Vulnerability Discovery and Exploitation of Virtualization Solutions for Cloud Computing and Desktops

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- My main focus is iOS/Android/macOS and sandboxes. But recently shifted to hypervisors, basebands, firmwares etc.
- pwn2own 2016 Mac OS X Team
- Mobile pwn2own 2016 iOS team
- pwn2own 2017 VMWare escape team
- Mobile pwn2own 2017 iOS Wifi + baseband team

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- Senior student at Zhejiang University
- Interested in hypervisors, will do basebands in future
- CTF player in AAA (sometimes A*0*E), DEFCON 25 & 26

About Tencent Keen Security Lab

- Previously known as KeenTeam
- White Hat Security Researchers
- Several times pwn2own winners
- We are based in Shanghai, China
- Our blog is https://keenlab.tencent.com/en/
- Twitter @keen_lab

Agenda

01 Overview of Virtualization Solutions

02 Attack Surface

03 VirtualBox

- Architecture
- Attack Surface
- VM Escape

04 QEMU VM Escape

- Bug
- Exploitation

05 Conclusions

Overview of Virtualization Solutions

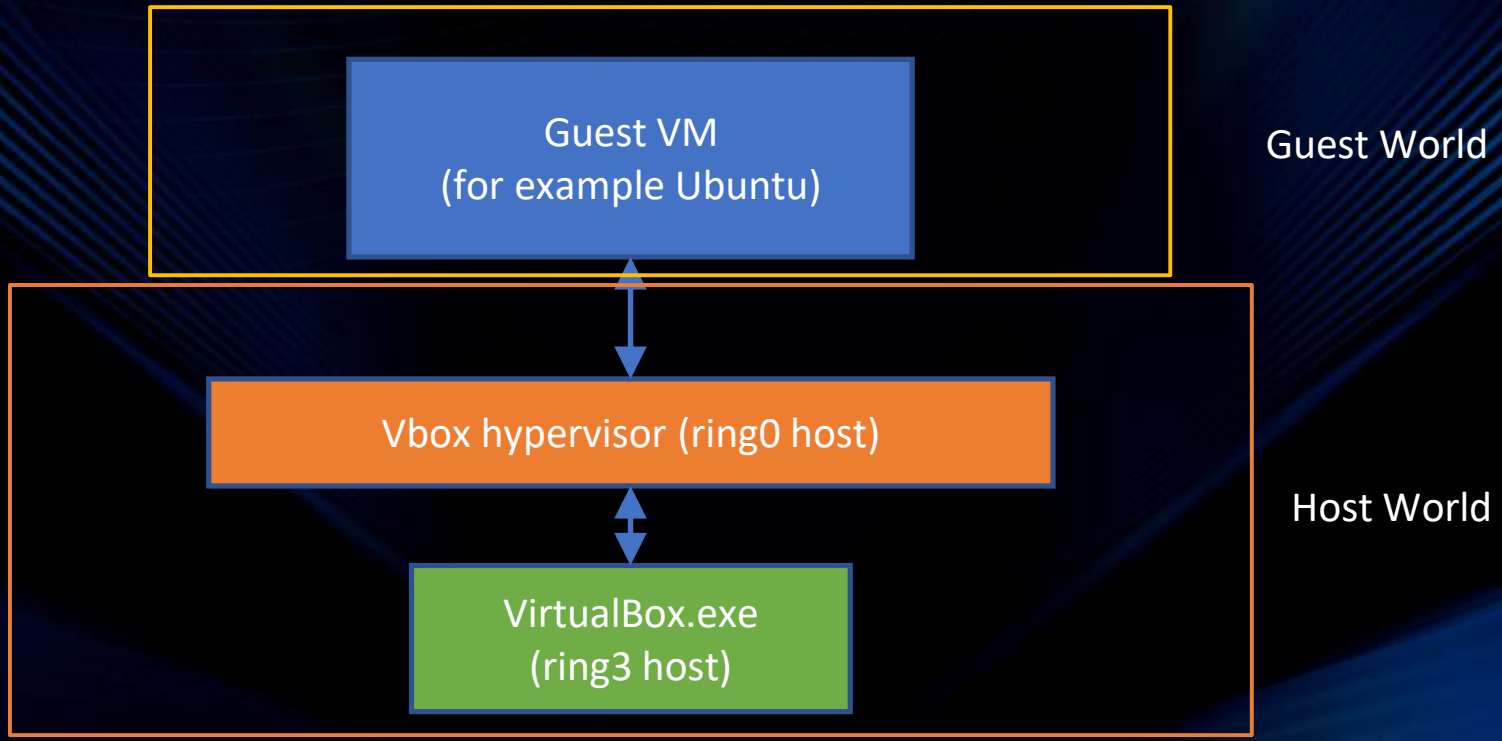
Virtualization Solutions (main players)

- Microsoft: Hyper-V
- VMWare: Workstation, ESXi, Fusion
- **Qemu (and kvm)**
- XEN
- **Virtualbox**
- Others

All you need to know about virtualization in 1 slide (almost)

- Nowadays mostly hardware based virtualization for performance.
- Runs a “VM” natively on the CPU, trapping on certain **privileged** events to the hypervisor to handle them
- Otherwise just runs at native performance.
- Emulated (fake usually old well supported hardware) (vbox, vmware, qemu)
- Paravirtualized. Implement functionalities mostly with hypercalls (xen, hyper-v)
- A virtualization solution usually consists of software running in host ring0 and host ring3. Both of them can be a target for bugs.

VirtualBox example



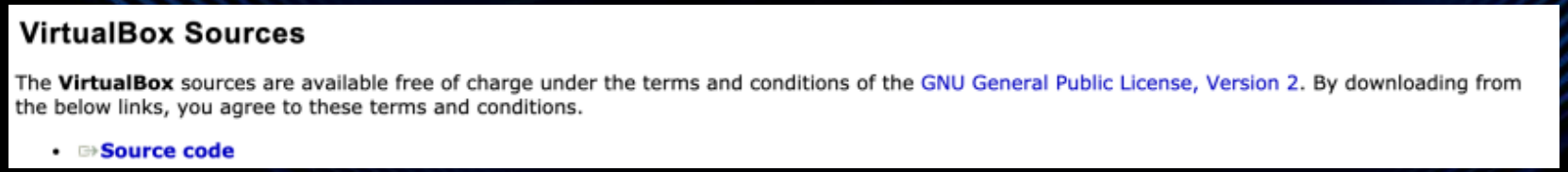
Code Split

- The virtualization code can be in ring0 and ring3 of the host.
- Both have several advantages and disadvantages
- Code in ring0 will run faster, at least 2 less context switch
- Code in ring3 is less critical, a bug will not panic the host machine like it would in ring0
- Easier to debug and develop code in ring3, and make async code in ring3 compared to a ring0 environment.

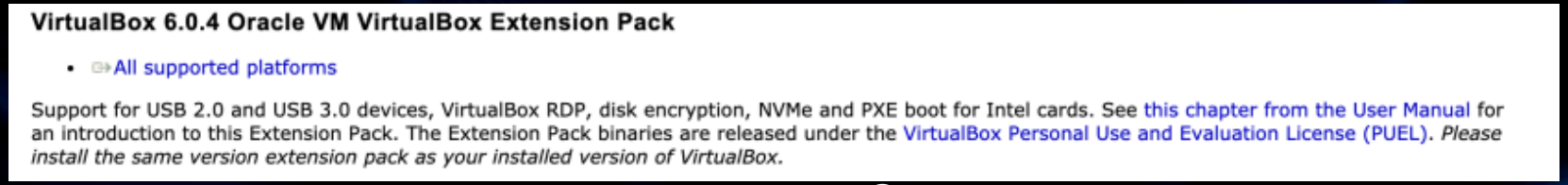
VIRTUALBOX

The code

- Virtualbox is opensource, which ease a lot the bug hunting process.



- Opensource except the ”extensions” which are shipped as binaries



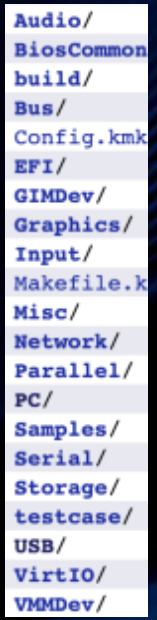
- Good place to look for 0days if you ask me ☺ just sayin’

Previous Work on Virtual Box

- Niklas Baumstark - Unboxing Your VirtualBoxes
  - Explores Process Hardening, guest-to-host attack surface
- Niklas Baumstark - Thinking outside the Virtual Box
  - HGCM (Host Guest Communication Manager) attacks
- Francisco Falcon - Breaking Out of VirtualBox through 3D Acceleration
  - Bugs and exploitation of the 3d acceleration
- https://github.com/MorteNoir1/virtualbox_e1000_0day e1000 network card guest to host escape
- Niklas on SSD https://ssd-disclosure.com/archives/3649
  - VBVA bug (graphics)

Attack Surface

- Emulated devices
  - Source code: VBox/Devices
  - Notes: some of them are not enabled in default configuration
- Host Services (stuff like copy paste, 3d, shared folders)
  - Source code: VBox/HostServices
  - Notes: MOST of them are not enabled in default configuration (!)
- Network Stack
- Hypervisor itself, smaller but at higher privilege level
- Misc/Others



Let's Pick Emulated devices and see where to look for bugs

1. Find the relevant code src/VBox/Devices/USB/DevOHCI.cpp
   - USB device, default
   - OHCI usb controller
2. Find the controller specifications and study them how to talk with the controller
   - http://www.scaramanga.co.uk/stuff/qemu-usb/hcir1_0a.pdf
   - Linux kernel driver code
   - lspci, cat /proc/iomem, cat /proc/ioports to see the interfaces
3. Audit the code or fuzz

Checking the device attack surface from the guest

- Legacy hardware interfaces
- Ioports (cat /proc/ioports)
- IOMem (cat /proc/iomem)

```
  3e6e2000-3e93dfff : Kernel bss
7fff0000-7fffffff : ACPI Tables
80000000-fdffffff : PCI Bus 0000:00
  e0000000-e7ffffff : 0000:00:02.0
  f0000000-f001ffff : 0000:00:03.0
    f0000000-f001ffff : e1000
  f0400000-f07fffff : 0000:00:04.0
    f0400000-f07fffff : vboxguest
  f0800000-f0803fff : 0000:00:04.0
  f0804000-f0807fff : 0000:00:05.0
    f0804000-f0807fff : ICH HD audio
```

```
  4100-4108 : piix4_smbus
d000-d007 : 0000:00:03.0
  d000-d007 : e1000
d020-d03f : 0000:00:04.0
d040-d047 : 0000:00:0d.0
  d040-d047 : ahci
d048-d04b : 0000:00:0d.0
  d048-d04b : ahci
d050-d057 : 0000:00:0d.0
  d050-d057 : ahci
d058-d05b : 0000:00:0d.0
  d058-d05b : ahci
d060-d06f : 0000:00:0d.0
  d060-d06f : ahci
```

IOPorts

- Separate address space
- Legacy concept
- 16 bits address
- Use special in/out instructions
- Talk to devices instead of memory
- Privileged instruction, but you can use them from ring 3 by lowering the privilege level with iopl(3)

```
  4100-4108 : piix4_smbus
d000-d007 : 0000:00:03.0
  d000-d007 : e1000
d020-d03f : 0000:00:04.0
d040-d047 : 0000:00:0d.0
  d040-d047 : ahci
d048-d04b : 0000:00:0d.0
  d048-d04b : ahci
d050-d057 : 0000:00:0d.0
  d050-d057 : ahci
d058-d05b : 0000:00:0d.0
  d058-d05b : ahci
d060-d06f : 0000:00:0d.0
  d060-d06f : ahci
```

5.1.9 I/O Instructions

These instructions move data between the processor's I/O ports and a register or memory.

```
IN    Read from a port
OUT   Write to a port
INS/INSB  Input string from port/Input byte string from port
INS/INSW  Input string from port/Input word string from port
INS/INSD  Input string from port/Input doubleword string from port
OUTS/OUTSB    Output string to port/Output byte string to port
OUTS/OUTSW    Output string to port/Output word string to port
OUTS/OUTSD    Output string to port/Output doubleword string to port
```

IOMem

- Addresses that look like physical addresses but they are not actually ram.
- When you write or read to those addresses on the bus, it will actually talk to the device
- Use /dev/mem and mmap it into your usermode process.
- Example code on the right

```
3e6e2000-3e93dfff : Kernel bss
7fff0000-7fffffff : ACPI Tables
80000000-fdffffff : PCI Bus 0000:00
  e0000000-e7ffffff : 0000:00:02.0
  f0000000-f001ffff : 0000:00:03.0
    f0000000-f001ffff : e1000
  f0400000-f07fffff : 0000:00:04.0
    f0400000-f07fffff : vboxguest
  f0800000-f0803fff : 0000:00:04.0
  f0804000-f0807fff : 0000:00:05.0
    f0804000-f0807fff : ICH HD audio
```

```
volatile void* mmap_devmem_range(uint64_t start, uint64_t len) {
    volatile void* base_addr = NULL;
    int fd = open("/dev/mem", O_RDWR);
    if (fd < 0) {
        DIE("Unable to open /dev/mem\n");
    }

    debug_printf("mmap start 0x%lx len 0x%lx\n\n", start, len);
    base_addr = mmap(0, len, PROT_READ|PROT_WRITE, MAP_SHARED, fd, start);

    if (base_addr == NULL || base_addr == MAP_FAILED) {
        perror("mmap");
        DIE("Unable to mmap the  window\n");
    }

    return base_addr;
}
```

IOMem and physical memory maps quirks

- Be careful when you are writing to devices AND mappings of raw physical memory.
- Your writes can be cached.
- Use memory barriers to prevent this, in asm
- We just saved you lot of debugging, you are welcome ☺

```
asm volatile("" ::: "memory");
```

Auditing the device

```
int rc = PDMDevHlpMMIORegister(pDevIns, GCPhysAddress, cb, NULL /*pvUser*/,
                               IOMMMIO_FLAGS_READ_DWORD | IOMMMIO_FLAGS_WRITE_DWORD_ZEROED
                               | IOMMMIO_FLAGS_DBGSTOP_ON_COMPLICATED_WRITE,
                               ohciMmioWrite, ohciMmioRead, "USB OHCI");
if (RT_FAILURE(rc))
```

- Callbacks for MMIO read and write in read
- Writing or reading to those locations will trigger some operations on the device
- For example changing the status

```
static int HcRhStatus_w(POHCI pThis, uint32_t iReg, uint32_t val)
{
#ifdef IN_RING3
    /* log */
    uint32_t old = pThis->RootHub.status;
    uint32_t chg;
    if (val & ~0x80038003)
        Log2(("HcRhStatus_w: Unknown bits %#x are set!!!\n", val & ~0x80038003));
    if ( (val & OHCI_RHS_LPSC) && (val & OHCI_RHS_LPS) )
        Log2(("HcRhStatus_w: Warning both CGP and SGP are set! (Clear/Set Global Power)\n"));
    if ( (val & OHCI_RHS_DRWE) && (val & OHCI_RHS_CRWE) )
        Log2(("HcRhStatus_w: Warning both CRWE and SRWE are set! (Clear/Set Remote Wakeup Enable)\n"));


    /* write 1 to clear OCIC */
    if ( val & OHCI_RHS_OCIC )
        pThis->RootHub.status &= ~OHCI_RHS_OCIC;

    /* SetGlobalPower */
    if ( val & OHCI_RHS_LPSC )
    {
        unsigned i;
        Log2(("ohci: %s: global power up\n", pThis->PciDev.pszNameR3));
        for (i = 0; i < OHCI_NDP_CFG(pThis); i++)
```

Auditing the device

- Study how the communication works first
- Be very aware that attacker controlled input is not only from the registers, but also from guest physical memory.
- The host will map it,

fetch it or write (TOCTOU vulnerabilities(!),

Races etc)

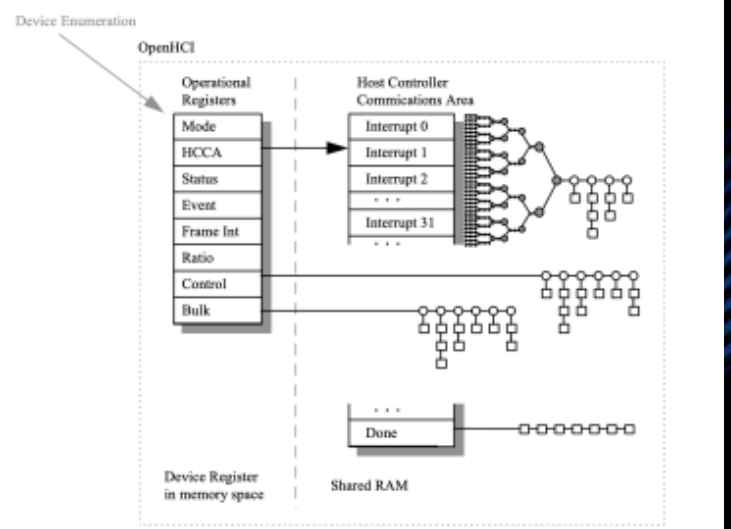


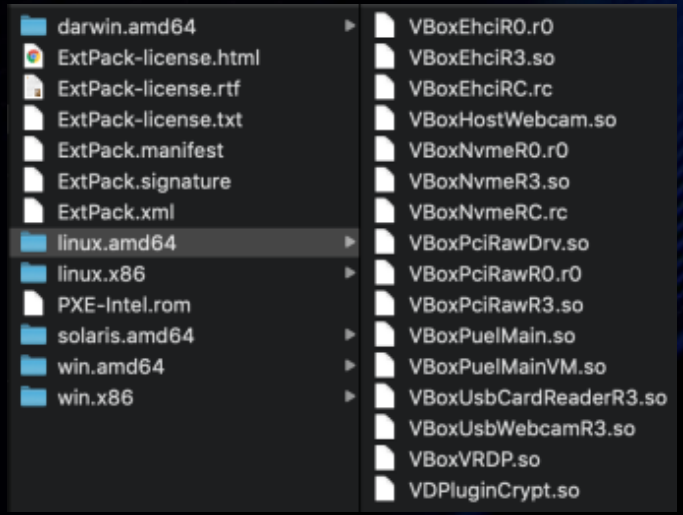
Figure 3-2: Communication Channels

```
/**
 * Reads physical memory.
 */
DECLINLINE(void) ohciR3PhysRead(POHCI pThis, uint32_t Addr, void *pvBuf, size_t cbBuf)
{
    if (cbBuf)
        PDMDevHlpPhysRead(pThis->CTX_SUFF(pDevIns), Addr, pvBuf, cbBuf);
}

/**
 * Writes physical memory.
 */
DECLINLINE(void) ohciR3PhysWrite(POHCI pThis, uint32_t Addr, const void *pvBuf, size_t cbBuf)
{
    if (cbBuf)
        PDMDevHlpPCIPhysWrite(pThis->CTX_SUFF(pDevIns), Addr, pvBuf, cbBuf);
}
```

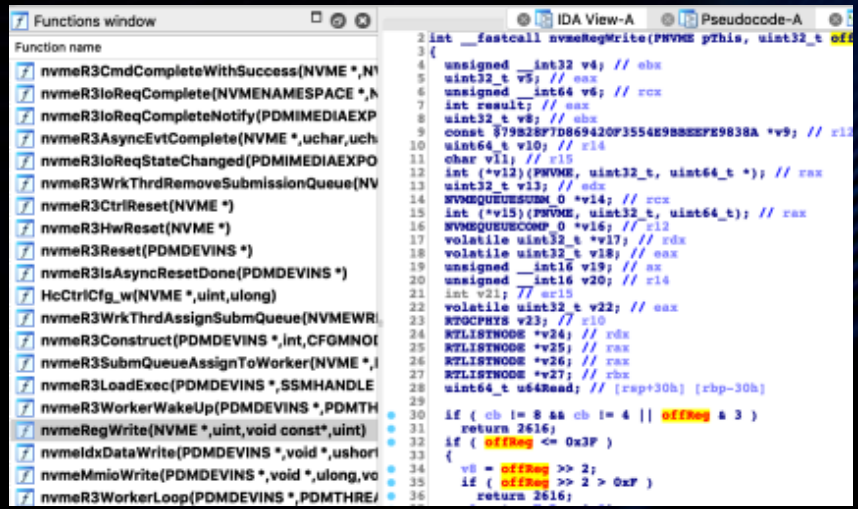
Extensions

- Oracle_VM_VirtualBox_Extension_Pack-6.0.4.vbox-extpack
- Actually a gzip file, rename and extract
- Modules for additional proprietary stuff, including devices
- For example, XHCI and EHCI USB Controllers (2.0 and 3.0)
- All platforms, pick your poison and load into IDA



Extensions

- They have symbols, easier to RE
- They use the same APIs as the opensource part so you can port some structures
- Some stuff is C++ so more RE/ IDA work is required
- No one looked into those publicly to the best of my knowledge.
- If you want some easy bugs it might be a good place ☺



Useful Tricks

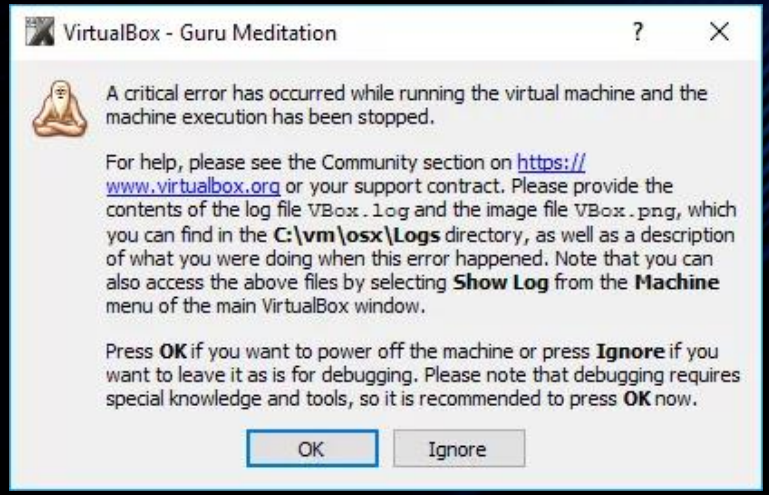
- It's easier to develop the exploit in guest userland instead of guest kernel.
- Sometimes you need to map some memory, and get the physical address in the guest.
- Rebuild the kernel without the devmem restriction. Map anything through /dev/mem and mmap
- Get the physical address from the virtual address with the code on the right using pagemap

```
unsigned long virtual_to_pfn(void *addr) {
    int fd = open("/proc/self/pagemap", O_RDONLY);
    if (fd < 0) {
        DIE("cannot open /proc/self/pagemap\n");
    }
    unsigned long addr_ul = (unsigned long) addr;
    unsigned long data = 0;
    int pagesize = getpagesize();
    unsigned long index = (addr_ul/pagesize)*sizeof(data);
    debug_printf("pagesize is 0x%x addr_ul is 0x%lx index is 0x%lx\n", pagesize, addr_ul, index);
    if (pread(fd, &data, sizeof(data), index) != sizeof(data)) {
        DIE("cannot read content of pagemap for 0x%lx\n", addr_ul);
    }

    return data & 0x7fffffffffffff;
}
```

A word on fuzzing

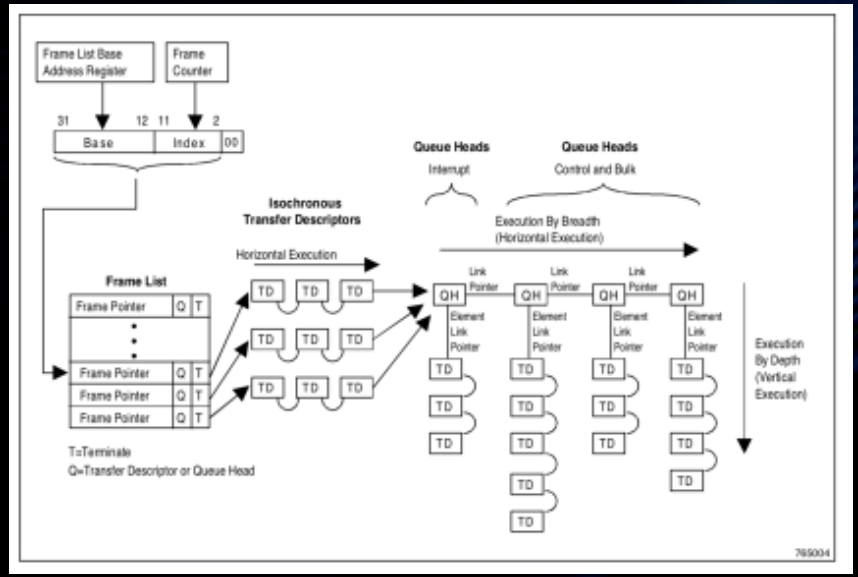
- Fuzzing emulated hardware on VirtualBox is a little bit frustrating and fragile
- It's very easy to jump to GURU MEDITATION MODE
- Triggered often by some asserts and checks
- That's why I quickly stopped fuzzing and just audited
- Bugs are still abundant so no problem.



VBOX DEMO

Finding bugs by checking OTHER hypervisors

- By checking other bugs affecting other hypervisors you can easily find bugs in different products.
- Recently we got a bug collision with Amat at p2o, on vmware.
- He found and used one of our same bug to escape vmware
- Race condition in UHCI (usb 1.0)



Finding bugs by checking OTHER hypervisors

- Vmware was mapping the guest physical memory in host usermode
- Then fetching the length of the usb packets, and using it to allocate the memory
- Then fetching this length again to perform the memory copy
- Typical Double Fetch resulting in a very exploitable heap overflow
- Was affecting workstation and ESXi
- We had it for almost 2 years, now unfortunately it’s dead
- My point is, you can find similar problems to fetching in VirtualBox
- Dig into the code and have fun yourself!

QEMU

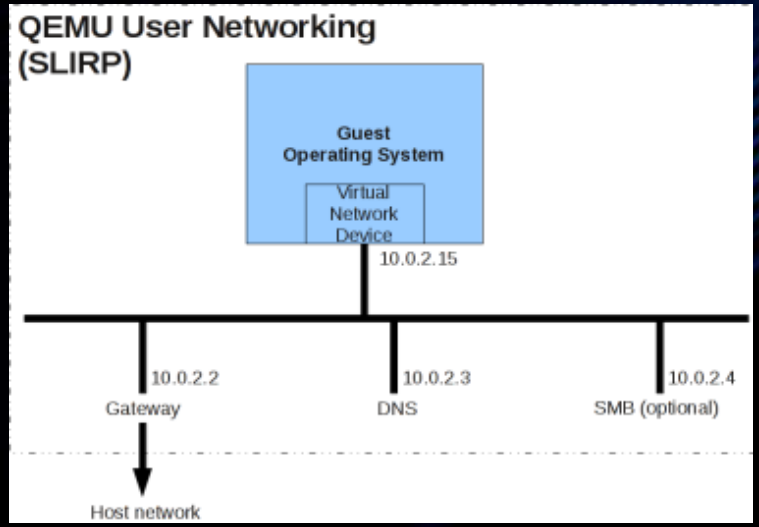
SLiRP

- TCP/IP emulator
- Emulates a PPP, SLIP, or CSLIP connection to the Internet
- Pretty old code can be found:
  https://sourceforge.net/projects/slirp/
- Used in QEMU and VirtualBox
- History bugs
  - https://bugs.chromium.org/p/project-zero/issues/detail?id=1086
    Slirp bug in VirtualBox by Jann Horn, Google Project Zero
  - https://www.voidsecurity.in/2018/11/virtualbox-nat-dhcpbootp-server.html
    VirtualBox NAT DHCP/BOOTP server vulnerabilities by Reno Robert

SLiRP in QEMU

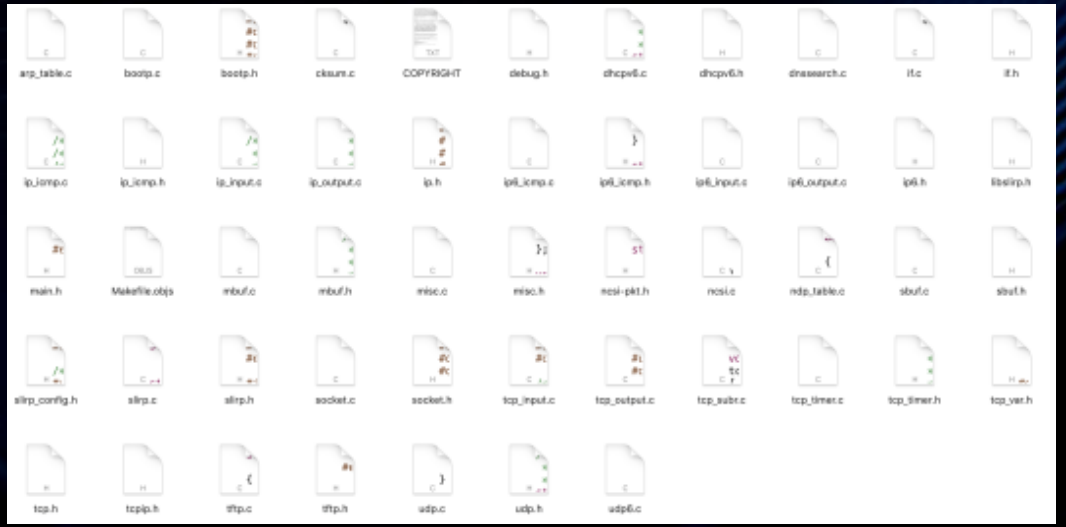
- The default network backend
- Many functionalities:
  - DHCP
  - DNS server
  - TFTP server (optional)
  - SMB server (optional)
  - Forward host ports to guest

  -net user,hostfwd=tcp::2222-:22



SLiRP in QEMU

- Source structure
- Large attack surface
- Not like the typical device drivers which means it’s not well studied



CVE-2019-6778

- Some special ports in TCP emulation
  - 113 (*Identification protocol*)
  - 21 (*ftp*)
  - 544 (*kshell*)
  - 6667 6668 (*IRC*)
  - …
- Handled in *slirp/tcp_subr.c:tcp_emu*

CVE-2019-6778

- Two important data structures
  - *mbuf*
    Store data from IP layer
  - *sbuf*
    Store data from TCP layer

```
// slirp/sbuf.h
struct sbuf {
    uint32_t sb_cc;     /* actual chars in buffer */
    uint32_t sb_datalen;    /* Length of data  */
    char    *sb_wptr;   /* write pointer. points to where the next
                 * bytes should be written in the sbuf */
    char    *sb_rptr;   /* read pointer. points to where the next
                 * byte should be read from the sbuf */
    char    *sb_data;   /* Actual data */
};
```

CVE-2019-6778

```
// slirp/tcp_subr.c:tcp_emu
case EMU_IDENT:
        /*
         * Identification protocol as per rfc-1413
         */

        {
            struct socket *tmpso;
            struct sockaddr_in addr;
            socklen_t addrlen = sizeof(struct sockaddr_in);
            struct sbuf *so_rcv = &so->so_rcv;

            memcpy(so_rcv->sb_wptr, m->m_data, m->m_len);   // copy user data to sbuf
            so_rcv->sb_wptr += m->m_len;
            so_rcv->sb_rptr += m->m_len;
            m->m_data[m->m_len] = 0; /* NULL terminate */
            if (strchr(m->m_data, '\r') || strchr(m->m_data, '\n')) {
                ...
            }
            m_free(m);
            return 0;
        }
```

CVE-2019-6778

```
// slirp/sbuf.h
#define sbspace(sb) ((sb)->sb_datalen - (sb)->sb_cc)

// slirp/tcp_input.c:tcp_input
    } else if (ti->ti_ack == tp->snd_una &&
            tcpfrag_list_empty(tp) &&
            ti->ti_len <= sbspace(&so->so_rcv)) {   // check if there's enough space in sbuf
            ...
            if (so->so_emu) {
                if (tcp_emu(so,m)) sbappend(so, m); // call tcp_emu
```

CVE-2019-6778

- If one keeps sending data to port 113
- Heap overflow !

```
s = socket(AF_INET, SOCK_STREAM, 0);
ip_addr.sin_family = AF_INET;
ip_addr.sin_addr.s_addr = inet_addr("xxx"); // any IP you can connect
ip_addr.sin_port = htons(113); // vulnerable port
ret = connect(s, (struct sockaddr *)&ip_addr, sizeof(struct sockaddr_in));
memset(buf, 'A', 0x500);
while(1) {
    write(s, buf, 0x500);
}
```

Bug fix

- They didn’t know how to fix at first :)
- The final fix is simple but effective

```
diff --git a/slirp/tcp_subr.c b/slirp/tcp_subr.c
index 4a9a5b5edc..23a841f26e 100644
--- a/slirp/tcp_subr.c
+++ b/slirp/tcp_subr.c
@@ -634,6 +634,11 @@ tcp_emu(struct socket *so, struct mbuf *m)
                     socklen_t addrlen = sizeof(struct sockaddr_in);
                     struct sbuf *so_rcv = &so->so_rcv;

+                    if (m->m_len > so_rcv->sb_datalen
+                                   - (so_rcv->sb_wptr - so_rcv->sb_data)) {
+                        return 1;
+                    }
+
                     memcpy(so_rcv->sb_wptr, m->m_data, m->m_len);
                     so_rcv->sb_wptr += m->m_len;
                     so_rcv->sb_rptr += m->m_len;
```

Exploit

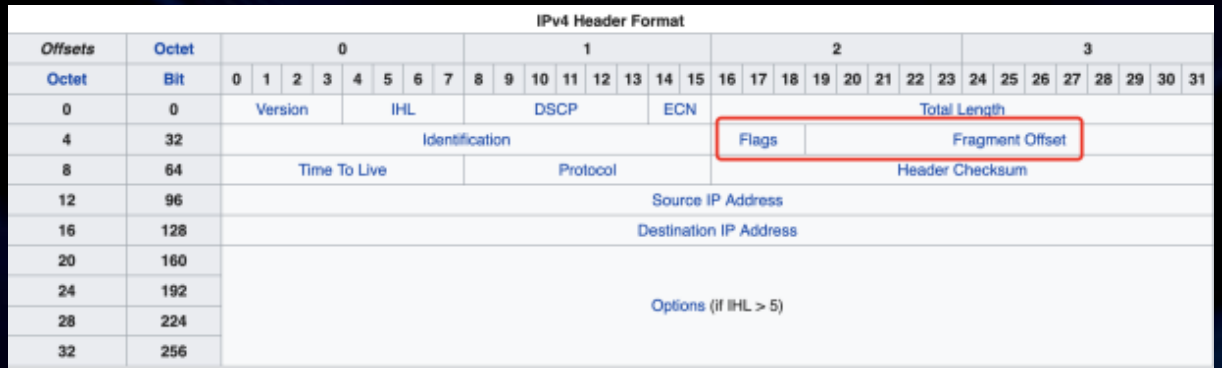
- What we're facing:
  - Overflow in a pure data buffer
  - No pointer
  - No fields like length etc
- How to control the heap?

IP fragmentation

- IPv4
- Breaks packets into smaller pieces (fragments)
- Small MTU network → Big MTU network
- The fragments are reassembled by the receiving host.

IP fragmentation

- Flags (3 bit)
  - Zero (1 bit)
  - Do not fragment flag (1 bit)
  - More fragments following flag (1 bit)
- Fragment offset (13 bit)



IPv4 Header Format

Offsets	Octet	0								1								2								3							
Octet	Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	0	Version				IHL				DSCP						ECN		Total Length															
4	32	Identification																Flags			Fragment Offset											
8	64	Time To Live								Protocol								Header Checksum															
12	96	Source IP Address																															
16	128	Destination IP Address																															
20	160	Options (if IHL > 5)																															
24	192																																
28	224																																
32	256																																

IP fragmentation

- QEMU will store the packet
- Allocate arbitrary *mbuf*

```
// slirp/mbuf.h
struct mbuf {
    /* XXX should union some of these! */
    /* header at beginning of each mbuf: */
    struct  mbuf *m_next;       /* Linked list of mbufs */
    struct  mbuf *m_prev;
    struct  mbuf *m_nextpkt;    /* Next packet in queue/record */
    struct  mbuf *m_prevpkt;    /* Flags aren't used in the output queue */
    int m_flags;        /* Misc flags */
    int m_size;         /* Size of mbuf, from m_dat or m_ext */
    struct  socket *m_so;
    caddr_t m_data;         /* Current location of data */
    int m_len;          /* Amount of data in this mbuf, from m_data */
    Slirp *slirp;
    bool    resolution_requested;
    uint64_t expiration_date;
    char   *m_ext;
    /* start of dynamic buffer area, must be last element */
    char    m_dat[];
};
```

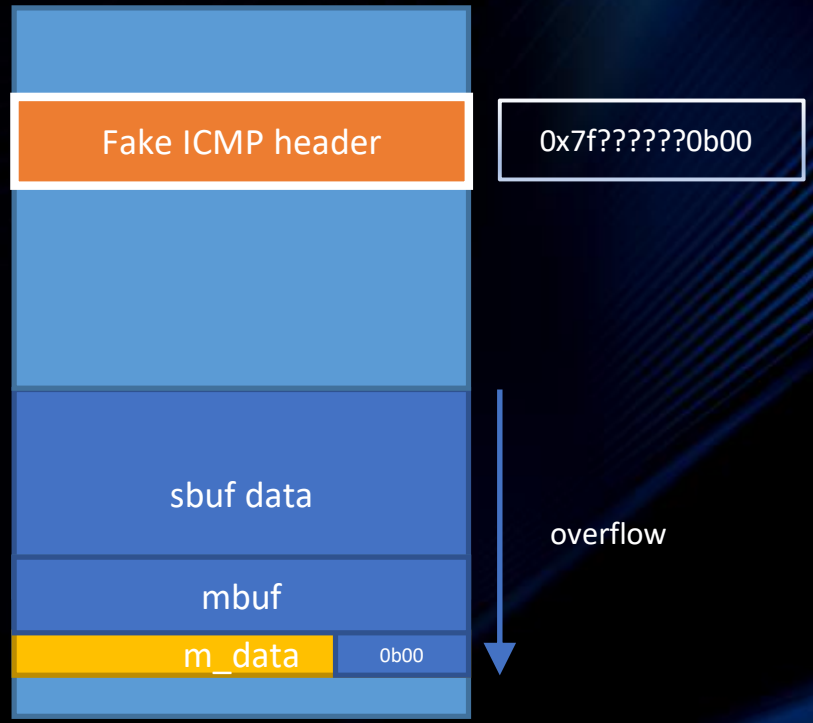
Arbitrary write

- Overflow *mbuf*
- *m_data* is a pointer to the data
- Reassemble all the data to the first *mbuf*

```
// slirp/ip_input.c:ip_reass
  while (q != (struct ipasfrag*)&fp->frag_link) {
      struct mbuf *t = dtom(slirp, q);
      q = (struct ipasfrag *) q->ipf_next;
      m_cat(m, t);
  }
```

Infoleak

1. Overflow the low bits of *m_data*, write a fake ICMP header.

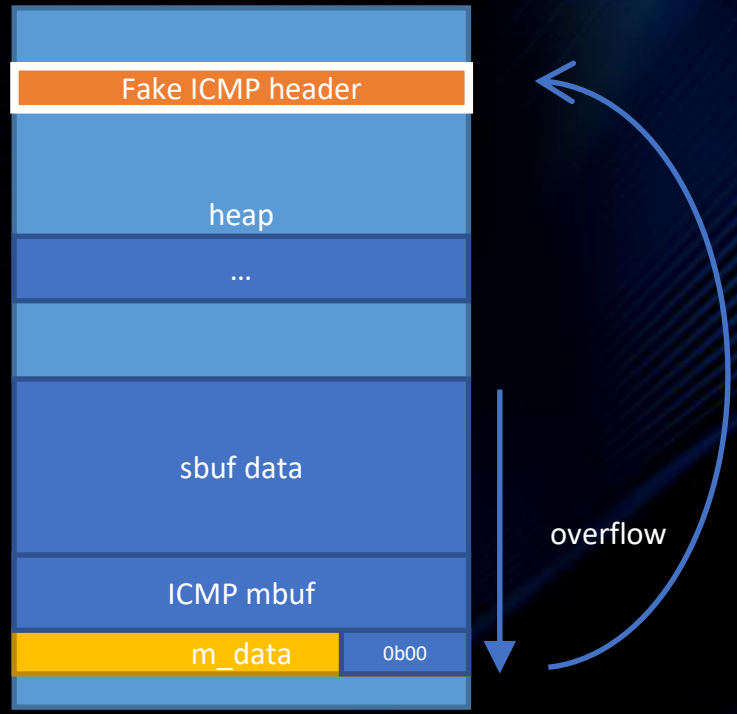


Infoleak

2. Send an ICMP request with MF=1.

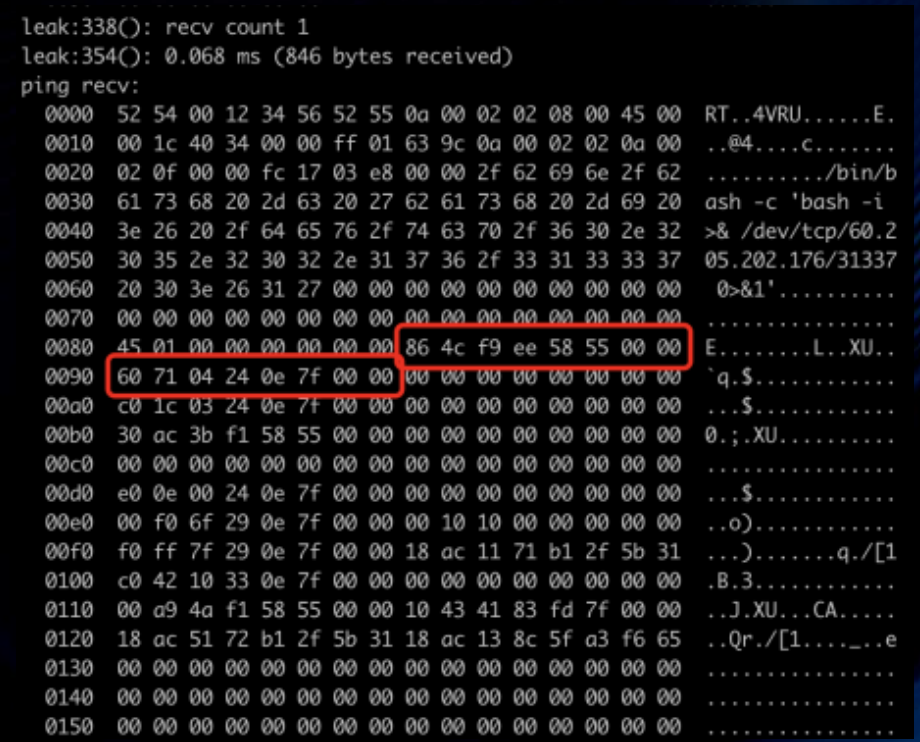
Infoleak

3. Overflow the ICMP *mbuf.m_data* low bits.
4. Send ICMP request with MF=0.



Infoleak

5. Receive gifts from host.



PC control

- Many failed tries 
  - GOT table is not writable. qemu-system has all modern protections.
  - Function pointers in heap, unstable and hard to trigger
  - No interesting structures in SLiRP
  - There do exist interesting structures in other modules. However, they’re in different heaps :(
  - …

PC control

- When time expires,
  ***cb(opaque)* will be executed**
- On bss
- Oops!

```
// include/qemu/timer.h
struct QEMUTimer {
    int64_t expire_time;        /* in nanoseconds */
    QEMUTimerList *timer_list;
    QEMUTimerCB *cb;  // function pointer
    void *opaque;     // first argument
    QEMUTimer *next;
    int attributes;
    int scale;
};
```

```
gdb-peda$ p *main_loop_tlg.tl[0]->active_timers
$7 = {
  expire_time = 0x184cefdfc240,
  timer_list = 0x55e5132d3840,
  cb = 0x55e510f9c149 <gui_update>,
  opaque = 0x55e5143ffde0,
  next = 0x55e5143ffe10,
  attributes = 0x0,
  scale = 0xf4240
}
```

QEMU DEMO

Conclusions

Conclusions

- Virtualization Software is not really that strange target. You just need to find the right bugs.
- It‘s easier than many popular targets
- It lacks often of sandbox
- In many cases it’s even worst, for example in VirtualBox from the host ring3 you can get ring0 privileges.
- SLiRP is a fruitful target in both QEMU and VirtualBox
- You can learn a lot from other hypervisors and transfer your knowledge.

QUESTIONS? THANK YOU


THANKS
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