFFFF006F0618A                DCB    0
FFFFFFF006F0618B                DCB    0
FFFFFFF006F0618C                DCB    0
FFFFFFF006F0618D                DCB    0
FFFFFFF006F0618E                DCB    0
FFFFFFF006F0618F                DCB    0
FFFFFFF006F06190                DCB    0
FFFFFFF006F06191                DCB    0
FFFFFFF006F06192                DCB    0
FFFFFFF006F06193                DCB    0
FFFFFFF006F06194                DCB    0
FFFFFFF006F06195                DCB    0
FFFFFFF006F06196                DCB    0
FFFFFFF006F06197                DCB    0
FFFFFFF006F06198                DCB 0x44 ; D
FFFFFFF006F06199                DCB 0xC3
FFFFFFF006F0619A                DCB 0x5E ; ^
FFFFFFF006F0619B                DCB    6
FFFFFFF006F0619C                DCB 0xF0
FFFFFFF006F0619D                DCB 0xFF
FFFFFFF006F0619E                DCB 0xFF
FFFFFFF006F0619F                DCB 0xFF
FFFFFFF006F061A0                DCB 0x48 ; H
FFFFFFF006F061A1                DCB 0xC3
FFFFFFF006F061A2                DCB 0x5E ; ^
FFFFFFF006F061A3                DCB    6
FFFFFFF006F061A4                DCB 0xF0
FFFFFFF006F061A5                DCB 0xFF
FFFFFFF006F061A6                DCB 0xFF
FFFFFFF006F061A7                DCB 0xFF
FFFFFFF006F061A8                DCB 0x44 ; D
FFFFFFF006F061A9                DCB 0x86
FFFFFFF006F061AA                DCB 0x4F ; O
FFFFFFF006F061AB                DCB    7
FFFFFFF006F061AC                DCB 0xF0
```



```
FFFFFFF006F06178 off_FFFFFFF006F06178 DCQ __ZN16IO80211Interface10gMetaClassE
FFFFFFF006F06178                                        ; DATA XREF: com.apple.plugin.IOgPTPPlugin:_
FFFFFFF006F06178                                        ; com.apple.driver.AppleBCMWLANCore:__got:of
FFFFFFF006F06178                                        ; IO80211Interface::gMetaClass
FFFFFFF006F06180                DCQ __ZN19IOEthernetInterface10gMetaClassE ; IOEthernetInterface::gM
FFFFFFF006F06188 ; `vtable for'IO80211Interface
FFFFFFF006F06188 __ZTV16IO80211Interface DCB    0      ; DATA XREF: sub_FFFFFFF0065F1D7C+28↑o
FFFFFFF006F06188                                        ; sub_FFFFFFF0065F1D7C+2C↑o ...
FFFFFFF006F06189                DCB    0
FFFFFFF006F0618A                DCB    0
FFFFFFF006F0618B                DCB    0
FFFFFFF006F0618C                DCB    0
FFFFFFF006F0618D                DCB    0
FFFFFFF006F0618E                DCB    0
FFFFFFF006F0618F                DCB    0
FFFFFFF006F06190                DCB    0
FFFFFFF006F06191                DCB    0
FFFFFFF006F06192                DCB    0
FFFFFFF006F06193                DCB    0
FFFFFFF006F06194                DCB    0
FFFFFFF006F06195                DCB    0
FFFFFFF006F06196                DCB    0
FFFFFFF006F06197                DCB    0
FFFFFFF006F06198 ; vtable_IO80211Interface vtableStart_IO80211Interface
FFFFFFF006F06198 vtableStart_IO80211Interface vtable_IO80211Interface <__ZN16IO80211InterfaceD1Ev, \
FFFFFFF006F06198                                        __ZN16IO80211InterfaceD0Ev, \
FFFFFFF006F06198                                        __ZNK8OSObject7releaseEi, \
FFFFFFF006F06198                                        __ZNK8OSObject14getRetainCountEv, \
FFFFFFF006F06198                                        __ZNK8OSObject6retainEv, \
FFFFFFF006F06198                                        __ZNK8OSObject7releaseEv, \
FFFFFFF006F06198                                        __ZNK8OSObject9serializeEP11OSSerialize, \
FFFFFFF006F06198                                        __ZNK16IO80211Interface12getMetaClassEv, \
FFFFFFF006F06198                                        __ZNK15OSMetaClassBase9isEqualToEPKS_, \
FFFFFFF006F06198                                        __ZNK8OSObject12taggedRetainEPKv, \
FFFFFFF006F06198                                        __ZNK8OSObject13taggedReleaseEPKv, \
FFFFFFF006F06198                                        __ZNK8OSObject13taggedReleaseEPKvi, \
FFFFFFF006F06198                                        __ZN8OSObject4initEv, \
FFFFFFF006F06198                                        __ZN16IO80211Interface4freeEv, \
```

Ryuk: Effects

- Vtable recognition and construction

```
[00000318 BYTES. COLLAPSED STRUCT vtable_IOSurface. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000118 BYTES. COLLAPSED STRUCT vtable_IOFence. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000120 BYTES. COLLAPSED STRUCT vtable_IOSurfaceClient. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000158 BYTES. COLLAPSED STRUCT vtable_IOSurfaceDeviceCache. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000890 BYTES. COLLAPSED STRUCT vtable_IOSurfaceRoot. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000968 BYTES. COLLAPSED STRUCT vtable_IOSurfaceRootUserClient. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000968 BYTES. COLLAPSED STRUCT vtable_IOSurfaceSendRight. PRESS CTRL-NUMPAD+ TO EXPAND]
```

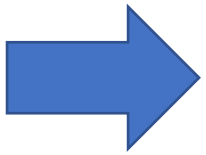
```
vtable_IOSurface struc ; (sizeof=0x318, mappedto_4
__ZN9IOSurfaceD1Ev dq ?                    ; XREF: IO
__ZN9IOSurfaceD0Ev dq ?                    ; XREF: IO
__ZNK8OSObject7releaseEi dq ?              ; 0xfbd0L
__ZNK8OSObject14getRetainCountEv dq ?      ; 0xfbc0L
__ZNK8OSObject6retainEv dq ?               ; 0xfbc8L
__ZNK8OSObject7releaseEv dq ?              ; 0xfbd8L
__ZNK8OSObject9serializeEP11OSSerialize dq ? ; 0xf
__ZNK9IOSurface12getMetaClassEv dq ?       ; 0x918L
__ZNK15OSMetaClassBase9isEqualToEPKS_ dq ? ; 0xfba
__ZNK8OSObject12taggedRetainEPKv dq ?      ; 0xfba8L
__ZNK8OSObject13taggedReleaseEPKv dq ?     ; 0xfbb0L
__ZNK8OSObject13taggedReleaseEPKvi dq ?    ; 0xfbb8L
__ZN15OSMetaClassBase25_RESERVEDOSMetaClassBase3Ev
__ZN15OSMetaClassBase25_RESERVEDOSMetaClassBase4Ev
__ZN15OSMetaClassBase25_RESERVEDOSMetaClassBase5Ev
__ZN15OSMetaClassBase25_RESERVEDOSMetaClassBase6Ev
__ZN15OSMetaClassBase25_RESERVEDOSMetaClassBase7Ev
__ZN8OSObject4initEv dq ?                  ; 0xf5d8L
__ZN9IOSurface4freeEv dq ?                 ; 0x1e48L
```

```
vtable_IOSurfaceRootUserClient struc ; (sizeof=0x968,
__ZN23IOSurfaceRootUserClientD1Ev dq ?     ; XREF: IOSurf
__ZN23IOSurfaceRootUserClientD0Ev dq ?     ; XREF: IOSurf
__ZNK8OSObject7releaseEi dq ?              ; 0xfbd0L
__ZNK8OSObject14getRetainCountEv dq ?      ; 0xfbc0L
__ZNK8OSObject6retainEv dq ?               ; 0xfbc8L
__ZNK8OSObject7releaseEv dq ?              ; 0xfbd8L
__ZNK8OSObject9serializeEP11OSSerialize dq ? ; 0xfbe0L
__ZNK23IOSurfaceRootUserClient12getMetaClassEv dq ? ;
__ZNK15OSMetaClassBase9isEqualToEPKS_ dq ? ; 0xfba0L
__ZNK8OSObject12taggedRetainEPKv dq ?      ; 0xfba8L
__ZNK8OSObject13taggedReleaseEPKv dq ?     ; 0xfbb0L
__ZNK8OSObject13taggedReleaseEPKvi dq ?    ; 0xfbb8L
__ZN15OSMetaClassBase25_RESERVEDOSMetaClassBase3Ev dq
__ZN15OSMetaClassBase25_RESERVEDOSMetaClassBase4Ev dq
__ZN15OSMetaClassBase25_RESERVEDOSMetaClassBase5Ev dq
__ZN15OSMetaClassBase25_RESERVEDOSMetaClassBase6Ev dq
__ZN15OSMetaClassBase25_RESERVEDOSMetaClassBase7Ev dq
__ZN12IOUserClient4initEv dq ?             ; 0xf2c8L
__ZN23IOSurfaceRootUserClient4freeEv dq ? ; 0x8180L
```

Ryuk: Effects

- Recover function names

sub_FFFFFFF00616803C	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168084	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061681C8	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168298	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061682DC	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168404	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168414	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168480	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061684EC	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168558	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061685C4	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168644	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061686F4	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168734	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF00616877C	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061687B4	com.apple.iokit.IOTimeSyncFamily:__text



- IOTimeSyncFilteredService::MetaClass::MetaClass(void)
- **OSMetaClass::~OSMetaClass()**
- IOTimeSyncFilteredService::IOTimeSyncFilteredService...
- IOTimeSyncFilteredService::IOTimeSyncFilteredService...
- j_IOService::~IOService()
- **IOTimeSyncFilteredService::~IOTimeSyncFilteredSe...**
- IOTimeSyncFilteredService::~IOTimeSyncFilteredServic...
- **IOTimeSyncFilteredService::getMetaClass(void)**
- IOTimeSyncFilteredService::MetaClass::MetaClass(void)
- **IOTimeSyncFilteredService::MetaClass::alloc(void)**
- IOTimeSyncFilteredService::IOTimeSyncFilteredService...
- IOTimeSyncFilteredService::IOTimeSyncFilteredService...
- **IOTimeSyncFilteredService::init(OSDictionary *)**
- **IOTimeSyncFilteredService::free(void)**
- **IOTimeSyncFilteredService::start(IOTimeSyncFilter...**
- **IOTimeSyncFilteredService::stop(IOTimeSyncFilter...**

Ryuk: Effects

- Recover function names, resolve variable and argument types, function pointer and member variable recognition

```
__int64 __fastcall sub_FFFFFFF006542814(_QWORD *a1, __int64 a2)
{
  __int64 v2; // x19
  _QWORD *v3; // x20
  __int64 result; // x0
  __int64 v5; // x21
  __int64 v6; // x8

  v2 = a2;
  v3 = a1;
  result = sub_FFFFFFF006544D0C(a2, qword_FFFFFFF006EED5E0);
  v3[27] = result;
  if ( result )
  {
    (*(void (**)(void))(*(_QWORD *)result + 32LL))();
    result = (*(__int64 (__fastcall **)(_QWORD *, __int64))(qword_FFFFFFF006EEC290 + 696))(v3, v2);
    if ( (_DWORD)result )
    {
      v5 = (*(__int64 (__fastcall **)(_QWORD *))(*v3 + 880LL))(v3);
      if ( v5
        && (v6 = sub_FFFFFFF00653ED58(v3), (v3[28] = v6) != 0LL)
        && !(*(unsigned int (__fastcall **)(__int64, __int64))(*(_QWORD *)v5 + 152LL))(v5, v6) )
      {
        result = 1LL;
      }
      else
      {
        (*(void (__fastcall **)(_QWORD *, __int64))(*v3 + 688LL))(v3, v2);
        result = 0LL;
      }
    }
  }
  return result;
}
```

```
void __cdecl IOAVControllerUserClient::start(IOAVControllerUserClient *this, IOAVController *provider)
{
  const void *v2; // x2
  IOAVControllerUserClient *v3; // x20
  IOAVController *v4; // x0
  unsigned __int64 v5; // x1
  IOWorkLoop *v6; // x21
  IOEventSource *v7; // x8

  v3 = this;
  v4 = (IOAVController *)OSMetaClassBase::safeMetaCast((OSMetaClassBase *)provider, off_FFFFFFF006EED5E0, v2);
  v3->member27 = (__int64)v4;
  if ( v4 )
  {
    v4->vtable->__ZNK8OSObject6retainEv((OSObject *)v4);
    if ( IOUserClient_vtableRef32->vtable.__ZN9IOService5startEPS_((IOService *)v3) )
    {
      v6 = v3->vtable->__ZNK9IOService11getWorkLoopEv((IOService *)v3);
      if ( !v6
        || (v7 = (IOEventSource *)sub_FFFFFFF00653ED58((OSObject *)v3, v5), (v3->member28 = (__int64)v7) == 0)
        || (unsigned int)v6->vtable->__ZN10IOWorkLoop14addEventSourceEP13IOEventSource(v6, v7) )
      {
        v3->vtable->__ZN24IOAVControllerUserClient4stopEPS_(v3);
      }
    }
  }
}
```

Ryuk: Effects

- UI support

```
__int64 __cdecl IOSurfaceRoot::newUserClient(IOSurfaceRoot *this, task *a2, void *a3, unsigned
{
  IOUserClient **v5; // r15@1
  task *v6; // rbx@1
  __int64 v7; // rsi@2
  IOSurface *v8; // r13@2
  signed int ret; // er14@2
  IOSurfaceSendRight *v10; // rax@3
  IOSurfaceSendRight *v11; // rbx@3
  IOSurfaceRootUserClient *v12; // rax@6
  IOSurfaceRootUserClient *v13; // r13@6

  v5 = a5;
  v6 = a2;
  *a5 = 0LL;
  if ( type )
  {
    v7 = type;
    v8 = (IOSurface *)this->vtable->__ZN13IOSurfaceRoot13LookupSurfaceEjP4task(this, type, v6);
    ret = -536870199;
```

Ryuk: Effects

- UI support

```
__int64 __cdecl IOSurfaceRoot::lookupSurface(IOSurfaceRoot *this, unsigned int a2, task *a3)
{
  task *v3; // r15@1
  IOSurfaceRootUserClient *v4; // rax@1
  IOSurfaceRootUserClient *v5; // r14@1
  __int64 v6; // rax@3
  __int64 v7; // r15@3

  v3 = a3;
  v4 = IOSurfaceRoot::userClientForTask(this, a3);
  v5 = v4;
  if ( v4 )
    IOLockLock(v4->mLock);
  IORecursiveLockLock(this->mRecursiveLock1);
  LODWORD(v6) = ((int (__fastcall *)(_QWORD, _QWORD, _QWORD, _QWORD))this->vtable->__ZN13IOSurf
                 this,
                 a2,
                 v3,
                 v5);
  v7 = v6;
  if ( v6 )
    (*(void (__fastcall **)(__int64))(*(_QWORD *)v6 + 32LL))(v6);
  IORecursiveLockUnlock(this->mRecursiveLock1);
  if ( v5 )
  {
    IOLockUnlock(v5->mLock);
    ((void (__fastcall *)(IOSurfaceRootUserClient *))v5->vtable->__ZNK8OSObject7releaseEv)(v5);
  }
  return v7;
}
```

Functions window

Function name

- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient__sMeth
- IOMobileFramebufferUserClient::stop(I
- IOMobileFramebufferUserClient::client
- sub_FFFFFFF00654B810
- IOMobileFramebufferUserClient__swap
- sub_FFFFFFF00654B87C

Line 31366 of 86627

IDA Vie... | Pseudocod... | Structu... | Names win... | Strings win... | Program Segmentat... | En... | Imp... | Exp...

```
1  __int64 __fastcall IOMobileFramebufferUserClient::sMethod56(IOMobileFramebufferUserClient *target, void *reference, IOExternalMethodArguments *arguments)
2  {
3    char *v3; // x8
4    uint64_t v4; // x1
5
6    if ( arguments->structureInputSize != 136 )
7      return 3758097090LL;
8    v3 = (char *)arguments->structureInput;
9    if ( *v3 )
10     v4 = 0LL;
11   else
12     v4 = (uint64_t)(v3 + 8);
13   return target->mProvider->vtable->IOMobileFramebuffer::virtualFunc251_ImpByChild(
14            target->mProvider,
15            v4,
16            *((unsigned int *)v3 + 32),
17            *((unsigned int *)v3 + 33));
18 }
```

010B350C IOMobileFramebufferUserClient::sMethod56:13 (FFFFFFF00654B50C)

Ryuk: Implementation

- 1. Class recognition and construction
  - Functions in __mod_init_func section register all classes

macOS

```
__mod_init_func:000000000000E090 ; Segment type: Pure data
__mod_init_func:000000000000E090 ; Segment alignment 'qword' can not be represented in assembly
__mod_init_func:000000000000E090 __mod_init_func segment para public 'DATA' use64
__mod_init_func:000000000000E090                 assume cs:__mod_init_func
__mod_init_func:000000000000E090                 ;org 0E090h
__mod_init_func:000000000000E090                 dq offset __GLOBAL__sub_I_IOSurface_cpp
__mod_init_func:000000000000E098                 dq offset __GLOBAL__sub_I_IOSurfaceClient_cpp
__mod_init_func:000000000000E0A0                 dq offset __GLOBAL__sub_I_IOSurfaceDeviceCache_cpp
__mod_init_func:000000000000E0A8                 dq offset __GLOBAL__sub_I_IOSurfaceRoot_cpp
__mod_init_func:000000000000E0B0                 dq offset __GLOBAL__sub_I_IOSurfaceRootUserClient_cpp
__mod_init_func:000000000000E0B8                 dq offset __GLOBAL__sub_I_IOSurfaceSendRight_cpp
__mod_init_func:000000000000E0B8 __mod_init_func ends
```

iOS

```
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED75D8 ; Segment type: Pure data
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED75D8                 AREA com.apple.iokit.IOSurface:__mod_init_func,
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED75D8                 ; ORG 0xFFFFFFF006ED75D8
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED75D8                 DCQ IOSurface_InitFunc_0
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED75E0                 DCQ IOSurface_InitFunc_1
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED75E8                 DCQ IOSurface_InitFunc_2
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED75F0                 DCQ IOSurface_InitFunc_3
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED75F8                 DCQ IOSurface_InitFunc_4
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED7600                 DCQ IOSurface_InitFunc_5
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED7608                 DCQ IOSurface_InitFunc_6
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED7610                 DCQ IOSurface_InitFunc_7
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED7618                 DCQ IOSurface_InitFunc_8
com.apple.iokit.IOSurface:__mod_init_func:FFFFFFF006ED7618 ; com.apple.iokit.IOSurface__mod_init_func ends
```

Ryuk: Implementation

- 1. Class recognition and construction
  - Functions in __mod_init_func section register all classes

macOS

```
                public __GLOBAL__sub_I_IOSurfaceRootUserClient_cpp
__GLOBAL__sub_I_IOSurfaceRootUserClient_cpp proc near
                                        ; DATA XREF: __mod_init_func:000000000000E0B0 o
                push    rbp
                mov     rbp, rsp
                lea     rdi, __ZN23IOSurfaceRootUserClient10gMetaClassE ; IOSurfaceRootUserClient::gMetaClass
                lea     rsi, aIosurfacerootu ; "IOSurfaceRootUserClient"
                mov     rdx, cs:__ZN12IOUserClient10gMetaClassE_0 ; IOUserClient::gMetaClass
                mov     ecx, 150h
                call    __ZN11OSMetaClassC2EPKcPKS_j ; OSMetaClass::OSMetaClass(char const*,OSMetaClass const*,uint)
                lea     rax, off_10110
                mov     cs:__ZN23IOSurfaceRootUserClient10gMetaClassE, rax ; IOSurfaceRootUserClient::gMetaClass
                pop     rbp
                retn
__GLOBAL__sub_I_IOSurfaceRootUserClient_cpp endp
```

iOS

```
                EXPORT IOSurface_InitFunc_6
IOSurface_InitFunc_6                    ; DATA XREF: com.apple.iokit.IOSurface:  mod init func

var_s0          = 0

                STP             X29, X30, [SP,#-0x10+var_s0]!
                MOV             X29, SP
                ADRP            X0, #qword_FFFFFFF0076EBC30@PAGE
                ADD             X0, X0, #qword_FFFFFFF0076EBC30@PAGEOFF
                ADRP            X1, #aIosurfacerootu@PAGE ; "IOSurfaceRootUserClient"
                ADD             X1, X1, #aIosurfacerootu@PAGEOFF ; "IOSurfaceRootUserClient"
                ADRP            X2, #qword_FFFFFFF006ED7350@PAGE
                LDR             X2, [X2,#qword_FFFFFFF006ED7350@PAGEOFF]
                MOV             W3, #0x150
                BL              sub_FFFFFFF0064CC910
                ADRP            X8, #unk_FFFFFFF006ED8F20@PAGE
                ADD             X8, X8, #unk_FFFFFFF006ED8F20@PAGEOFF
                ADD             X8, X8, #0x10
                STR             X8, [X0]
                LDP             X29, X30, [SP+var_s0],#0x10
                RET
```

Class Name

Class Size

Parent Class Info

Registration

*Note: multiple inheritance is excluded in libkern

Ryuk: Implementation

- 1. Class recognition and construction
  - Functions in __mod_init_func section register all classes

macOS

```
__int64 (__fastcall **_GLOBAL__sub_I_IOSurfaceRootUserClient_cpp())(IOSurfaceR
{
  __int64 (__fastcall **result)(IOSurfaceRootUserClient::MetaClass *__hidden);

  OSMetaClass::OSMetaClass(
    &IOSurfaceRootUserClient::gMetaClass,
    "IOSurfaceRootUserClient",
    IOUserClient::gMetaClass,
    336LL);
  result = off_10110;
  IOSurfaceRootUserClient::gMetaClass = off_10110;
  return result;
}
```

iOS

```
_QWORD *IOSurface_InitFunc_6()
{
  _QWORD *result; // x0

  result = (_QWORD *)sub_FFFFFFF0064CC910(&qword_FFFFFFF0076EBC30, aIosurfacerootu, qword_FFFFFFF006ED7350, 336LL);
  *result = &unk_FFFFFFF006ED8F30;
  return result;
}
```

Class Name

Class Size

Parent Class Info

*Note: multiple inheritance is excluded in libkern

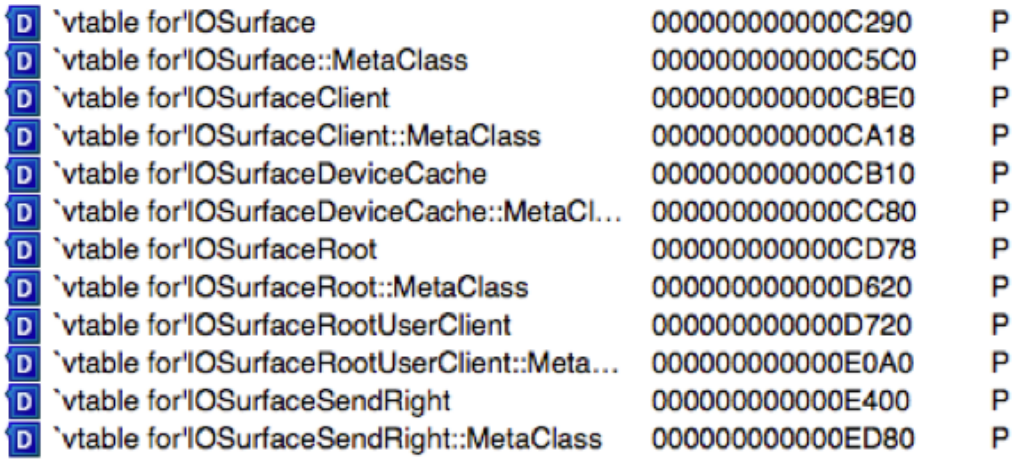
Ryuk: Implementation

- 1. Class recognition and construction: Effect
  - Structures representing classes are created

```
[00000090 BYTES. COLLAPSED STRUCT IODMAEventSource. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000078 BYTES. COLLAPSED STRUCT IOFilterInterruptEventSource. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000060 BYTES. COLLAPSED STRUCT IOTimerEventSource. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000E8 BYTES. COLLAPSED STRUCT IOBufferMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000078 BYTES. COLLAPSED STRUCT IODMACommand. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000090 BYTES. COLLAPSED STRUCT IOInterleavedMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000D0 BYTES. COLLAPSED STRUCT IOMapper. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000030 BYTES. COLLAPSED STRUCT IOMemoryCursor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000030 BYTES. COLLAPSED STRUCT IONaturalMemoryCursor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000030 BYTES. COLLAPSED STRUCT IOBigMemoryCursor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000030 BYTES. COLLAPSED STRUCT IOLittleMemoryCursor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000060 BYTES. COLLAPSED STRUCT IOMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000B0 BYTES. COLLAPSED STRUCT IOGeneralMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000188 BYTES. COLLAPSED STRUCT IOMemoryMap. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000070 BYTES. COLLAPSED STRUCT IOMultiMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000030 BYTES. COLLAPSED STRUCT IORangeAllocator. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000070 BYTES. COLLAPSED STRUCT IOSubMemoryDescriptor. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000E0 BYTES. COLLAPSED STRUCT IOPlatformExpert. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000F0 BYTES. COLLAPSED STRUCT IODTPlatformExpert. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000098 BYTES. COLLAPSED STRUCT IOPlatformExpertDevice. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000090 BYTES. COLLAPSED STRUCT IOPlatformDevice. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000E0 BYTES. COLLAPSED STRUCT IOPanicPlatform. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000B8 BYTES. COLLAPSED STRUCT IOCPU. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000B8 BYTES. COLLAPSED STRUCT IOCPUInterruptController. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000118 BYTES. COLLAPSED STRUCT IODTNVRAM. PRESS CTRL-NUMPAD+ TO EXPAND]
[00000098 BYTES. COLLAPSED STRUCT IODMAController. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000A0 BYTES. COLLAPSED STRUCT IOInterruptController. PRESS CTRL-NUMPAD+ TO EXPAND]
[000000C8 BYTES. COLLAPSED STRUCT IOSharedInterruptController. PRESS CTRL-NUMPAD+ TO EXPAND]
```

Ryuk: Implementation

- 2. Vtable recognition and construction
  - On macOS, vtables have symbols and known addresses, no need to find



Ryuk: Implementation

- 2. Vtable recognition and construction
  - On iOS, step 1: adjust the __const section
    - Vtables are in __const section, but IDA pro makes it disappear

```
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FC8                 DCB 0xF0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FC9                 DCB 0xC0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FCA                 DCB 0x6D
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FCB                 DCB   7
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FCC                 DCB 0xF0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FCD                 DCB 0xFF
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FCE                 DCB 0xFF
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FCF                 DCB 0xFF
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD0                 DCB 0xB8
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD1                 DCB 0xC2
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD2                 DCB 0x6D
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD3                 DCB   7
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD4                 DCB 0xF0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD5                 DCB 0xFF
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD6                 DCB 0xFF
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD7                 DCB 0xFF
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD8 unk_FFFFFFF006E04FD8 DCB
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD8
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD9                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FDA                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FDB                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FDC                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FDD                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FDE                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FDF                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE0                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE1                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE2                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE3                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE4                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE5                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE6                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE7                 DCB   0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE8                 DCB 0x18
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE9                 DCB 0x47
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FEA                 DCB 0x15
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FEB                 DCB   6
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FEC                 DCB 0xF0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FED                 DCB 0xFF
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FEE                 DCB 0xFF
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FEF                 DCB 0xFF
```

```
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FC8                 DCQ unk_FFFFFFF0076DC0F0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD0                 DCQ unk_FFFFFFF0076DC2B8
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD8 off_FFFFFFF006E04FD8 DCQ 0          ; DATA XREF: com.app
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FD8                                    ; com.apple.iokit.IO
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE0                 DCQ 0
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FE8                 DCQ sub_FFFFFFF006154718
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FF0                 DCQ sub_FFFFFFF00615471C
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E04FF8                 DCQ __ZNK8OSObject7releaseEi ; OSObject::rel
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05000                 DCQ __ZNK8OSObject14getRetainCountEv ; OSObj
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05008                 DCQ __ZNK8OSObject6retainEv ; OSObject::reta
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05010                 DCQ __ZNK8OSObject7releaseEv ; OSObject::rel
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05018                 DCQ __ZNK8OSObject9serializeEP11OSSerialize
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05020                 DCQ sub_FFFFFFF006154734
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05028                 DCQ __ZNK15OSMetaClassBase9isEqualToEPKS_ ;
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05030                 DCQ __ZNK8OSObject12taggedRetainEPKv ; OSObj
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05038                 DCQ __ZNK8OSObject13taggedReleaseEPKv ; OSOb
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05040                 DCQ __ZNK8OSObject13taggedReleaseEPKvi ; OSO
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05048                 DCQ __ZN8OSObject4initEv ; OSObject::init(vo
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05050                 DCQ sub_FFFFFFF006154E68
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05058                 DCQ __ZNK15IORegistryEntry12copyPropertyEPKc
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05060                 DCQ __ZNK15IORegistryEntry12copyPropertyEPK8
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05068                 DCQ __ZNK15IORegistryEntry12copyPropertyEPK8
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05070                 DCQ __ZNK15IORegistryEntry15copyParentEntryE
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05078                 DCQ __ZNK15IORegistryEntry14copyChildEntryEP
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05080                 DCQ __ZN15IORegistryEntry17runPropertyAction
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05088                 DCQ __ZN9IOService4initEP12OSDictionary ; IO
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05090                 DCQ __ZN15IORegistryEntry16setPropertyTableE
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E05098                 DCQ __ZN15IORegistryEntry11setPropertyEPK8OS
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E050A0                 DCQ __ZN15IORegistryEntry11setPropertyEPK8OS
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E050A8                 DCQ __ZN15IORegistryEntry11setPropertyEPKcP8
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E050B0                 DCQ __ZN15IORegistryEntry11setPropertyEPKcS1
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E050B8                 DCQ __ZN15IORegistryEntry11setPropertyEPKcb
com.apple.iokit.IONetworkingFamily:__const:FFFFFFF006E050C0                 DCQ __ZN15IORegistryEntry11setPropertyEPKcyj
```

Ryuk: Implementation

- 2. Vtable recognition and construction
  - On iOS, step 2: find address of class's metaclass object
    - Functions in __mod_init_func section are parsed again

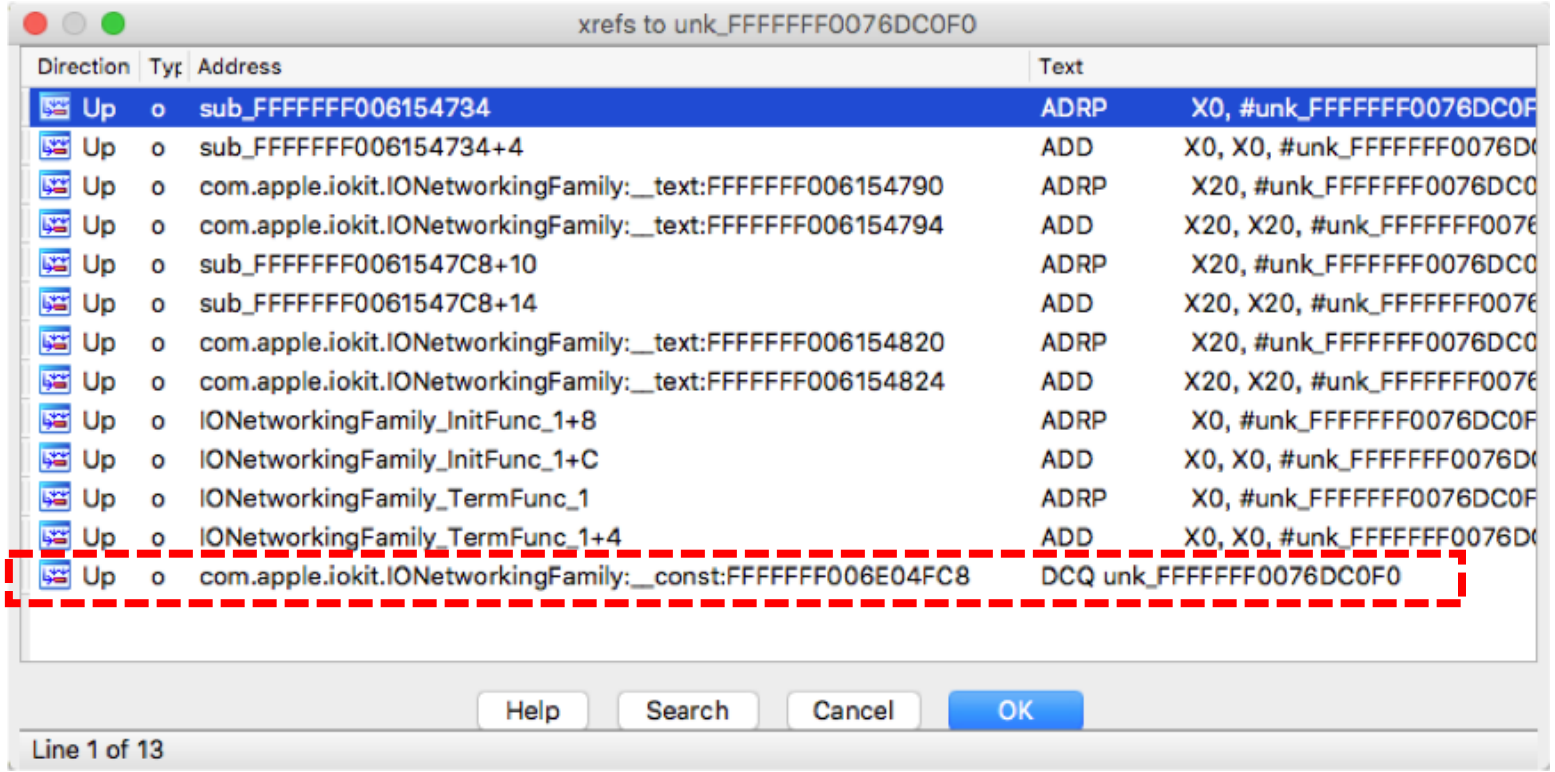
```
_QWORD *IONetworkingFamily_InitFunc_1()
{
  _QWORD *result; // x0

  result = (_QWORD *)sub_FFFFFFF006166E44(&unk_FFFFFFF0076DC0F0, aIoethernetinte, &unk_FFFFFFF0076DC2B8, 328LL);
  *result = &unk_FFFFFFF006E056E0;
  return result;
}
```

Addrss of class's metaclass object

```
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0F0 unk_FFFFFFF0076DC0F0 DCB     0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0F0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0F1                       DCB     0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0F2                       DCB     0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0F3                       DCB     0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0F4                       DCB     0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0F5                       DCB     0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0F6                       DCB     0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0F7                       DCB     0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0F8                       DCB     0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0F9                       DCB     0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0FA                       DCB     0
com.apple.iokit.IONetworkingFamily:__common:FFFFFFF0076DC0FB                       DCB     0
```

- 2. Vtable recognition and construction
  - On iOS, step 3: Get xrefs to metaclass object
    - The xref in const section nears the vtable



Ryuk: Implementation

- 2. Vtable recognition and construction
  - On iOS, step 3: Get xrefs to metaclass object
    - Data before vtables is in some specific format

Ryuk: Implementation

- 2. Vtable recognition and construction: Effects
  - Create structures representing vtables and set the first member of classes as an pointer to their vtable

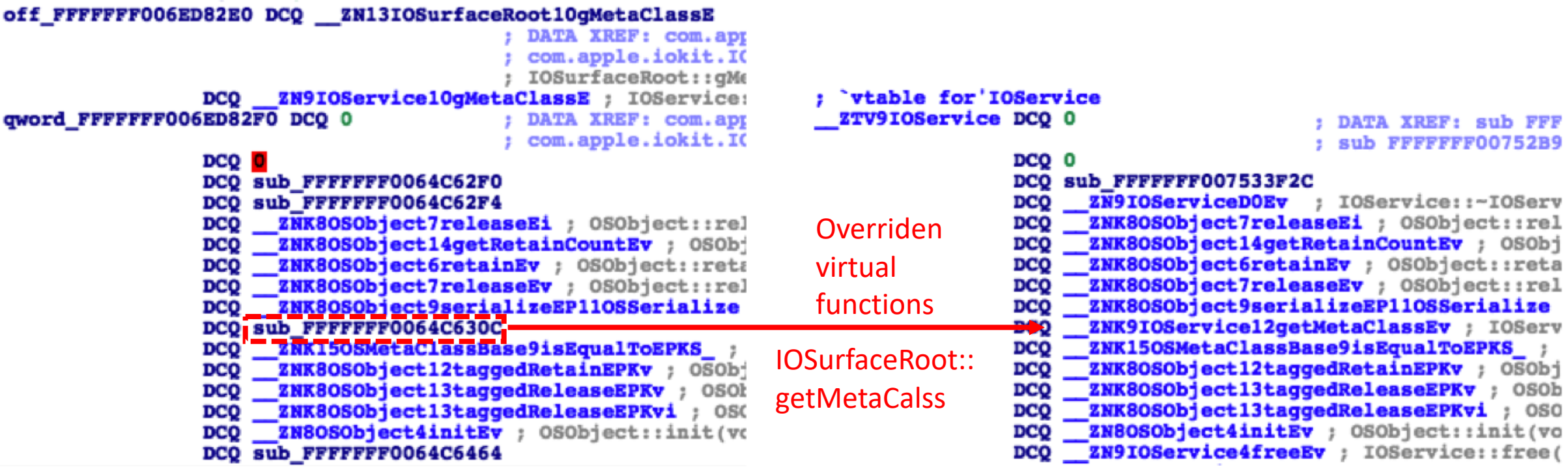
```
[000006E0 BYTES. COLLAPSED STRUCT vtable_IOEthernetInterface.

vtable_IOEthernetInterface struc ; (sizeof=0x6E0, mappedto_5666)
                                 ; XREF: whole_vtable_IOEthernet
                                 ; com.apple.iokit.IONetworking
__ZN19IOEthernetInterfaceD1Ev DCQ ?     ; 0xffffff006154718L
__ZN19IOEthernetInterfaceD0Ev DCQ ?     ; 0xffffff00615471cL
__ZNK8OSObject7releaseEi DCQ ?          ; 0xffffff0074f8644L
__ZNK8OSObject14getRetainCountEv DCQ ?  ; 0xffffff0074f8658L
__ZNK8OSObject6retainEv DCQ ?           ; 0xffffff0074f8660L
__ZNK8OSObject7releaseEv DCQ ?          ; 0xffffff0074f8670L
__ZNK8OSObject9serializeEP11OSSerialize DCQ ? ; 0xffffff0074f8680L
__ZNK19IOEthernetInterface12getMetaClassEv DCQ ? ; 0xffffff006154734L
__ZNK15OSMetaClassBase9isEqualToEPKS_ DCQ ? ; 0xffffff0074f63e0L
__ZNK8OSObject12taggedRetainEPKv DCQ ?  ; 0xffffff0074f8768L
__ZNK8OSObject13taggedReleaseEPKv DCQ ? ; 0xffffff0074f87fcL
__ZNK8OSObject13taggedReleaseEPKvi DCQ ? ; 0xffffff0074f880cL
__ZN8OSObject4initEv DCQ ?              ; 0xffffff0074f88f4L
__ZN19IOEthernetInterface4freeEv DCQ ?  ; 0xffffff006154e68L
__
```

```
IOEthernetInterface struc
vtable          DCQ ?
member1         DCQ ?
member2         DCQ ?
member3         DCQ ?
member4         DCQ ?
member5         DCQ ?
member6         DCQ ?
member7         DCQ ?
member8         DCQ ?
member9         DCQ ?
member10        DCQ ?
member11        DCQ ?
member12        DCQ ?
member13        DCQ ?
member14        DCQ ?
```

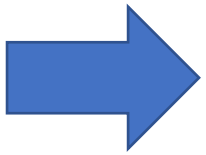
Ryuk: Implementation

- 3. Recover function names (virtual functions on iOS)
  - Most classes inherit from basic classes in iokit framework like IOService, OSObject, etc., which have meaningful function names
  - Replace the class name in the overriden virtual functions



- 3. Recover function names (virtual functions on iOS): Effects

sub_FFFFFFF00616803C	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168084	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061681C8	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168298	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061682DC	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168404	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168414	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168480	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061684EC	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168558	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061685C4	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168644	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061686F4	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF006168734	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF00616877C	com.apple.iokit.IOTimeSyncFamily:__text
sub_FFFFFFF0061687B4	com.apple.iokit.IOTimeSyncFamily:__text



- IOTimeSyncFilteredService::MetaClass::MetaClass(void)
- **OSMetaClass::~OSMetaClass()**
- IOTimeSyncFilteredService::IOTimeSyncFilteredService...
- IOTimeSyncFilteredService::IOTimeSyncFilteredService...
- j_IOService::~IOService()
- **IOTimeSyncFilteredService::~IOTimeSyncFilteredSe...**
- IOTimeSyncFilteredService::~IOTimeSyncFilteredServic...
- **IOTimeSyncFilteredService::getMetaClass(void)**
- IOTimeSyncFilteredService::MetaClass::MetaClass(void)
- **IOTimeSyncFilteredService::MetaClass::alloc(void)**
- IOTimeSyncFilteredService::IOTimeSyncFilteredService...
- IOTimeSyncFilteredService::IOTimeSyncFilteredService...
- **IOTimeSyncFilteredService::init(OSDictionary *)**
- **IOTimeSyncFilteredService::free(void)**
- **IOTimeSyncFilteredService::start(IOTimeSyncFilter...**
- **IOTimeSyncFilteredService::stop(IOTimeSyncFilter...**

- 4. Resolve variable and argument types
  - Step 1: Figure out the creation of variables

Allocation
```
OSMetaClass::allocClassWithName("IOSurface", (const char *)task);
```

Allocation
```
__ZNK23IOSurfaceRootUserClient9MetaClass5allocEv(off_FFFFFFF006ED8928);
```

Constructor
```
IOCommandGate::IOCommandGate(v3);
```

Cast
```
OSMetaClassBase::safeMetaCast(v5, (const OSMetaClassBase *)IOSurfaceRootUserClient::metaClass, v6);
```

Ryuk: Implementation

- 4. Resolve variable and argument types
  - Step 2: Variable types are decided

```
void __cdecl IOAVControllerUserClient::start(IOAVControllerUserClient *this, IOAVController *provider)
{
  const void *v2; // x2
  IOAVControllerUserClient *v3; // x20
  IOAVController *v4; // x0
  unsigned __int64 v5; // x1
  IOWorkLoop *v6; // x21
  IOEventSource *v7; // x8

  v3 = this;
  v4 = (IOAVController *)OSMetaClassBase::safeMetaCast((OSMetaClassBase *)provider, off_FFFFFFF006EED5E0, v2);
  v3->member27 = (__int64)v4;
  if ( v4 )
  {
    v4->vtable->__ZNK8OSObject6retainEv((OSObject *)v4);
    if ( IOUserClient_vtableRef32->vtable.__ZN9IOService5startEPS_((IOService *)v3) )
    {
      v6 = v3->vtable->__ZNK9IOService11getWorkLoopEv((IOService *)v3);
      if ( !v6
        || (v7 = (IOEventSource *)sub_FFFFFFF00653ED58((OSObject *)v3, v5), (v3->member28 = (__int64)v7) == 0)
        || (unsigned int)v6->vtable->__ZN10IOWorkLoop14addEventSourceEP13IOEventSource(v6, v7) )
      {
        v3->vtable->__ZN24IOAVControllerUserClient4stopEPS_(v3);
      }
    }
  }
}
```

Ryuk: Implementation

- 5. UI support
- Purposes:
  - Jump to virtual function's (or children's) implementation when double-click on function pointers
  - Keep the name and type consistency between function pointer and their implementation
- Implementation:
  - Register action to double-click events
  - Register action to key events
  - Register action to name change events
  - Register action to type change events

Ryuk: Benefits

- For manual review:
  - Function names are meaningful
  - Function pointers are recognized
  - Member variable are recognized
  - Variable types are known
  - You can jump to virtual function’s implementation from their pointers with just a double-click
- For static analysis:
  - Variable types are resolved
  - Call targets of function pointers are known
  - Further CFG can be easily constructed

Conclusions

- Explanation and illustration of 2 new CVEs in macOS drivers
- Illustration of whole exploit chain of privilege escalation on macOS
- Innovative exploitation techniques on latest macOS
- Ryuk: a new tool for assisting the analysis of macOS and iOS drivers

- Most important!
  - Ryuk: https://github.com/bxl1989/Ryuk

Thanks