Tencent

The Art of Exploiting Unconventional Use-after-free Bugs in Android Kernel

Di Shen a.k.a. Retme (@returnsme)

Keen Lab of Tencent

whoami

- Di Shen a.k.a. Retme (@returnsme)
- Member of Keen Lab
- Android Kernel vulnerability hunting and exploitation since 2014
- Aim: to work out universal rooting exploit for Android
- Trophy:
  - CVE-2016-6787 & CVE-2017-0403 (kernel/events/core.c)
  - CVE-2015-1805 (fs/pipe.c) ’s first working exploit
  - CVE-2015-4421,4422 (Huawei TrustZone)
  - KNOX Bypassing on Samsung Galaxy S7 (BHUSA 17’)
  - Exploiting Wireless Extension for all common Wi-Fi chipsets (BHEU 16’)
  - And more To Be Announced in the future
- Available on https://github.com/retme7/My-Slides

Agenda

- Rooting Android: Current situation
- Overview of exploiting UAF in kernel
  - Conventional approach
  - Afterwards: Gain root
- The Unconventional UAFs
  - Implementation of perf system
  - Exploiting CVE-2017-0403
  - Exploiting CVE-2016-6787
- Conclusion

Tencent

KEEN security lab

Rooting Android: Current situation

- Universal exploitable vulnerability is rare
  - Available attack surface:
    - Generic Linux syscalls
    - Android universal drivers like Binder, ION, Ashmem

Tencent

KEEN security lab

Rooting Android: Current situation

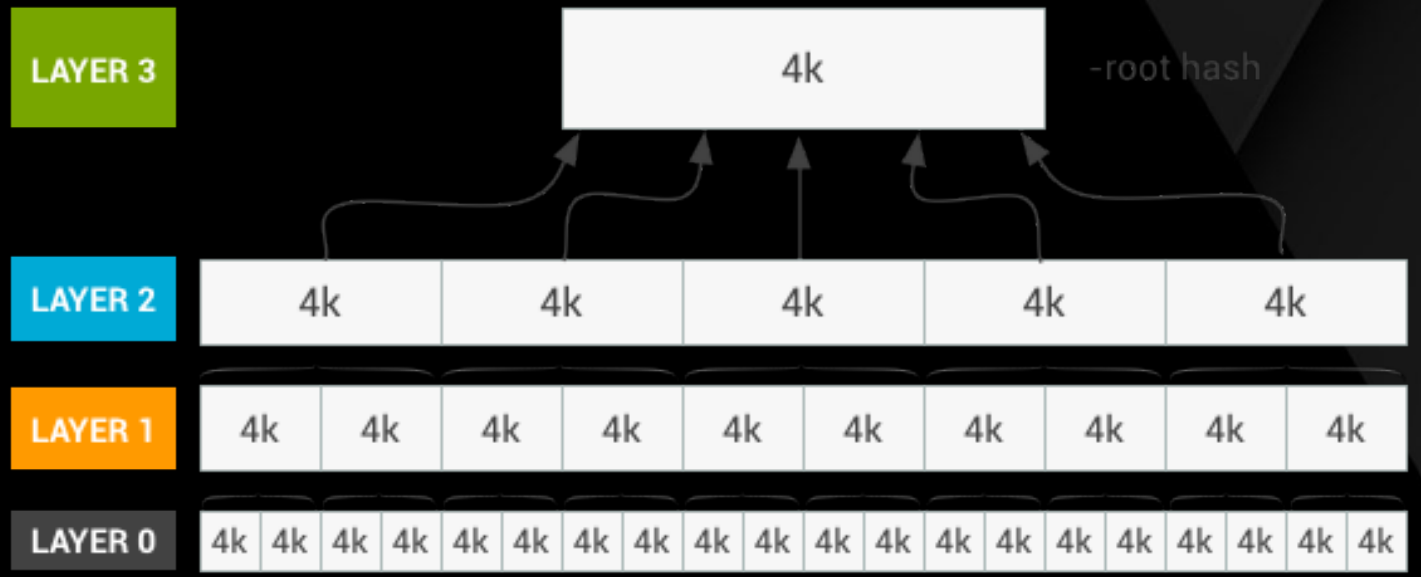
- Enforced SELinux policy
  - Most of device drivers are inaccessible
  - Many syscalls are not reachable from untrusted Application
  - Sockets ioctl commands are partially restricted

Tencent

KEEN security lab

Rooting Android: Current situation

- Verified Boot through dm-verity kernel feature
  - The gained root privilege is nonpersistent



Rooting Android: Future challenges

- Privileged Access Never (PAN)
- KASLR
- Pointer Authentication

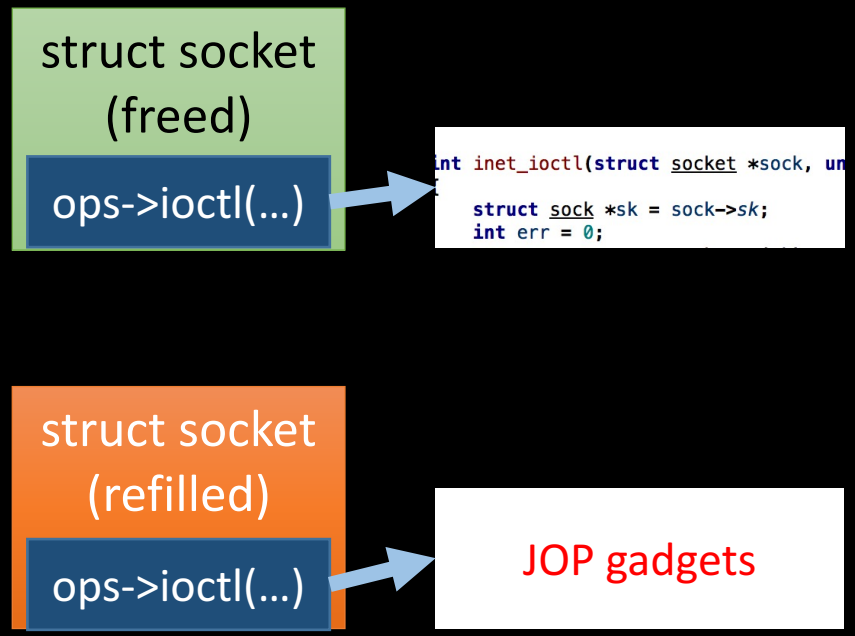
Tencent

KEEN security lab

Overview of exploiting UAF in kernel

- An easily exploitable UAF bug normally has following features:
  - Has a function pointer in freed object
  - Attacker has plenty of time to refill the freed object.

Conventional approach to UAF exploitation



- Free the victim object
- Refill the object with malformed data by heap spraying or ret2dir
- Let the function pointer point to ROP/JOP gadgets in kernel
- Ask kernel reference this function pointer to achieve arbitrary kernel code execution

Tencent

Afterwards, from code execution to root

KEEN security lab

However…

- Not every UAF bug in kernel is so that idealized
- More unconventional situation to deal with…
  - The victim object may don’t have a function pointer
  - The kernel may crash soon after UAF triggered
  - The attacker may cannot fully controlled the freed object

The unconventional UAFs I found

- All found in sys_perf_event_open()
  - Perf system is pretty buggy
  - Reachable by application last year
  - But now it’ s restricted by a feature called “perf_event_paranoid”

The unconventional UAFs I found

- CVE-2017-0403
  - Ever affected all devices shipped with 3.10 or earlier Linux kernel
  - More than 14 million users of KingRoot gain root privilege on their smart phones
- CVE-2016-6787
  - Ever affected all Qualcomm-based devices. (Only Qucalcomm enabled hardware perf event…)
  - A part of my exploit chain to bypass Samsung KNOX 2.6

sys_perf_event_open()

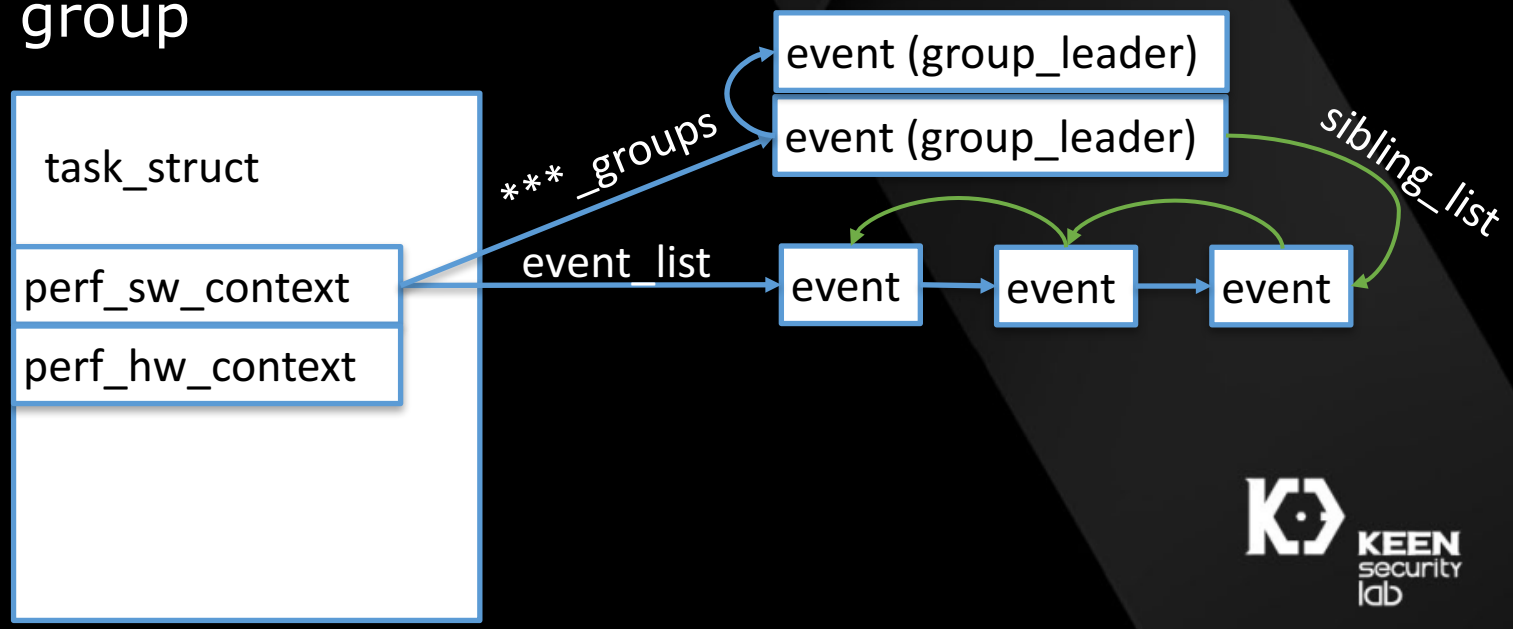
- Will create a perf_event
- Input: perf_event_attr
  - A description of what kind of performance event you need
- Input: group_fd (optional)
  - Specify the group leader of new perf_event
- Return the fd of perf_event to user space

```
/**
 * sys_perf_event_open - open a performance event, associate it to a task/cpu
 *
 * @attr_uptr:  event_id type attributes for monitoring/sampling
 * @pid:        target pid
 * @cpu:        target cpu
 * @group_fd:       group leader event fd
 */
SYSCALL_DEFINE5(perf_event_open,
        struct perf_event_attr __user *, attr_uptr,
        pid_t, pid, int, cpu, int, group_fd, unsigned long, flags)
{
    struct perf_event *group_leader = NULL, *output_event = NULL;
    struct perf_event *event, *sibling;
    struct perf_event_attr attr;
    struct perf_event_context *ctx;
    struct file *event_file = NULL;
    struct fd group = {NULL, 0};
    struct task_struct *task = NULL;
    struct pmu *pmu;
    int event_fd;
    int move_group = 0;
    int err;
    int f_flags = O_RDWR;
```

Key kernel objects in perf system

Tencent

- perf_event
  - A performance event which is registered by user
- perf_event_context
  - The container of all perf events created in one process
  - Each process has two contexts, one for software events, other one for hardware events
- Perf group and group leader
  - Multiple events can form a group
  - One event is the leader



KEEN security lab

move_group

- Happens when user try to create a hardware event in pure software group.

```
if (group_leader &&
    (is_software_event(event) != is_software_event(group_leader))) {
    if (is_software_event(event)) {
        /*
         * If event and group_leader are not both a software
         * event, and event is, then group leader is not.
         *
         * Allow the addition of software events to !software
         * groups, this is safe because software events never
         * fail to schedule.
         */
        pmu = group_leader->pmu;
    } else if (is_software_event(group_leader) &&
               (group_leader->group_flags & PERF_GROUP_SOFTWARE)) {
        /*
         * In case the group is a pure software group, and we
         * try to add a hardware event, move the whole group to
         * the hardware context.
         */
        move_group = 1;
    }
}
```

CVE-2016-6787

Remove the group_leader from origin software context and then install it to hardware context

```
if (move_group) {
    struct perf_event_context *gctx = group_leader->ctx;

    mutex_lock(&gctx->mutex);
    perf_remove_from_context(group_leader, false);

    /*
     * Removing from the context ends up with disabled
     * event. What we want here is event in the initial
     * startup state, ready to be add into new context.
     */
    perf_event__state_init(group_leader);
    list_for_each_entry(sibling, &group_leader->sibling_list,
                group_entry) {
        perf_remove_from_context(sibling, false);
        perf_event__state_init(sibling);
        put_ctx(gctx);
    }
    mutex_unlock(&gctx->mutex);
    put_ctx(gctx);
}
```

```
if (move_group) {
    synchronize_rcu();
    perf_install_in_context(ctx, group_leader, group_leader->cpu);
    get_ctx(ctx);
    list_for_each_entry(sibling, &group_leader->sibling_list,
                group_entry) {
        perf_install_in_context(ctx, sibling, sibling->cpu);
        get_ctx(ctx);
    }
}
```

Remove every event from software context, and then install it to new hardware context

'move_group' leads to reducing context's refcont by one

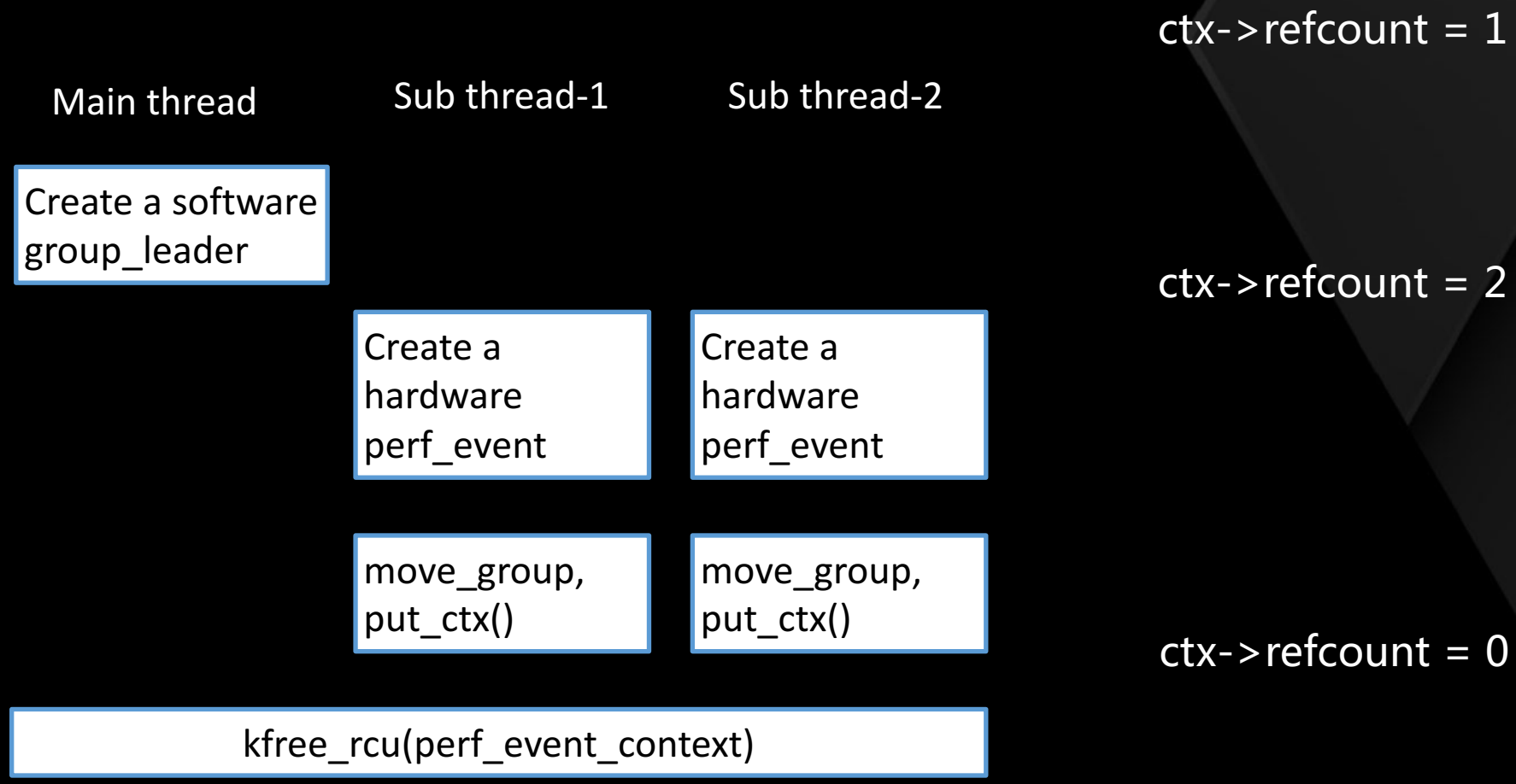
CVE-2016-6787

- move_group ignored the concurrency issues
- UAF happens due to race condition
- Attacker trigger the move_group on same group leader simultaneously ,
- The ref count of group_leader->ctx may be reduced to zero
- task_struct->perf_event_ctxp[perf_sw_context] will be freed accidently

```
static void put_ctx(struct perf_event_context *ctx)
{
    if (atomic_dec_and_test(&ctx->refcount)) {
        if (ctx->parent_ctx)
            put_ctx(ctx->parent_ctx);
        if (ctx->task)
            put_task_struct(ctx->task);
        kfree_rcu(ctx, rcu_head);
    }
}
```

The object is freed

Free perf_event_context (PoC)



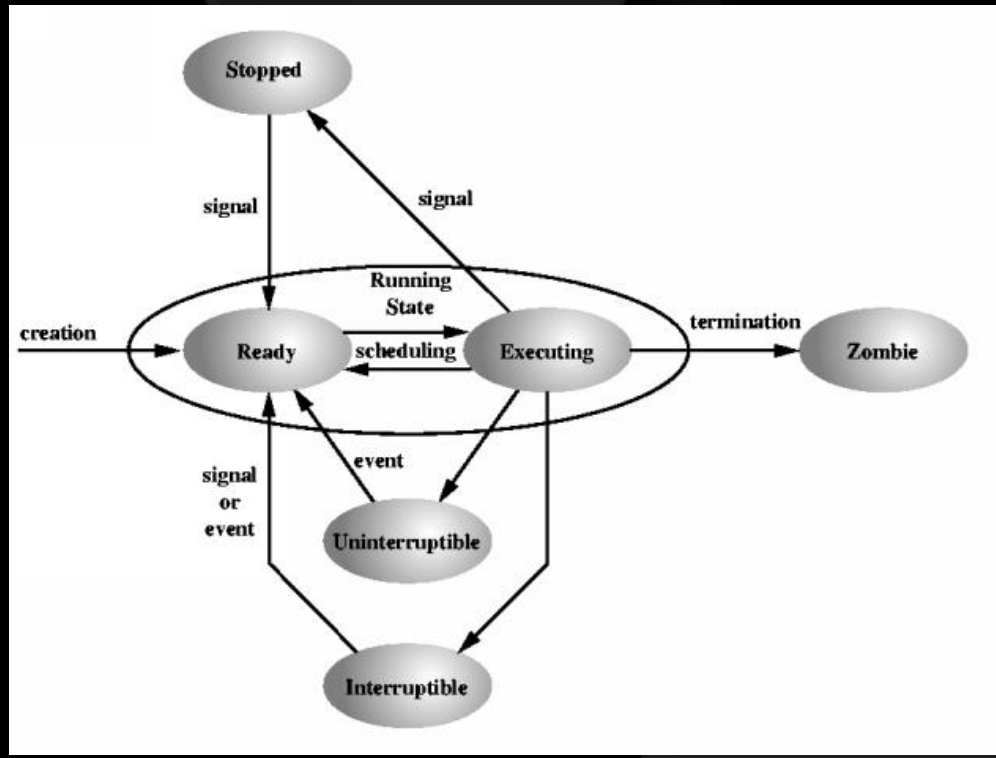
Kernel crashed instantly

- Kernel crashed soon after we freed the perf_event_context
- Thread scheduler need to dereference this object pointer consecutively
- We don't have plenty of time to refill the object ☹

```
<1>[67760.887267] Unable to handle kernel paging request at virtual address bfb8c160
<1>[67760.887314] pgd = ffffffc0475b1000
<1>[67760.887333] [bfb8c160] *pgd=0000000000000000
<0>[67760.887374] Internal error: Oops: 96000005 [#1] PREEMPT SMP
<4>[67760.887412] CPU: 1 PID: 10819 Comm: qoc_report Tainted: G        W    3.10.73-ga5cec12 #1
<4>[67760.887436] task: ffffffc03cbe8ac0 ti: ffffffc024438000 task.ti: ffffffc024438000
<4>[67760.887481] PC is at perf_event_context_sched_in.isra.72+0x30/0xbc
<4>[67760.887505] LR is at perf_event_context_sched_in.isra.72+0x20/0xbc
<4>[67760.887527] pc : [<ffffffc0002b3c44>] lr : [<ffffffc0002b3c34>] pstate: 60000185
<4>[67760.887545] sp : ffffffc02443bae0
<4>[67760.887562] x29: ffffffc02443bae0 x28: 0000000000000a60
<4>[67760.887603] x27: ffffffc0c1198e66 x26: ffffffc0c1198e6c
<4>[67760.887645] x25: ffffffc000e01000 x24: ffffffc024438000
<4>[67760.887687] x23: 0000000000000000 x22: ffffffc00e9a6b80
<4>[67760.887731] x21: ffffffc03cbe8ac0 x20: 00000000bfb8c000
<4>[67760.887773] x19: ffffffc0acbe5400 x18: ffffffc00e9f3d28
<4>[67760.887816] x17: 0000000000000000 x16: 0000000000000000
<4>[67760.887858] x15: 0000000000000000 x14: 0fffffffffffffe
<4>[67760.887901] x13: 0000000000000030 x12: 0101010101010101
<4>[67760.887944] x11: 7f7f7f7f7f7f7f7f x10: feff676273687672
<4>[67760.887987] x9 : ffffffc02443bb90 x8 : ffffffc03cbe9020
<4>[67760.888029] x7 : 0000000000000180 x6 : ffffffc00160f850
<4>[67760.888072] x5 : ffffffc0c1197db8 x4 : ffffffc00110a70e
<4>[67760.888114] x3 : 0000000000000000 x2 : 0000007f848ab098
<4>[67760.888157] x1 : ffffffc0019d93b8 x0 : 00000000bfb8c000
<4>[67760.888198]
<0>[67760.888219] Process qoc_report (pid: 10819, stack limit = 0xffffffc024438058)
<4>[67760.888237] Call trace:
<4>[67760.888267] [<ffffffc0002b3c44>] perf_event_context_sched_in.isra.72+0x30/0xbc
<4>[67760.888295] [<ffffffc0002b3d04>] __perf_event_task_sched_in+0x34/0x144
<4>[67760.888328] [<ffffffc00024925c>] finish_task_switch+0x104/0x120
<4>[67760.888363] [<ffffffc000c83a04>] __schedule+0x928/0xb38
<4>[67760.888390] [<ffffffc000c83c78>] schedule+0x64/0x70
<4>[67760.888416] [<ffffffc000c82870>] do_nanosleep+0x7c/0x100
<4>[67760.888448] [<ffffffc0002418b8>] hrtimer_nanosleep+0x94/0x108
<4>[67760.888473] [<ffffffc0002419ac>] SyS_nanosleep+0x80/0x98
<0>[67760.888502] Code: f0004ea1 f9459021 f8605820 8b000294 (f940b280)
<4>[67760.888527] ---[ end trace 278ee17304bbc989 ]---
```

Solution: freeze thread after free

- Keep thread scheduler away from me
- Switch the status of attacker’s thread from running to (un)interruptible
- The thread will be frozen and kernel won’t crash as soon as perf_event_context freed



How to freeze a thread from user land?

- Sleep() ? Not working
- Use futex_wait_queue_me()

switch to interruptible

freezable_schedule()

```
static void futex_wait_queue_me(struct futex_hash_bucket *hb, struct futex_q *q,
                struct hrtimer_sleeper *timeout)
{
    /*
     * The task state is guaranteed to be set before another task can
     * wake it. set_current_state() is implemented using set_mb() and
     * queue_me() calls spin_unlock() upon completion, both serializing
     * access to the hash list and forcing another memory barrier.
     */
    set_current_state(TASK_INTERRUPTIBLE);
    queue_me(q, hb);

    /* Arm the timer */
    if (timeout) {
        hrtimer_start_expires(&timeout->timer, HRTIMER_MODE_ABS);
        if (!hrtimer_active(&timeout->timer))
            timeout->task = NULL;
    }

    /*
     * If we have been removed from the hash list, then another task
     * has tried to wake us, and we can skip the call to schedule().
     */
    if (likely(!plist_node_empty(&q->list))) {
        /*
         * If the timer has already expired, current will already be
         * flagged for rescheduling. Only call schedule if there
         * is no timeout, or if it has yet to expire.
         */
        if (!timeout || timeout->task)
            freezable_schedule();
    }
    __set_current_state(TASK_RUNNING);
} « end futex_wait_queue_me »
```

Main thread

Sub thread-1

Sub thread-2

Create a software group_leader

Phase 1

Create a hardware perf_event

Create a hardware perf_event

move_group, put_ctx()

move_group, put_ctx()

kfree_rcu(perf_event_context)

futex_wait_queue_me()

Spraying the heap by using ‘ret2dir’ trick, fill a malformed perf_event_context{} in every 1024 bytes

Phase 2

Use futex_wake() wake up main thread

Phase 3

schedule()

finish_task_switch()

perf_event_context_sched_in()

ctx->pmu->pmu_disable()

Code flow controlled

Phase 4

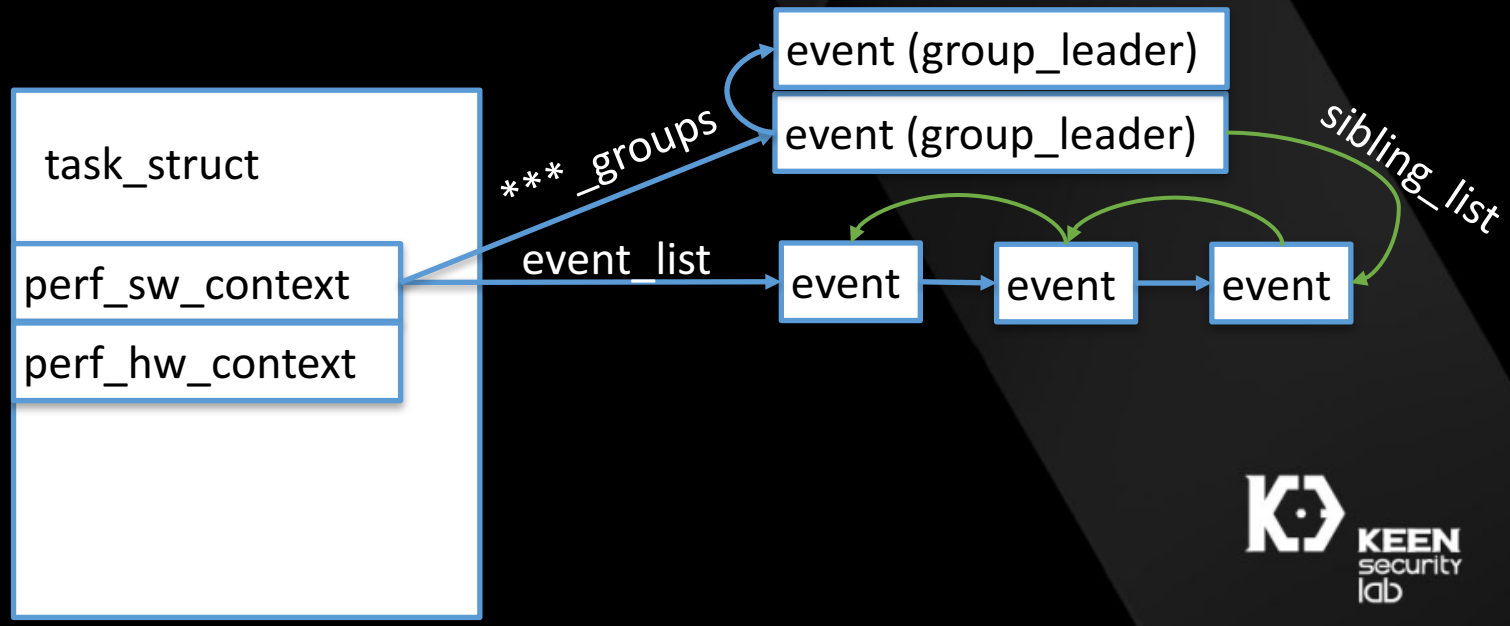
A brief summary of CVE-2016-6787

- Easy to win the race, and trigger the bug
- **Hard to refill the freed object (no time)**
- Easy to control the code flow (corrupted object has function pointer)
- Proposed an approach to freezing thread to gain more time to refill object

Tencent

Review: relationship between perf event, group and group leader

- Group leader has a sibling_list
- sibling_list is a list of perf events which belongs this group



KEEN security lab

CVE-2017-0403 (PoC)

- Create a perf event as ‘A’
- Create another perf event as ‘B’, specify ‘A’ as its group leader
- Free ‘A’ , the group leader
- Free ‘B’, a sibling of group ←---- UAF happens here

Root cause

- Now group leader ‘A’ is freed
- Kernel doesn’t empty its sibling list
- Leads to leaving a dangling pointer in sibling’s event->group_entry

```
static void perf_group_detach(struct perf_event *event)
{
        struct perf_event *sibling, *tmp;
        struct list_head *list = NULL;

        /*
         * We can have double detach due to exit/hot-unplug + close.
         */
        if (!(event->attach_state & PERF_ATTACH_GROUP))
                return;

        event->attach_state &= ~PERF_ATTACH_GROUP;

        /*
         * If this is a sibling, remove it from its group.
         */
        if (event->group_leader != event) {
                list_del_init(&event->group_entry);
                event->group_leader->nr_siblings--;
                goto out;
        }

        if (!list_empty(&event->group_entry))
                list = &event->group_entry;

        /*
         * If this was a group event with sibling events then
         * upgrade the siblings to singleton events by adding them
         * to whatever list we are on.
         */
        list_for_each_entry_safe(sibling, tmp, &event->sibling_list, group_entry) {
                if (list)
                        list_move_tail(&sibling->group_entry, list);
                sibling->group_leader = sibling;
```

Root cause

- Later on the sibling ‘B’ is freed
- list_del_event()
- list_del_init(&event->group_entry);
- overwrite a pointer to the freed group leader.

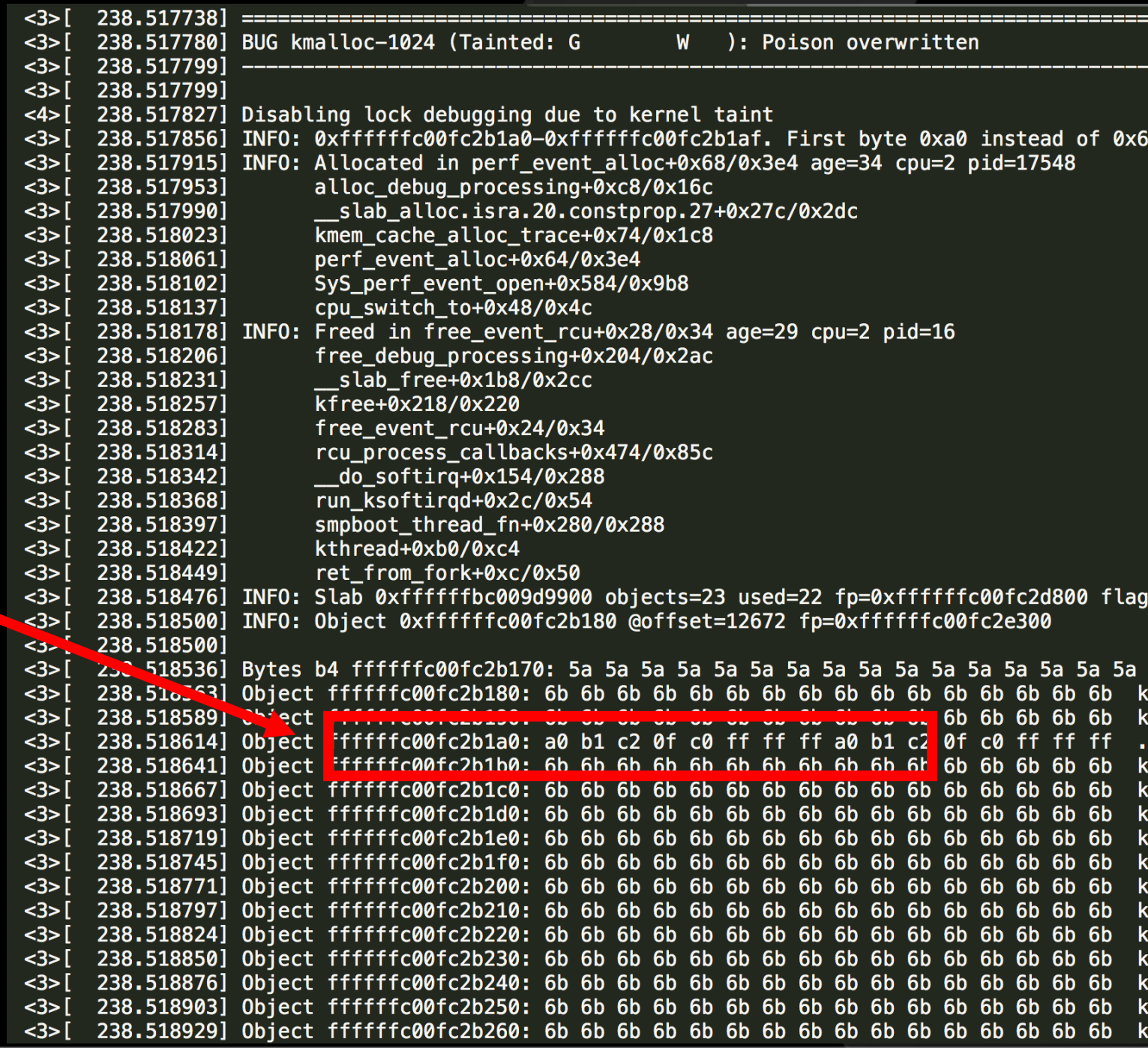
```
static void perf_group_detach(struct perf_event *event)
{
        struct perf_event *sibling, *tmp;
        struct list_head *list = NULL;

        /*
         * We can have double detach due to exit/hot-unpl
         */
        if (!(event->attach_state & PERF_ATTACH_GROUP))
                return;

        event->attach_state &= ~PERF_ATTACH_GROUP;

        /*
         * If this is a sibling, remove it from its group
         */
        if (event->group_leader != event) {
                list_del_init(&event->group_entry);
                event->group_leader->nr_siblings--;
                goto out;
        }
```

- SLUB poison information
- 0xffffc00fc2b1a0 is overwritten to (group_leader+ 0x20)



The unconventional scenario

- The only thing I can do is overwriting the freed object as following

```
*(size_t*)(freed_object + 0x20) = (freed_object + 0x20)
```

Pipe subsystem in Linux

Tencent

- readv() & writev(): read/write multiple buffers through pipe
- Use an array of struct iovec{iov_base,iov_len} to describe user buffers
- When no contents available from the write end, readv() may block in kernel
- Then an array of struct iovec{} may stay in kernel's heap

KEEN security lab

Compromise pipe system

Tencent

- Call readv()
- rw_copy_check_uvector() confirm every iov_base must points to userland space.
- An array of struct iovec{} now is in heap. Nothing comes from the write end of pipe, so readv() block.

iov_base	iov_len	iov_base	iov_len	iov_base	iov_len

- If you can somehow overwrite the iovec{}, modify the iov_base to a kernel address. Emmm…

kernel_addr	iov_len	kernel_addr	iov_len	kernel_addr	iov_len

KEEN security lab

Compromise pipe system

- Now write something to another end of pipe
- pipe_iov_copy_to_user() won't check the iov_base again.
- Buffers you wrote to pipe will be copied to **the kernel address**

```
static int
pipe_iov_copy_to_user(struct iovec *iov, const void *from, unsigned long len,
                      int atomic)
{
        unsigned long copy;

        while (len > 0) {
                while (!iov->iov_len)
                        iov++;
                copy = min_t(unsigned long, len, iov->iov_len);

                if (atomic) {
                        if (__copy_to_user_inatomic(iov->iov_base, from, copy
                                return -EFAULT;
                } else {
                        if (copy_to_user(iov->iov_base, from, copy))
                                return -EFAULT;
                }
                from += copy;
                len -= copy;
                iov->iov_base += copy;
                iov->iov_len -= copy;
        }
        return 0;
}
```

Solution: convert UAF to arbitrary R/W

Tencent

1 ↓ the 1st freed object, address is A

Freed	Data	Freed	Data	Freed	.....

↓the 2nd freed object, address is B = A + 0x400

Freed	Data	Freed	Data	.....

2 Use iovec to spray the heap

base	len	base	len	base	.....

base	len	base	len	.....

3 Trigger UAF, write two 8-bytes value "A+0x20" to address = A+0x20

base	len	A + 0x20	A+0x20	base	.....

base	len	base	len	.....

4 Write a buffer to pipe , the buffer will be copied to (A + 0x20)

base	len	KADDR	8	KADDR	.....

KADDR	8	KADDR	8	.....

5 Write a buffer to pipe again , it will be copied to **KADDR**

KADDR can be any address value, we achieved arbitrary kernel memory overwriting

KEEN security lab

A brief summary of CVE-2017-0403

- Attacker lost the file descriptor of freed object
- Cannot achieve code execution via refilling object's function pointer
- Only be able to write the address value of freed object twice to freed object
- Proposed a new approach: compromising pipe system

Conclusion

- Most UAF bugs looks not exploitable, but there may be another way
- No idea? Put it down for a while, but do not let it go…
- Be familiar with kernel’s source code, kernel’s own feature may help your exploitation (e.g. pipe for CVE-2017-0403)

Tencent

KEEN
security
lab