# Port(al) to the iOS Core

## Introduction to a previously private iOS Kernel Exploitation Technique

March, 2017

# ipc_port_t (II)

IPC ports are internally hold in the following structure

defined in /osfmk/ipc/ipc_port.h

```
    natural_t ip_sprequests:1,  /* send-possible requests outstanding */
          ip_spimportant:1, /* ... at least one is importance donating */
          ip_impdonation:1, /* port supports importance donation */
          ip_tempowner:1,   /* dont give donations to current receiver */
          ip_guarded:1,         /* port guarded (use context value as guard) */
          ip_strict_guard:1,    /* Strict guarding; Prevents user manipulation of context values directly */
          ip_reserved:2,
          ip_impcount:24;   /* number of importance donations in nested queue */

    mach_vm_address_t ip_context;


#if MACH_ASSERT
#define IP_NSPARES      4
#define IP_CALLSTACK_MAX    16
    queue_chain_t   ip_port_links;  /* all allocated ports */
    thread_t    ip_thread;  /* who made me?  thread context */
    unsigned long   ip_timetrack;   /* give an idea of "when" created */
    uintptr_t   ip_callstack[IP_CALLSTACK_MAX]; /* stack trace */
    unsigned long   ip_spares[IP_NSPARES]; /* for debugging */
#endif  /* MACH_ASSERT */
};
```

# ipc_object_t (I)

common data structure for IPC objects like ports

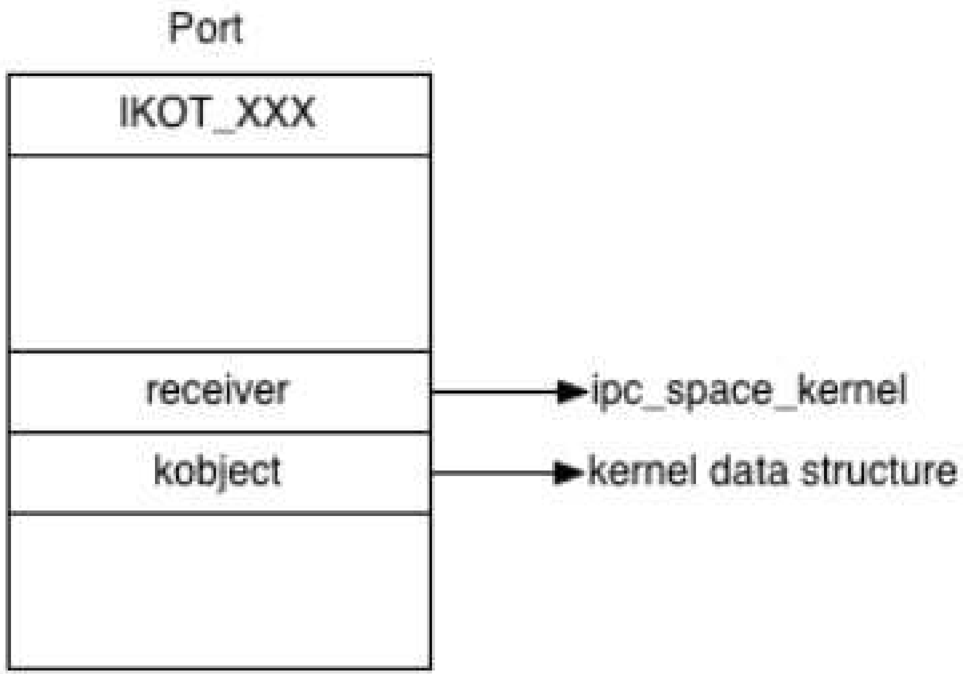
defined in /osfmk/ipc/ipc_object.h

```
/*
 * The ipc_object is used to both tag and reference count these two data
 * structures, and (Noto Bene!) pointers to either of these or the
 * ipc_object at the head of these are freely cast back and forth; hence
 * the ipc_object MUST BE FIRST in the ipc_common_data.
 *
 * If the RPC implementation enabled user-mode code to use kernel-level
 * data structures (as ours used to), this peculiar structuring would
 * avoid having anything in user code depend on the kernel configuration
 * (with which lock size varies).
 */
struct ipc_object {
    ipc_object_bits_t io_bits;
    ipc_object_refs_t io_references;
    lck_spin_t  io_lock_data;
};
```

# Ports as Handles to Kernel Objects / Data Structures

- **io_bits** field filled with **kobject type**
- **receiver** field points to **ipc_space_kernel**
- **kobject** field points to kernel data structure



# Possible Kobject Types

IPC Kobject types are defined in

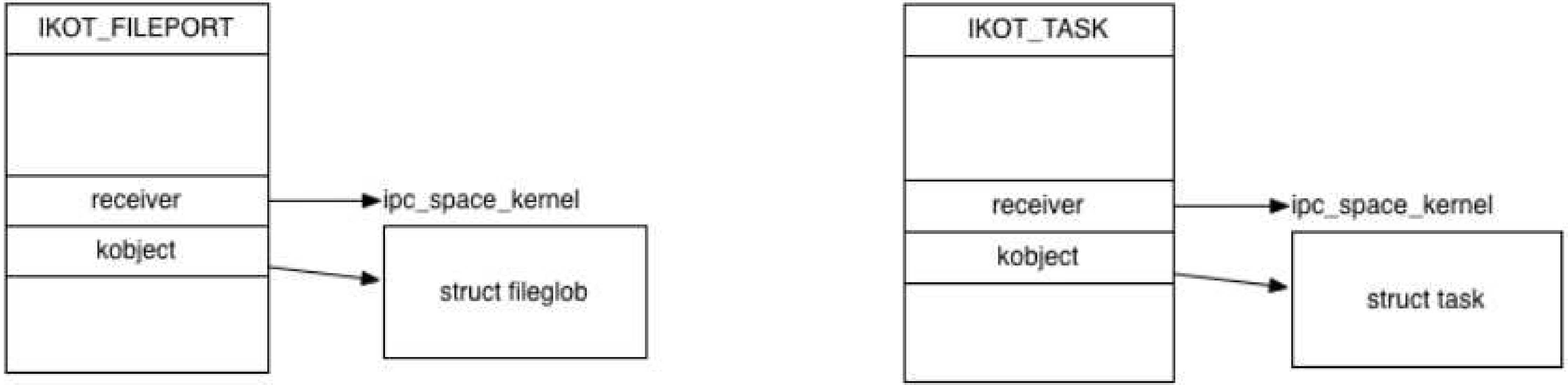
/osfmk/ipc/ipc_kobject.h

```
#define IKOT_NONE                0
#define IKOT_THREAD              1
#define IKOT_TASK                2
#define IKOT_HOST                3
#define IKOT_HOST_PRIV           4
#define IKOT_PROCESSOR           5
#define IKOT_PSET                6
#define IKOT_PSET_NAME           7
#define IKOT_TIMER               8
#define IKOT_PAGING_REQUEST      9
#define IKOT_MIG                 10
#define IKOT_MEMORY_OBJECT       11
#define IKOT_XMM_PAGER           12
#define IKOT_XMM_KERNEL          13
#define IKOT_XMM_REPLY           14
#define IKOT_UND_REPLY           15
#define IKOT_HOST_NOTIFY         16
#define IKOT_HOST_SECURITY       17
#define IKOT_LEDGER              18
#define IKOT_MASTER_DEVICE       19
```

```
#define IKOT_TASK_NAME           20
#define IKOT_SUBSYSTEM           21
#define IKOT_IO_DONE_QUEUE       22
#define IKOT_SEMAPHORE           23
#define IKOT_LOCK_SET            24
#define IKOT_CLOCK               25
#define IKOT_CLOCK_CTRL          26
#define IKOT_IOKIT_SPARE         27
#define IKOT_NAMED_ENTRY         28
#define IKOT_IOKIT_CONNECT       29
#define IKOT_IOKIT_OBJECT        30
#define IKOT_UPL                 31
#define IKOT_MEM_OBJ_CONTROL     32
#define IKOT_AU_SESSIONPORT      33
#define IKOT_FILEPORT            34
#define IKOT_LABELH              35
#define IKOT_TASK_RESUME         36
#define IKOT_VOUCHER             37
#define IKOT_VOUCHER_ATTR_CONTROL 38
```

# Examples

- **kobject** always points to an **IKOT** specified data structure



# What are Mach Messages?

# What are Mach Messages?

- data structures sent to or received from Mach Ports
  - header with routing information for kernel
  - optionally descriptors for COMPLEX messages
  - data that is only between sender and receiver
- used for IPC and the Mach API
- sent to kernel via mach traps

# Simple vs. Complex Messages

- simple messages are just data blobs

```
typedef struct
{
        mach_msg_header_t       header;
        char                    body[];
} mach_msg_simple_t;
```

- complex messages contain descriptors with special meaning for kernel
  - **MACH_MSG_PORT_DESCRIPTOR** - embedding a port in a message
  - **MACH_MSG_OOL_DESCRIPTOR** - attaching OOL data to message
  - **MACH_MSG_OOL_PORTS_DESCRIPTOR** - attaching OOL ports array to message

```
typedef struct
{
        mach_msg_header_t       header;
        mach_msg_body_t         body;
        mach_msg_descriptor_t   desc[x];
        char                    data[];
} mach_msg_complex_t;
```

# Mach Message Header

```
typedef struct
{
  mach_msg_bits_t    msgh_bits;
  mach_msg_size_t    msgh_size;
  mach_port_t        msgh_remote_port;
  mach_port_t        msgh_local_port;
  mach_port_name_t   msgh_voucher_port;
  mach_msg_id_t      msgh_id;
} mach_msg_header_t;
```

- msgh_remote_port: where to send to
- msgh_local_port: where to get reply from
- msgh_id: id between sender and receiver

# Sending and Receiving Messages

- Mach messages are sent via mach traps

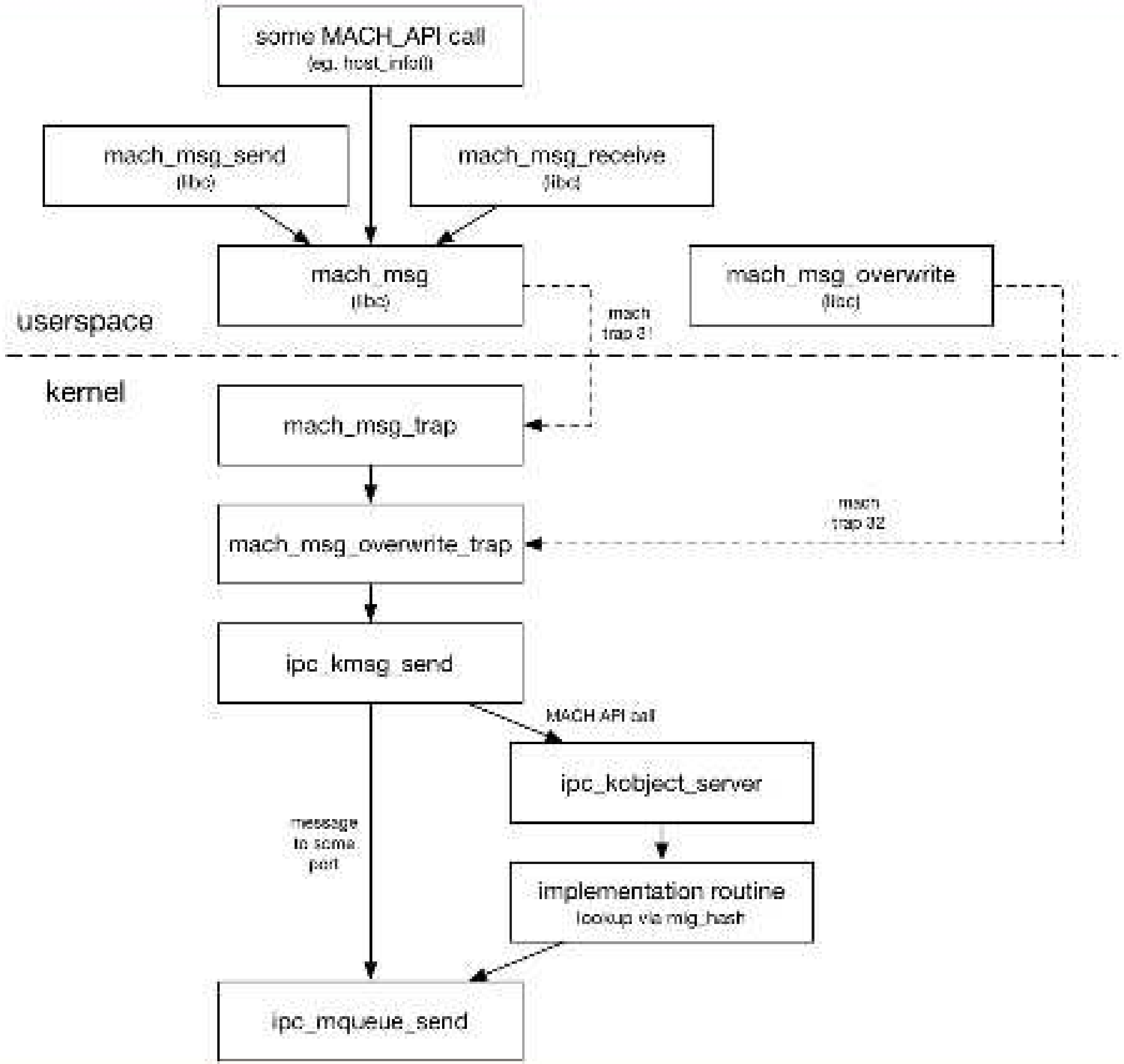
```
mach_msg_return_t
mach_msg(msg, option, send_size, rcv_size, rcv_name, timeout, notify)
    mach_msg_header_t *msg;
    mach_msg_option_t option;
    mach_msg_size_t send_size;
    mach_msg_size_t rcv_size;
    mach_port_t rcv_name;
    mach_msg_timeout_t timeout;
    mach_port_t notify;

mach_msg_return_t
mach_msg_overwrite(msg, option, send_size, rcv_limit, rcv_name, timeout,
           notify, rcv_msg, rcv_scatter_size)
    mach_msg_header_t *msg;
    mach_msg_option_t option;
    mach_msg_size_t send_size;
    mach_msg_size_t rcv_limit;
    mach_port_t rcv_name;
    mach_msg_timeout_t timeout;
    mach_port_t notify;
    mach_msg_header_t *rcv_msg;
    mach_msg_size_t rcv_scatter_size;
```

# Who am I?

- Stefan Esser
- from Germany
- in Information Security since 1998
- SektionEins GmbH from (2007 - 2016)
- Antid0te UG (2013 - now)

# Sending Mach Messages (Function Overview)



# What is the Mach API?

- programming interface offering huge number of functions
- internally converts C style function calls into messages
- first parameter is always the kernel object port to send message to
- usually they manipulate the objects behind the kernel object ports

- special code path detects if **receiver=ipc_space_kernel**
- header's id field selects what API is called

# Mach API Example: vm_write()

- C level call to **vm_write()** automatically converted into Mach message
  - **target_task** set as remote port
  - **id** set to 3807

```
kern_return_t vm_write
     (vm_task_t                target_task,
      vm_address_t             address,
      pointer_t                data,
      mach_msg_type_number_t   data_count);
```

```
typedef struct {
    mach_msg_header_t Head;
    /* start of the kernel processed data */
    mach_msg_body_t msgh_body;
    mach_msg_ool_descriptor_t data;
    /* end of the kernel processed data */
    NDR_record_t NDR;
    vm_address_t address;
    mach_msg_type_number_t dataCnt;
} __Request__vm_write_t;
```

# Heap-Feng-Shui for Ports?

# Ports as Target

- **kernel object ports** point to kernel data structures
- overwriting/replacing them would allow calling APIs on fake data structures
- wide variety of **IKOT** types means many types to choose from
  - IKOT_FILEPORT - fileglob structure has function pointer list
  - IKOT_IOKIT_CONNECT - C++ object with vtable pointer
  - ...

# Filling the Heap with Ports?

- so should we create a lot of ports to fill the heap?
- would be possible but ports are stored in their own memory zone
- memory corruptions usually involve other memory zones
- cross zone attacks are possible but not KISS

➡ let's add a level of indirection

# Filling the Heap with Pointers to Ports?

- instead of filling the heap with **ipc_port_t** structures fill it with pointers
- overwriting a pointer to an **ipc_port_t** still allows to create a fake port
- idea is that pointers are likely allocated in same memory zones as buffers
- when in same memory zone exploitation gets a lot easier

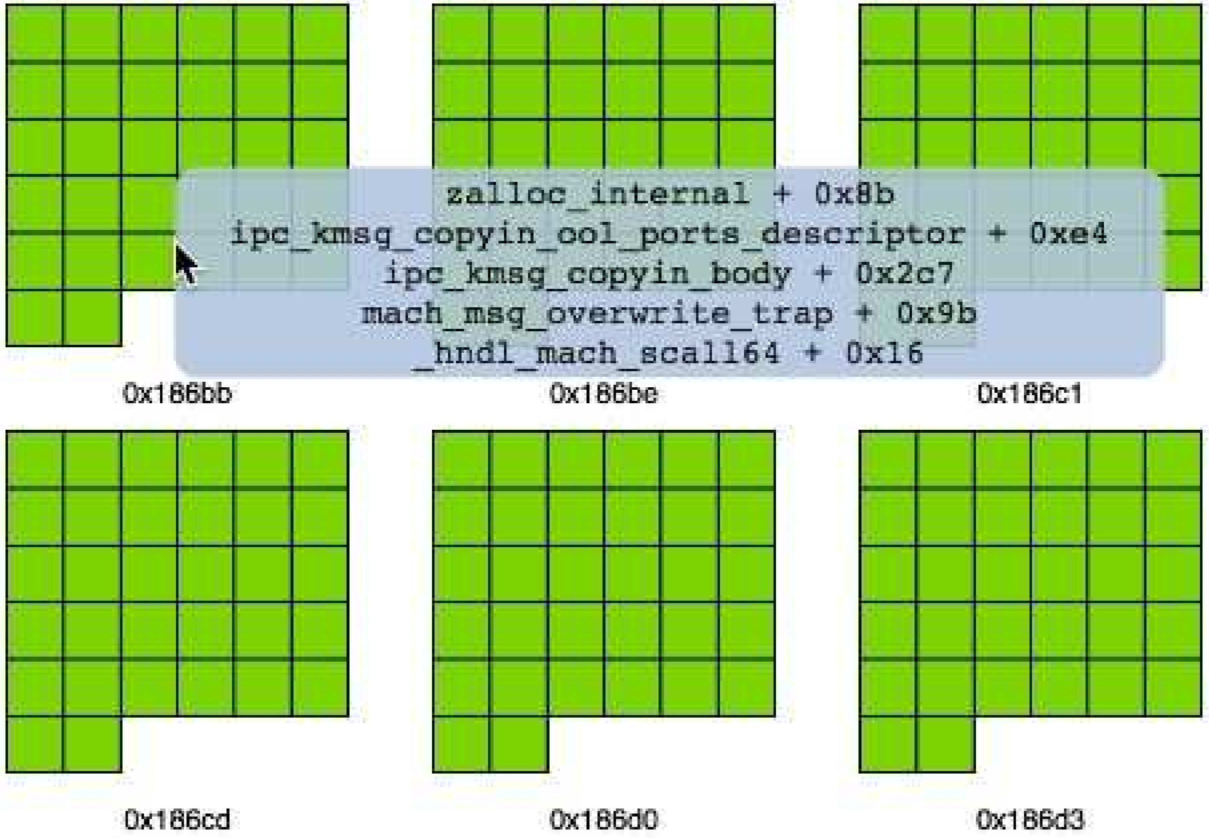
# How to fill the memory with Port pointers?

- we can fill the memory with pointers to ports by Mach messages
- we use **MACH_MSG_OOL_PORTS_DESCRIPTOR** for this
- kernel will allocate memory via **kalloc()** to store pointers in memory
- arbitrary sized allocations by sending right amount of ports

```
/* calculate length of data in bytes, rounding up */
ports_length = count * sizeof(mach_port_t);
names_length = count * sizeof(mach_port_name_t);

if (ports_length == 0) {
    return user_dsc;
}

data = kalloc(ports_length);
```

# How to fill the memory with Port pointers? (II)

- sending enough messages will fill up the heap pretty quickly
- we can send **MACH_PORT_NULL** or **MACH_PORT_DEAD**



# Poking holes...

- poking holes in the allocation is done by receiving selected messages
- kernel code will free the previously allocated memory
- deallocation is fine grained because we select what messages to receive
- keep in mind the heap randomization since iOS 9.2

```
/* copyout to memory allocated above */
void *data = dsc->address;
if (copyoutmap(map, data, rcv_addr, names_length) != KERN_SUCCESS)
    *mr |= MACH_MSG_VM_SPACE;
kfree(data, ports_length);
```

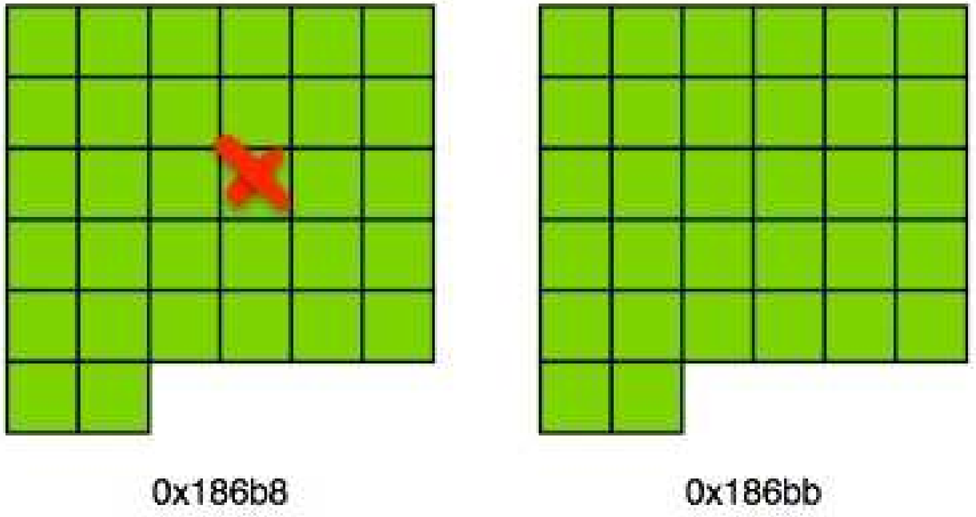
# What is this talk about?

- a “new” (set of) iOS kernel exploitation technique(s)
- previously only discussed in my iOS Kernel Exploitation trainings
- part of teaching material since around 2015
- trainee from Dec 2016 leaked it within one month to developers of Yalu
- who then distributed an iOS 10.2 jailbreak using this technique in Jan 2017

# Corrupting Port Pointers

- when messages are received all ports within are registered in IPC space
- corrupting any of the allocated pointer lists allows injecting a fake port
- user space can access the fake port

```
/* copyout port rights carried in the message */

for ( i = 0; i < count ; i++) {
    ipc_object_t object = (ipc_object_t)objects[i];

    *mr |= ipc_kmsg_copyout_object(space, object,
                disp, &names[i]);
}
```



# Faking Ports

# How to fake a port? (I)

- fake pointer must point to something that looks like a port
- we need to setup a number of fields for our port to work
  - **io_bits** - select one of the possible types and make it active
  - **io_references** - better give it some references
  - **io_lock_data** - must be valid lock data
  - **kobject** - pointer to a fake data structure
  - **receiver** - we cannot fill out because we don't know **ipc_space_kernel**

# How to fake a port? (II)

- fake port and fake data must be in attacker controlled memory
- it is required to know address of that memory
- easy to do for 64 bit devices (except iPhone 7) because of user land dereferences
- requires additional information leaks for iPhone 7 and 32 bit devices (unless already privileged outside the sandbox)

# What can we do with such a faked port?

- because we cannot fill in **receiver** not a fully usable port
- it works fine when used as argument to
  - syscalls
  - mach traps
  - as additional parameter Mach API (not 1st argument)
- but it will NOT work as first argument to a MachAPI
  (for this we need the receiver to be ipc_space_kernel)

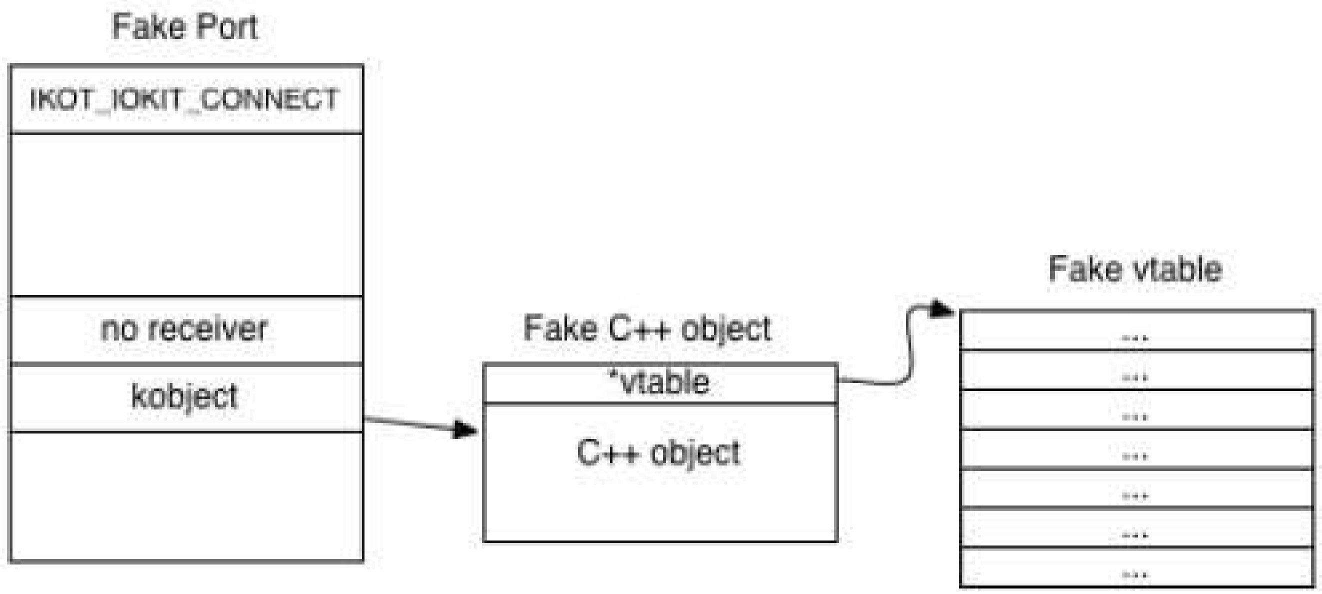
  

# Some Examples

- some examples of ports we can fake
  - IKOT_IOKIT_CONNECT - driver connection to a IOUserClient derived object
  - IKOT_CLOCK - clock object
  - IKOT_TASK - task object

# Faking IOKit Driver Connection Ports

- ports of type **IKOT_IOKIT_CONNECT** can be used via **iokit_user_client_trap()**
- **kobject** pointer points to a C++ object
- good target because it allows control of the **method table**
- see “HITB2013 - Tales from iOS 6 Exploitation” for example



# Faking Clock Ports (I)

- ports of type **IKOT_CLOCK** can be used via **clock_sleep_trap()**
- **kobject** pointer points to a struct clock
- looks like a good target because there is a function pointer list

```
/*
 * Actual clock object data structure. Contains the machine
 * dependent operations list and clock operation ports.
 */
struct  clock {
    clock_ops_t         cl_ops;         /* operations list */
    struct ipc_port     *cl_service;    /* service port */
    struct ipc_port     *cl_control;    /* control port */
};
```

pointer to list of function pointers

# Faking Clock Ports (II)

- code of **clock_sleep_internal()** will not allow a fake **clock struct**
- only the valid **SYSTEM_CLOCK** pointer is accepted
- otherwise function errors out - triggering code execution not possible

```
if (clock == CLOCK_NULL)
    return (KERN_INVALID_ARGUMENT);

if (clock != &clock_list[SYSTEM_CLOCK])
    return (KERN_FAILURE);

/*
 * Check sleep parameters. If parameters are invalid
 * return an error, otherwise post alarm request.
 */
(*clock->cl_ops->c_gettime)(&clock_time);

chkstat = check_time(sleep_type, sleep_time, &clock_time);
if (chkstat < 0)
    return (KERN_INVALID_VALUE);
```

← validation against our fake clock struct pointer

# Faking Clock Ports (III)

- wait a second!
- a wrong clock pointer will lead to **KERN_FAILURE**
- a good pointer with bad other arguments leads to **KERN_INVALID_VALUE**

```
if (clock == CLOCK_NULL)
    return (KERN_INVALID_ARGUMENT);

if (clock != &clock_list[SYSTEM_CLOCK])
    return (KERN_FAILURE);

/*
 * Check sleep parameters. If parameters are invalid
 * return an error, otherwise post alarm request.
 */
(*clock->cl_ops->c_gettime)(&clock_time);

chkstat = check_time(sleep_type, sleep_time, &clock_time);
if (chkstat < 0)
    return (KERN_INVALID_VALUE);
```

error if our pointer is not pointing to the SYSTEM_CLOCK

error if our pointer was okay but other arguments bad

# Previous iOS Kernel Heap Feng Shui / Exploitation Techniques

- **BlackHat 2012 - iOS Kernel Heap Armageddon Revisited**
  - Author: Stefan Esser
  - Idea: Fill kernel heap with C++ objects via OSUnserializeXML() and overwrite them
  - Status: Apple mitigated but a slightly modified technique still usable in iOS 10

- **Hack In The Box 2012 - iOS 6 Security**
  - Author(s): Mark Dowd / Tarjei Mandt
  - Idea: Fill heap with vm_copy_t structures and get information leaks and extended buffer overflows from overwriting them
  - Status: Apple added mitigations so that technique got less and less valuable

# Faking Clock Ports (IV)

- if we can change **kobject** we can bruteforce the **SYSTEM_CLOCK** address
- userland dereference makes this easy on 64 bit pre iPhone 7
- this reveals pointer inside kernel image and therefore breaks KASLR

```
our_fake_port->io_bits = IKOT_CLOCK | IO_BITS_ACTIVE;
our_fake_port->kobject = low_kernel_address;

while (1) {
   our_fake_port->kobject+= 8;
   kret = clock_sleep_trap(magicport, 0x12345, 0, 0, NULL);

   if (kret != KERN_FAILURE) {
      break;
   }
}
```

# Faking Task Ports (I)

- ports of type **IKOT_TASK** have **kobject** pointer pointing to a **task struct**
- unfortunately cannot be used directly in task Mach API functions
- but there are other usages like

**pid_for_task()** - return the pid for a given task

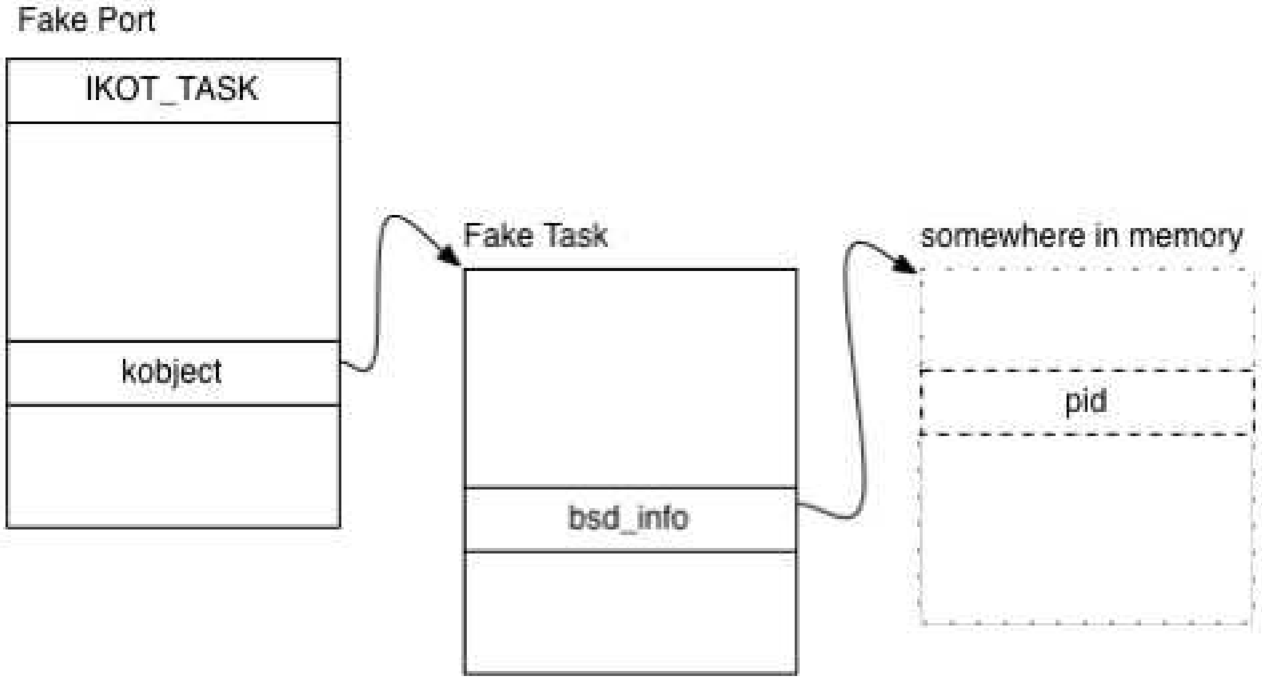
```
t1 = port_name_to_task(t);

if (t1 == TASK_NULL) {
   err = KERN_FAILURE;
   goto pftout;
} else {
   p = get_bsdtask_info(t1);
   if (p) {
      pid  = proc_pid(p);
```

reads pointer to struct proc from our fake struct task

returns pid from without struct proc

# Faking Task Ports (II)

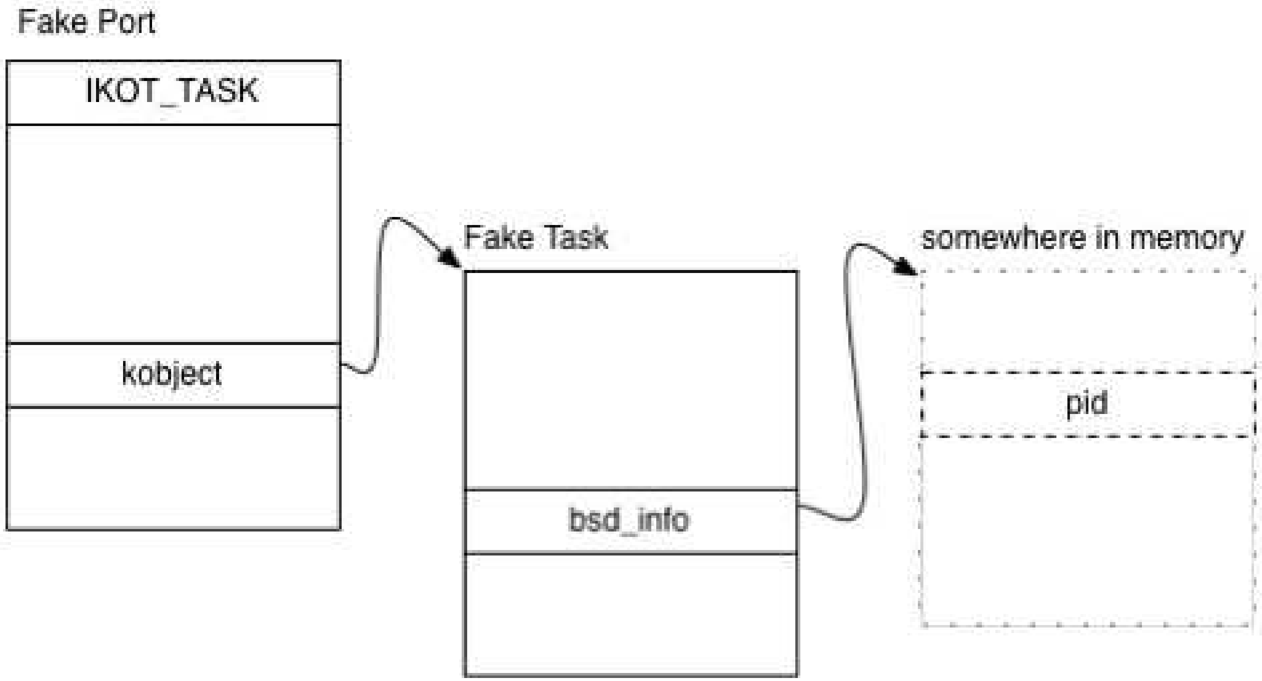
- our fake **IKOT_TASK** port points to a fake **task struct**
- the **bsd_info** fields points anywhere in memory
- **pid_for_task()** will read back at offset 0x10
- allows to read from anywhere in kernel memory



# Faking Task Ports (III)

- if we can change **kobject** we can read everything
- userland dereference makes this easy on 64 bit pre iPhone 7
- this allows to read important variables like **ipc_space_kernel**
- this means afterwards we can use Mach API with our fake port



# Kernel Task Port

Our Port(al) to the Core

# Kernel Task Port

- among all the ports in an iOS system the **kernel task port** is the holy grail
- with access to the **kernel task port** we can manipulate the kernel memory
  - **vm_read** - allows reading kernel memory
  - **vm_write** - allows writing kernel memory
  - **vm_allocate** - allows allocating memory inside the kernel address space
  - ...
- whoever has access to the kernel task port more or less controls the system
- to turn out fake task port into a kernel task port we need to know **kernel_task** and **ipc_space** kernel

# Attack Plan for 64 bit devices (except iPhone 7)

- **Corruption Phase**
  - perform heap feng shui with OOL_PORTS_DESCRIPTORS
  - corrupt any of the "sprayed" port pointers
  - receive all messages to get access to port

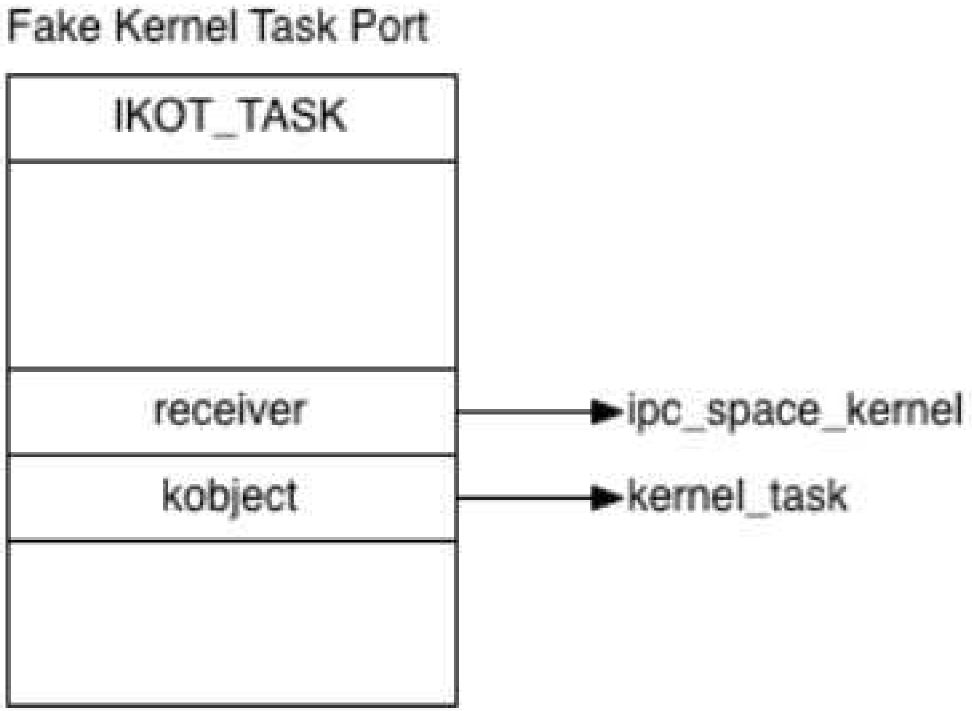
- **Post Corruption Phase**
  - fake a CLOCK port to break KASLR - via bruteforce of clock address
  - fake a TASK port and TASK struct to have arbitrary kernel read
  - read ipc_space_kernel and kernel_task
  - fake a kernel TASK port

# Faking the KERNEL TASK Port (I)

- with **ipc_space_kernel** our fake ports can be used in Mach API
- with **kernel_task** we can fake a kernel task port
- mach API gives us read/write access to kernel memory

- **Game Over!**



# Conclusion

# Conclusion

- overwriting port pointers
  - allows to gain code execution
  - or full read write access to kernel memory

- heap feng shui with mach messages and **OOL_PORTS_DESCRIPTOR**
  - gives fine grained control over heap
  - fills heap with port pointers that when corrupted

- post corruption code is fully reusable for different corruptions (64bit before i7)

# Status of public iOS Kernel Exploitation

- everybody is using the public heap feng shui techniques
- bugs are often overflows or UAF
- exploitation often targets **vm_map_copy_t** or kernel **C++ objects**
- Apple keeps adding mitigations against the publicly seen techniques
- public techniques become less and less usable

➡ we need a different / new technique

# Questions ?

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# Ingredients of our Kernel Exploitation Technique(s)

1. idea for a different / new kernel data structure to attack
2. way to fill the kernel heap with this structure or pointers to it
3. strategy how to continue once overwritten

 

# What Kernel Data Structure should we attack?

- there are for sure many data structures in the kernel
- but when you look at the Mach part of the kernel
- one data structure jumps into your face immediately

➡ mach ports!

 

# What are Mach Ports?

# What are Mach Ports?

- likely the most important data structure in Mach part of kernel
- have multiple purposes
  - act like handles to kernel objects / subsystems
  - allow sending / receiving messages for IPC
- stored internally in **ipc_port_t** structure

  

# ipc_port_t (I)

IPC ports are internally hold in the following structure defined in /osfmk/ipc/ipc_port.h

```
struct ipc_port {

    /*
     * Initial sub-structure in common with ipc_pset
     * First element is an ipc_object second is a
     * message queue
     */
    struct ipc_object ip_object;
    struct ipc_mqueue ip_messages;

    union {
        struct ipc_space *receiver;
        struct ipc_port *destination;
        ipc_port_timestamp_t timestamp;
    } data;

    union {
        ipc_kobject_t kobject;
        ipc_importance_task_t imp_task;
        uintptr_t alias;
    } kdata;

    struct ipc_port *ip_nsrequest;
    struct ipc_port *ip_pdrequest;
    struct ipc_port_request *ip_requests;
    struct ipc_kmsg *ip_premsg;

    mach_port_mscount_t ip_mscount;
    mach_port_rights_t ip_srights;
    mach_port_rights_t ip_sorights;
```

  