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Heap Exploitation Abstraction by Example

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Who are we

- Patroklos Argyroudis, argp
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  - Topics: kernel/heap exploitation, auditing
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Outline

- Example: FreeBSD kernel memory allocator (UMA)
- Example: Linux kernel memory allocator (SLUB)
- Example: jemalloc userland memory allocator
- Abstracting heap exploitation

Related Work

- “Attacking the Core: Kernel Exploiting Notes” [1]
  - twiz, sgrakkyu, Phrack, 2007
  - Linux (heap), Solaris (stack)
- “Kernel Wars” [2]
  - signedness.org, Black Hat EU, 2007
  - *BSD (mbuf), Windows (stack)

Related Work

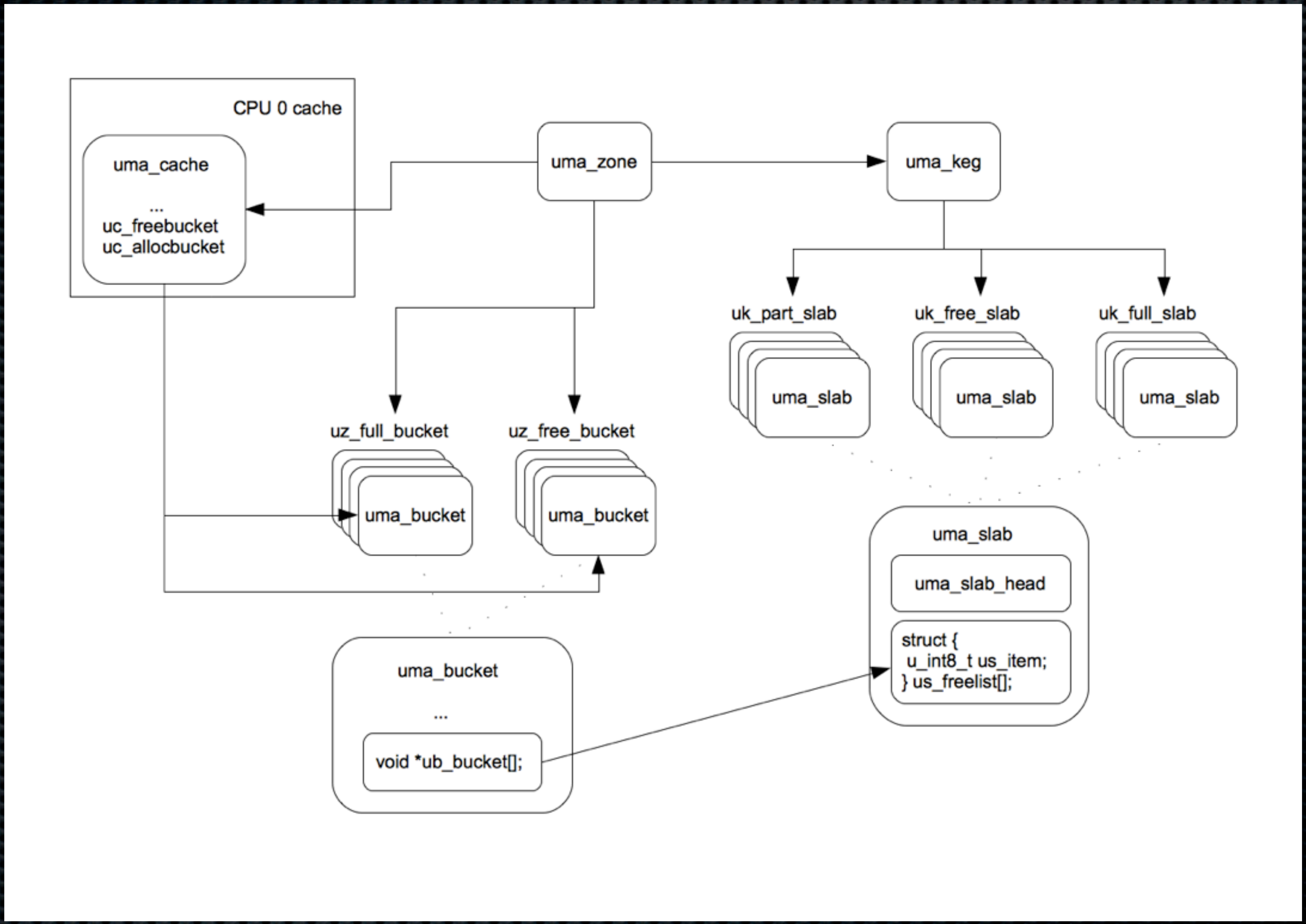
- “Exploitation in the Modern Era (Blueprint)” [3]
  - Chris Valasek, Ryan Smith, Black Hat EU, 2011
  - First attempt to abstract exploitation
- “Patras Heap Massacre” [4]
  - Chariton Karamitas, Patroklos Argyroudis, Fosscomm, 2011
  - Attempt to abstract heap exploitation

Example: FreeBSD UMA

Universal Memory Allocator

- FreeBSD’s kernel memory allocator
  - Funded by Nokia for a proprietary project
  - The IPSO firewall/security appliance (thanks FX!)
  - Donated to FreeBSD
- Functions like a traditional slab allocator
  - Large areas, or slabs, of memory are pre-allocated
  - malloc(9) returns a free slot

UMA Architecture



UMA Architecture

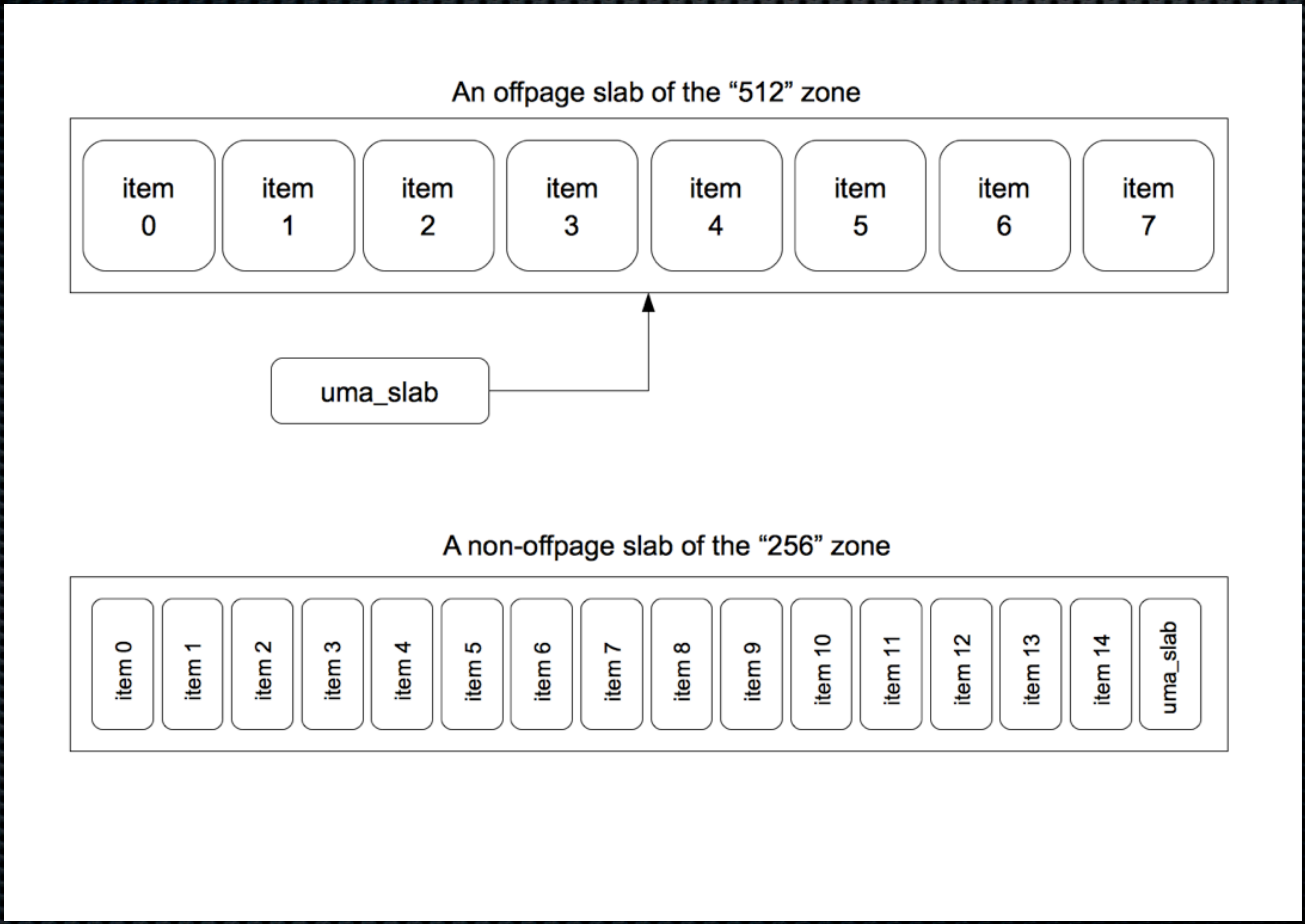
- Each zone (uma_zone) holds buckets (uma_bucket) of items
- The items are allocated on the zone's slabs (uma_slab)
- Each zone is associated with a keg (uma_keg)
- The keg holds the corresponding zone's slabs
- Each slab is of the same size as a page frame (usually 4096 bytes)
- Each slab has a slab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

vmstat(8)

```
ITEM                     SIZE  LIMIT     USED    FREE      REQ FAIL SLEEP

UMA Kegs:                 208,      0,      84,      1,      84,   0,    0
UMA Zones:                512,      0,      84,      0,      84,   0,    0
UMA Slabs:                568,      0,     872,      3,    3612,   0,    0
UMA RCntSlabs:            568,      0,     195,      1,     195,   0,    0
UMA Hash:                 256,      0,       3,     12,       3,   0,    0
16 Bucket:                152,      0,      39,     11,      39,   0,    0
32 Bucket:                280,      0,      23,      5,      23,   0,    0
64 Bucket:                536,      0,      15,      6,      15,  57,    0
128 Bucket:              1048,      0,      19,      2,      19, 569,    0
VM OBJECT:                216,      0,     846,     72,   15779,   0,    0
MAP:                      232,      0,       7,     25,       7,   0,    0
KMAP ENTRY:               120,  15004,      33,    122,    5952,   0,    0
MAP ENTRY:                120,      0,     543,    108,   35870,   0,    0
fakepg:                   120,      0,       0,      0,       0,   0,    0
mt_zone:                 4112,      0,     301,     10,     301,   0,    0
16:                        16,      0,    2485,    203,   38918,   0,    0
32:                        32,      0,    2780,    250,   19562,   0,    0
64:                        64,      0,    5223,    153,   34106,   0,    0
128:                      128,      0,    7156,    123,   10268,   0,    0
256:                      256,      0,     830,     40,    3359,   0,    0
512:                      512,      0,     347,     52,    3699,   0,    0
1024:                    1024,      0,      50,    142,    6246,   0,    0
:
```

Slabs



An offpage slab of the "512" zone
item 0
item 1
item 2
item 3
item 4
item 5
item 6
item 7
uma_slab
A non-offpage slab of the "256" zone
item 0
item 1
item 2
item 3
item 4
item 5
item 6
item 7
item 8
item 9
item 10
item 11
item 12
item 13
item 14
uma_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;	/* partially allocated slabs */
	LIST_HEAD(,uma_slab)	uk_free_slab;	/* empty slab list */
	LIST_HEAD(,uma_slab)	uk_full_slab;	/* full slabs */

	u_int32_t	uk_recurse;	/* Allocation recursion count */
	u_int32_t	uk_align;	/* Alignment mask */
	u_int32_t	uk_pages;	/* Total page count */
	u_int32_t	uk_free;	/* Count of items free in slabs */
	u_int32_t	uk_size;	/* Requested size of each item */
	u_int32_t	uk_rsize;	/* Real size of each item */
	u_int32_t	uk_maxpages;	/* Maximum number of pages to alloc */

	uma_init	uk_init;	/* Keg's init routine */
	uma_fini	uk_fini;	/* Keg's fini routine */
	uma_alloc	uk_allocf;	/* Allocation function */
	uma_free	uk_freef;	/* Free routine */

	struct vm_object	*uk_obj;	/* Zone specific object */
	vm_offset_t	uk_kva;		/* Base kva for zones with objs */
	uma_zone_t	uk_slabzone;	/* Slab zone backing us, if OFFPAGE */

	u_int16_t	uk_pgoff;	/* Offset to uma_slab struct */
	u_int16_t	uk_ppera;	/* pages per allocation from backend */
	u_int16_t	uk_ipers;	/* Items per slab */
	u_int32_t	uk_flags;	/* Internal flags */
};
```

uma_zone

```c
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_slaballoc	uz_slab;	/* Allocate a slab from the backend. */
	uma_ctor	uz_ctor;	/* Constructor for each allocation */
	uma_dtor	uz_dtor;	/* Destructor */
	uma_init	uz_init;	/* Initializer for each item */
	uma_fini	uz_fini;	/* Discards memory */

	u_int32_t	uz_flags;	/* Flags inherited from kegs */
	u_int32_t	uz_size;	/* Size inherited from kegs */

	u_int64_t	uz_allocs UMA_ALIGN; /* Total number of allocations */
	u_int64_t	uz_frees;	/* Total number of frees */
	u_int64_t	uz_fails;	/* Total number of alloc failures */
	u_int64_t	uz_sleeps;	/* Total number of alloc sleeps */
	uint16_t	uz_fills;	/* Outstanding bucket fills */
	uint16_t	uz_count;	/* Highest value ub_ptr can have */

	/*
	 * This HAS to be the last item because we adjust the zone size
	 * based on NCPU and then allocate the space for the zones.
	 */
	struct uma_cache	uz_cpu[1]; /* Per cpu caches */
};
```

Code Execution

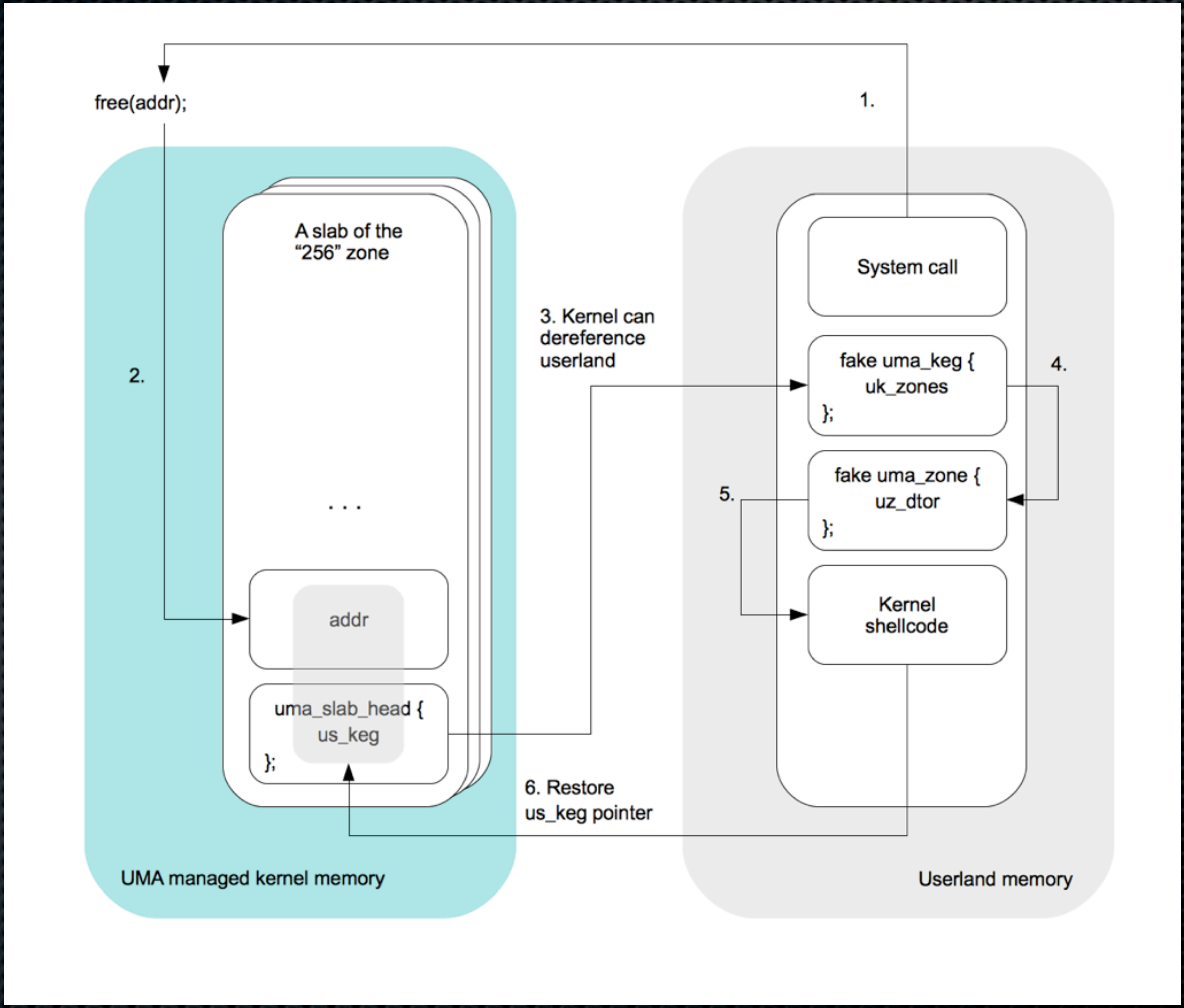
```
uma_zfree_arg(uma_zone_t zone, void *item, void *udata)
{
        uma_cache_t cache;
        uma_bucket_t bucket;
        int bflags;
        int cpu;

#ifdef UMA_DEBUG_ALLOC_1
        printf("Freeing item %p to %s(%p)\n", item, zone->uz_name, zone);
#endif
        CTR2(KTR_UMA, "uma_zfree_arg thread %x zone %s", curthread,
            zone->uz_name);

        /* uma_zfree(..., NULL) does nothing, to match free(9). */
        if (item == NULL)
                return;

        if (zone->uz_dtor)
                zone->uz_dtor(item, zone->uz_size, udata);
```

uz_dtor Hijacking



Example: Linux SLUB

SLUB

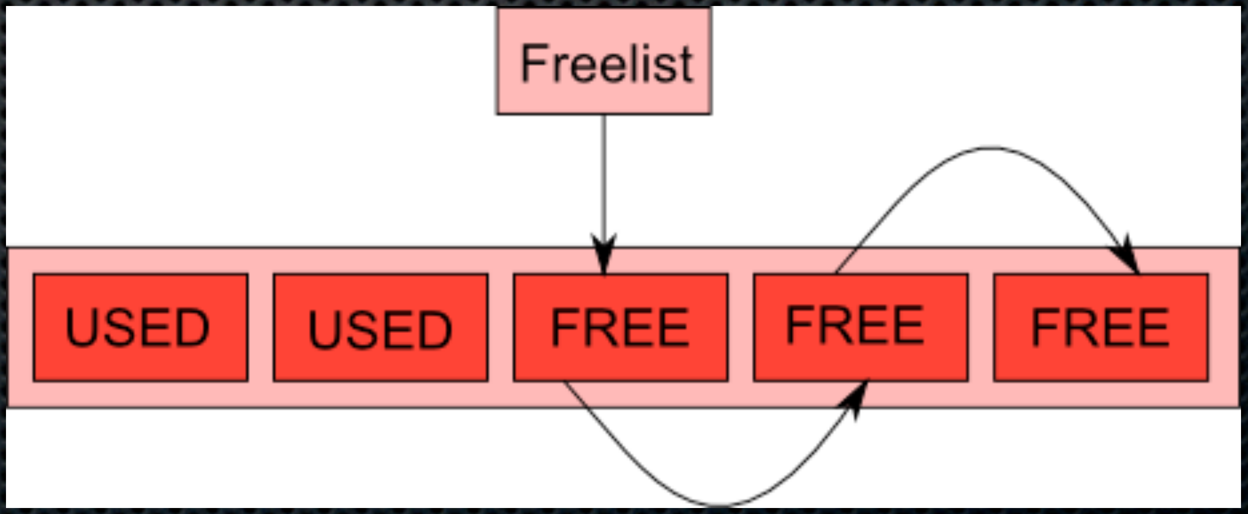
- Organizes physical memory frames in “caches” (UMA: kegs)
- Each cache holds slabs (UMA: slab) of objects (UMA: items) of the same size
  - kmalloc-32, kmalloc-64, task_struct, mm_struct
- Objects on a slab are contiguous
- A slab may have both allocated (used) and deallocated (free) objects

SLUB's slabs

- Each slab is at least PAGE_SIZE bytes (default 4096 bytes)
- A slab may span many pages
  - kmalloc-32: 128 objects * 32 bytes == 4096 bytes
  - task_struct (1088 bytes): 30 objects * 1088 bytes == 32640
  - A task_struct slab spans 8 pages
- Each CPU core has its own slabs

Metadata?

- No separate/dedicated metadata structures stored on the slabs
- Each free object stored on a slab has a next-free-object pointer
- Each slab has a page structure (struct page) that has a pointer (freelist) to the slab's first free object



SLUB's behavior

- Partial slabs: some free and some used objects
- New requests satisfied from partial slabs
  - Least-recently-used (LRU) policy
  - No partial slabs → allocation of new slab
- Generic slabs (e.g. kmalloc-32) are used to store different objects of the same size
  - Different kernel structures, buffers, etc
  - Contiguous

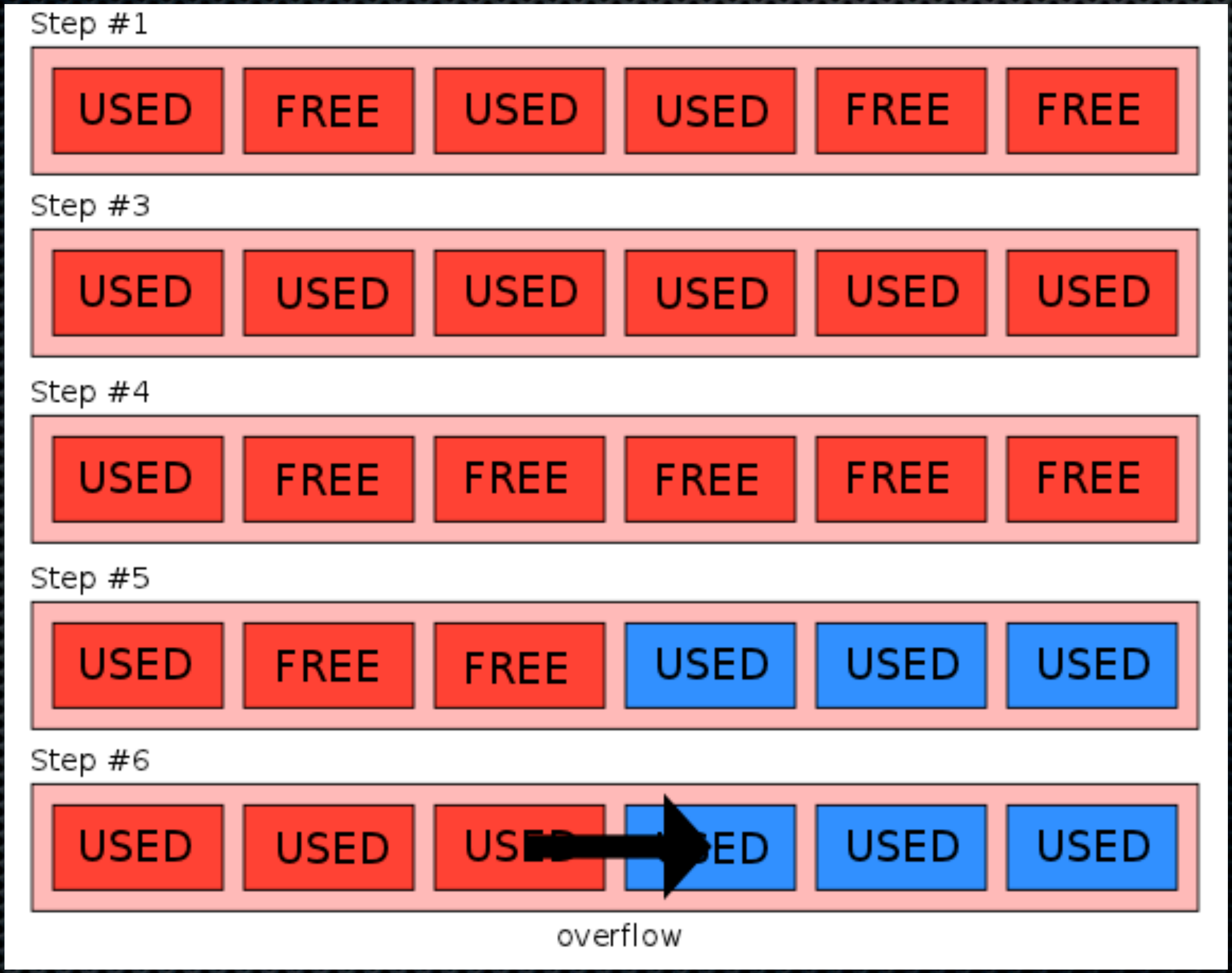
SLUB Exploitation

- Attack alternatives
  - Corrupt metadata of free objects on a slab
  - Corrupt adjacent objects on a slab
- We need a suitable kernel structure to corrupt
- We can allocate/deallocate from userland
- Same size as the object/structure we can overflow from
- Bring target slab to a predictable state in order to have the victim structure after the structure we can overflow from

SLUB Exploitation Algorithm

- Find free objects on target slab:
  - cat /proc/slabinfo
- Ensure allocations/deallocation happen on the slabs of the same CPU: sched_setaffinity(2)
- Consume a large number of objects that go on the target slab (reducing fragmentation)
- Deallocate a small number of objects from the target slab
- Allocate a <u>smaller</u> number of our selected victim objects
- Trigger the heap overflow bug overflowing onto the victim object

SLUB Exploitation



Victim Structure

- Traditionally struct shmid_kernel
- Allocations/deallocations controlled from userland
  - Allocation: shmget(2)
  - Deallocation: ipcrm(1)
- Leads to structure with yummy function pointers

shmid_kernel

```
struct shmid_kernel /* private to the kernel */
{
        struct kern_ipc_perm    shm_perm;
        struct file *           shm_file;
        unsigned long           shm_nattch;
        unsigned long           shm_segsz;
        time_t                  shm_atim;
        time_t                  shm_dtim;
        time_t                  shm_ctim;
        pid_t                   shm_cprid;
        pid_t                   shm_lprid;
        struct user_struct      *mlock_user;
};
```

file

```
struct file {
        /*
         * fu_list becomes invalid after file_free is called and queued via
         * fu_rcuhead for RCU freeing
         */
        union {
                struct list_head        fu_list;
                struct rcu_head         fu_rcuhead;
        } f_u;
        struct path             f_path;
#define f_dentry        f_path.dentry
#define f_vfsmnt        f_path.mnt
        const struct file_operations    *f_op;
        spinlock_t              f_lock;  /* f_ep_links, f_flags, no IRQ */
#ifdef CONFIG_SMP
        int                     f_sb_list_cpu;
#endif
        atomic_long_t           f_count;
        unsigned int            f_flags;
        fmode_t                 f_mode;
        loff_t                  f_pos;
        struct fown_struct      f_owner;
        const struct cred       *f_cred;
        struct file_ra_state    f_ra;

        u64                     f_version;
#ifdef CONFIG_SECURITY
        void                    *f_security;
#endif
        /* needed for tty driver, and maybe others */
        void                    *private_data;

#ifdef CONFIG_EPOLL
        /* Used by fs/eventpoll.c to link all the hooks to this file */
        struct list_head        f_ep_links;
#endif /* #ifdef CONFIG_EPOLL */
        struct address_space    *f_mapping;
#ifdef CONFIG_DEBUG_WRITECOUNT
        unsigned long f_mnt_write_state;
#endif
};
```

file_operations

```
struct file_operations {
        struct module *owner;
        loff_t (*llseek) (struct file *, loff_t, int);
        ssize_t (*read) (struct file *, char __user *, size_t, loff_t *);
        ssize_t (*write) (struct file *, const char __user *, size_t, loff_t *);
        ssize_t (*aio_read) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
        ssize_t (*aio_write) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
        int (*readdir) (struct file *, void *, filldir_t);
        unsigned int (*poll) (struct file *, struct poll_table_struct *);
        long (*unlocked_ioctl) (struct file *, unsigned int, unsigned long);
        long (*compat_ioctl) (struct file *, unsigned int, unsigned long);
        int (*mmap) (struct file *, struct vm_area_struct *);
        int (*open) (struct inode *, struct file *);
        int (*flush) (struct file *, fl_owner_t id);
        int (*release) (struct inode *, struct file *);
        int (*fsync) (struct file *, int datasync);
        int (*aio_fsync) (struct kiocb *, int datasync);
        int (*fasync) (int, struct file *, int);
        int (*lock) (struct file *, int, struct file_lock *);
        ssize_t (*sendpage) (struct file *, struct page *, int, size_t, loff_t *, int);
        unsigned long (*get_unmapped_area)(struct file *, unsigned long, unsigned long, unsigned long, unsigned long);
        int (*check_flags)(int);
        int (*flock) (struct file *, int, struct file_lock *);
        ssize_t (*splice_write)(struct pipe_inode_info *, struct file *, loff_t *, size_t, unsigned int);
        ssize_t (*splice_read)(struct file *, loff_t *, struct pipe_inode_info *, size_t, unsigned int);
        int (*setlease)(struct file *, long, struct file_lock **);
        long (*fallocate)(struct file *file, int mode, loff_t offset,
                          loff_t len);
};
```

Example: jemalloc

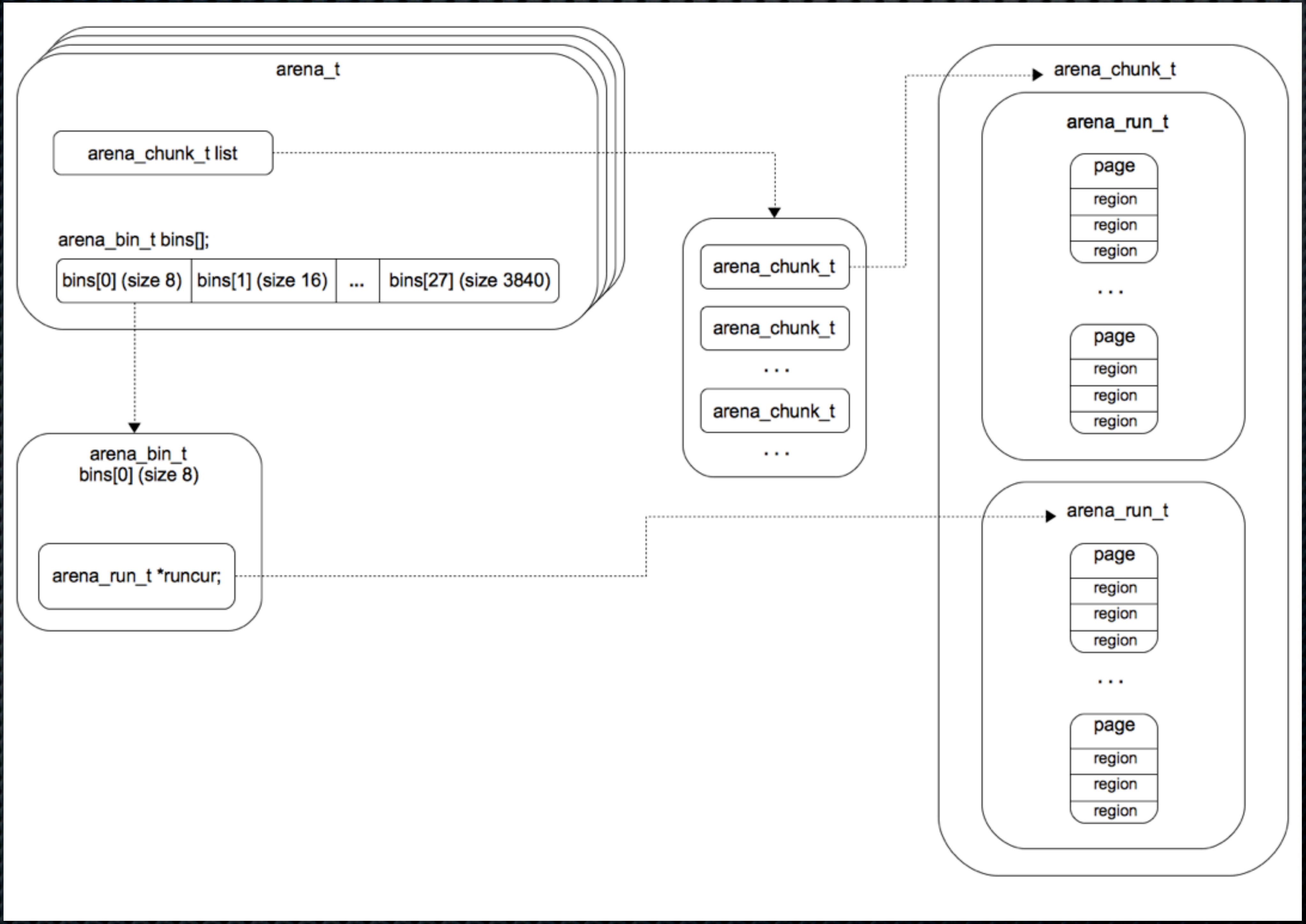
jemalloc

- FreeBSD needed a high performance, SMP-capable userland (libc) allocator
- Mozilla Firefox (Windows, Linux, Mac OS X)
- NetBSD libc
- Standalone version
- Facebook, to handle the load of its web services
- Defcon CTF is based on FreeBSD

jemalloc overview

- Memory is divided into chunks, always of the same size
- Chunks store all jemalloc data structures and user-requested memory (regions)
- Chunks are further divided into runs
- Runs keep track of free/used regions of specific sizes
- Regions are the heap items returned by malloc()
- Each run is associated with a bin, which stores trees of free regions (of its run)

jemalloc Architecture



jemalloc Exploitation

- Adjacent memory overwrite
- Metadata overwrite
  - Run header corruption
  - Chunk header corruption
  - Magazine (a.k.a thread cache) corruption
- For the details attend our Black Hat USA 2012 talk!

Abstracting Heap Exploitation

UMA - SLUB - jemalloc

- End-user allocations: UMA - items, SLUB - objects, jemalloc - regions
- Allocation containers: UMA - slabs, SLUB - slabs, jemalloc - runs
- Container groupings: UMA - kegs, SLUB - caches, jemalloc - chunks
- Execution-specific metadata:
  - UMA - zone, Linux kernel - zone, jemalloc - arena
  - UMA - buckets, SLUB - N/A, jemalloc - bins

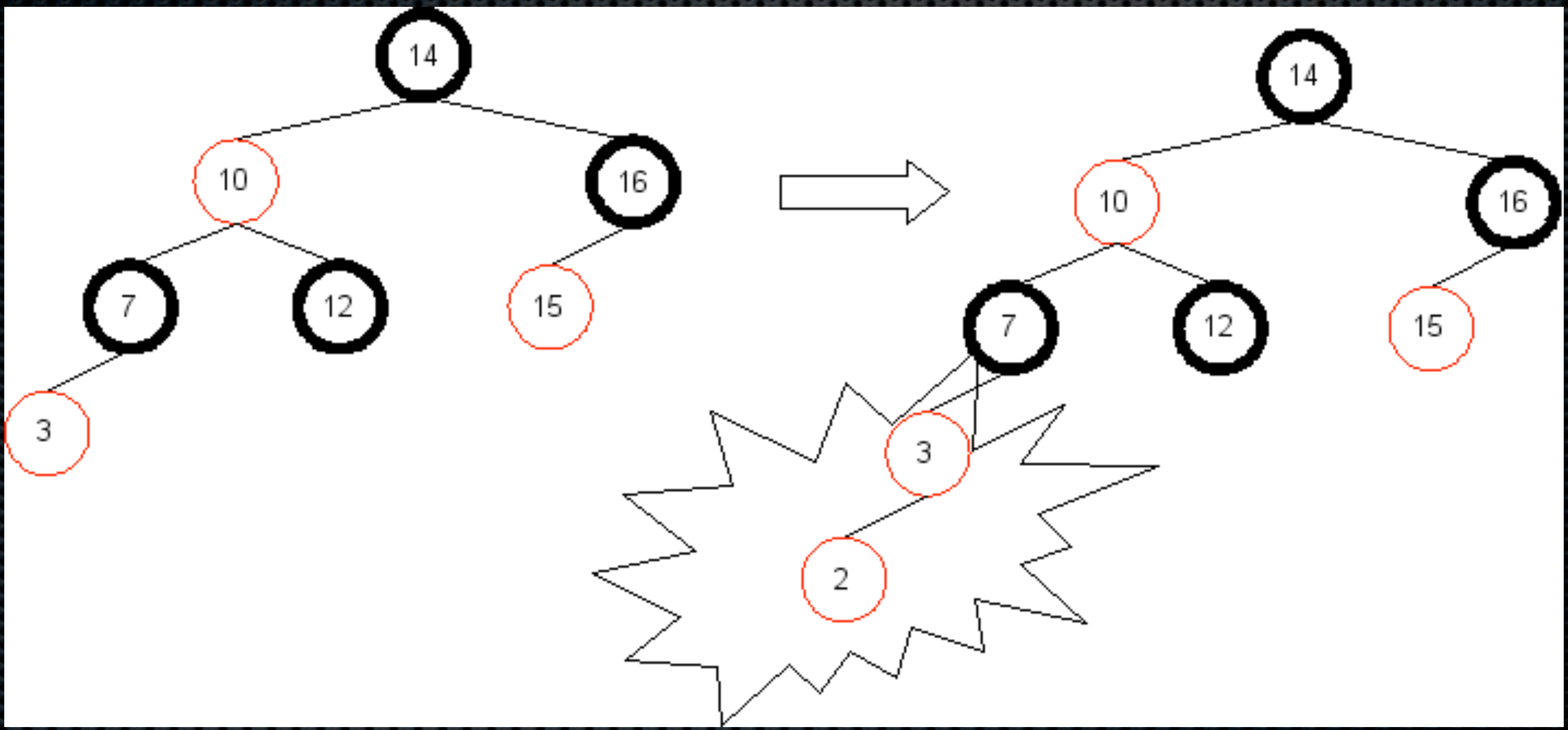
Value of Abstraction

- Chris Valasek's and Ryan Smith's Black Hat EU 2011 talk on abstracting exploitation through primitives [3]
- Back in CS 101 we were taught that <u>abstraction</u> is the most important skill of a computer scientist
- Specific exploitation techniques <u>will</u> become obsolete
- Our 2 drachmas are to abstract heap exploitation and have “primitives” that can be applied to new targets

Memory Allocators as Weird Machines

- Weird machine: The state machine of the target program after memory corruption [5, 6]
- In our case
  - State machine: Memory allocator
  - Weird machine: Post-corruption memory allocator
  - New states, unexpected by the developer
  - However reachable due to the memory corruption

Heap Weird Machines



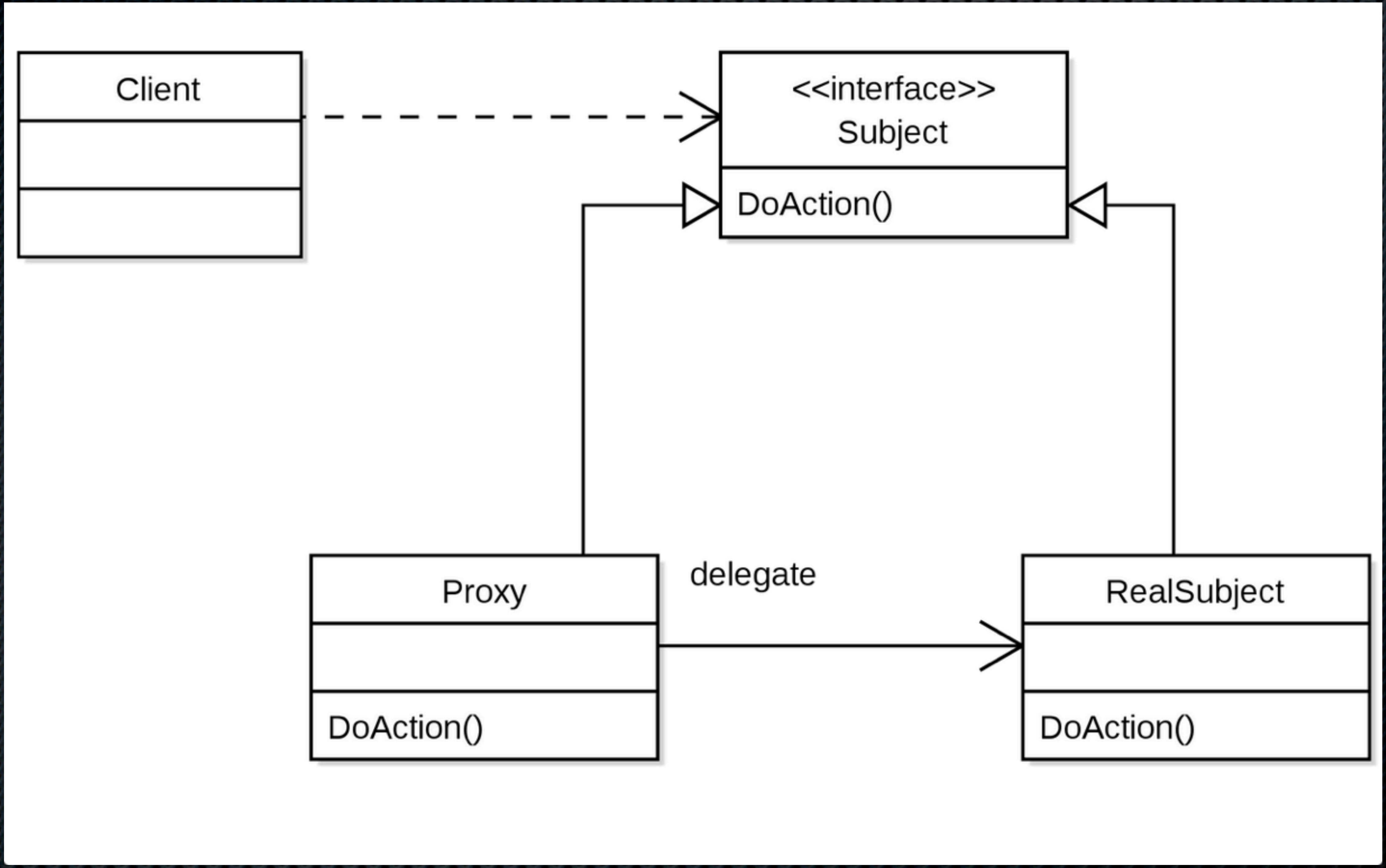
Heap Weird Machines

- Our memory allocator model: deterministic automaton (threads not taken into account)
- Metadata corruption abstraction
  - Corruption of the automaton’s transition function
  - New states are reachable - most dead but not all
- Data (e.g. adjacent item) corruption abstraction
  - Manipulation of the automaton’s determinacy
  - We control the order of transitions

The Weirding Module ;)

- The target heap manager should be treated as a high level API
  - For allocations and deallocations
- “Applications” that use the allocator (Javascript, system calls, incoming packets) provide a way to proxy these API calls
- Attacker → Application (Proxy) → Allocator

The Weirding Module ;)



Conclusion

- Future work
  - Operational semantics (formal notation)
  - More examples on both allocators and exploits
- Acknowledgments
  - Dr ;) Dimitris Glynos
  - Chris Valasek
  - Sergey Bratus

References

- [1] “Attacking the Core: Kernel Exploiting Notes”, twiz, sgrakkyu, Phrack, 2007
- [2] “Kernel Wars”, signedness.org, Black Hat EU, 2007
- [3] “Exploitation in the Modern Era (Blueprint)”, Chris Valasek, Ryan Smith, Black Hat EU, 2011
- [4] “Patras Heap Massacre”, Chariton Karamitas, Patroklos Argyroudis, Fosscomm, 2011
- [5] “Exploit Programming”, Sergey Bratus et al, ;login:, 2011
- [6] “Exploitation and State Machines”, Halvar Flake, Infiltrate, 2011