Attacking the XNU Kernel in El Capitan

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About Me

- Independent vulnerability researcher from Venice, Italy
- Focusing on Apple's products, particularly attracted by jailbreaking techniques
- Author of several XNU Kernel-related CVEs and exploits
  - "vpwn" (< 10.10.2 LPE) - CVE-2015-1140 / CVE-2015-5865
  - "tpwn" (< 10.11 LPE) - CVE-2015-5932 / CVE-2015-5847 / CVE-2015-5864
  - "npwn" (10.11 SIP bypass) - CVE-2015-6974

Why attack XNU?

- XNU has been a target primarily for iOS jailbreaking
- Yosemite enforces KEXT signatures
- El Capitan introduces “System Integrity Protection”
  - System-wide, kernel-enforced sandbox profile that prevents access to system resources
- Attacking the kernel is a viable way to bypass rootless and sandbox

the xnu heap

A quick overview

The XNU Heap: Zone Allocator (zalloc)

- zinit(…) / zalloc(zone) / zfree(zone, ptr)
- Each zone has a LIFO linked list containing free chunks
- Allocations in a zone are same-sized
- When allocating from a zone without free chunks, a new page is mapped in, page is split in chunks and each chunk is added to the free list
- Discussed in detail in countless talks by Stefan Esser

The XNU Heap: Zone Allocator (zalloc)

- No inline metadata for allocated chunks, free list metadata on free chunks
- Free list metadata is not an interesting target due to hardening
- Application metadata is the only target
- Different zones use different areas of memory, so cross-zone attacks aren't feasible
- This does not apply to large allocations

The XNU Heap: Zone Allocator (kalloc)

- kalloc(size), kfree(ptr, size)
- Wrapper around zalloc
- Registers several generic zones with various sizes
- Essentially provides a malloc-like interface, but lack of metadata in allocated chunks requires passing “size” to kfree

The XNU Heap: Zone Allocator (kalloc)

zone name	elem size	cur size	max size	cur #elts	max #elts	cur inuse	alloc size	alloc count	
kalloc.16	16	1664K	1751K	106496	112100	95001	4K	256	C
kalloc.32	32	2272K	2627K	72704	84075	58856	4K	128	C
kalloc.48	48	4256K	5911K	90794	126113	83520	4K	85	C
kalloc.64	64	9172K	13301K	146752	212816	87246	4K	64	C
kalloc.80	80	20672K	29927K	264601	383068	255865	4K	51	C
kalloc.96	96	1736K	2335K	18517	24911	13912	8K	85	C
kalloc.128	128	7672K	8867K	61376	70938	59846	4K	32	C
kalloc.160	160	1552K	1556K	9932	9964	9123	8K	51	C
kalloc.256	256	23680K	29927K	94720	119709	91884	4K	16	C
kalloc.288	288	2300K	2594K	8177	9226	8068	20K	71	C
kalloc.512	512	52740K	101004K	105480	202009	99398	4K	8	C
kalloc.1024	1024	24132K	29927K	24132	29927	22996	4K	4	C
kalloc.1280	1280	768K	768K	614	615	475	20K	16	C
kalloc.2048	2048	9572K	19951K	4786	9975	4181	4K	2	C
kalloc.4096	4096	5052K	13301K	1263	3325	1261	4K	1	C
kalloc.8192	8192	6432K	7882K	804	985	799	8K	1	C

kalloc zones on 10.11

(output of “zprint kalloc” as root)

(for some reason “zprint kalloc” segfaults in 10.11, but “zprint | grep kalloc” works)

vm_map_copy corruption

A quick overview of 10.10 techniques

The XNU Heap: vm_map_copy in 10.10

- Introduced as an easy way to do data-only memory leaks by Tarjei Mandt and Mark Dowd's HITB2012KUL "iOS 6 Security" presentation
- vm_map_copy is a structure used to hold a copy of some data
- For small amounts of data the kernel heap is used
- Targeted by an endless amount of kernel exploits

The XNU Heap: vm_map_copy in 10.10

- Allocated with kalloc(sizeof(struct vm_map_copy) + data_size)
    - **Controlled size!**
- Can be created and accessed easily via OOL mach_msg data
- Completely unaffected by sandboxing

The XNU Heap: vm_map_copy in 10.10

```
10.10 source:

struct vm_map_copy {
    int          type;
#define VM_MAP_COPY_ENTRY_LIST      1
#define VM_MAP_COPY_OBJECT      2
#define VM_MAP_COPY_KERNEL_BUFFER   3
    vm_object_offset_t  offset;
    vm_map_size_t       size;
    union {
        struct vm_map_header    hdr;    /* ENTRY_LIST */
        vm_object_t         object; /* OBJECT */
        struct {
        void                *kdata;     /* KERNEL_BUFFER */
        vm_size_t           kalloc_size;  /* size of this copy_t */
        } c_k;
    } c_u;
};
```

Usual info-leak targets

x86_64 sizeof(struct vm_map_copy) = 0x58

tpwn: a 10.10 kernel exploit

tpwn: a 10.10 kernel exploit

- Released in Aug 2015
- 0-day at the time
    - CVE-2015-5932 / CVE-2015-5847 / CVE-2015-5864
- Core issue is a type confusion in handling mach ports in io_service_open_extended
- Ports passed as "task" with a non-IKOT_TASK type would cause NULL to be passed as pointer to task struct to IOUserClients (CVE-2015-5932)

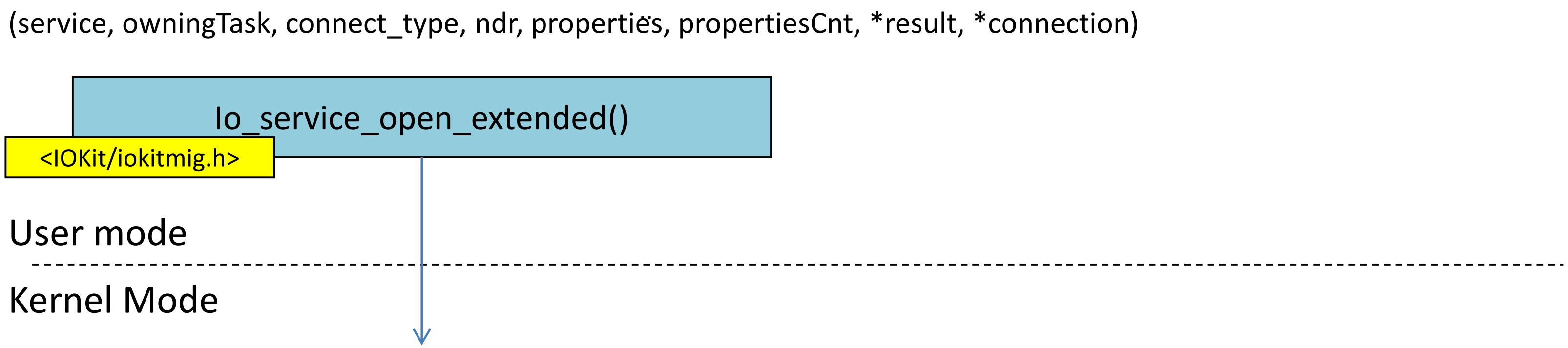
tpwn: __PAGEZERO strikes again

- The Mach-O format defines __PAGEZERO as a guard area
  - 32-bit: 4K, used to trap NULL pointer dereferences
- Apple enforces “hard page zero” to prevent mapping NULL
- But

```
#if __x86_64__
        /*
         * On x86, for compatibility, don't enforce the hard page-zero restriction for 32-bit binaries.
         */
        if ((imgp->ip_flags & IMGPF_IS_64BIT) == 0) {
                enforce_hard_pagezero = FALSE;
        }
#endif
```

Page zero is left wide open in 32-bit binaries!

tpwn: a 10.10 kernel exploit



`io_service_open_extended` is one of several undocumented MIG functions to communicate with IOKit drivers from user mode

tpwn: a 10.10 kernel exploit

(service, owningTask, connect_type, ndr, properties, propertiesCnt, *result, *connection)

Io_service_open_extended()

<IOKit/iokitmig.h>

User mode

Kernel Mode

Io_service_open_extended()

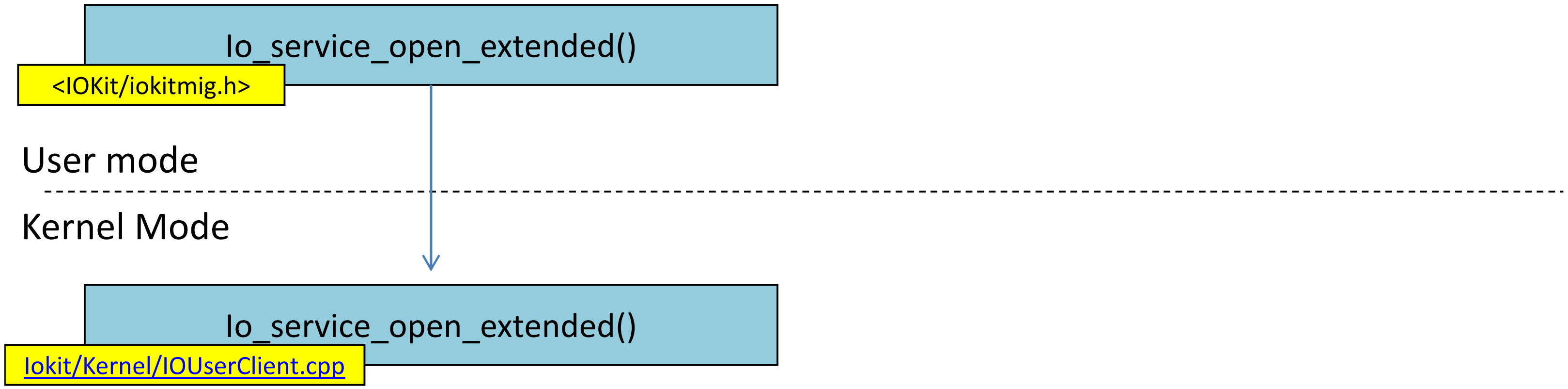
Iokit/Kernel/IOUserClient.cpp

```
/* Routine io_service_open_ndr */
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 );

    do
    {
        if (properties)
        {
            ...
```

Note NO CHECK ON owningTask!

tpwn: a 10.10 kernel exploit

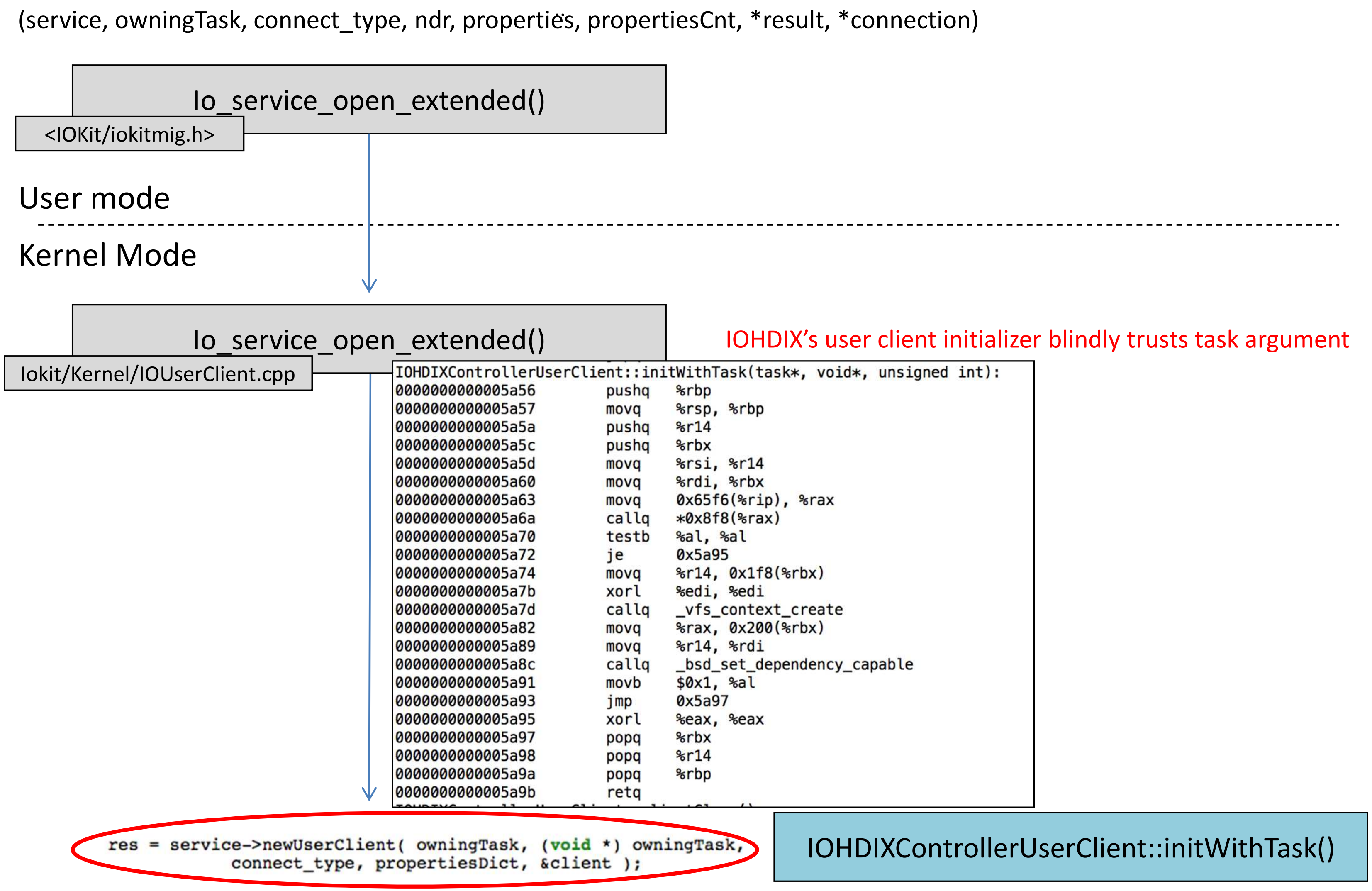
(service, owningTask, connect_type, ndr, properties, propertiesCnt, *result, *connection)



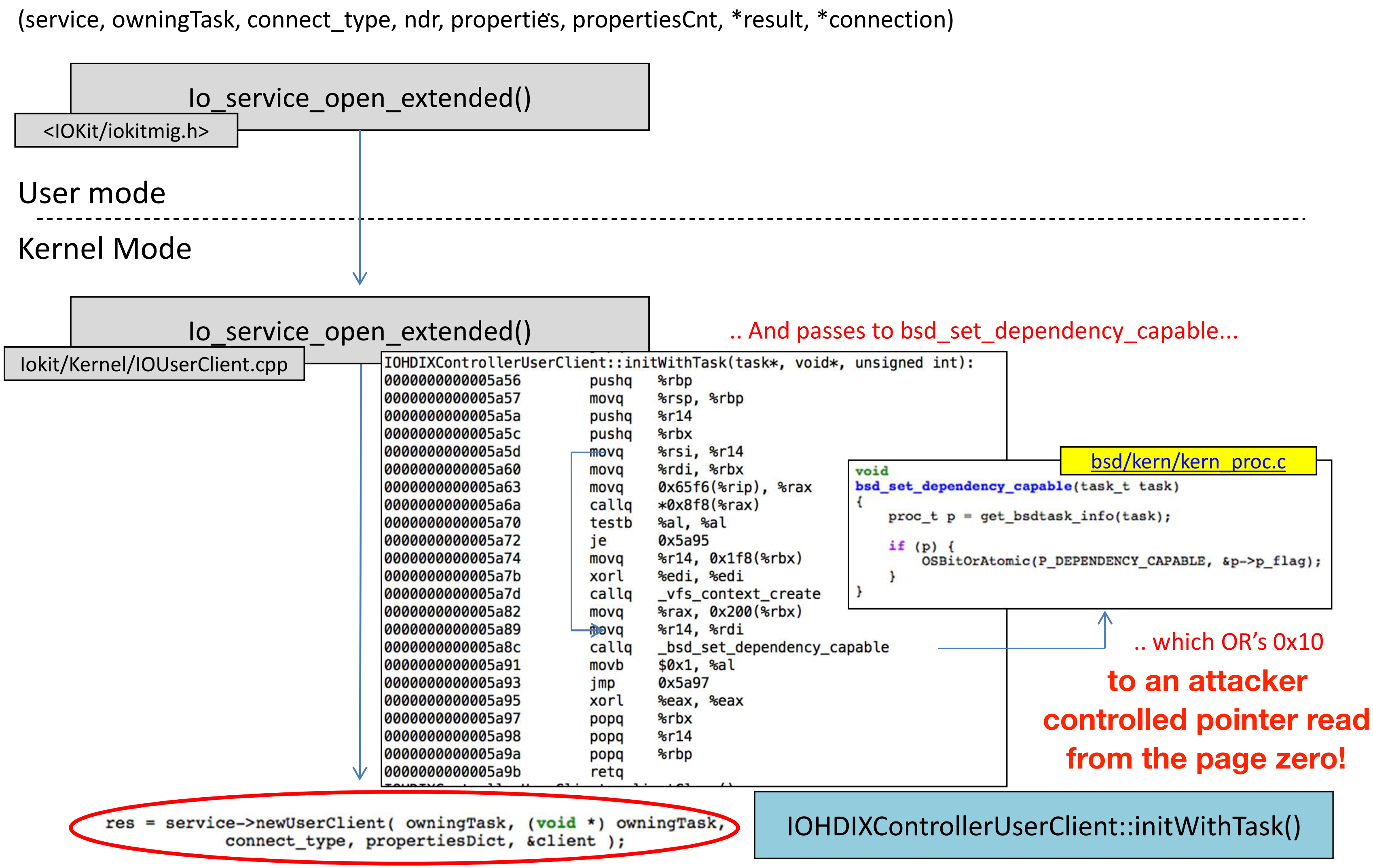

```
/* Routine io_service_open_ndr */
kern_return_t is_io_service_open_extended(
        io_object_t _service,
        task_t owningTask,
        uint32_t connect_type,
        NDR_record_t ndr,
        io_buf_ptr_t properties,
        mach_msg_type_number_t propertiesCnt,
        kern_return_t * result,
        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 );

    do
    {
        if (properties)
        {

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

owningTask then gets passed to User Clients

tpwn: a 10.10 kernel exploit



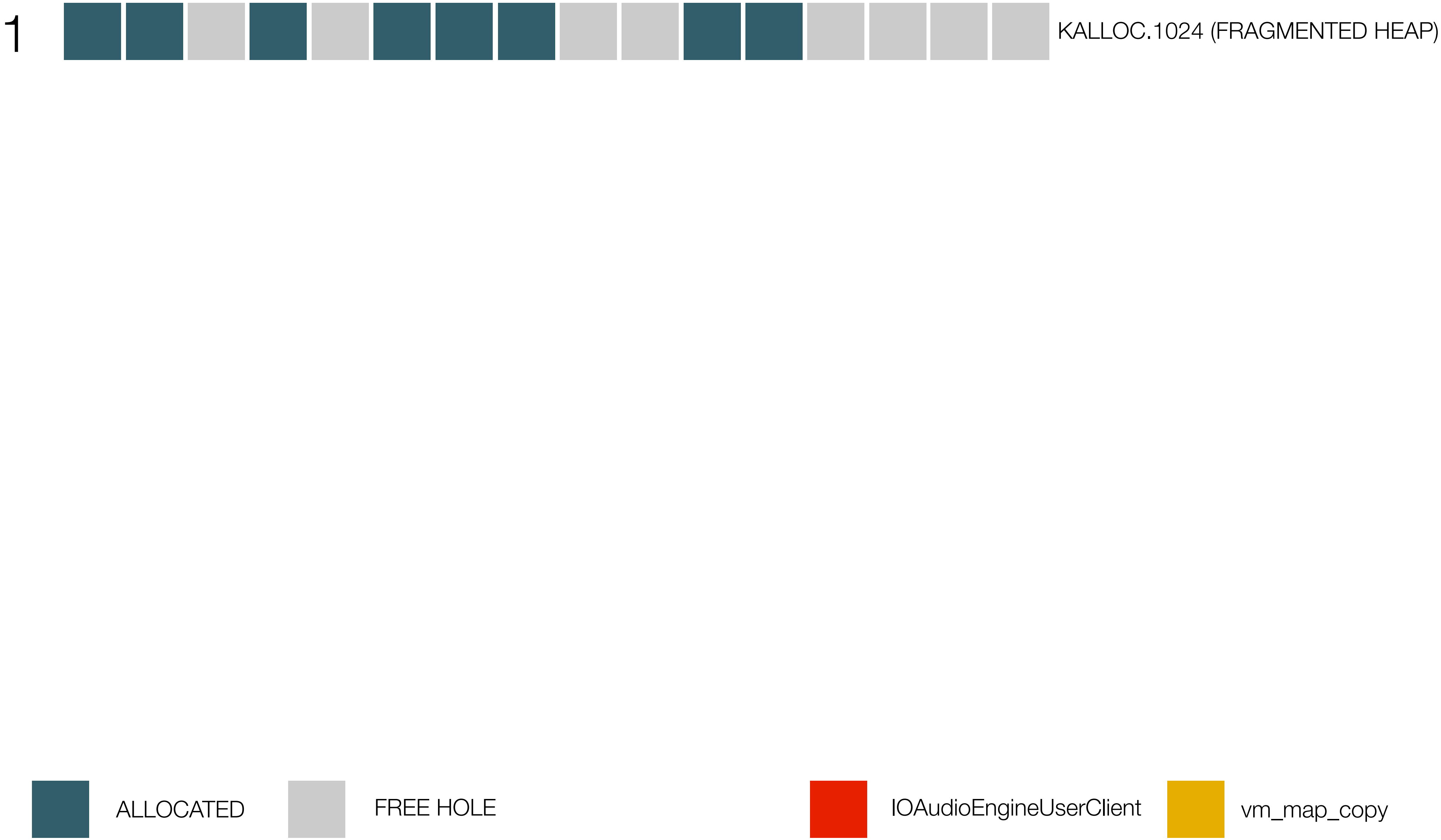
tpwn: a 10.10 kernel exploit



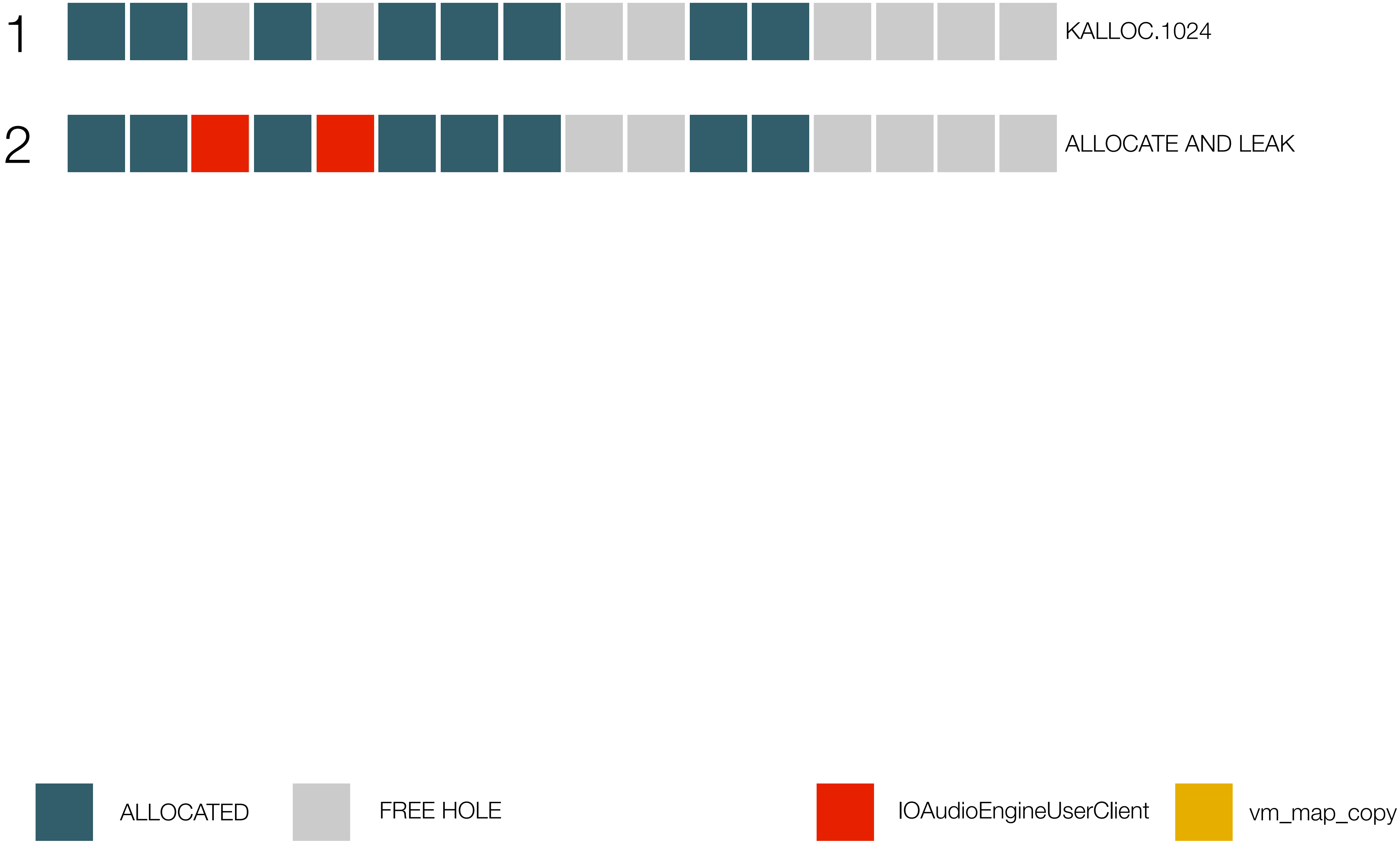
tpwn: a 10.10 kernel exploit

- Using an heap info leak (CVE-2015-5864) we can locate a C++ object in kalloc.1024
- We need to locate a vm_map_copy and make sure it’s adjacent to a C++ object
- Corrupt the size of the vm_map_copy to read the C++ object’s memory
- Derive kASLR slide from there
- Gain instruction pointer control, pivot the stack

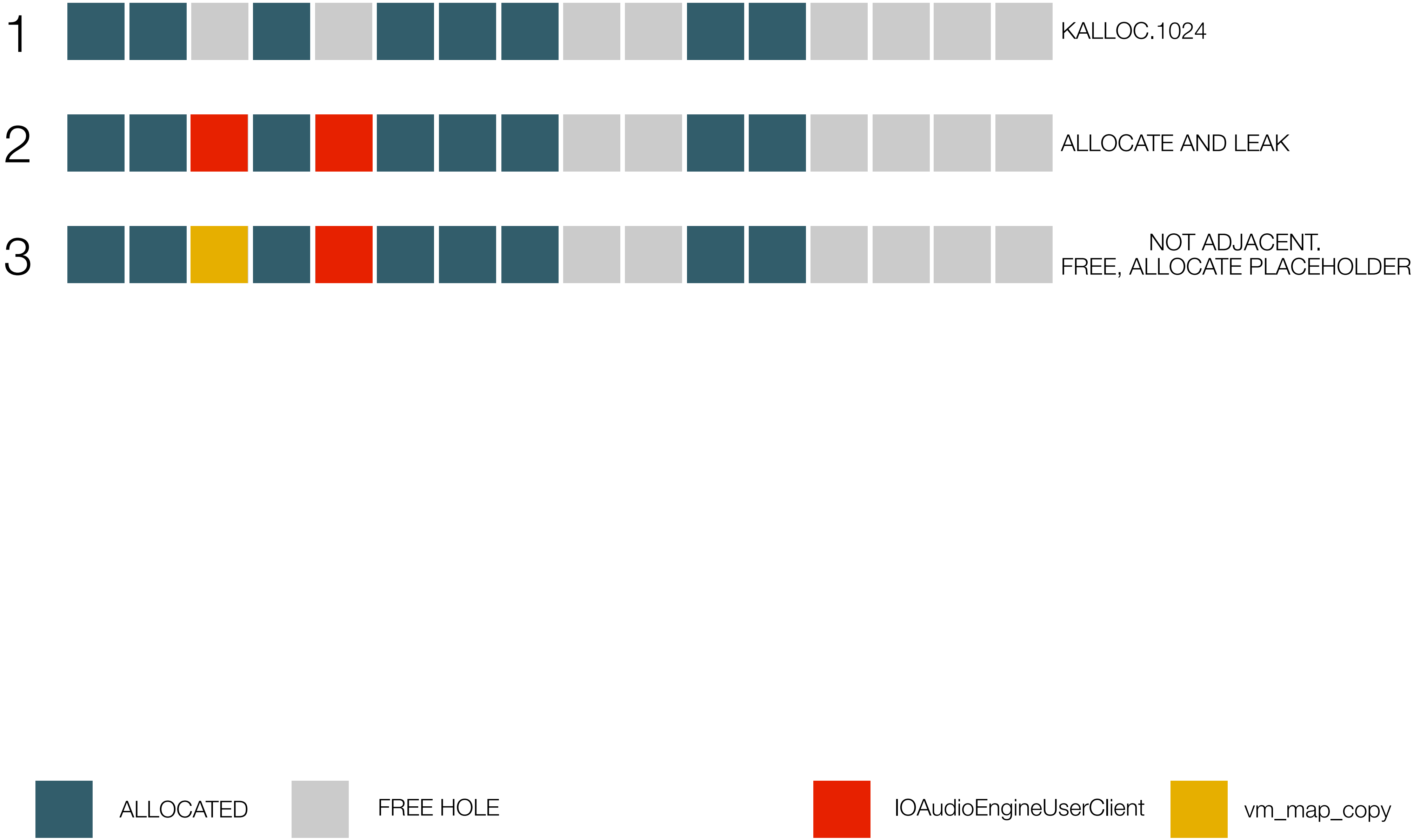
tpwn: controlling the heap layout



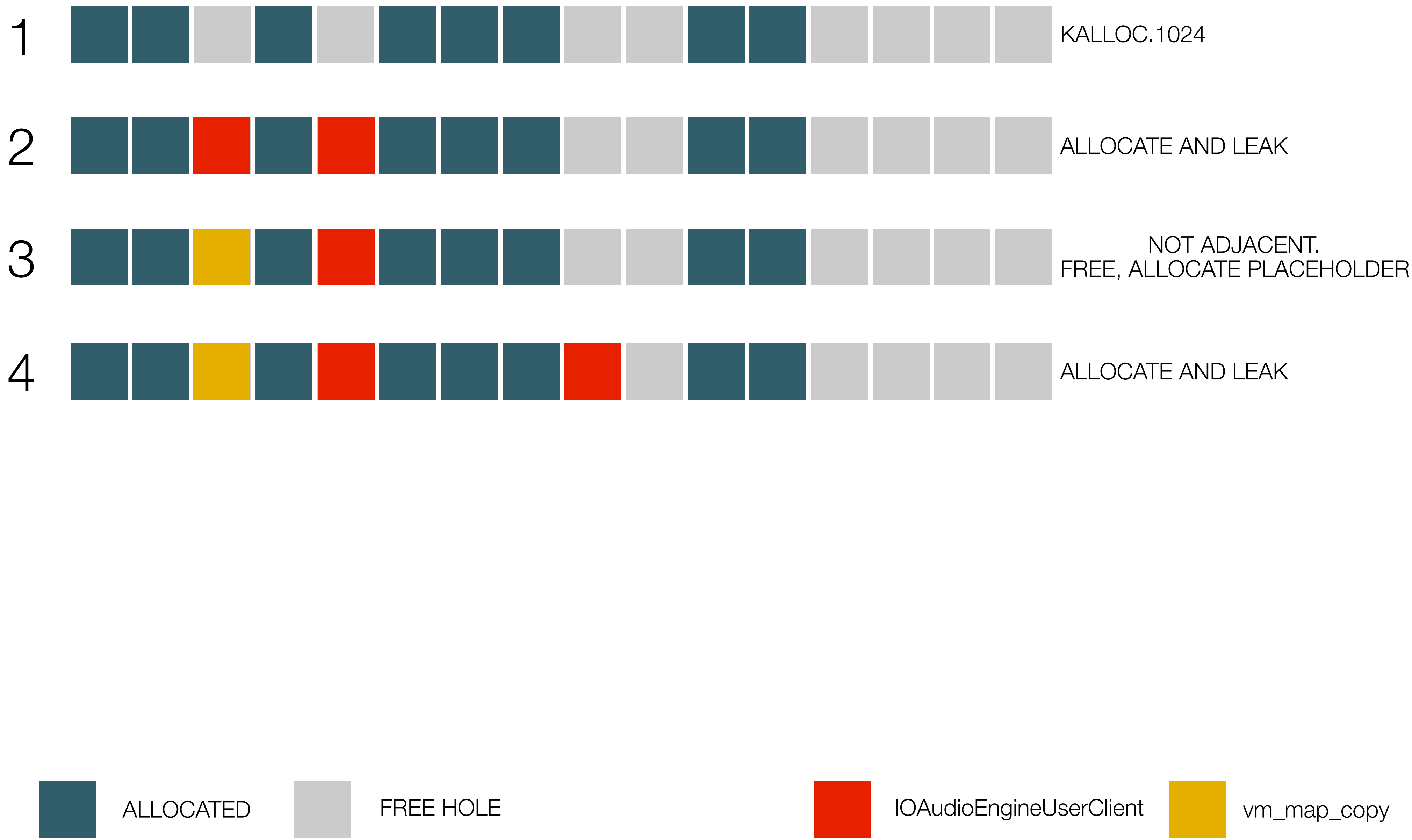
tpwn: controlling the heap layout



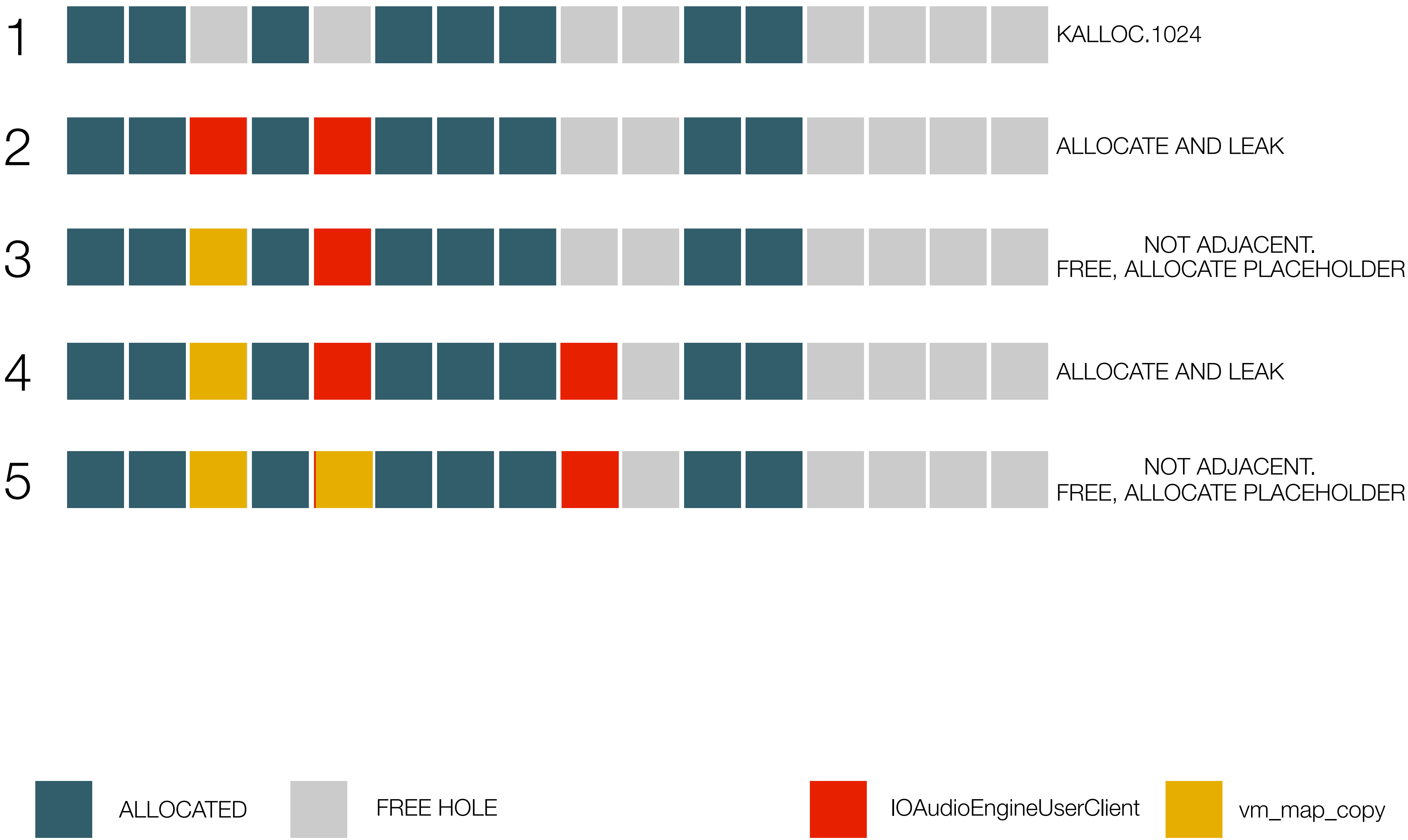
tpwn: controlling the heap layout



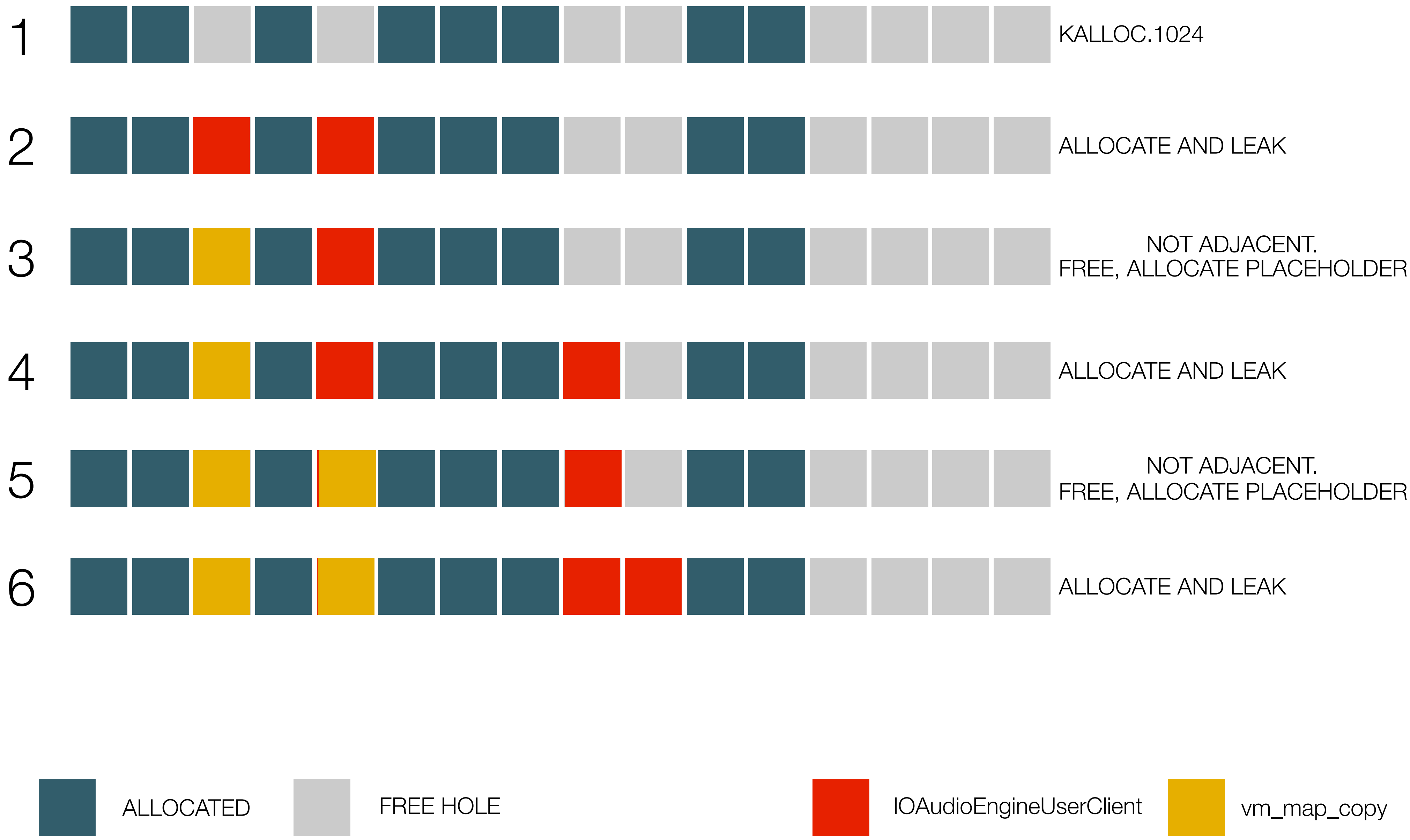
tpwn: controlling the heap layout



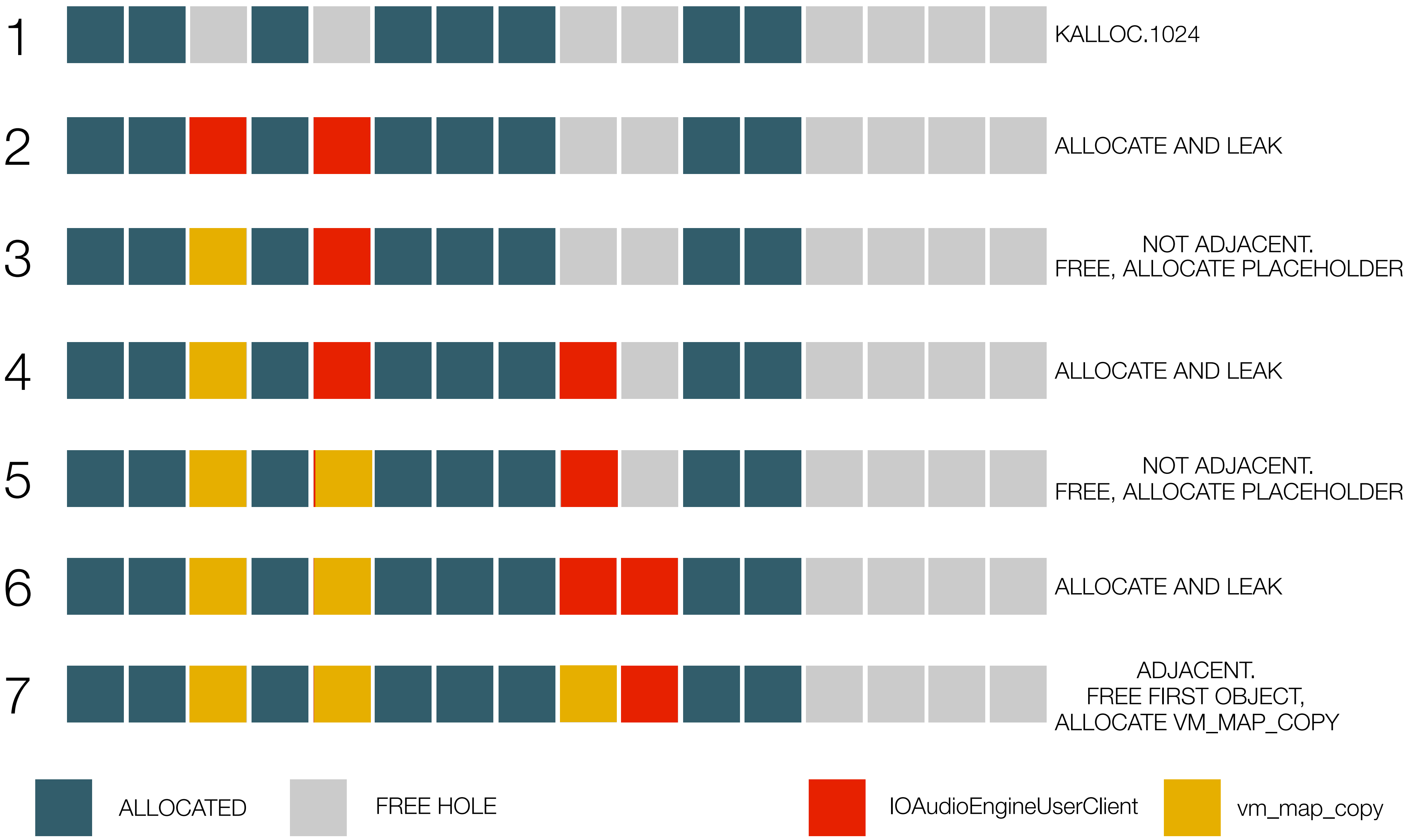
tpwn: controlling the heap layout



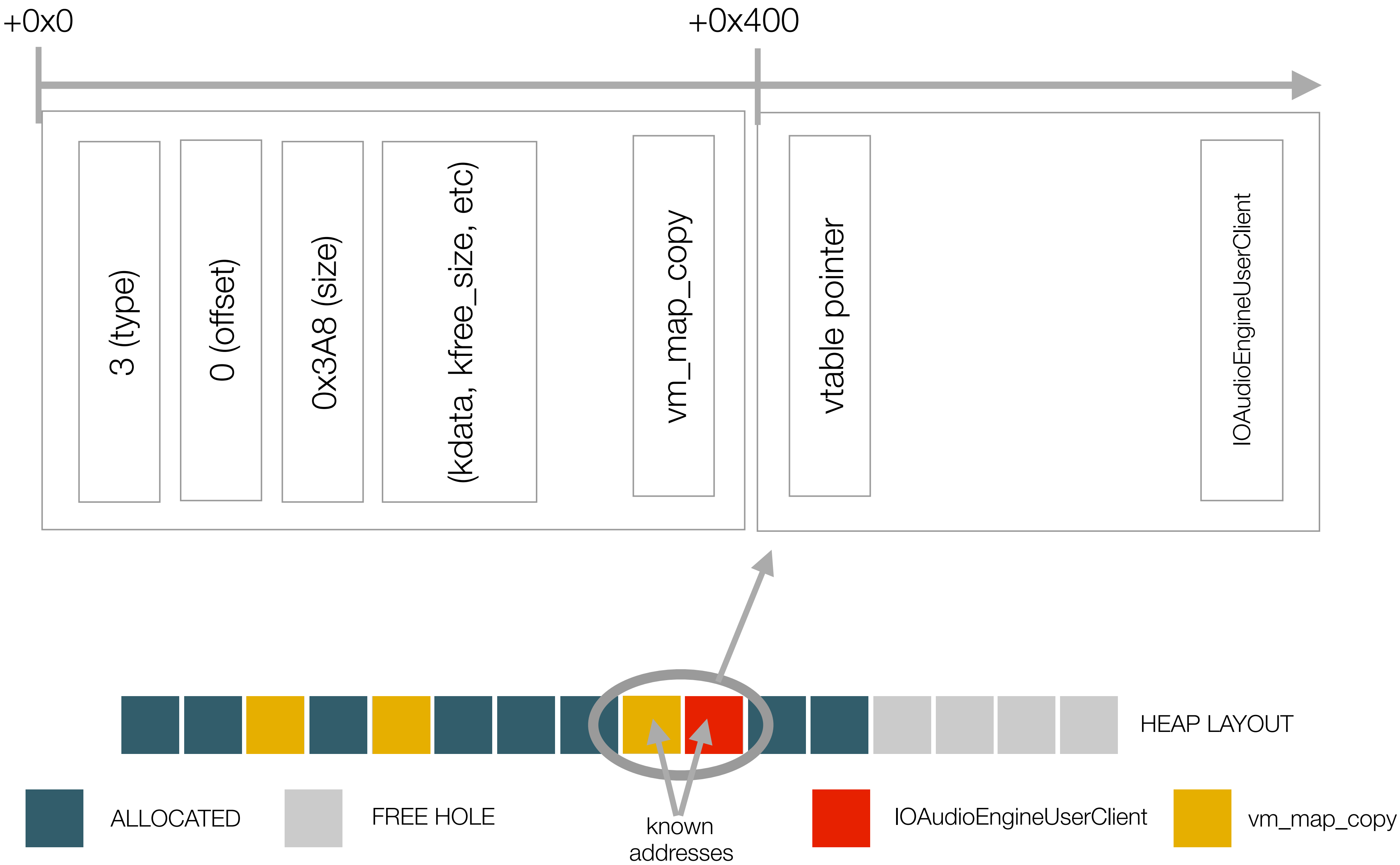
tpwn: controlling the heap layout



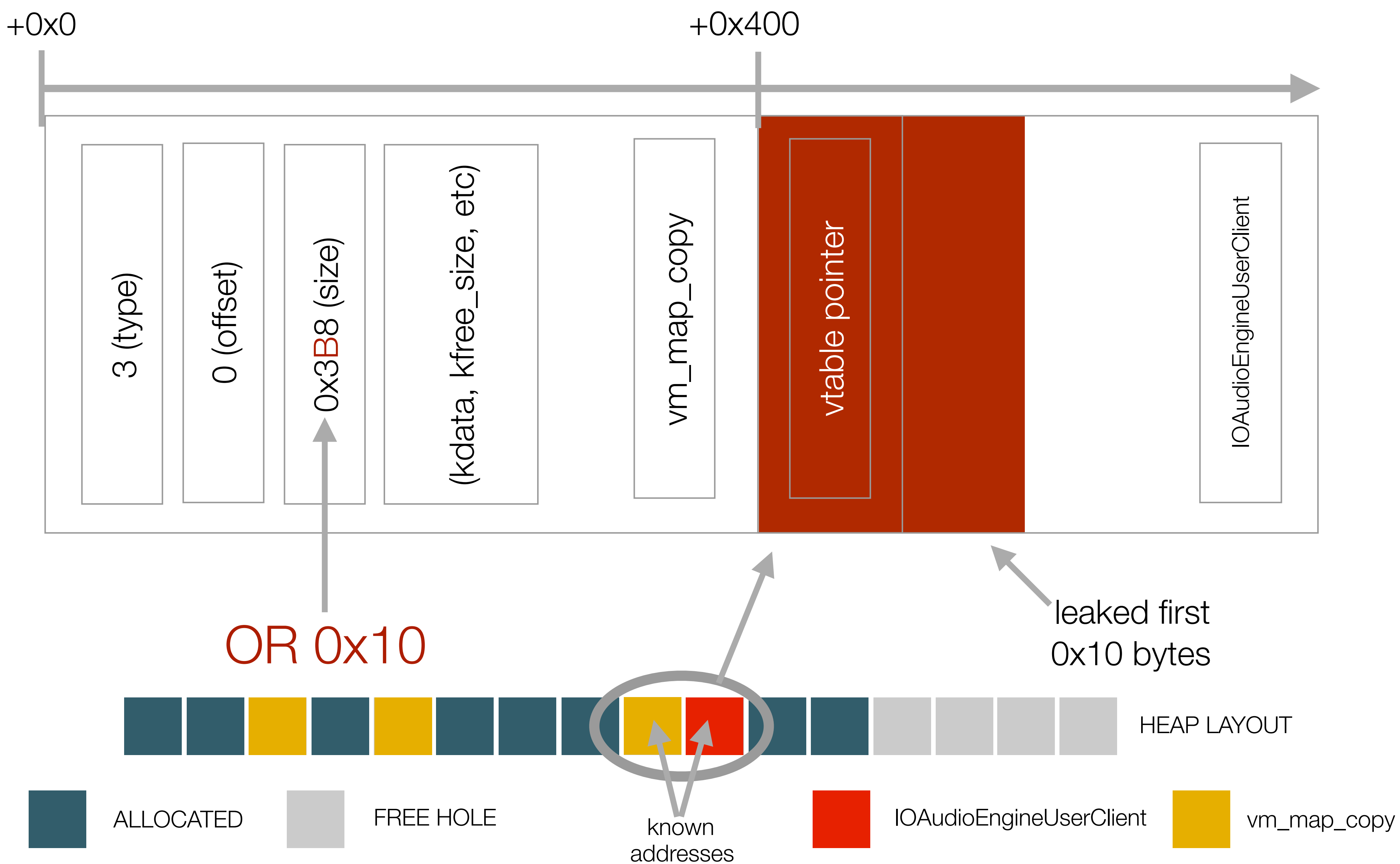
tpwn: controlling the heap layout



tpwn: 10.10 kASLR leaking strategy



tpwn: 10.10 kASLR leaking strategy



tpwn: a 10.10 kernel exploit

- Result:

```
[qwertyoruiop@qwertyoruiops-iMac:~/xnux/x]$ make
gcc *.m -o tpwn -framework IOKit -framework Foundation -m32 -Wl,-pagezero_size,0
 -O3
strip tpwn
[qwertyoruiop@qwertyoruiops-iMac:~/xnux/x]$ ./tpwn
leaked kaslr slide, @ 0x0000000000000000
sh-3.2# uname -a
Darwin qwertyoruiops-iMac.local 14.4.0 Darwin Kernel Version 14.4.0: Thu May 28
11:35:04 PDT 2015; root:xnu-2782.30.5~1/RELEASE_X86_64 x86_64
sh-3.2#
```

https://github.com/kpwn/tpwn

(fairly straightforward code)

vm_map_copy corruption

10.11 Info Leaking Strategies

The XNU Heap: vm_map_copy in 10.11

- Structure has been changed in 10.11
- On x86_64 sizeof(vm_map_copy) is 0x18 now

```
10.11 debug kernel:
struct vm_map_copy
{
  int type;
  vm_object_offset_t offset;
  vm_map_size_t size;
  vm_map_copy::$30C14F0EB10F809AE5F27A96BE564370 c_u;
};

union vm_map_copy::$30C14F0EB10F809AE5F27A96BE564370
{
  vm_map_header hdr;
  vm_object_t object;
  uint8_t_0 kdata[];
};
```

```
10.10 source:

struct vm_map_copy {
    int         type;
#define VM_MAP_COPY_ENTRY_LIST      1
#define VM_MAP_COPY_OBJECT      2
#define VM_MAP_COPY_KERNEL_BUFFER   3
    vm_object_offset_t  offset;
    vm_map_size_t       size;
    union {
        struct vm_map_header    hdr;    /* ENTRY_LIST */
        vm_object_t         object; /* OBJECT */
        struct {
        void            *kdata;       /* KERNEL_BUFFER */
        vm_size_t       kalloc_size;  /* size of this copy_t */
        } c_k;
    } c_u;
};
```

The XNU Heap: vm_map_copy in 10.11

- Size to kfree and data size have been unified
    - Cannot read adjacent memory without corrupting it, since increasing data size past heap allocation boundaries will free into the wrong zone
- Pointer to data has been removed
    - Can’t read data pointer off adjacent vm_map_copy
    - Can’t swap data pointer to leak arbitrary memory
- New techniques are needed

vm_map_copy: Leaking adjacent data in 10.11

- Leaking adjacent bytes can now be done only by first reading and corrupting, then writing back the read data
  - Not as reliable as corrupting data size since it involves a re-allocation

Leaking heap pointers in 10.11

- You can’t read the data pointer off a vm_map_copy to leak heap pointers since it has been removed from the structure
- Heap address leaks are useful since they allow you to locate controlled data in the kernel heap
- Just use another structure containing heap pointers
- The free list is an easy target

Leaking heap pointers in 10.11

- Allocate two adjacent vm_map_copy structures
- Free the second
- Corrupt the first to increase size
- Read the first (leaking adjacent memory)
- Allocate a new vm_map_copy with the leaked data
- Allocate two vm_map_copy structures in the same zone, second you allocate will be located at the pointer you've leaked off the free list

Leaking arbitrary memory in 10.11

- You can't swap the data pointer off a vm_map_copy to get arbitrary memory leaks since it has been removed from the structure
- OSData is a kernel C++ object used to represent generic data. On x86_64 it lives in kalloc.48
- Use io_service_open_extended's OSUnserializeXML to create OSData objects
    - Although dated, the "iOS Kernel Heap Armageddon" talk by Esser explains more about OSUnserializeXML and libkern objects

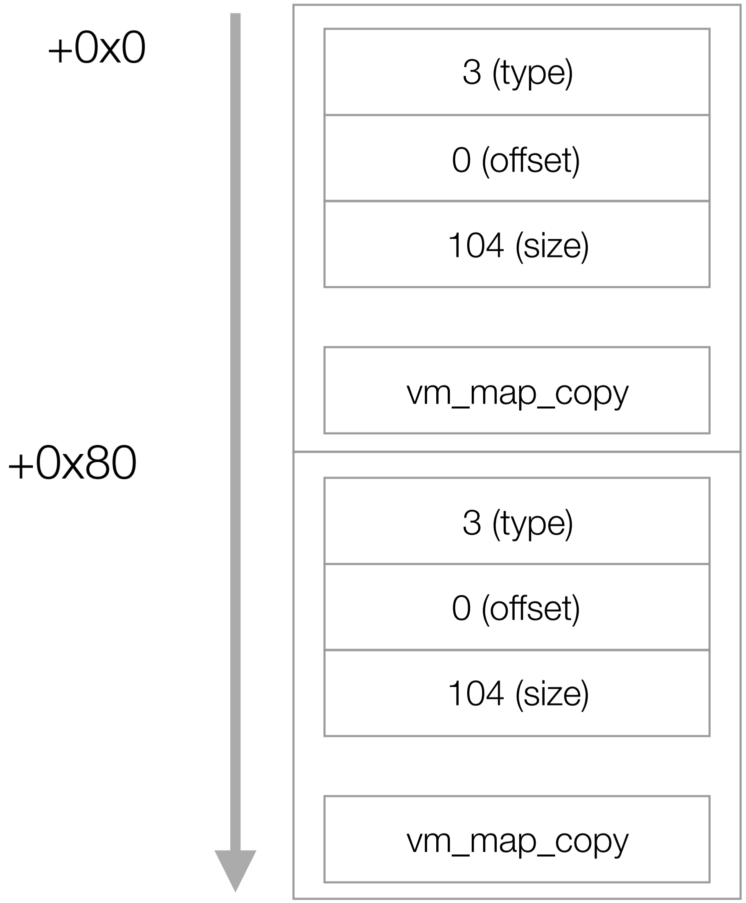
Leaking arbitrary memory in 10.11

- Allocate two adjacent vm_map_copy structures
- Corrupt the first one's size
- Read out the data, change the second structure's size to 24, write it back
- Read the second vm_map_copy out, causing a wrong free to the kalloc.48 zone
- Allocate OSData

Leaking arbitrary memory in 10.11

- OSData object now overlaps vm_map_copy's data
- Can read/write to it in userland
- vtable pointer leaks kASLR slide
- Data pointer leaks a pointer to arbitrary user-controlled data
- Changing the data pointer and setting capacity to 0xFFFFFFFF allows arbitrary memory leaks on 10.11 -> Just use IORegistryEntryCreateCFProperties to retrieve data

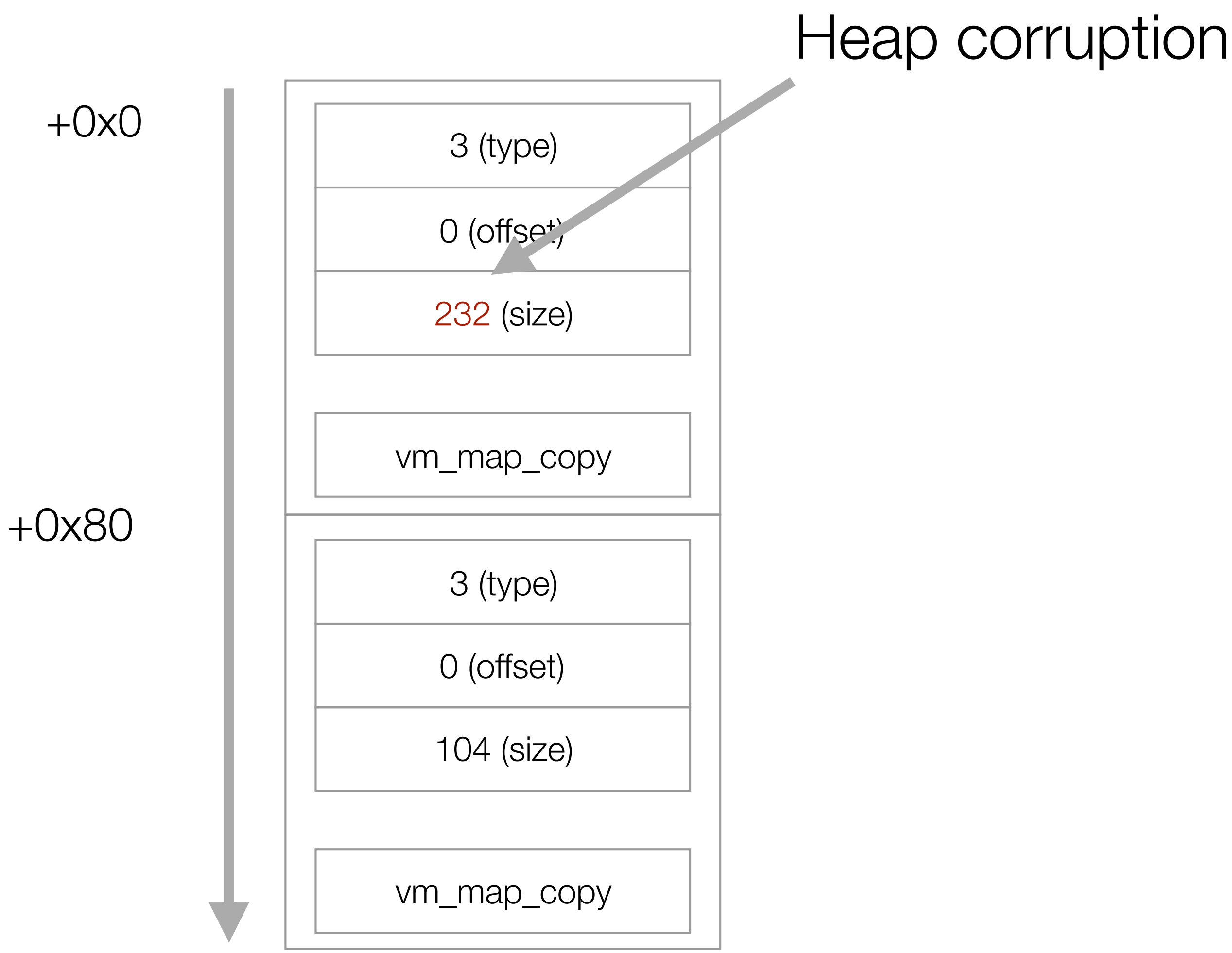
Leaking arbitrary memory in 10.11



overlapping heap chunk   heap chunk

(assuming kalloc.128)

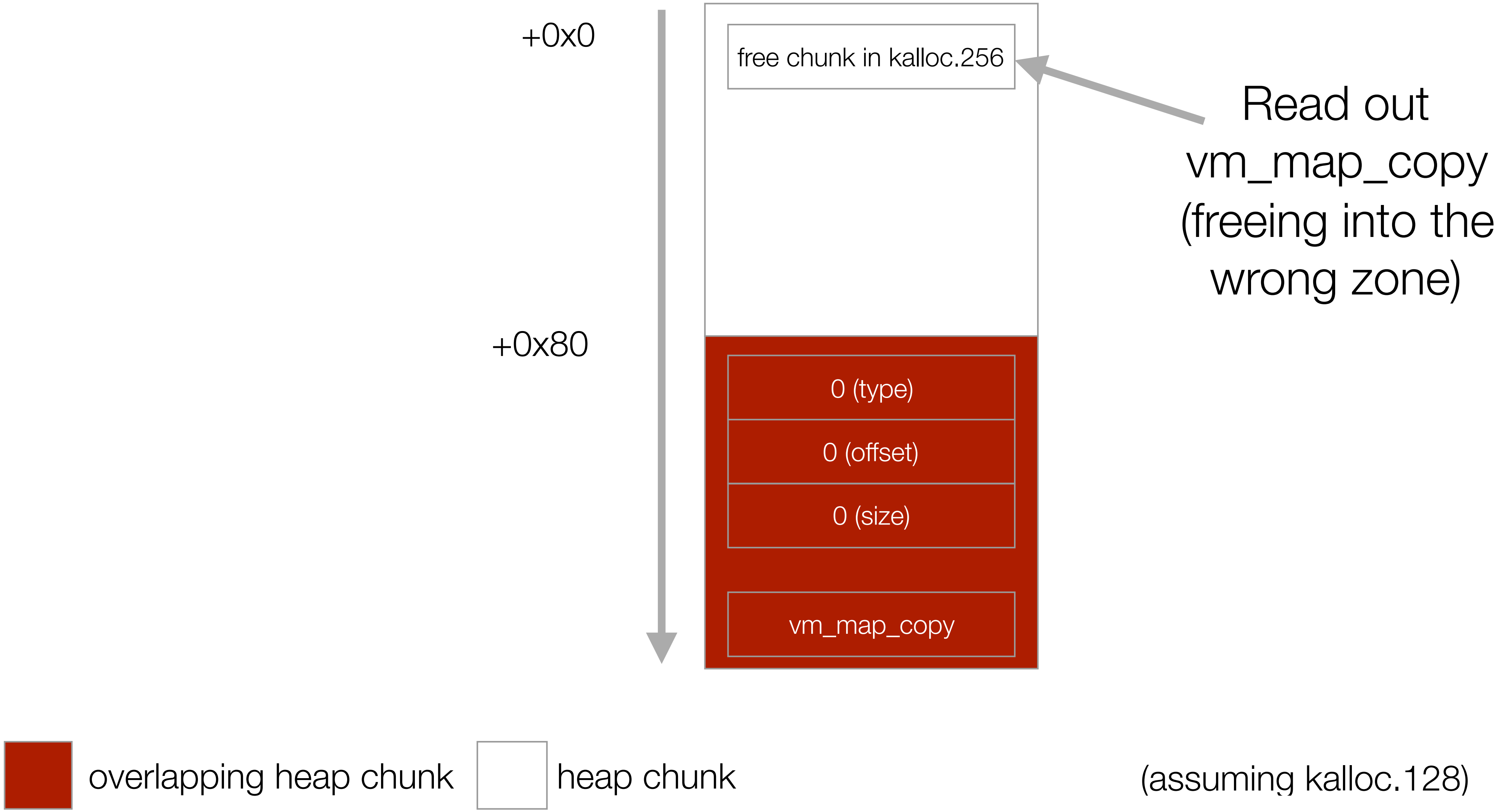
Leaking arbitrary memory in 10.11



overlapping heap chunk | heap chunk

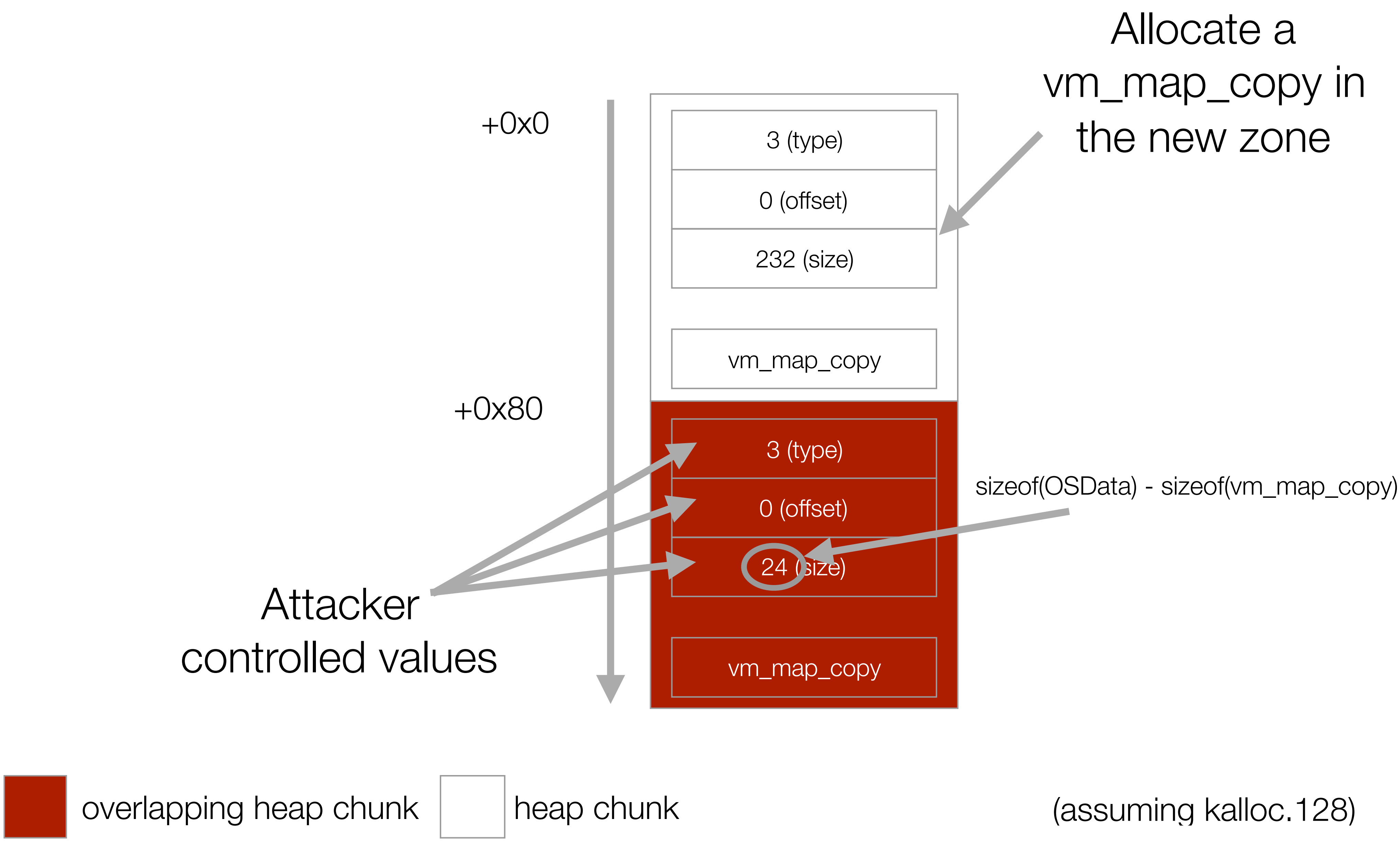
(assuming kalloc.128)

Leaking arbitrary memory in 10.11



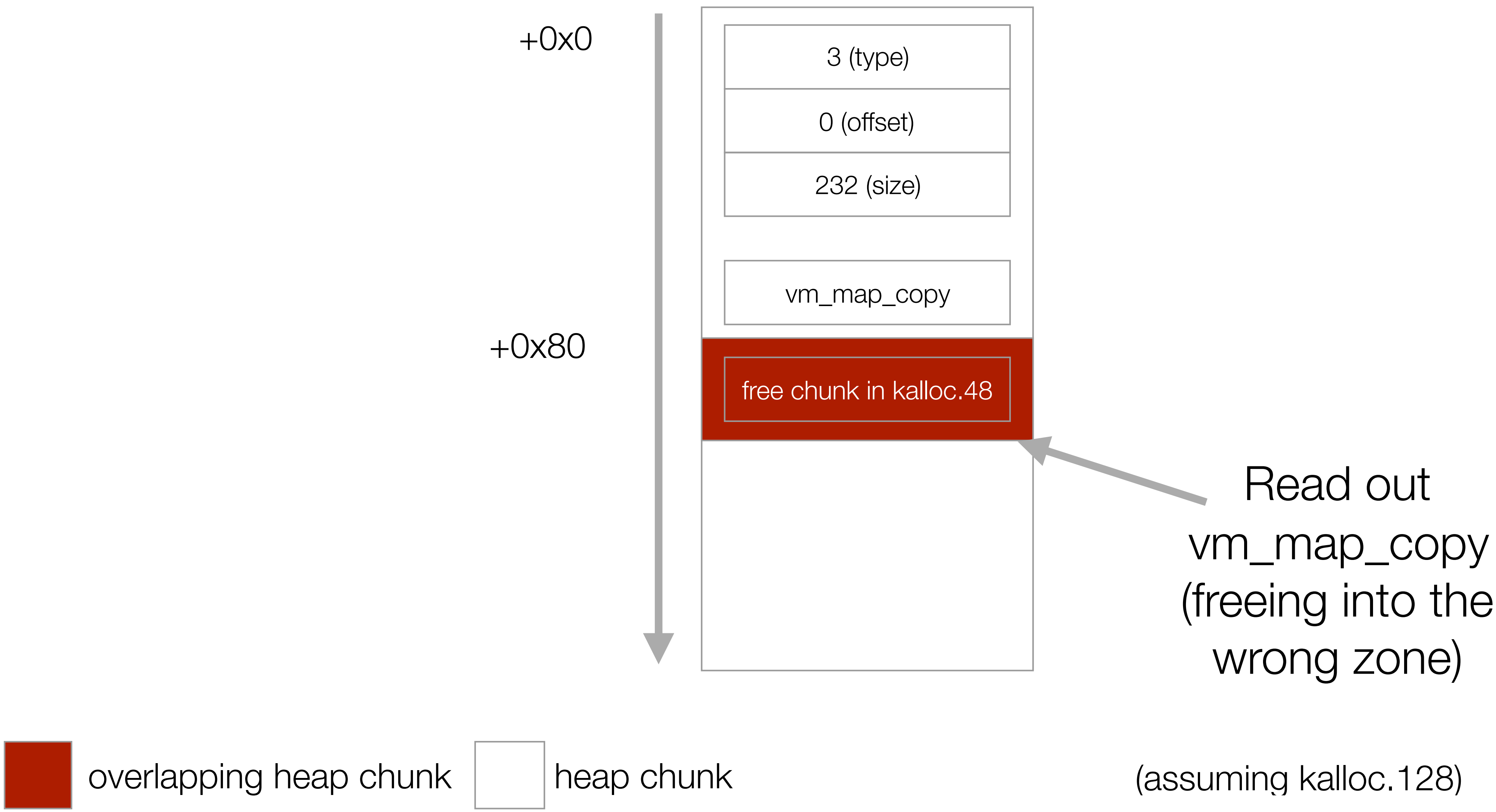
(assuming kalloc.128)

Leaking arbitrary memory in 10.11



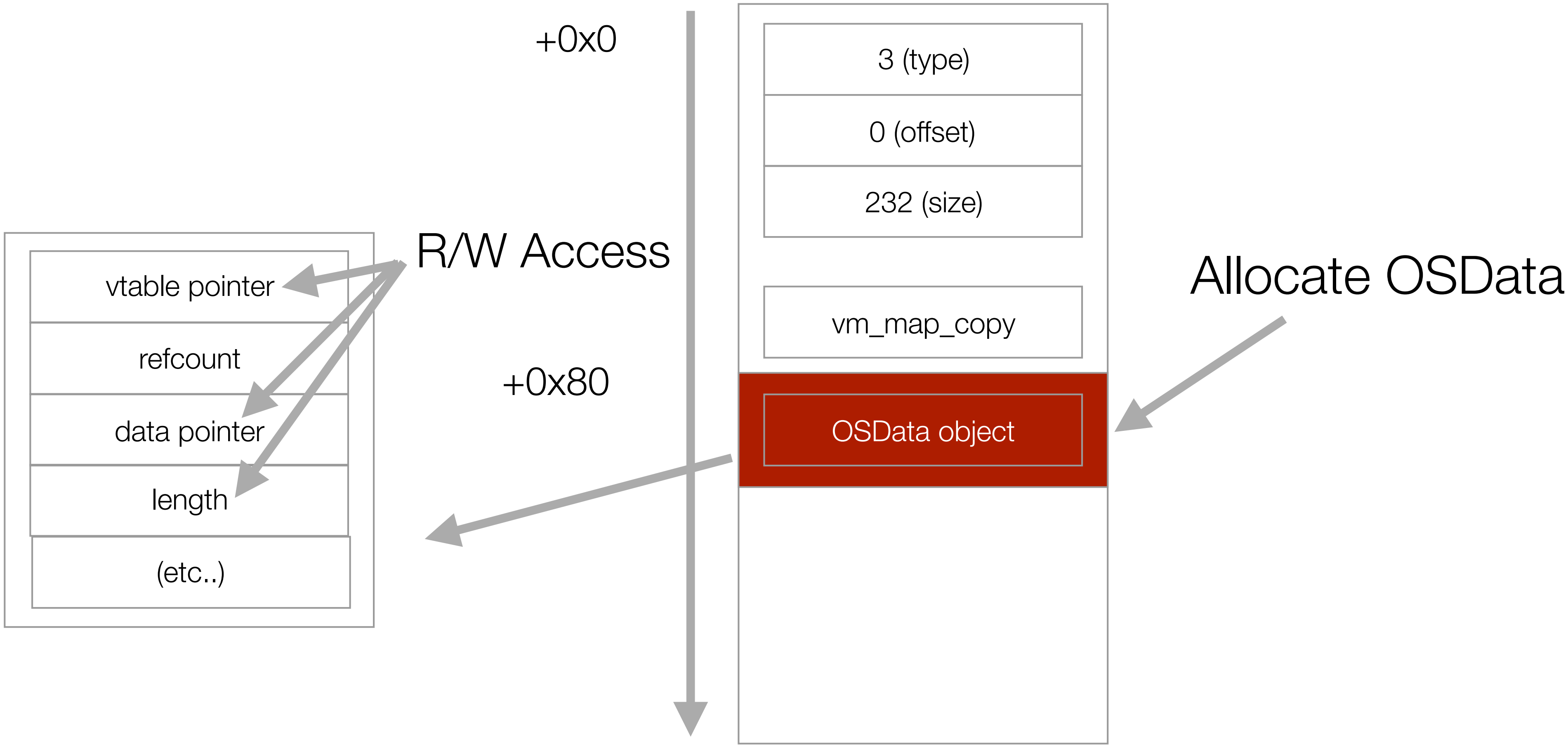
(assuming kalloc.128)

Leaking arbitrary memory in 10.11



(assuming kalloc.128)

Leaking arbitrary memory in 10.11



(assuming kalloc.128)

zalloc() timing attack

A new technique to increase heap feng shui reliability

zalloc() Timing Attack

- Most heap attacks require adjacent allocations of some sort
- You can get adjacent allocations fairly easily by emptying the free list since the layout of allocations in newly mapped pages is deterministic
- However you don't get to know exactly when a particular free list runs out unless uid=0 and PE_i_can_has_debugger() returns 1
- You can try to guess by picking an "high enough" number of allocations, but this yields to probabilistic exploits (which are good enough for e.g. jailbreaking)

zalloc() Timing Attack

- You can get adjacent allocations fairly easily by emptying the free list since **the layout of allocations in newly mapped pages is deterministic**
- Mapping pages is expensive
- Expensive enough to detect it in userland?

zalloc() Timing Attack

- In kalloc.1024, using a heap info leak to verify adjacency

time of execution of a mach_msg call with OOL data

vm_map_copyin

(newly mapped page)

```
timing attack: 1089 [0xffffff8066f16c00]
timing attack: 343 [0xffffff8066f16800]
timing attack: 334 [0xffffff8066f16400]
timing attack: 436 [0xffffff8066f16000]
timing attack: 1457 [0xffffff8066f18c00]
timing attack: 386 [0xffffff8066f18800]
timing attack: 369 [0xffffff8066f18400]
timing attack: 360 [0xffffff8066f18000]
timing attack: 1293 [0xffffff8066f19c00]
timing attack: 353 [0xffffff8066f19800]
timing attack: 362 [0xffffff8066f19400]
timing attack: 350 [0xffffff8066f19000]
timing attack: 1199 [0xffffff8066f1dc00]
timing attack: 346 [0xffffff8066f1d800]
timing attack: 333 [0xffffff8066f1d400]
timing attack: 346 [0xffffff8066f1d000]
timing attack: 1897 [0xffffff8066f1ec00]
timing attack: 349 [0xffffff8066f1e800]
timing attack: 334 [0xffffff8066f1e400]
timing attack: 353 [0xffffff8066f1e000]
timing attack: 1169 [0xffffff8066f1fc00]
timing attack: 347 [0xffffff8066f1f800]
timing attack: 401 [0xffffff8066f1f400]
timing attack: 389 [0xffffff8066f1f000]
timing attack: 1293 [0xffffff8066f22c00]
timing attack: 369 [0xffffff8066f22800]
timing attack: 351 [0xffffff8066f22400]
timing attack: 400 [0xffffff8066f22000]
timing attack: 1130 [0xffffff8066f24c00]
```

zalloc() Timing Attack

- You can get adjacent allocations fairly easily by emptying the free list since the layout of allocations in **newly mapped pages** is deterministic
- Mapping pages is expensive
- Expensive enough to detect it in userland? Yes!

zalloc() Timing Attack

- A good target to time is vm_map_copyin
- Create a bunch of vm_map_copy structs via mach_msg
- Read them out
- Recreate them, timing and keeping an average
- You are guaranteed that the average doesn’t represent newly mapped memory
- Keeping those allocated, allocate more, timing mach_msg

zalloc() Timing Attack

- Once you get a mach_msg taking more time than the average * 1.5, a new page has just been mapped in
- Number of free list entries added = PAGE_SIZE/zone size
- Do more mach_msg timing
- A time spike is expected to happen after “number of free list entries added” allocations
- If it does, for additional reliability, do it again for another page

zalloc() Timing Attack

- Once you have pages filled with adjacent vm_map_copy structures, you can easily craft the heap layout by poking holes and reallocating the objects that most suit your needs

- Limit the number of allocations to some reasonable number to avoid running out of kernel memory

- On failure you can just fall back to a probabilistic approach

zalloc() Timing Attack: A practical use case

- In some rare cases extremely precise heap layout control is required to have any form of meaningful reliability
- An example is IOHIDFamily's CVE-2015-6974
- Fixed in 10.11.1, found independently by multiple parties*
- Used by Pangu9 and npwn
- Required uid=0 on OS X, container sandbox escape on iOS.
- Terminating an IOHIDUserDevice after creating one drops the reference count without setting pointers to it to NULL

*so far I'm aware of me, @panguteam and @cererdlong

CVE-2015-6974: A textbook Use-After-Free

```
IOReturn IOHIDResourceDeviceUserClient::terminateDevice()
{
    if (_device) {
        _device->terminate();
    }
    OSSafeRelease(_device);

    return kIOReturnSuccess;
}
```

Free

```
if ( arguments->scalarInput[0] )
    AbsoluteTime_to_scalar(&timestamp) = arguments->scalarInput[0];
else
    clock_get_uptime( &timestamp );

if ( !arguments->asyncWakePort ) {
    ret = _device->handleReportWithTime(timestamp, report);
    report->release();
} else {

      return ret;
```

controlled register

Use

return value passed to userland

Both of these functions are IOExternalMethods

CVE-2015-6974: OS”notso”SafeRelease

```
IOReturn IOHIDResourceDeviceUserClient::terminateDevice()
{
    if (_device) {
        _device->terminate();
    }
    OSSafeRelease(_device);

    return kIOReturnSuccess;
}
```

what Apple did

```
/*! @function OSSafeRelease
 *  @abstract Release an object if not <code>NULL</code>.
 *  @param    inst  Instance of an OSObject, may be <code>NULL</code>.
 */
#define OSSafeRelease(inst)       do { if (inst) (inst)->release(); } while (0)

/*! @function OSSafeReleaseNULL
 *  @abstract Release an object if not <code>NULL</code>, then set it to <code>NULL</code>.
 *  @param    inst  Instance of an OSObject, may be <code>NULL</code>.
 */
#define OSSafeReleaseNULL(inst)   do { if (inst) (inst)->release(); (inst) = NULL; } while (0)
```

what Apple really wanted to do

CVE-2015-6974

```
ret = _device->handleReportWithTime(timestamp, report);
```

vcall on free'd object at vtable+0x948

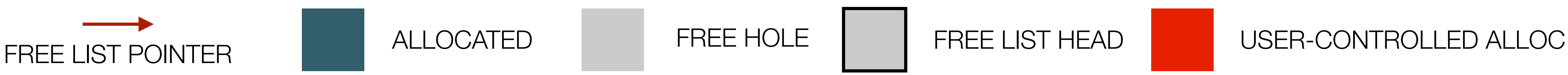
The bug allows you to control the vtable pointer used for this call
1st argument: pointer to UaF'd allocation
2nd argument: controlled 64 bit value

By controlling the vtable pointer you can get code exec easily with these constraints:

- on non-SMEP OS X you can point the vtable in userland and jump to user memory
- on non-SMAP OS X you can point the vtable in userland and ROP with a kASLR info leak
- on iOS and SMAP OS X you need to use an heap info leak as well as a kASLR info leak

CVE-2015-6974

An alternate avenue for exploitation for SMAP / iOS requires a **tightly controlled heap layout**.
The vtable index for the vcall is 0x948 and the object lives in kalloc.256.



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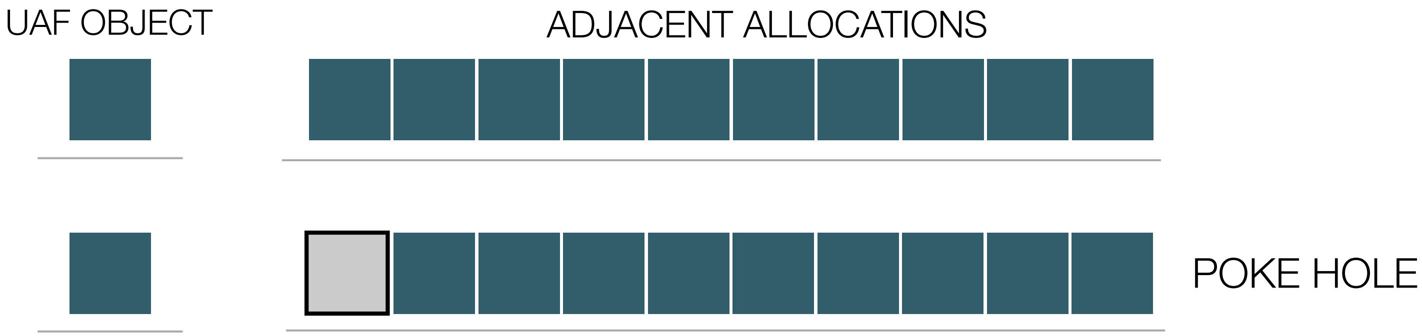

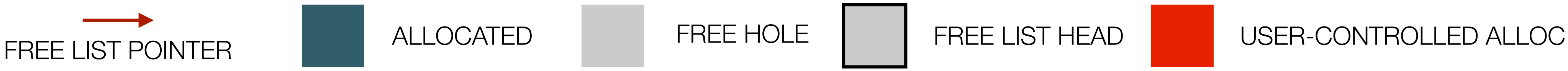

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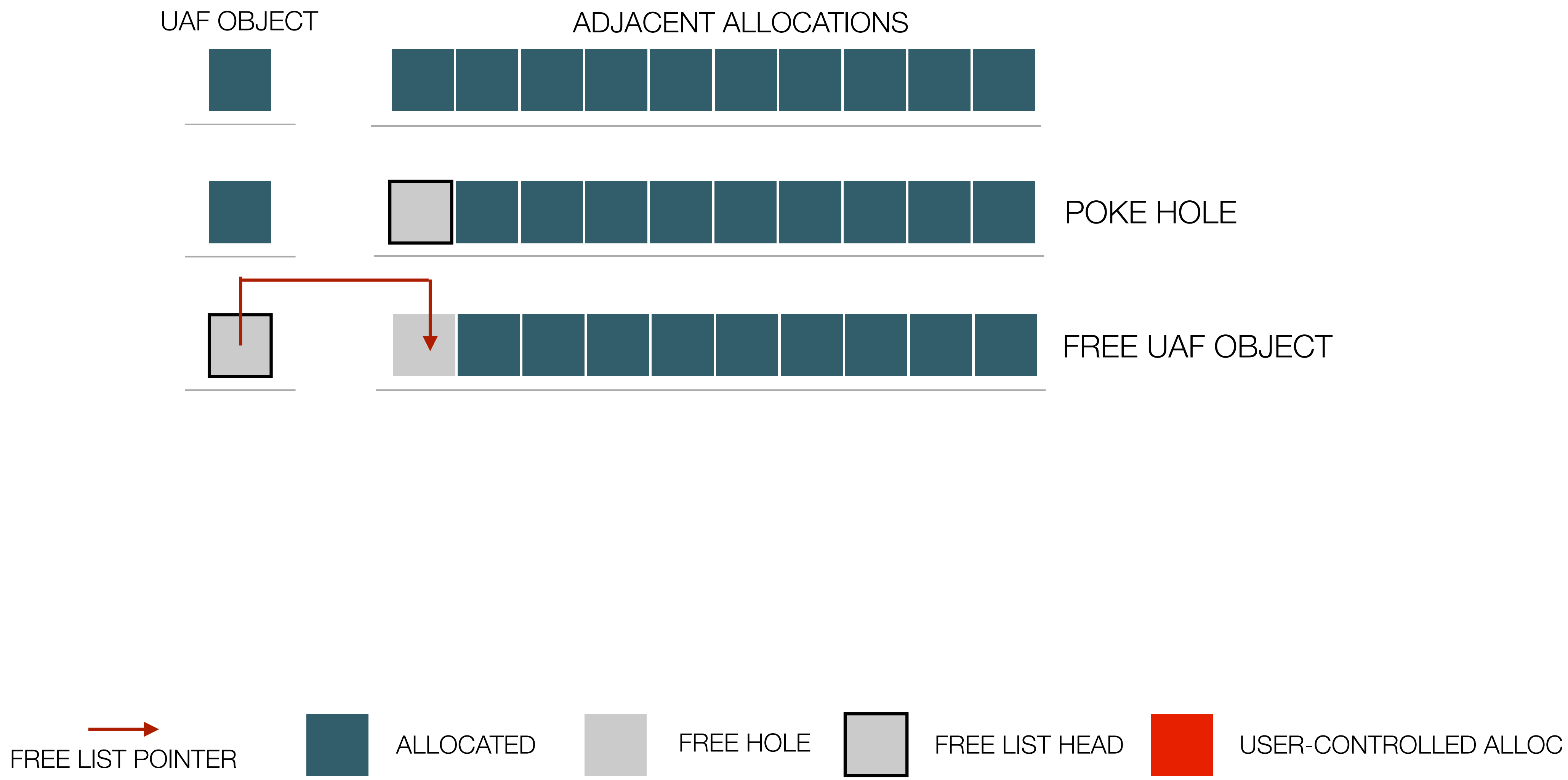

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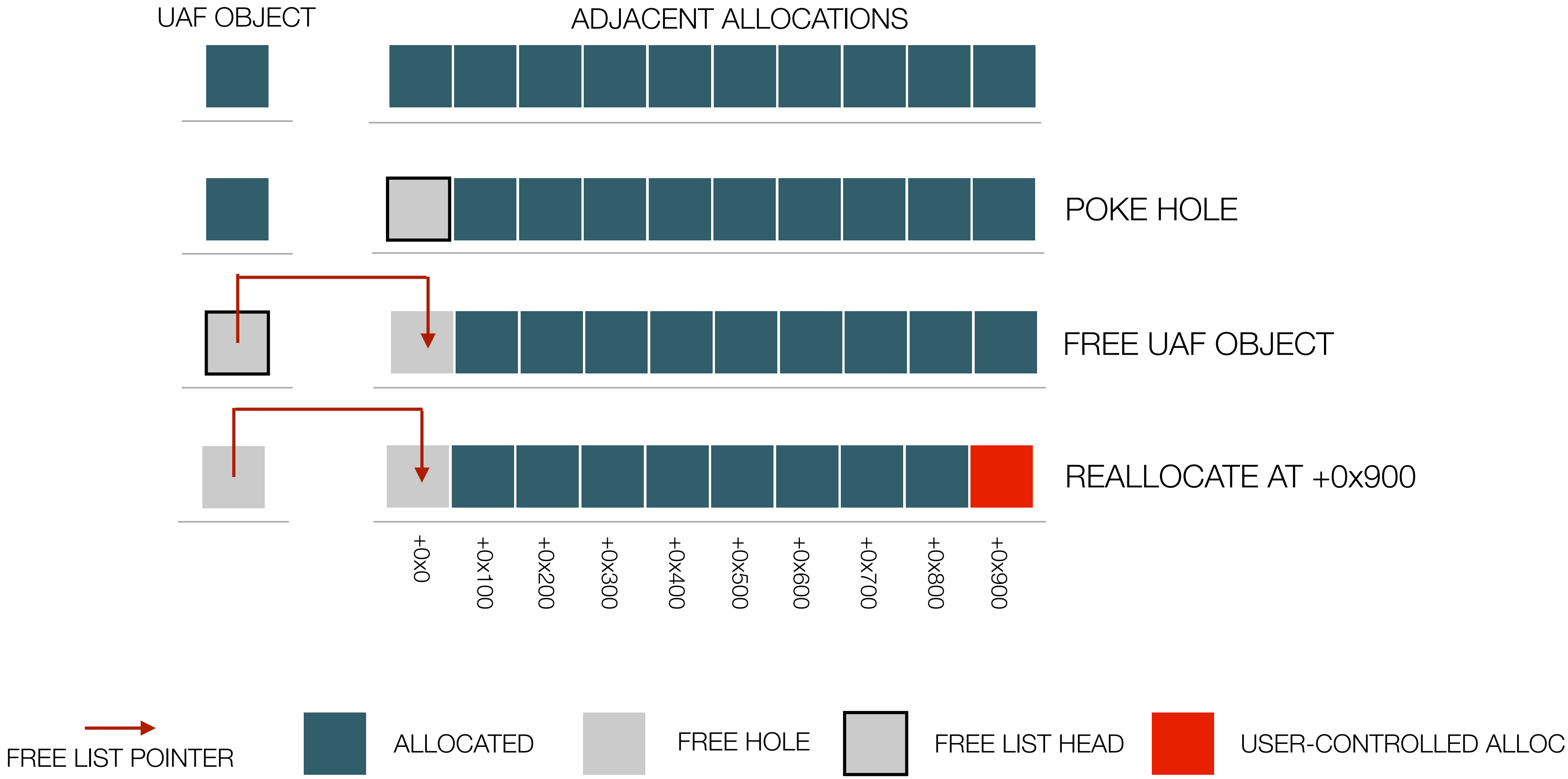

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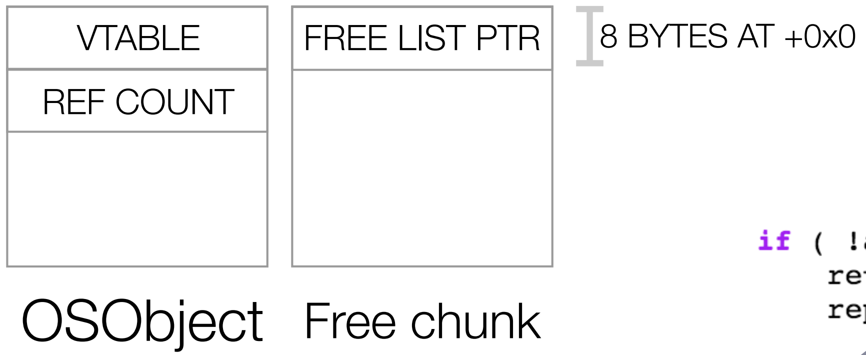
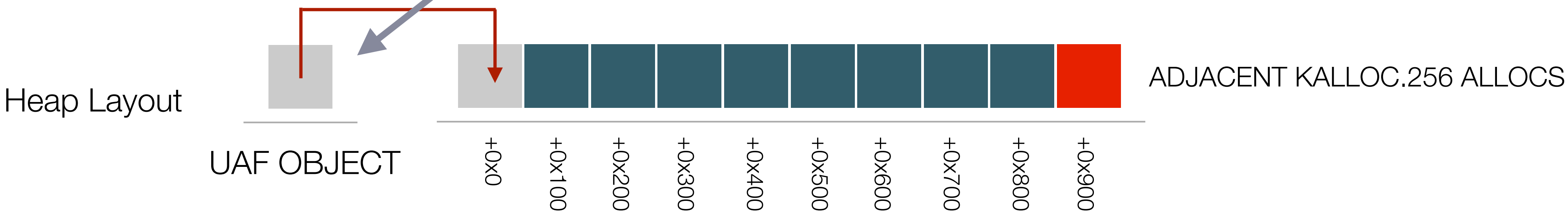



```
if ( !arguments->asyncWakePort ) {
    ret = _device->handleReportWithTime(timestamp, report);
    report->release();
```



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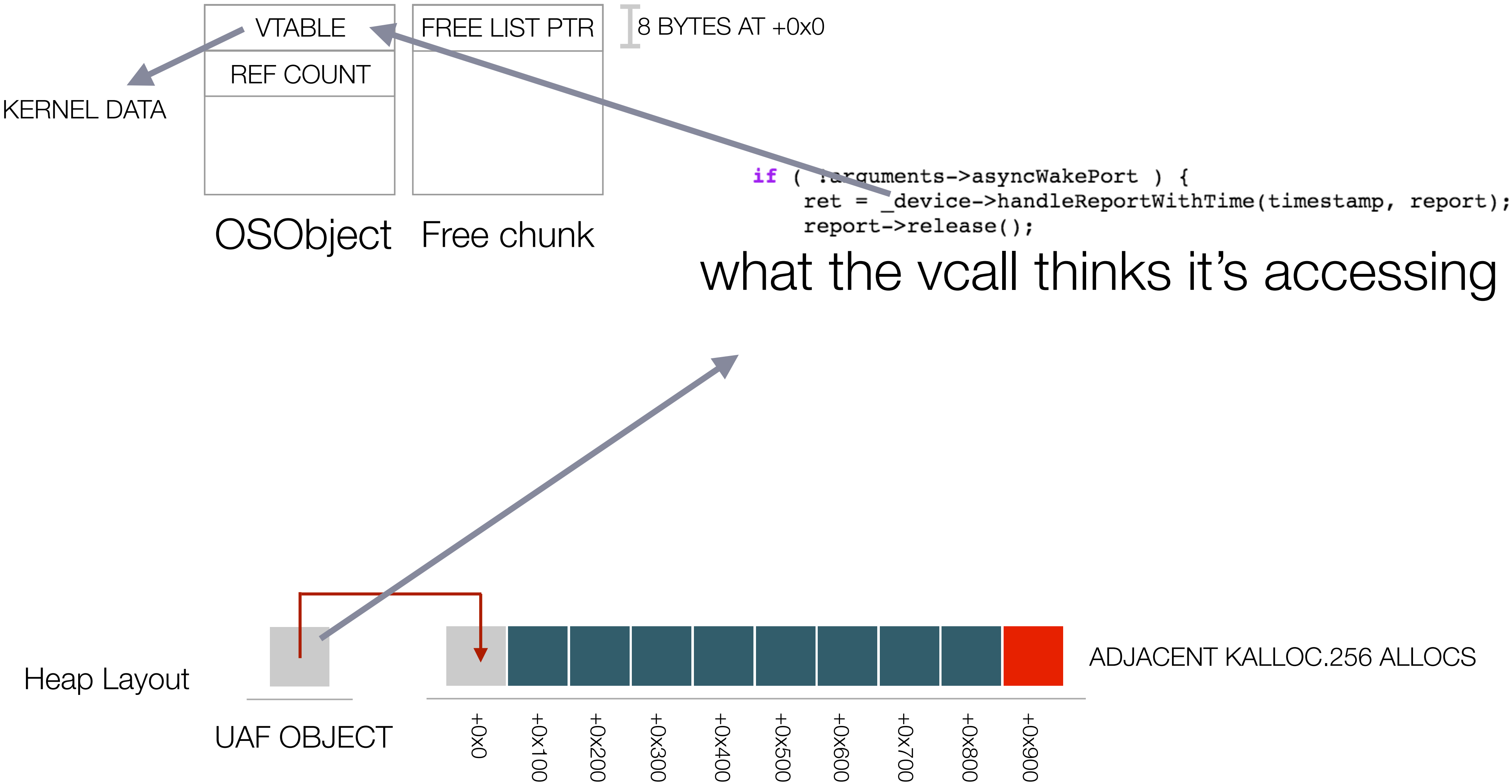

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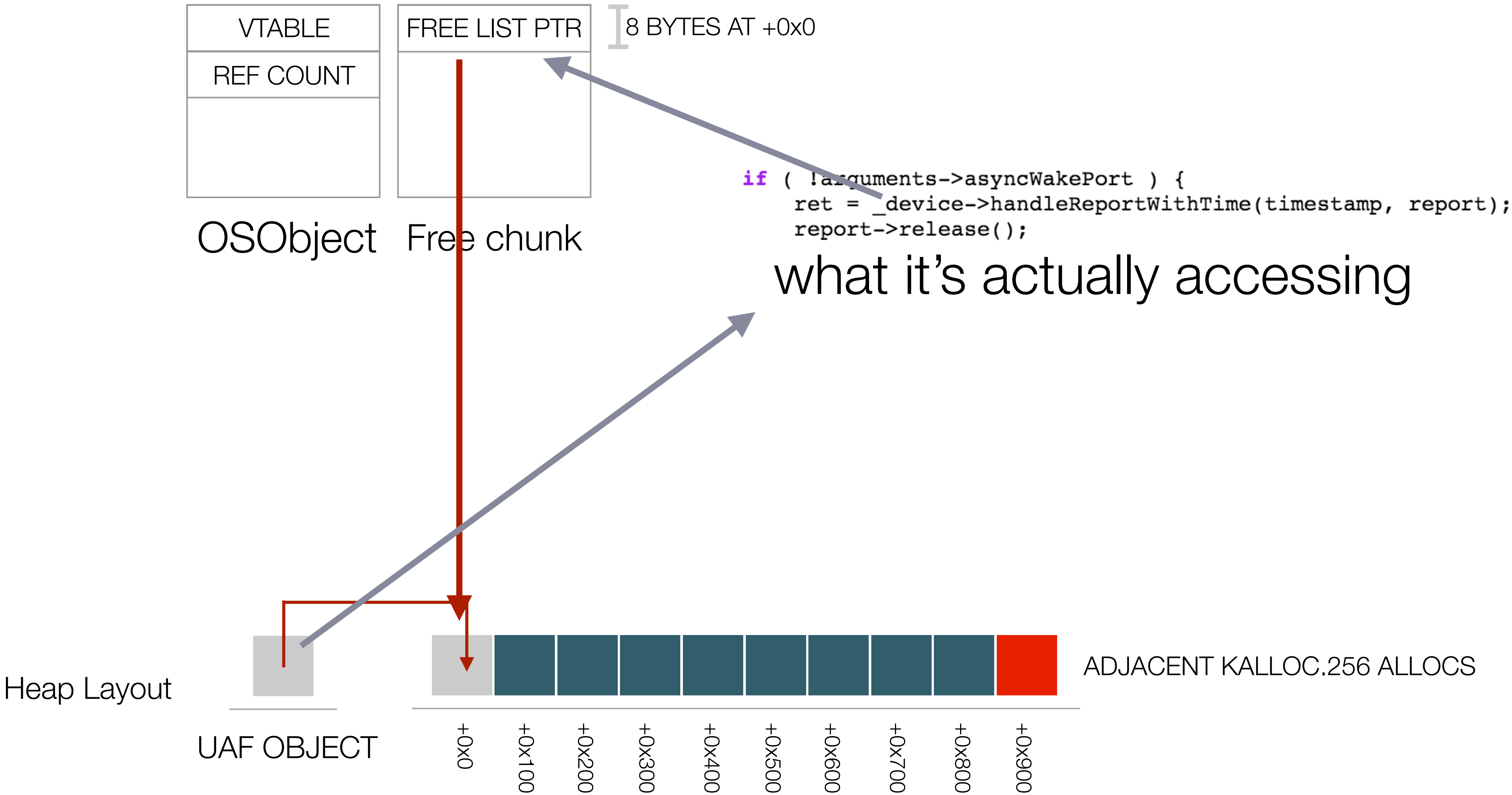

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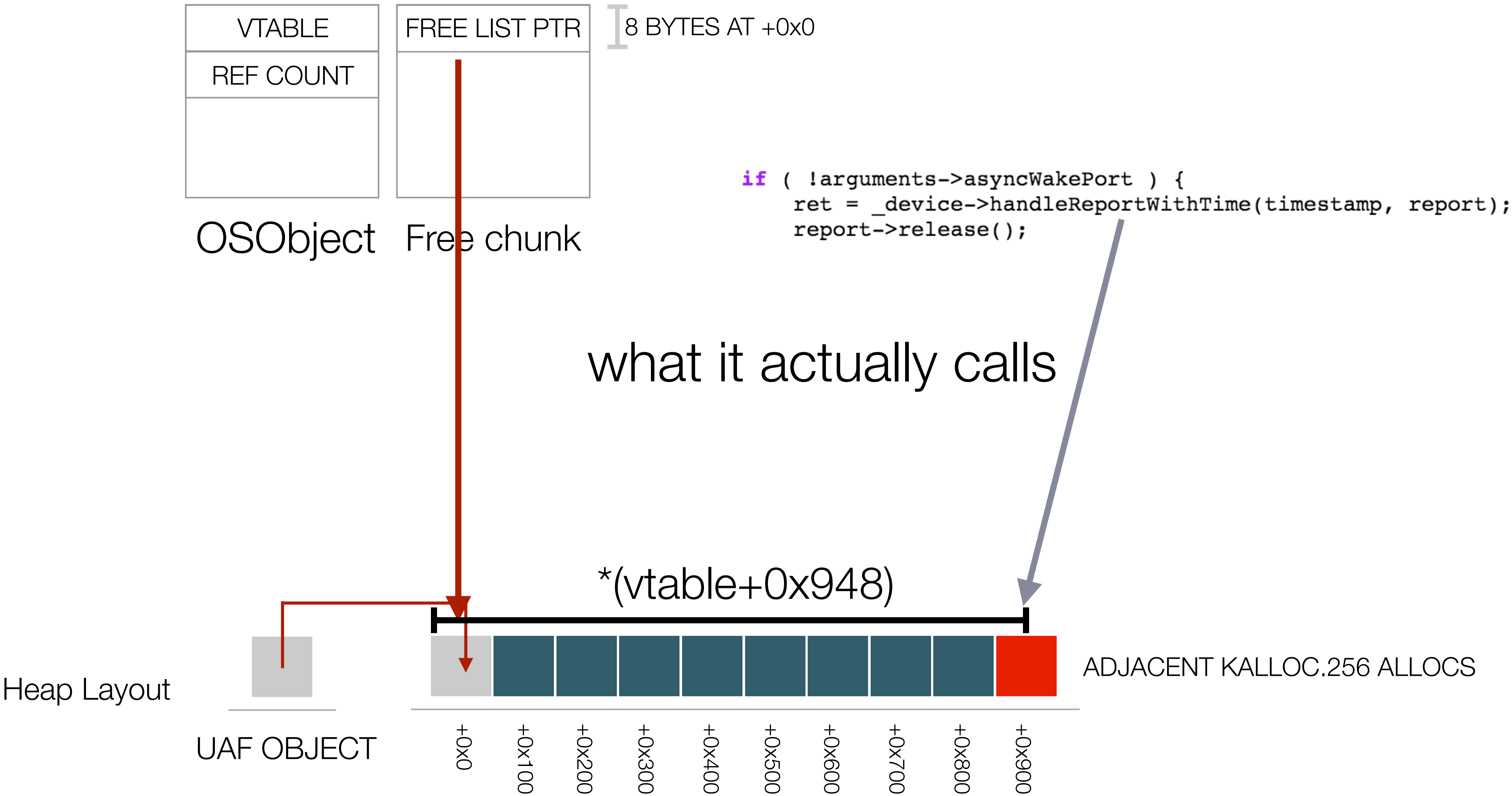

CVE-2015-6974

- We can now control the instruction pointer and the 2nd argument
- First argument is a pointer to the UaF'd allocation
- kASLR slide not leaked yet
  - In npwn I used “kas_info”, which could be considered cheating but is still allowed on SIP-protected 10.11.1
  - Alternative kASLR leaking strategy (used by Pangu9): abuse the UaF like a type confusion

Disabling System Integrity Protection

- Pedro Vilaça (@osxreverser) discussed _csr_set_allow_all for his “rootfool” kernel extension
- We can just redirect the vcall to _csr_set_allow_all
- As long as the first argument is non-NULL, it’ll disable SIP for good
- ROP is not needed at all

Demo!

Black Hat Sound Bytes

- The rapid growth in use of sandboxing technology is pushing many attackers to kernel attacks.
- Apple has been trying to harden the kernel heap for years now but it’s still fairly easy to carry out attacks.
- The zalloc timing attack can prove useful in many situations

Questions?

Twitter: @qwertyoruiop
Mail: me at qwertyoruiop dot com

Thanks to:

- windknown (@windknown) & Pangu Team (@PanguTeam)
    - Pangu9 was amazing stuff!
- Steven De Franco (@iH8sn0w)
- Filippo Bigarella (@FilippoBiga)
- Joshua Hill (@p0sixninja)
- Nicholas Allegra (@comex)
- Jonathan Levin (@Technologeeks / http://newosxbook.com/)
- Stefan Esser (@i0n1c)
    - Make sure you've read his XNU exploitation papers!
- Pedro Vilaça (@osxreverser)
- Mark Dowd (@mdowd)
- Tarjei Mandt (@kernelpool)