Eternal War in XNU Kernel Objects

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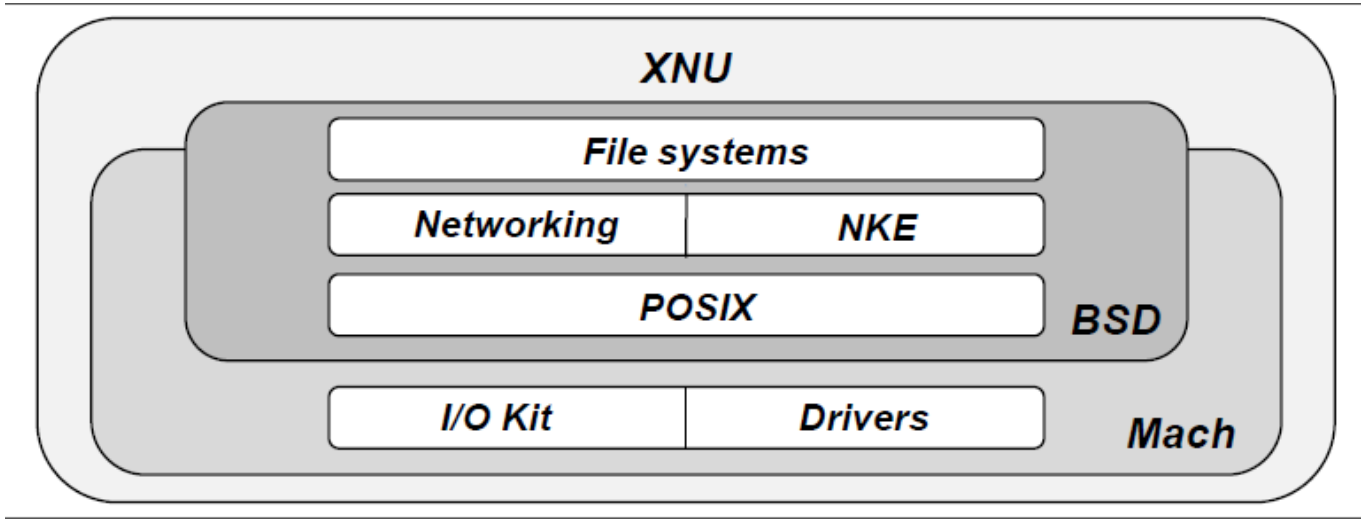
Apple Devices & Jailbreaking

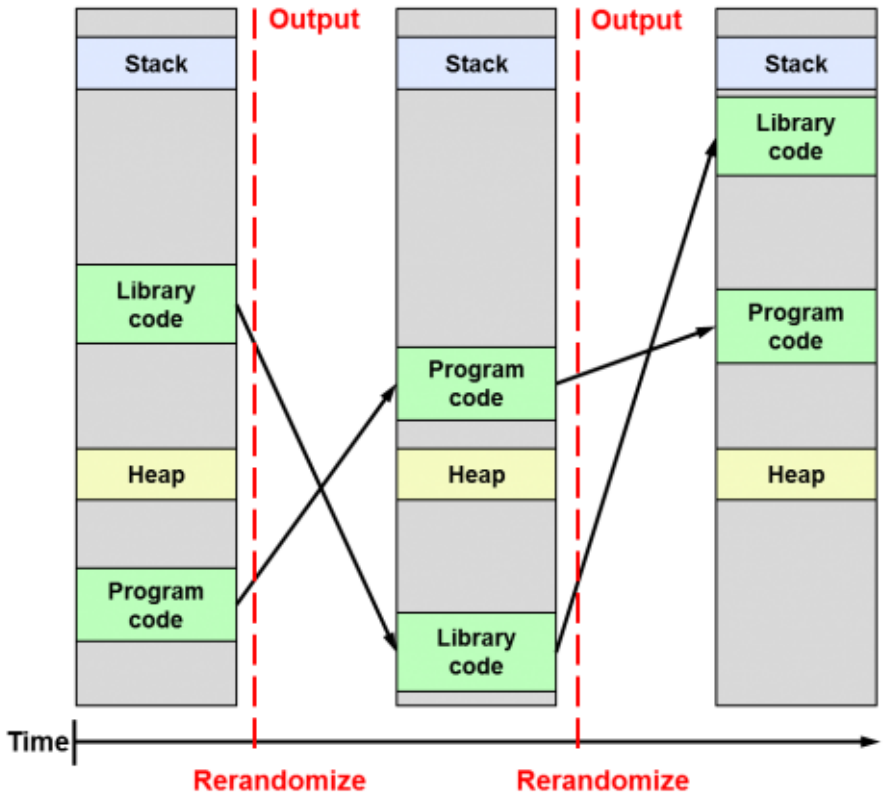
- **Jailbreaking** in general means breaking the device out of its "jail".
- Apple devices (e.g., iPhone, iPad) are most famous "**jail**" devices among the world.
- iOS, macOS, watchOS, and tvOS are **operating systems** developed by Apple Inc and used in Apple devices.

XNU



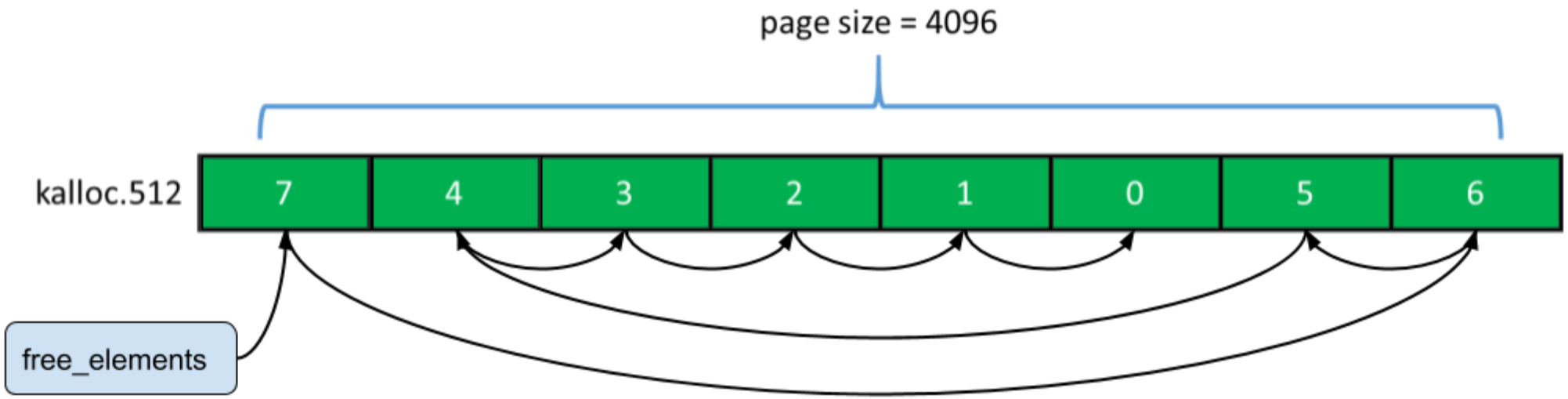
- All systems deploy a same hybrid kernel structure called **XNU**.
- There are cases that **kernel vulnerabilities** have been used to escalate the privileges of attackers and get full control of the system (hence jailbreak the device).
- Accordingly, Apple has deployed multiple **security mechanisms** that make the exploitation of the device harder.

Mitigation - DEP/KASLR



- Apple deployed Data Execution Prevention (**DEP**) and Kernel Address Space Layout Randomization (**KASLR**) from iOS 6 and macOS 10.8.
- **DEP** enables the system to mark relevant pages of memory as non-executable to prevent code injection attack. To break the DEP protection, code-reuse attacks (e.g., ROP) were proposed.
- To make these addresses hard to predict, **KASLR** memory protection randomizes the locations of various memory segments. To bypass KASLR, attackers usually need to leverage information leakage bugs.

Mitigation – Zone Elements Randomization



- In previous XNU, the elements inside a zone are allocated in **linear** order.
- To make the adjacent object hard to predict, Apple deployed a mitigation called **random_free_to_zone** in iOS 9.2. The XNU will randomly choose the **first** or **last** position in a zone and add it into the free_elements list.

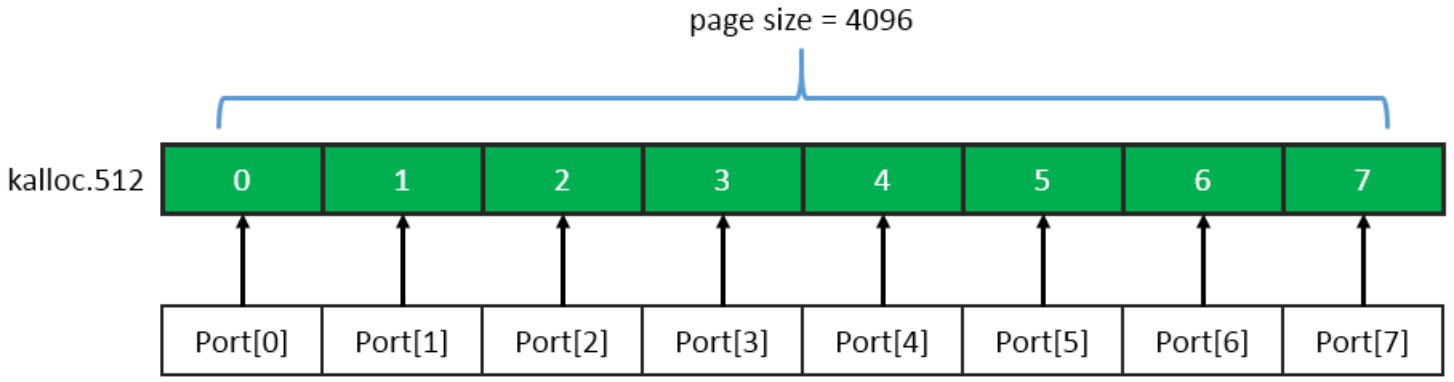
Mitigation – Zone Elements Randomization

random_free_to_zone() in XNU (added in iOS 9.2):

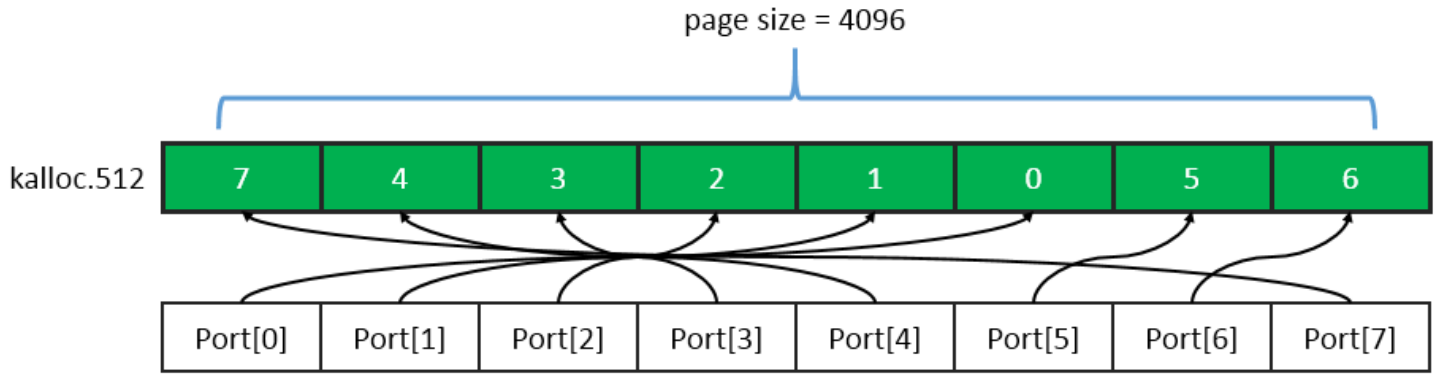
```
2548  static void
2549  random_free_to_zone(
2550              zone_t      zone,
2551              vm_offset_t     newmem,
2552              vm_offset_t     first_element_offset,
2553              int         element_count,
2554              unsigned int    *entropy_buffer)
2555  {
2556  ...
2557
2558      assert(element_count  <= ZONE_CHUNK_MAXELEMENTS);
2559      elem_size = zone->elem_size;
2560      last_element_offset = first_element_offset + ((element_count * elem_size) - elem_size);
2561      for (index = 0; index < element_count; index++) {
2562          assert(first_element_offset <= last_element_offset);
2563          if (
2564              random_bool_gen_bits(&zone_bool_gen, entropy_buffer, MAX_ENTROPY_PER_ZCRAM, 1)) {
2565              element_addr = newmem + first_element_offset;
2566              first_element_offset += elem_size;
2567          } else {
2568              element_addr = newmem + last_element_offset;
2569              last_element_offset -= elem_size;
2570          }
2571          if (element_addr != (vm_offset_t)zone) {
2572              zone->count++;  /* compensate for free_to_zone */
2573              free_to_zone(zone, element_addr, FALSE);
2574          }
2575          zone->cur_size += elem_size;
```

Mitigation – Zone Elements Randomization

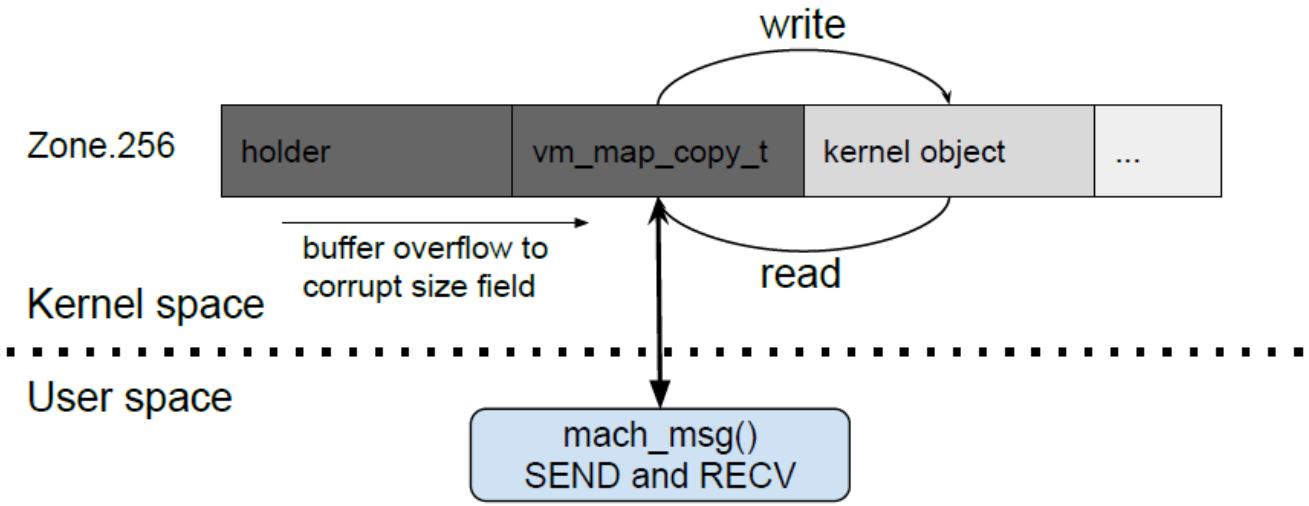
- **Before** random_free_to_zone mitigation:



- **After** random_free_to_zone mitigation:



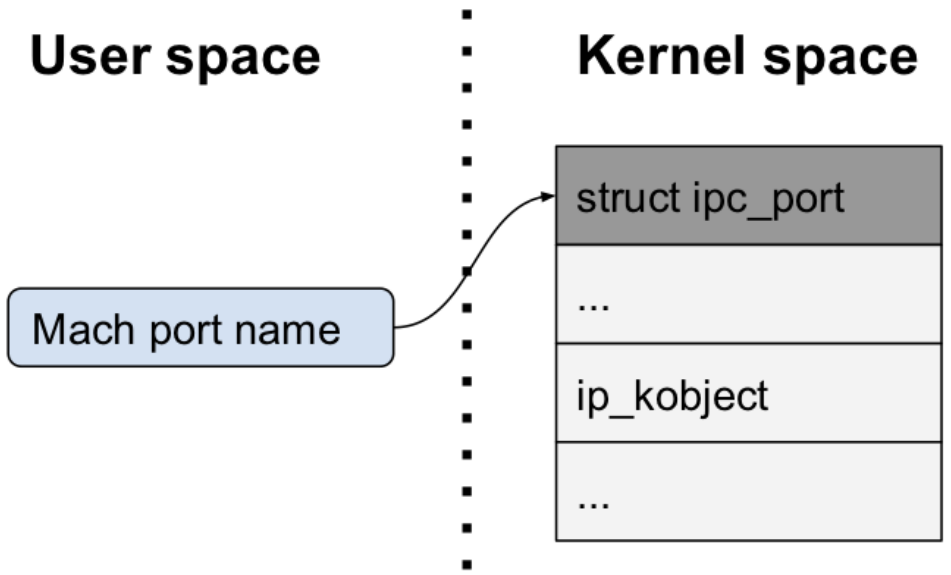
Mitigation - Wrong Zone Free Protection



- An attacker can use a memory corruption vulnerability to change the size value of a kernel object to a **wrong** size (e.g., 512) and receive (free) the object. After that, the attacker can allocate a new kernel object with the changed size (e.g., 512) into the original kalloc.256 zone.

- To mitigate this attack, Apple added a new **zone_metadata_region** structure for each zone in iOS 10.

New Target - Mach Port in User Space



- A Mach port in XNU is a kernel controlled **communication channel**. It provides basic operations to pass messages between threads.
- **Ports** are used to represent resources, services, and facilities (e.g., hosts, tasks, threads, memory objects, and clocks) thus providing **object-style** access to these abstractions.
- In user space, Mach ports are **integer numbers** like handlers for kernel objects.

New Target – Struct ipc_port in Kernel Space

struct ipc_port	
io_bits	io_references
io_lock_data	
...	
struct ipc_space *receiver;	
ipc_kobject_t ip_kobject;	
...	
mach_vm_address_t ip_context;	
...	

- In the kernel, a Mach port is represented by a pointer to an **ipc_port** structure.
- There are **40** types of ipc_port objects in XNU and **io_bits** field defines the type of it. io_references field counts the reference number of the object. Locking related data is stored in the io_lock_data field.
- Receiver field is a pointer that points to receiver’ s **IPC** space (e.g. ipc_space_kernel). **ip_kobject** field points to a kernel data structure according to the kernel object type.

(Mach) Port-oriented Programming (POP)

- The main goal is to obtain multiple **primitives** to read/write kernel memory and execute arbitrary kernel code, even in the case that multiple **mitigations** are deployed in the system.

(MACH) PORT-ORIENTED PROGRAMMING

- Attackers leverage a special kernel object, i.e., ipc_port, to obtain multiple primitives, including kernel read/write and arbitrary code execution, by issuing system calls in user mode. Since the proposed method is mainly based on the ipc_port kernel object, we call it **(Mach) Port-oriented Programming (POP)**.

- Note that POP technology was **not created** by **us**. We saw it in many **public** exploits and then **summarize** this code reuse attack technique for systematic study.

MIG in Source Code

```
const struct mig_subsystem *mig_e[] = {
        (const struct mig_subsystem *)&mach_vm_subsystem,
        (const struct mig_subsystem *)&mach_port_subsystem,
        (const struct mig_subsystem *)&mach_host_subsystem,
        (const struct mig_subsystem *)&host_priv_subsystem,
        (const struct mig_subsystem *)&host_security_subsystem,
        (const struct mig_subsystem *)&clock_subsystem,
        (const struct mig_subsystem *)&clock_priv_subsystem,
        (const struct mig_subsystem *)&processor_subsystem,
        (const struct mig_subsystem *)&processor_set_subsystem,
        (const struct mig_subsystem *)&is_iokit_subsystem,
    (const struct mig_subsystem *)&lock_set_subsystem,
    (const struct mig_subsystem *)&task_subsystem,
    (const struct mig_subsystem *)&thread_act_subsystem,
#ifdef VM32_SUPPORT
    (const struct mig_subsystem *)&vm32_map_subsystem,
#endif
    (const struct mig_subsystem *)&UNDReply_subsystem,
    (const struct mig_subsystem *)&mach_voucher_subsystem,
    (const struct mig_subsystem *)&mach_voucher_attr_control_subsystem,

#if     XK_PROXY
        (const struct mig_subsystem *)&do_uproxy_xk_uproxy_subsystem,
#endif /* XK_PROXY */
#if     MACH_MACHINE_ROUTINES
        (const struct mig_subsystem *)&MACHINE_SUBSYSTEM,
#endif  /* MACH_MACHINE_ROUTINES */
#if     MCMSG && iPSC860
    (const struct mig_subsystem *)&mcmsg_info_subsystem,
#endif  /* MCMSG && iPSC860 */
};
```

xnu-3248.60.10 〉 osfmk 〉 mach 〉 mach_host.defs 〉 No Selection

```
225  *  Return statistics from this host.
226  */
227 routine host_statistics(
228         host_priv    : host_t;
229         flavor       : host_flavor_t;
230     out host_info_out    : host_info_t, CountInOut);
231
232 routine host_request_notification(
233         host         : host_t;
234         notify_type  : host_flavor_t;
235         notify_port  : mach_port_make_send_once_t);
```

xnu-3248.60.10 〉 osfmk 〉 kern 〉 host.c 〉 host_statistics

```
299 kern_return_t
300 host_statistics(host_t host, host_flavor_t flavor,
        host_info_t info, mach_msg_type_number_t * count)
301 {
302     uint32_t i;
303
304     if (host == HOST_NULL)
305         return (KERN_INVALID_HOST);
306
307     switch (flavor) {
308     case HOST_LOAD_INFO: {
309         host_load_info_t load_info;
310
311         if (*count < HOST_LOAD_INFO_COUNT)
312             return (KERN_FAILURE);
```

MIG in Kernel Cache

```
__constdata:FFFFFF8000C5FD00                public _host_priv_subsystem
__constdata:FFFFFF8000C5FD00 _host_priv_subsystem dq offset _host_priv_server_routine
__constdata:FFFFFF8000C5FD00                                        ; DATA XREF:  host priv
__constdata:FFFFFF8000C5FD00                                        ;  host priv server+44↑o
__constdata:FFFFFF8000C5FD08                db  90h
__constdata:FFFFFF8000C5FD09                db    1
__constdata:FFFFFF8000C5FD0A                db    0
__constdata:FFFFFF8000C5FD0B                db    0
__constdata:FFFFFF8000C5FD0C                db 0AAh
__constdata:FFFFFF8000C5FD0D                db    1
__constdata:FFFFFF8000C5FD0E                db    0
__constdata:FFFFFF8000C5FD0F                db    0
__constdata:FFFFFF8000C5FD10                db  34h ; 4
__constdata:FFFFFF8000C5FD11                db  10h
__constdata:FFFFFF8000C5FD12                db    0
__constdata:FFFFFF8000C5FD13                db    0
__constdata:FFFFFF8000C5FD14                db    0
__constdata:FFFFFF8000C5FD15                db    0
__constdata:FFFFFF8000C5FD16                db    0
__constdata:FFFFFF8000C5FD17                db    0
__constdata:FFFFFF8000C5FD18                db    0
__constdata:FFFFFF8000C5FD19                db    0
__constdata:FFFFFF8000C5FD1A                db    0
__constdata:FFFFFF8000C5FD1B                db    0
__constdata:FFFFFF8000C5FD1C                db    0
__constdata:FFFFFF8000C5FD1D                db    0
__constdata:FFFFFF8000C5FD1E                db    0
__constdata:FFFFFF8000C5FD1F                db    0
__constdata:FFFFFF8000C5FD20                db    0
__constdata:FFFFFF8000C5FD21                db    0
__constdata:FFFFFF8000C5FD22                db    0
__constdata:FFFFFF8000C5FD23                db    0
__constdata:FFFFFF8000C5FD24                db    0
__constdata:FFFFFF8000C5FD25                db    0
__constdata:FFFFFF8000C5FD26                db    0
__constdata:FFFFFF8000C5FD27                db    0
__constdata:FFFFFF8000C5FD28                dq offset sub_FFFFFF80002C0DA0
__constdata:FFFFFF8000C5FD30                db    2
```

```
1  __int64 __fastcall host_priv_server_routine(__int64 a1)
2  {
3    signed __int64 v1; // rcx
4    __int64 result; // rax
5    signed __int64 v3; // rcx
6
7    v1 = *(signed int *)(a1 + 28);
8    result = 0LL;
9    if ( v1 >= 400 )
10   {
11     v3 = v1 - 400;
12     if ( (signed int)v3 <= 25 )
13       result = (__int64)*(&host_priv_subsystem + 5 * v3 + 5);
14   }
15   return result;
16 }
```

```
1  char __fastcall sub_FFFFFF80002C0FC0(mach_msg_header_t *a1, mach_msg_header_t *a2)
2  {
3    mach_msg_id_t v2; // ecx
4    host_t v3; // eax
5    mach_msg_size_t v4; // eax
6    mach_msg_size_t v5; // eax
7    unsigned __int64 v6; // rax
8    __int64 *v7; // rax
9    unsigned __int64 v8; // rax
10   __int64 *v9; // rax
11
12   if ( kdebug_enable & 1 )
13   {
14     v8 = __readgsqword(8u);
15     if ( v8 )
16       v9 = *(__int64 **)(v8 + 976);
17     else
18       v9 = 0LL;
19     sub_FFFFFF80006DFDC0(0LL, 0xFF000649, 0LL, 0LL, 0LL, 0LL, v9);
20     if ( (a1->msgh_bits & 0x80000000) != 0 )
21       goto LABEL_15;
22   }
23   else if ( (a1->msgh_bits & 0x80000000) != 0 )
24   {
25 LABEL_15:
26     a2[1].msgh_reserved = -304;
27     goto LABEL_16;
28   }
29   if ( a1->msgh_size != 48 )
30     goto LABEL_15;
31   a2[1].msgh_id = 68;
32   v2 = 68;
33   if ( a1[1].msgh_id < 0x44u )
34     v2 = a1[1].msgh_id;
35   a2[1].msgh_id = v2;
36   v3 = convert_port_to_host_priv(*(_QWORD *)&a1->msgh_remote_port);
37   v4 = host_statistics(v3, a1[1].msgh_reserved, (host_info_t)&a2[2], (mach_msg_type_number_t *)&a2[1].msgh_id);
38   a2[1].msgh_reserved = v4;
39   if ( v4 )
40   {
41     a2[1].msgh_reserved = v4;
42 LABEL_16:
43     LOBYTE(v5) = NDR_record.mig_vers;
44     *(NDR_record_t *)&a2[1].msgh_remote_port = NDR_record;
45     return v5;
46   }
47   *(NDR_record_t *)&a2[1].msgh_remote_port = NDR_record;
48   v5 = 4 * a2[1].msgh_id + 48;
49   a2->msgh_size = v5;
50   if ( kdebug_enable & 1 )
51   {
52     v6 = __readgsqword(8u);
53     if ( v6 )
54       v7 = *(__int64 **)(v6 + 976);
55     else
56       v7 = 0LL;
57     LOBYTE(v5) = sub_FFFFFF80006DFDC0(0LL, 0xFF00064A, 0LL, 0LL, 0LL, 0LL, v7);
58   }
59   return v5;
60 }
```

General Purpose Primitives

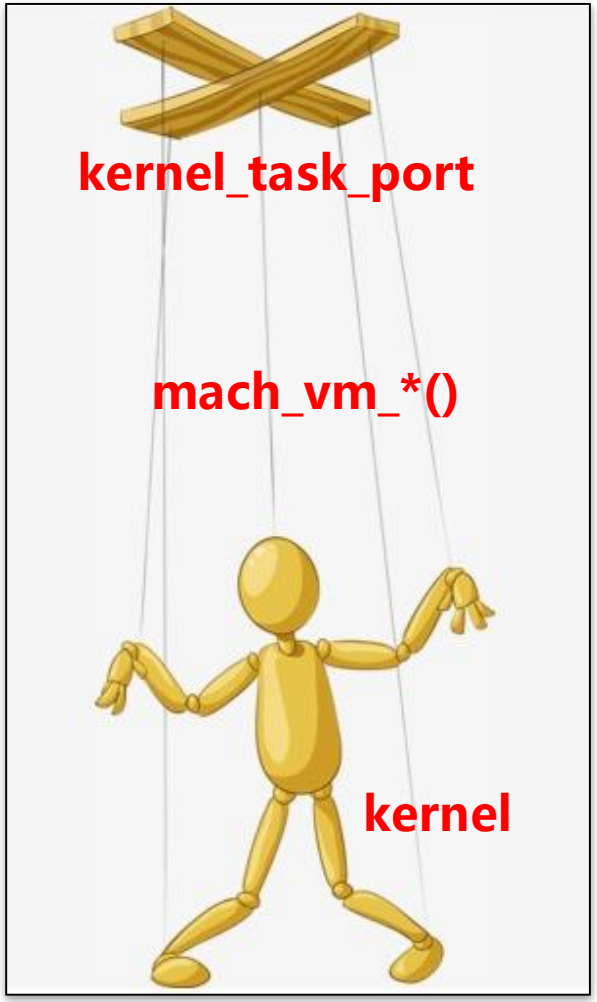
Category	Syscall number	Object types
RAW_PORT	36	IKOT_NONE
HOST	52	IKOT_HOST, IKOT_HOST_PRIV, IKOT_HOST_NOTIFY, IKOT_HOST_SEC
PROCESSOR	16	IKOT_PROCESSOR, IKOT_PSET, IKOT_PSET_NAME
TASK	163	IKOT_TASK, IKOT_TASK_NAME, IKOT_TASK_RESUME, IKOT_MEM_OBJ, IKOT_UPL, IKOT_MEM_OBJ_CONTROL, IKOT_NAMED_ENTRY
THREAD	28	IKOT_THREAD
DEVICE	86	IKOT_MASTER_DEVICE, IKOT_IOKIT_SPARE, IKOT_IOKIT_CONNECT
SYNC	29	IKOT_SEMAPHORE, IKOT_LOCK_SET
MACH_VOUCHER	7	IKOT_VOUCHER, IKOT_VOUCHER_ATTR_CONTROL
TIME	10	IKOT_TIMER, IKOT_CLOCK, IKOT_CLOCK_CTRL
MISC	18	IKOT_PAGING_REQUEST, IKOT_MIG, IKOT_XMM_PAGER, IKOT_XMM_KERNEL, IKOT_XMM_REPLY,IKOT_UND_REPLY,IKOT_LEDGER, IKOT_SUBSYSTEM, IKOT_IO_DONE_QUEUE, IKOT_AU_SESSIONPORT, IKOT_FILEPORT
Sum	445	

- The Mach subsystem receives incoming **Mach messages** and processes them by performing the requested **operations** to multiple **resources** such as processors, tasks and threads. This approach allows attackers to achieve general and useful **primitives** through Mach messages **without** hijacking the control flow.

General Purpose Primitives for Host

- Mach represents the overall computer system as a **host** object.
- Through **host_*()** system calls, a userspace app can retrieve information (e.g., host_info()) or set properties (e.g.,host_set_multiuser_config_flags()) for a host.
- Moreover, with a send right to **host_priv** port (like **root** user) and related system calls like host_processor_set_priv(), an attacker can gain send rights to other **powerful ports** (e.g.,processor_set port).

General Purpose Primitives for VM



Virtual memory management:

- XNU provides a powerful set of routines, **mach_vm_*()** system calls, to userspace apps for manipulating task **memory** spaces.
- With an information leak vulnerability or an arbitrary kernel memory read primitive, the attacker could retrieve other tasks' map pointers and craft **fake** tasks to manage other processes' memory space (especially for **kernel**'s memory space).

Querying Primitives

```
kern_return_t
mach_port_kobject(
      ipc_space_t                space,
      mach_port_name_t           name,
      natural_t                  *typep,
      mach_vm_address_t          *addrp)
{
 ...

   *typep = (unsigned int) ip_kotype(port);
   *addrp =  VM_KERNEL_ADDRPERM\
             (VM_KERNEL_UNSLIDE(kaddr));
   ip_unlock(port);
   return KERN_SUCCESS;
}
```

- Querying primitives have a characteristic that the **return value** of the system call could be used to **leak** kernel information, e.g., speculating executed code paths.
- For example, mach_port_kobject() is a system call retrieve the type and **address** of the kernel object.
- Both Pangu and TaiG's jailbreaks used it to break KASLR in iOS 7.1 - 8.4, until Apple **removed** the address querying code in the release version (*addrp = 0;).

Querying Primitives

```
kern_return_t clock_sleep_trap(
struct clock_sleep_trap_args *args)
{
mach_port_name_t clock_name = args->clock_name;
...
if (clock_name == MACH_PORT_NULL)
        clock = &clock_list[SYSTEM_CLOCK];
else
        clock = port_name_to_clock(clock_name);
...
if (clock != &clock_list[SYSTEM_CLOCK])
        return (KERN_FAILURE);
...
return KERN_SUCCESS;
}
```

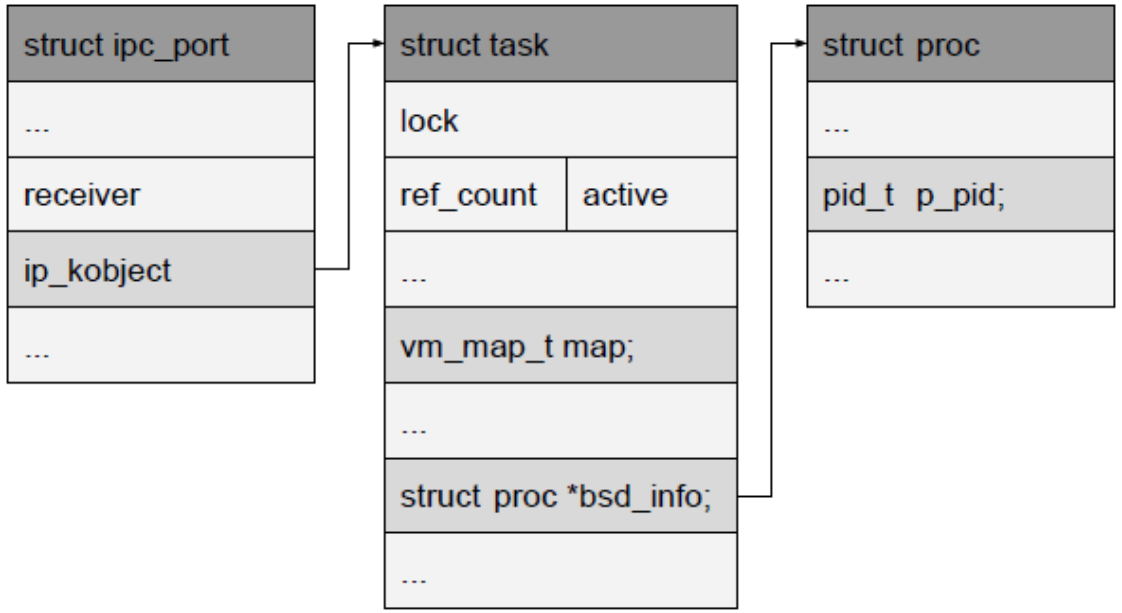
- clock_sleep_trap() is a system call expecting its first argument (if not NULL) to be a send right to the **global** system clock, and it will return **KERN_SUCCESS** if the port name is correct.
- If the attacker can manipulate an ipc_port kernel object and **change** its **ip_kobject** field, a side channel attack could be launched to break KASLR.

Memory Interoperation Primitives

```
kern_return_t pid_for_task(
struct pid_for_task_args *args)
{
mach_port_name_t            t = args->t;
user_addr_t                 pid_addr  = args->pid;
...
t1 = port_name_to_task_inspect(t);
...
p = get_bsdtask_info(t1);
if (p) {
        pid  = proc_pid(p);
        err = KERN_SUCCESS;
}
copyout(&pid, pid_addr, sizeof(int));
...
}
```

- By using **type confusion** attack, we can leverage some system calls to copy sensitive data between kernel space and user space. Specifically, some memory interoperation primitives are not used for the **original intention** of the design.
- **pid_for_task()** is such a system call which returns the **PID** number corresponding to a particular Mach **task**.

Memory Interoperation Primitives

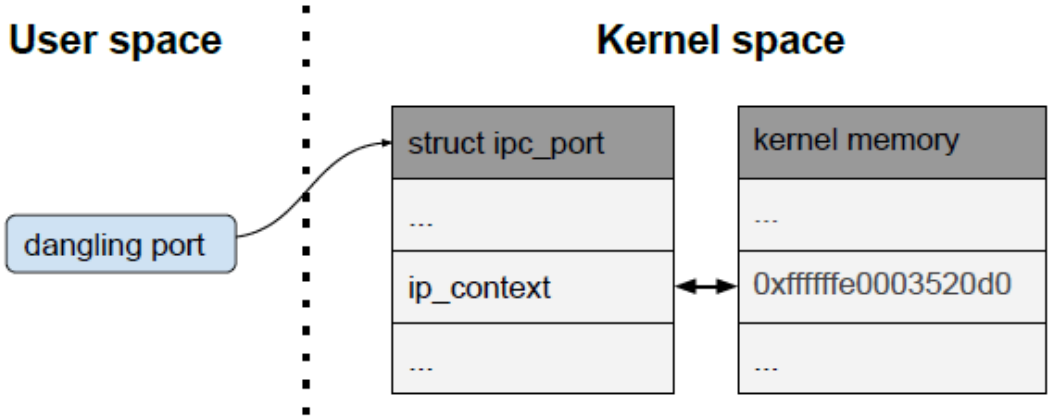


- The function calls port_name_to_task() to get a Mach **task** object, then invokes get_bsdtask_info() to get the **bsd_info** of the Mach task. After getting bsd_info, the function calls proc_pid() to get **PID** number of the Mach task and uses **copyout()** to transmit the PID number to userspace.

- However, the function does not check the validity of the task, and directly returns the value of **task -> bsd_info -> p_pid** to user space after calling get_bsdtask_info() and proc_pid().

Memory Interoperation Primitives

```
static kern_return_t
mach_port_guard_locked(
    ipc_port_t      port,
    uint64_t        guard,
    boolean_t       strict)
{
    if (port->ip_context)
        return KERN_INVALID_ARGUMENT;

    port->ip_context = guard;
    port->ip_guarded = 1;
    port->ip_strict_guard = (strict)?1:0;
    return KERN_SUCCESS;
}
```



- A port referring to a freed ipc_port object is called a **dangling port**.
- System calls like mach_port_set/get_*(), mach_port_guard/unguard() are used to write and read the **member fields** of the ipc_port object.
- ip_context field in the ipc_port object is used to associate a userspace pointer with a port. By using mach_port_set/get_context() to a dangling port, the attacker can **retrieve** and **set** 64-bits value in the kernel space.

Arbitrary Code Execution Primitives

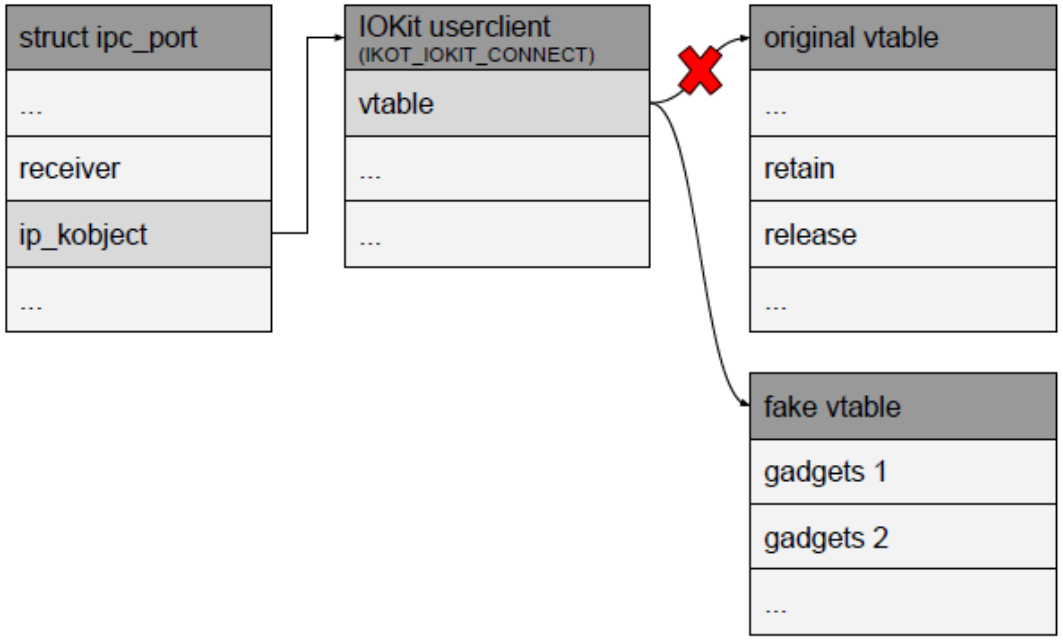
```
struct  clock   clock_list[] = {

    /* SYSTEM_CLOCK */
    { &sysclk_ops, 0, 0 },

    /* CALENDAR_CLOCK */
    { &calend_ops, 0, 0 }
};
```

```
struct clock_ops sysclk_ops = {
    NULL,
    rtclock_init,
    rtclock_gettime,
    rtclock_getattr,
};
```

```
/*
 * Get clock attributes.
 */
kern_return_t
clock_get_attributes(
    clock_t                 clock,
    clock_flavor_t          flavor,
    clock_attr_t            attr,       /* OUT */
    mach_msg_type_number_t  *count)     /* IN/OUT */
{
    if (clock == CLOCK_NULL)
        return (KERN_INVALID_ARGUMENT);
    if (clock->cl_ops->c_getattr)
        return (clock->cl_ops->c_getattr(flavor, attr, count));
    return (KERN_FAILURE);
}
```

- This type of primitives can be used to execute kernel code (e.g., a ROP chain or a kernel function) in **arbitrary** addresses.
- clock_get_attributes() is a system call to get attributes of target clock object. An attack can change the **global** function pointers or **fake** an object to hijack the control flow.
- This technique was used in the **Pegasus** APT attack in iOS 9.3.3.

Arbitrary Code Execution Primitives



- IOKit is an object-oriented device driver framework in XNU that uses a subset of **C++** as its language.
- If the attacker has the kernel write primitives, then he can change the **vtable** entry of an I/OKit userclient to hijack the control flow to the address of a ROP gadget to achieve a kernel code execution primitive.

Practical Case Study: Yalu Exp

```
kern_return_t
mach_voucher_extract_attr_recipe_trap(
struct mach_voucher_..._args *args)
{
...
 mach_msg_type_number_t sz = 0;

 copyin(args->recipe_size, (void *)&sz, \
       sizeof(sz));
...
 uint8_t *krecipe = kalloc((vm_size_t)sz);
...
 //args->recipe_size should be sz
 copyin(args->recipe, (void *)krecipe, \
       args->recipe_size)
...
}
```

- CVE-2017-2370 is a heap **buffer overflow** in mach_voucher_extract_attr_recipe_trap().
- The function first copies 4 bytes from the user space pointer args->recipe_size to the **sz** variable. After that, it calls kalloc(sz).
- The function then calls copyin() to copy args->recipe_size sized data from the user space to the **krecipe** (should be **sz**) sized kernel heap buffer. Consequently, it will cause a buffer overflow.

Practical Case Study: Yalu Exp

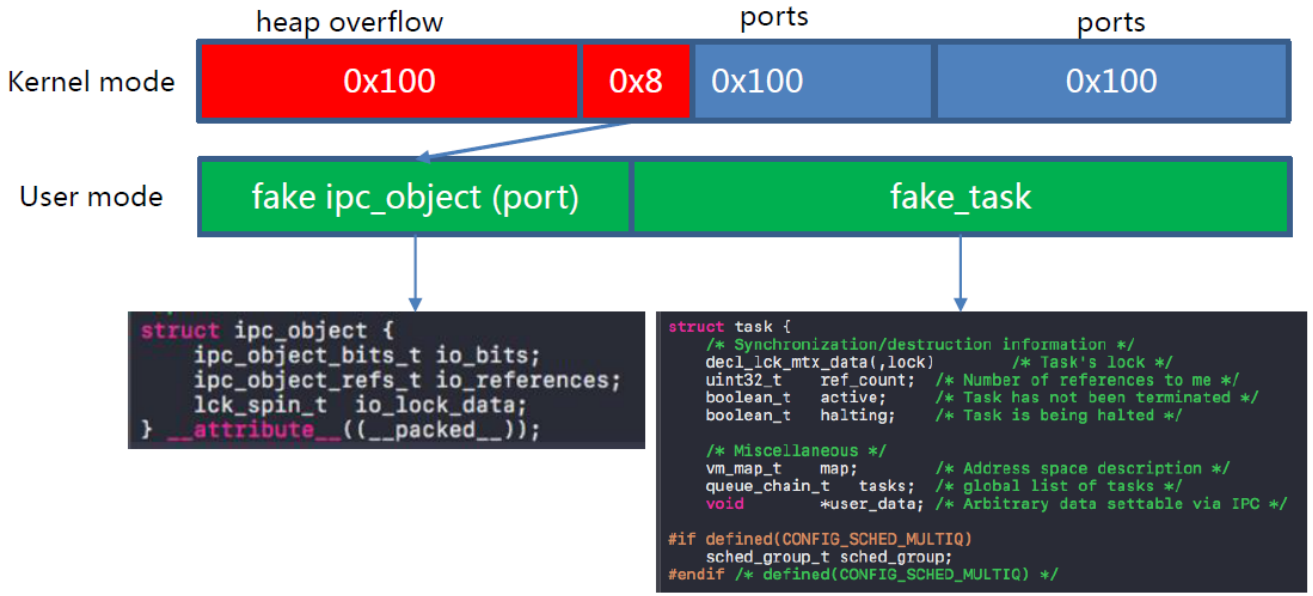
- **Before heap overflow**

```
(lldb) x/50x 0xffffff8029404c00
0xffffff8029404c00: 0xdeadbeefdeadbeef 0xffffffffffffffff
0xffffff8029404c10: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404c20: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404c30: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404c40: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404c50: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404c60: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404c70: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404c80: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404c90: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404ca0: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404cb0: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404cc0: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404cd0: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404ce0: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404cf0: 0xffffffffffffffff 0xdeadbeefdeadbeef
0xffffff8029404d00: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d10: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d20: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d30: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d40: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d50: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d60: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d70: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d80: 0xffffffffffffffff 0xffffffffffffffff
```

- **After heap overflow**

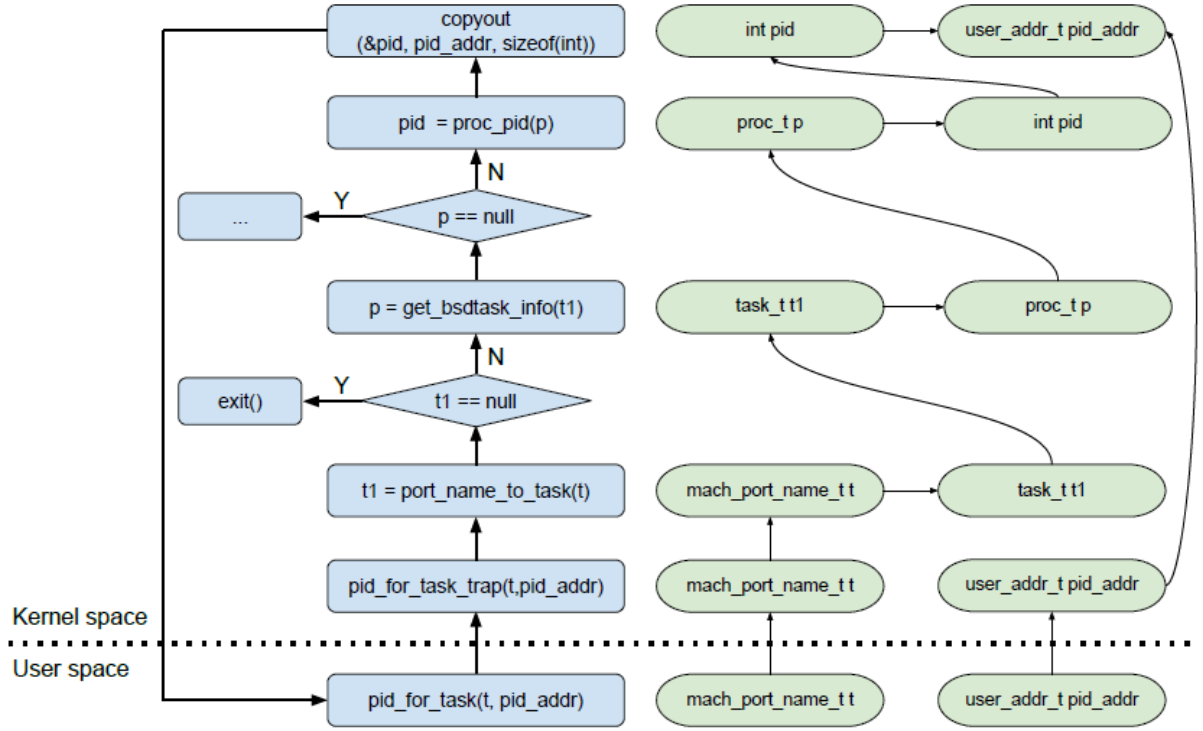
```
(lldb) x/50x 0xffffff8029404c00
0xffffff8029404c00: 0x4141414141414141 0x4141414141414141
0xffffff8029404c10: 0x4141414141414141 0x4141414141414141
0xffffff8029404c20: 0x4141414141414141 0x4141414141414141
0xffffff8029404c30: 0x4141414141414141 0x4141414141414141
0xffffff8029404c40: 0x4141414141414141 0x4141414141414141
0xffffff8029404c50: 0x4141414141414141 0x4141414141414141
0xffffff8029404c60: 0x4141414141414141 0x4141414141414141
0xffffff8029404c70: 0x4141414141414141 0x4141414141414141
0xffffff8029404c80: 0x4141414141414141 0x4141414141414141
0xffffff8029404c90: 0x4141414141414141 0x4141414141414141
0xffffff8029404ca0: 0x4141414141414141 0x4141414141414141
0xffffff8029404cb0: 0x4141414141414141 0x4141414141414141
0xffffff8029404cc0: 0x4141414141414141 0x4141414141414141
0xffffff8029404cd0: 0x4141414141414141 0x4141414141414141
0xffffff8029404ce0: 0x4141414141414141 0x4141414141414141
0xffffff8029404cf0: 0x4141414141414141 0x4141414141414141
0xffffff8029404d00: 0x4242424242424242 0x4242424242424242
0xffffff8029404d10: 0x4242424242424242 0x4242424242424242
0xffffff8029404d20: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d30: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d40: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d50: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d60: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d70: 0xffffffffffffffff 0xffffffffffffffff
0xffffff8029404d80: 0xffffffffffffffff 0xffffffffffffffff
```

Practical Case Study: Yalu Exp



- The exploit overflow those pointers and modify one ipc_object **pointer** to point to a **fake** ipc_object in user mode. The exploit creates a **fake** task in user mode for the fake port as well.
- After that, the exploit chain calls clock_sleep_trap() system call to **brute force** the address of the **global** system clock.

Practical Case Study: Yalu Exp



- The exploit sets io_bits of the fake ipc_object to IKOT_TASK and craft a **fake** task for the fake port. By setting the value at the faketask + bsdtask offset, an attacker could **read arbitrary** 32 bits kernel memory through pid_for_task() **without** break KASLR.

Practical Case Study: Yalu Exp

```
kern_return_t pid_for_task(struct pid_for_task_args *args)
{
    mach_port_name_t    t = args->t;
    user_addr_t     pid_addr  = args->pid;  //return value
    ...
    t1 = port_name_to_task(t);  //get faketask
    ...
    p = get_bsdtask_info(t1);   //get *(faketask + procoff)
    if (p) {
        pid  = proc_pid(p);     //get *(p + 0x10)
        err = KERN_SUCCESS;
    }
    ...
    //copy the value to pid_addr
    (void) copyout((char *) &pid, pid_addr, sizeof(int));
    return(err);
}
```

```
__int64 __fastcall get_bsdtask_info(__int64 a1)
{
  return *(_QWORD *)(a1 + 0x380);
}
```

```
signed __int64 __fastcall proc_pid(__int64 a1)
{
  signed __int64 result; // rax@1

  result = 0xFFFFFFFFLL;
  if ( a1 )
    result = *(_DWORD *)(a1 + 0x10);
  return result;
}
```

```
//copy the value to pid_addr
(void) copyout((char *) &pid, pid_addr, sizeof(int));
```

➡

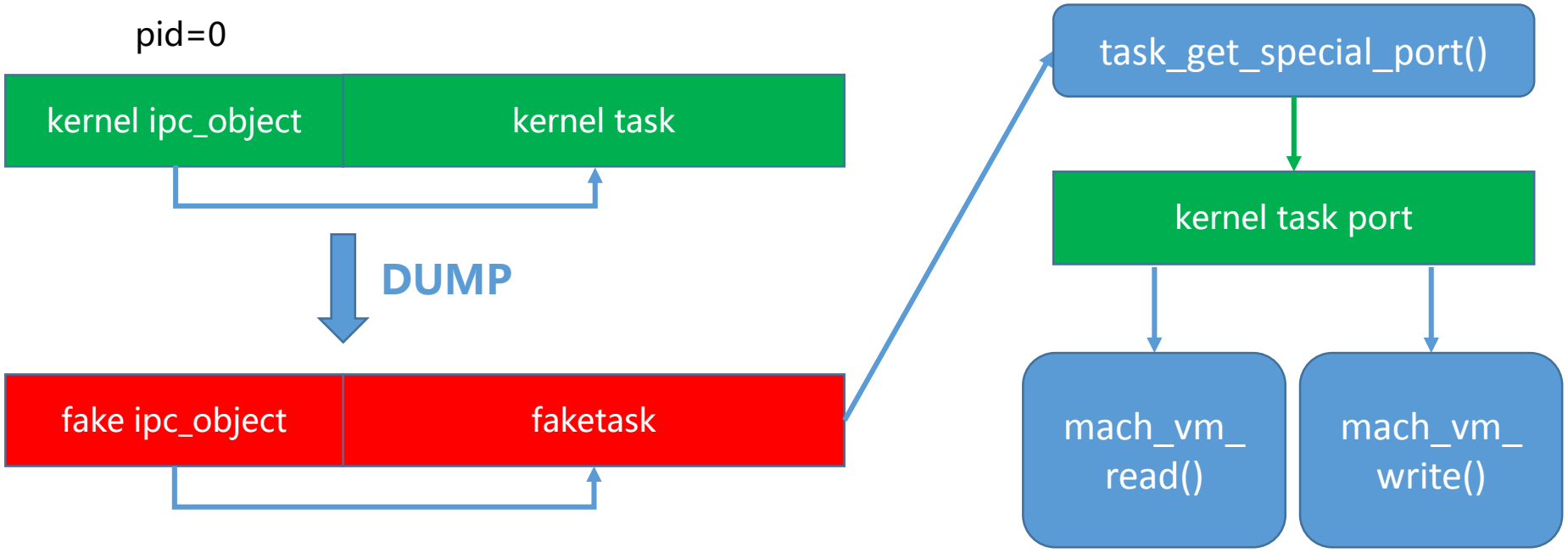
```
read 0xffffff800cc00000 : 0xfeedfacf
```

- As we mentioned before, the function doesn’ t check the **validity** of the task, and just return the value of *(*(faketask + 0x380) + 0x10).

Practical Case Study: Yalu Exp

- The attacker **dumps** kernel ipc_object and kernel task to a fake ipc_object and a fake task. By using task_get_special_port() to the fake ipc_object and task, the attacker could get the **kernel task port**.

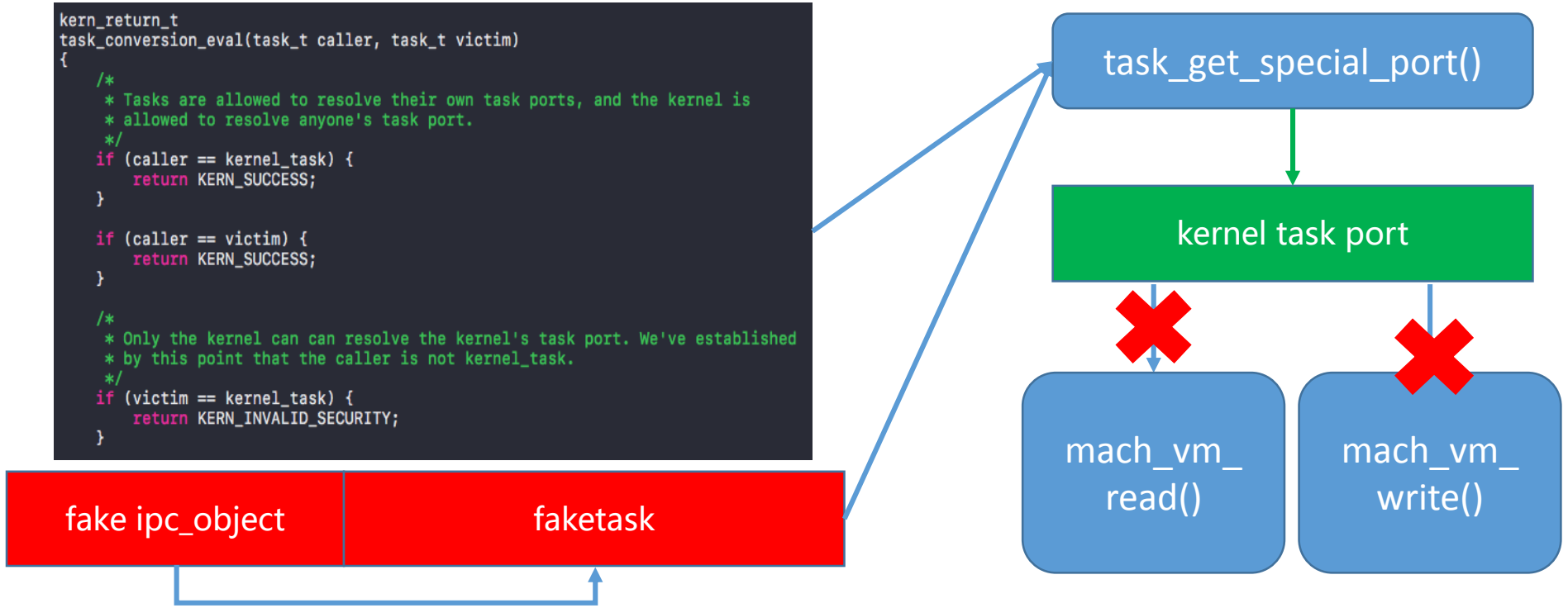
- Kernel task port can be used to do **arbitrary** kernel memory read and write.



iOS 11 Kernel Task Mitigation

- iOS 11 added a new **mitigation** that only the kernel can resolve the kernel’ s task port.
- We **cannot** use the task_get_special_port() trick on iOS 11.

```
kern_return_t
task_conversion_eval(task_t caller, task_t victim)
{
    /*
     * Tasks are allowed to resolve their own task ports, and the kernel is
     * allowed to resolve anyone's task port.
     */
    if (caller == kernel_task) {
        return KERN_SUCCESS;
    }

    if (caller == victim) {
        return KERN_SUCCESS;
    }

    /*
     * Only the kernel can can resolve the kernel's task port. We've established
     * by this point that the caller is not kernel_task.
     */
    if (victim == kernel_task) {
        return KERN_INVALID_SECURITY;
    }
```

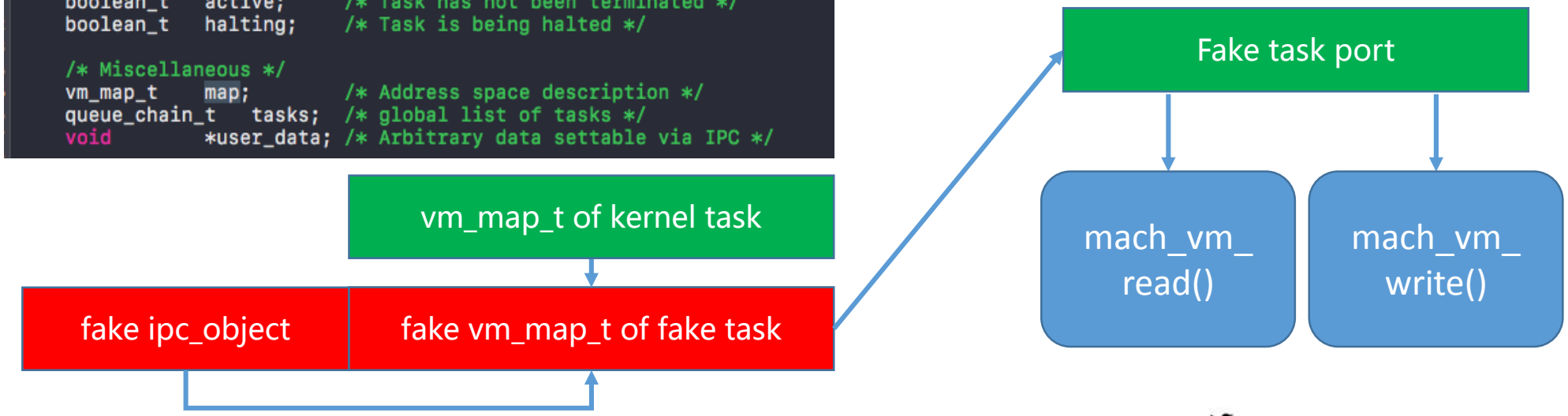


Mitigation bypass in Async_wake Exp

- The attacker cannot use a real kernel task port. But the attacker can copy reference pointer of kernel’ s **vm** to the fake task.

- Now the fake port has a same **address space** as the kernel task port. It’ s enough for the attacker to do arbitrary kernel read/write.

```
struct task {
    /* Synchronization/destruction information */
    decl_lck_mtx_data(,lock)         /* Task's lock */
    _Atomic uint32_t    ref_count;  /* Number of references to me */
    boolean_t    active;      /* Task has not been terminated */
    boolean_t    halting;     /* Task is being halted */

    /* Miscellaneous */
    vm_map_t     map;         /* Address space description */
    queue_chain_t    tasks;   /* global list of tasks */
    void         *user_data;  /* Arbitrary data settable via IPC */
```

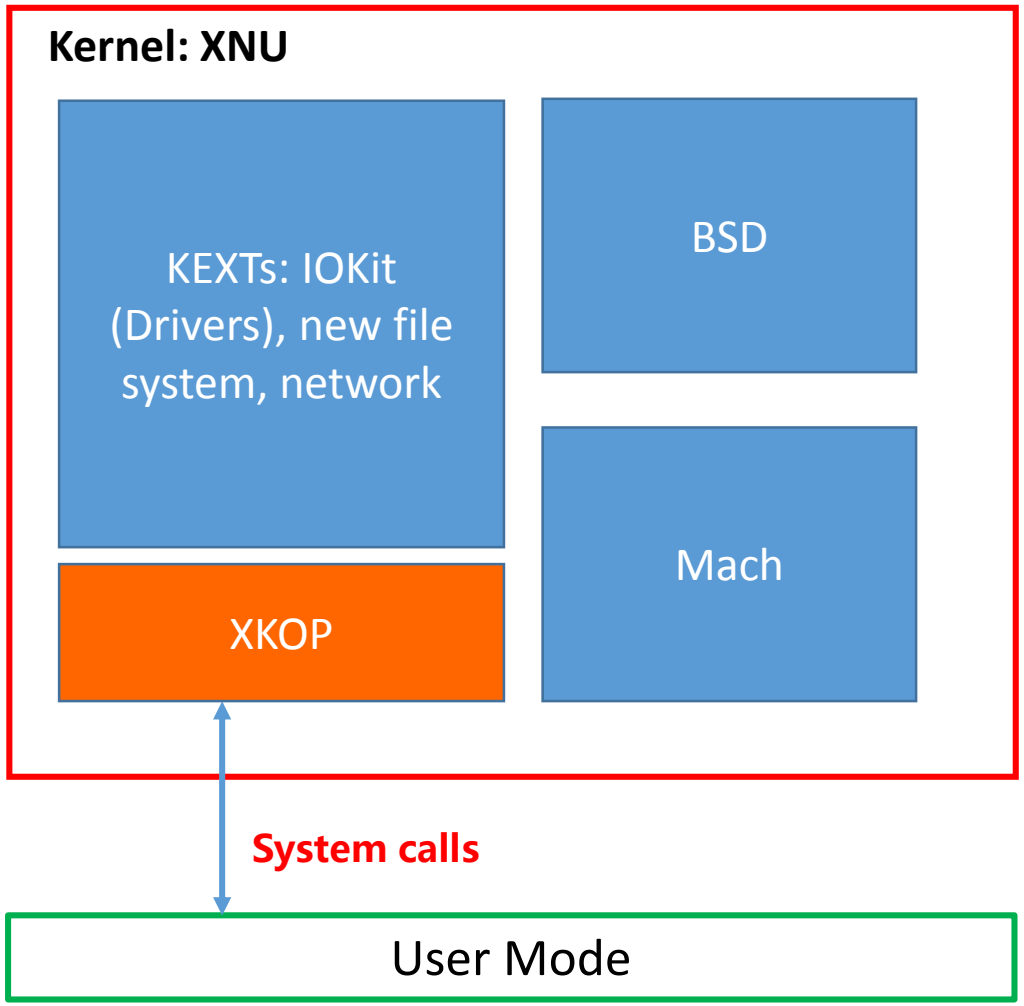


Enterprise Computer Security

Pic from time.com

- Lots of companies (e.g., Alibaba Inc and Tencent) offer Macbooks as work computers to their employees.
- **Problems:**
  1. macOS is not forced to upgrade like iOS.
  2. Less hardware based protections (e.g., AMCC and PAC) on Macbooks.
  3. Less secure sandbox rules than iOS.
- Hard to defend against advanced persistent threat (APT). Enterprise computers need a more **secure** system.

XNU Kernel Object Protector

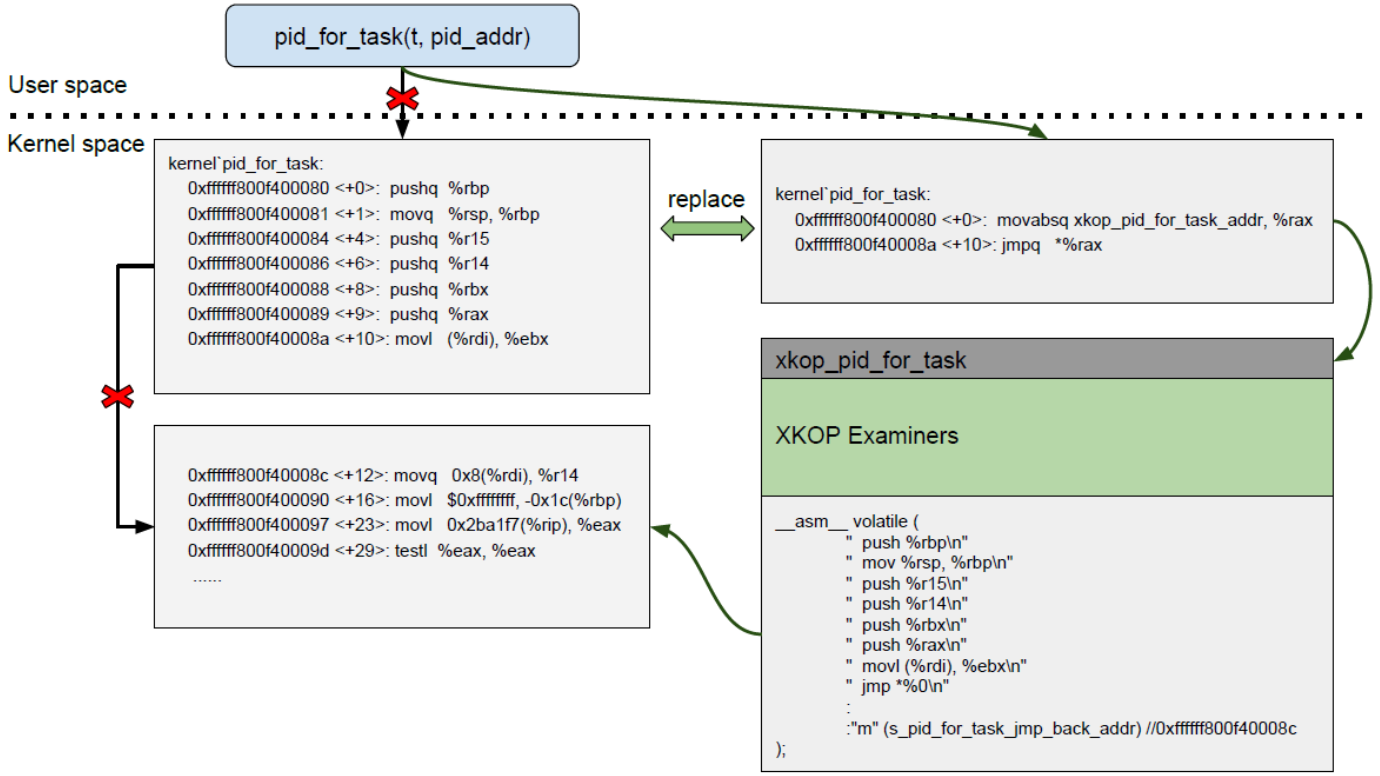


- To mitigate the APT and POP attack, we propose a framework called ***XNU Kernel Object Protector*** (XKOP).
- **Basic idea**: a kernel extension to implement inline hooking for specific system calls and deploy integrity check for ipc_port kernel objects.
- In addition, XKOP could bring **new** mitigations to **old** macOS versions.

Inline Hooking

- Our system needs to find reliable code points that the **examiners** could be executed.
- **KAuth** kernel subsystem exports a KPI that allows third-party developers to authorize actions within the kernel. However, the operation set is very limited.
- **MAC** framework is private and can only be used by Apple. In addition, the rules are hardcoded in the code of the XNU kernel.
- Finally, we choose **inline hooking**.

Inline Hooking



- Based on the examiners, XKOP replaces the original code entry of the target system call into a **trampoline**. The trampoline jumps to the **examiner** stored in the XKOP kernel extension. Then, the examiner verifies the **integrity** of the target kernel object.

Examiners

```
kern_return_t pid_for_task(struct pid_for_task_args *args)
{
    mach_port_name_t    t = args->t;
    user_addr_t     pid_addr  = args->pid;  //return value
    ...
    t1 = port_name_to_task(t);  //get faketask
    ...
    p = get_bsdtask_info(t1);   //get *(faketask + procoff)
    if (p) {
         pid  = proc_pid(p);    //get *(p + 0x10)
         err = KERN_SUCCESS;
    }
    ...
    //copy the value to pid_addr
    (void) copyout((char *) &pid, pid_addr, sizeof(int));
    return(err);
}
```

Kernel object address checker:
t1 should not be in the user space address. Must break KASLR first and put the payload into kernel. Just like a soft SMAP for old devices.

```
__int64 __fastcall get_bsdtask_info(__int64 a1)
{
  return *(_QWORD *)(a1 + 0x380);
}
```

Kernel object type examiner:
a1 should be a real badtask_info structure with a valid pid number.

Examiners

```
uint64_t textbase = 0xffffffff007004000;
while(1)
{
    k+=8;
    //guess the task of clock
    *(uint64_t*)(((uint64_t)fakeport) + 0x68) = textbase + k;
    *(uint64_t*)(((uint64_t)fakeport) + 0xa0) = 0xff;

    //fakeport->io_bits = IKOT_CLOCK | IO_BITS_ACTIVE ;
    kern_return_t kret = clock_sleep_trap(foundport, 0, 0, 0, 0);

    if (kret != KERN_FAILURE) {
        printf("task of clock = %llx\n",textbase + k);
        break;
        }
}
```

Through brute force attacks, clock_sleep_trap() can be used to guess the address of global clock object and break the KASLR.

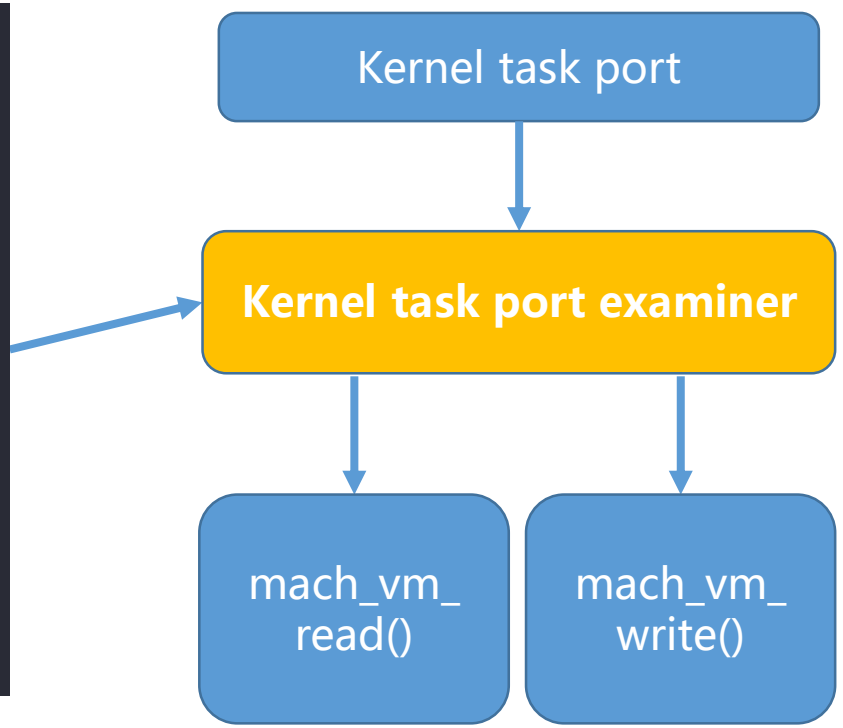
```
clock_t
port_name_to_clock(
    mach_port_name_t clock_name)
{
    clock_t     clock = CLOCK_NULL;
    ipc_space_t space;
    ipc_port_t  port;

    if (clock_name == 0)
        return (clock);
    space = current_space();
    if (ipc_port_translate_send(space, clock_name, &port) != KERN_SUCCESS)
        return (clock);
    if (ip_active(port) && (ip_kotype(port) == IKOT_CLOCK))
        clock = (clock_t) port->ip_kobject;
    ip_unlock(port);
    return (clock);
}
```

Kernel object querying examiner: if the function returns too many errors, warning the user or panic according to the configuration.

Examiners

- **Kernel task port examiner**: firstly, bring task_conversion_eval(task_t caller, task_t victim) mitigation to old macOS system versions. Only the kernel can resolve the kernel's task port.

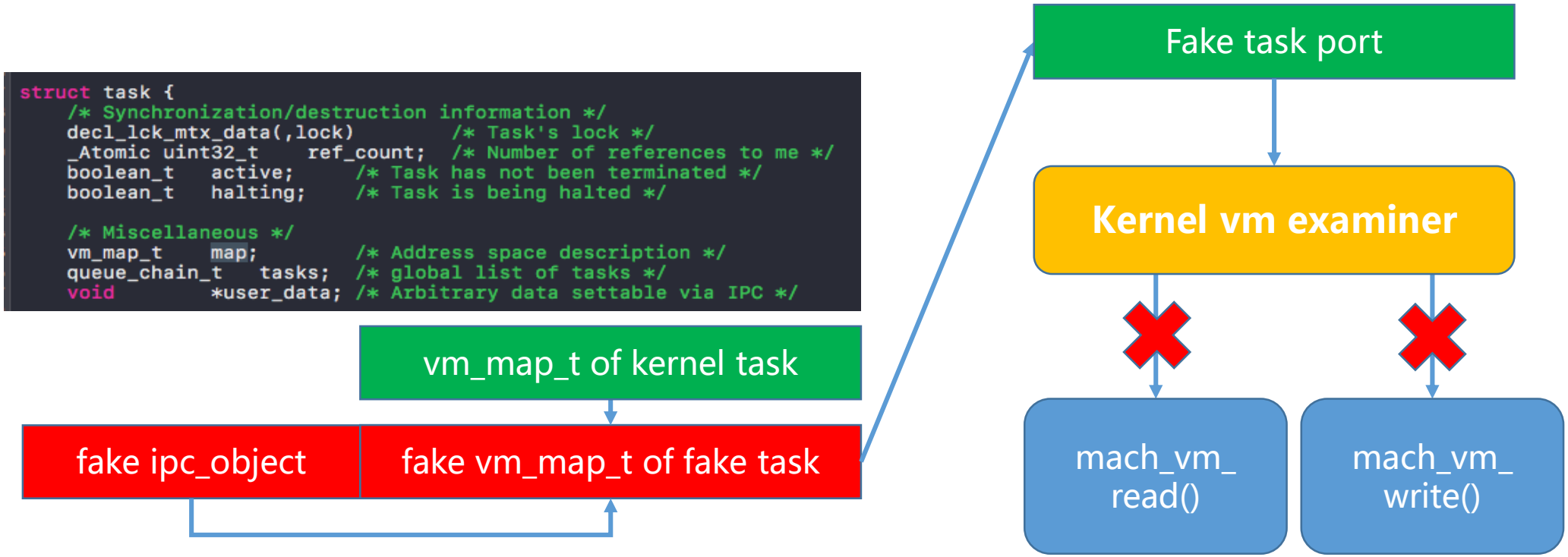
```
kern_return_t
task_conversion_eval(task_t caller, task_t victim)
{
    /*
     * Tasks are allowed to resolve their own task ports, and the kernel is
     * allowed to resolve anyone's task port.
     */
    if (caller == kernel_task) {
        return KERN_SUCCESS;
    }

    if (caller == victim) {
        return KERN_SUCCESS;
    }

    /*
     * Only the kernel can can resolve the kernel's task port. We've established
     * by this point that the caller is not kernel_task.
     */
    if (victim == kernel_task) {
        return KERN_INVALID_SECURITY;
    }
```



Examiners

- **Kernel vm examiner** for mach_vm_*(): if the caller process does not belong to kernel (pid == 0) and the target ipc_port object has the same map structure with the one of a kernel task, the examiner will trigger configured operations, e.g., error return or panic.

```
struct task {
    /* Synchronization/destruction information */
    decl_lck_mtx_data(,lock)         /* Task's lock */
    _Atomic uint32_t    ref_count;  /* Number of references to me */
    boolean_t    active;     /* Task has not been terminated */
    boolean_t    halting;    /* Task is being halted */

    /* Miscellaneous */
    vm_map_t     map;        /* Address space description */
    queue_chain_t    tasks;  /* global list of tasks */
    void         *user_data; /* Arbitrary data settable via IPC */
```



Evaluation

- We selected 4 kernel vulnerabilities (two for each version of macOS) and available exploits to **evaluate** the effectiveness of our system.

macOS version	Vulnerability (CVE)	XKOP Protection
10.12	CVE-2016-4669	YES
	CVE-2017-2370	YES
10.13	CVE-2017-13861	YES
	CVE-2018-4241	YES

- We first ensure that the **exploits** work on the corresponding systems, and then we deploy the XKOP framework and run the exploits again to check whether our system detects and blocks the attack.

```
19:01:13.225053  kernel    DEBUG!!!!!I am in pid_for_task!!!! s_pid_for_task_JmpBackAddr=0xffffff801bc0008c pid:7fff54feeab4 task:32d03
19:01:13.225571  kernel    port_name_to_task addr=ffffff801b6fc420
19:01:13.225578  kernel    task=0xac71000
19:01:13.225580  kernel    bsd_info=0xffffff801b6c7ff0
19:01:13.225583  kernel    pid=0x49624f89
19:01:13.225585  kernel    find PKOOP attack!!!!
```

- The experiment result shows that XKOP provides **deterministic** protection for every vulnerability and blocks each attempt to exploit the system.

Discussion

- Unfortunately, XKOP cannot mitigate **all** kinds of POP primitives:

  (1). Querying primitives use error return values to gain an extra source of information which is very similar to the **side-channel** attack.

  (2). No protection for arbitrary code execution primitives. Without hardware support, software-based CFI implementation can be very **expensive**. In addition, modern kernel could be patched by **pure data** which means kernel memory read and write primitives are enough for attackers to accomplish the aim.

- We may miss some potential vulnerabilities that can bypass XKOP protection. As an imperfect solution, XKOP supports **extensible** examiners to prevent new threats in the first place.

Conclusion

- We discuss the **mitigation** techniques in the XNU kernel, i.e., the kernel of iOS and macOS, and how these mitigations make the traditional exploitation technique ineffective.
- We summarize a new attack called **POP** that leverages multiple ipc_port kernel objects to bypass these mitigations.
- A defense mechanism called XNU Kernel Object Protector (**XKOP**) is proposed to protect the integrity of the kernel objects in the XNU kernel.

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- Mach portal: https://bugs.chromium.org/p/project-zero/issues/detail?id=965
- PassiveFuzzFrameworkOSX: https://github.com/SilverMoonSecurity/PassiveFuzzFrameworkOSX


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