Virtunoid: Breaking out of KVM

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KVM

- The new hotness for Virtualization on Linux
- Official virtualization platform for Ubuntu and RHEL.

Who am I?

- Kernel engineer at Ksplice (now Oracle).
- Open-source security hacker in my spare time.

Outline

KVM: The components

- `kvm.ko`
- `kvm-intel.ko` / `kvm-amd.ko`
- `qemu-kvm`

kvm.ko

- The core KVM kernel module
- Implements the virtual CPU and MMU (with the hardware's help).
- Emulates a few devices in-kernel for efficiency.
- Provides `ioctls` for communicating with the kernel module.
- Contains an emulator for a subset of x86 used in handling certain traps (!)

`kvm-intel.ko` / `kvm-amd.ko`

- Provides support for Intel's VMX and AMD's SVM virtualization extensions.
- Relatively small compared to the rest of KVM (one `.c` file each)

qemu-kvm

- Provides the most direct user interface to KVM.
- Based on the classic `qemu` emulator.
- Implements the bulk of the virtual devices a VM uses.
- Implements a wide variety of types of devices.
- An order of magnitude more code than the kernel module.
- There is work in progress to replace this component, but it's a ways out, if ever.

kvm.ko

- A tempting target – successful exploitation gets ring0 on the host without further escalation.
- Much less code than `qemu-kvm`, and much of that is dedicated to interfacing with `qemu-kvm`, not the guest directly.
- The x86 emulator is an interesting target.
  - A number of bugs have been discovered allowing privesc *within* the guest.
  - A lot of tricky code that is not often exercised.
  - Not the target of this talk, but I have some ideas for future work.
- Also, be on the lookout for privesc *within* either the host or guest.

kvm-intel.ko / kvm-amd.ko

- Not much direct attack surface.
- Largely straight-line code doing lots of low-level bit twiddling with the hardware structures.
- Lots of subtlety, possibly some more complex attacks.

`qemu-kvm`

- A veritable goldmine of targets.
- Hundreds of thousands of lines of device emulation code.
- Emulated devices communicate directly with the guest via MMIO or IO ports, lots of attack surface.
- Much of the code comes straight from qemu and is ancient.
- `qemu-kvm` is often sandboxed using SELinux or similar, meaning that successful exploitation will often require a second privesc within the host.
    - (Fortunately, Linux *never* has any of those)

RHSA-2011:0534-1

"It was found that the PIIX4 Power Management emulation layer in qemu-kvm did not properly check for hot plug eligibility during device removals. A privileged guest user could use this flaw to crash the guest or, possibly, execute arbitrary code on the host. (CVE-2011-1751)"

PIIX4

- The PIIX4 was a southbridge chip used in many circa-2000 Intel chipsets.
- The default southbridge emulated by `qemu-kvm`
- Includes ACPI support, a PCI-ISA bridge, an embedded MC146818 RTC, and much more.

Device Hotplug

- The PIIX4 supports PCI hotplug, implemented by writing values to IO port `0xae08`.
- `qemu-kvm` emulates this by calling `qdev_free(qdev);`, which calls a device's cleanup function and `free()`s it.
- Many devices weren't implemented with hotplug in mind!

The PCI-ISA bridge

- In particular, it should not be possible to unplug the ISA bridge.
- Among other things, the emulated MC146818 RTC hangs off the ISA bridge.
- KVM's emulated RTC is not designed to be unplugged; In particular, it leaves around dangling `QEMUTimer` objects when unplugged.

QEMUTimer

```
typedef void QEMUTimerCB(void *opaque);

struct QEMUTimer {
    ...
    int64_t expire_time; /* in nanoseconds */
    QEMUTimerCB *cb;
    void *opaque;
    struct QEMUTimer *next;
};

typedef struct RTCState {
  ...
  QEMUTimer *second_timer;
  ...
} RTCState;
```

Use-after-free

- Unplugging the virtual RTC `free()`s the `RTCState`
- It doesn't `free()` or unregister either of the timers.
- So we're left with dangling pointers from the `QEMUTimers`
- On the next second, we'll call `rtc_update_second(`*<freed RTCState>*`)`

Reproducer

```
#include <sys/io.h>

int main (void) {
    iopl(3);
    outl(2, 0xae08);
    return 0;
}
```

High-level TODO

1. Inject a controlled `QEMUTimer` into `qemu-kvm` at a known address
2. Eject the emulated ISA bridge
3. Force an allocation into the freed `RTCState`, with `second_timer` pointing at our dummy timer.

- When `rtc_update_second` next runs, *our* timer will get scheduled.
- One second later, boom.

1. Injecting data

- The guest's RAM is backed by a simple `mmap()`ed region inside the `qemu-kvm` process.
- So we allocate an object in the guest, and compute
  - `hva = physmem_base + gpa`
  - `gpa = (gva_to_gfn(gva) << PAGE_SHIFT)`
    `+ page_offset(gva)`
- For now, assume we can guess `physmem_base` (e.g. no ASLR)

hva host virtual address

gva guest virtual address

gpa guest physical address

gfn guest frame (physical page) number

qemu-kvm userspace network stack

- `qemu-kvm` contains a user-mode networking stack.
- Implements a DHCP server, DNS server, and a gateway NAT.

Userspace network stack packet delivery

- The user-mode stack normally handles packets synchronously.
- To prevent recursion, if a second packet is emitted while handling a first packet, the second packet is queued, using `malloc()`.

- The virtual network gateway responds synchronously to ICMP ping.

Putting it together

1. Allocate a fake `QEMUTimer`
   - Point `->cb` at the desired `%rip`.
2. Calculate its address in the host.
3. Write 2 to IO port `0xae08` to eject the ISA bridge.
4. ping the emulated gateway with ICMP packets containing pointers to your allocated timer in the host.

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- Disable NX in my BIOS and call it good enough for a demo.
- Do a ROP pivot, ROP to victory.
- Do something else clever.

Another look at QEMUTimer

```
struct QEMUTimer {
    ...
    int64_t expire_time; /* in nanoseconds */
    ...
    struct QEMUTimer *next;
};
```

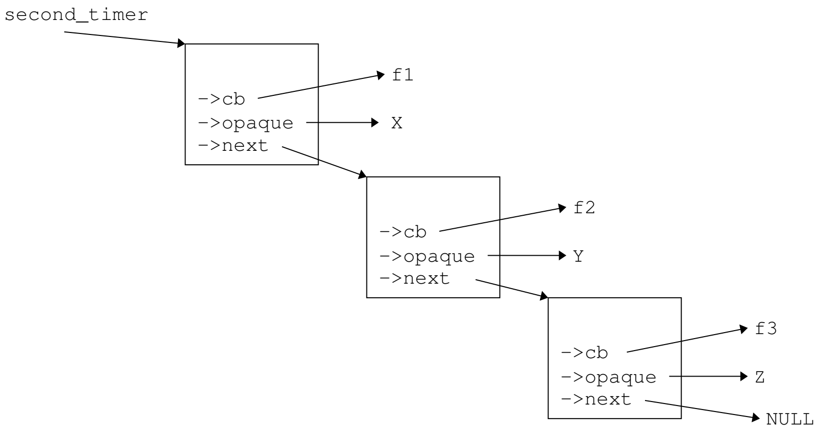
qemu_run_timers

```
static void qemu_run_timers(QEMUClock *clock)
{
    QEMUTimer **ptimer_head, *ts;
    int64_t current_time;

    current_time = qemu_get_clock_ns(clock);
    ptimer_head = &active_timers[clock->type];
    for(;;) {
        ts = *ptimer_head;
        if (!qemu_timer_expired_ns(ts, current_time))
            break;
        *ptimer_head = ts->next;
        ts->next = NULL;

        ts->cb(ts->opaque);
    }
}
```

Timer chains



$\Rightarrow$ `f1(X); f2(Y); f3(Z);`

More arguments

- amd64 calling convention: `%rdi`, `%rsi`, `%rdx`, ...
- Every version of `qemu_run_timers` I've checked leaves `%rsi` untouched.

More arguments

- ```
  set_rsi:
      movl %rdi, %rsi
      ret
  ```
- Let `f1 = set_rsi`
- `f2(Y, X)`
- Same trick doesn't work with `%rdx`.
  ```

set_rsi

```
void cpu_outl(pio_addr_t addr, uint32_t val)
{
    ioport_write(2, addr, val);
}
```

Getting to mprotect

```
int mprotect(const void *addr, size_t len, int prot);
#define PROT_EXEC 0x4
```

```
static uint32_t ioport_readl_thunk(void *opaque, uint32_t addr)
{
    IORange *ioport = opaque;
    uint64_t data;

    ioport->ops->read(ioport, addr - ioport->base, 4, &data);
    return data;
}
```

Putting it together

- Allocate a fake `IORangeOps`, with `fake_ops->read = mprotect`.
- Allocate a page-aligned `IORange`, with `->ops = fake_ops` and `->base = -PAGE_SIZE`.
- Copy shellcode immediately following the `IORange`.
- Construct a timer chain that calls
  - `cpu_outl(0, *)`
  - `ioport_readl_thunk(fake_ioport, 0)`
  - `fake_ioport + 1`

Why not ROP?

- Continued execution is dead simple.
- Reduced dependence on details of compiled code.
- I'm not that good at ROP :)

Addresses

- For a known qemu-kvm binary, we need two addresses.
  - The base address of the qemu-kvm binary, to find code addresses.
  - physmem_base, the address of the physical memory mapping inside qemu-kvm.

Option A

- Find an information leak.

Option B

- Assume non-PIE, and be clever.

fw_cfg

- Emulated IO ports `0x510` (address) and `0x511` (data)
- Used to communicate various tables to the qemu BIOS (e820 map, ACPI tables, etc)
- Also provides support for exporting writable tables to the BIOS.
- However, `fw_cfg_write` doesn't check if the target table is supposed to be writable!

Static data

- Several `fw_cfg` areas are backed by statically-allocated buffers.
- Net result: nearly 500 writable bytes inside static variables.

read4 your way to victory

- `mprotect` needs a page-aligned address, so these aren't suitable for our shellcode.
- But, we can construct fake timer chains in this space to build a `read4()` primitive.
- Follow pointers from static variables to find `physmem_base`
- Proceed as before.

Repeated timer chaining

- Previously, we ended timer chains with `->next = NULL`.
- Instead, end them with a timer that calls `rtc_update_second`.
- The timer we control will be scheduled once a second, and we can change `->cb` at any time.
- Now we can execute a `read4`, update structures based on the result, and then hijack the list again.

Conclusions

- VM breakouts aren't magic.
- Hypervisors are just as vulnerable as anything else.
- Device drivers are the weak spot.

Comparing with some past breakouts

2008 "Adventures with a certain Xen vulnerability", Xen, Invisible Things Lab

2009 "Cloudburst", Immunity, VMware

2011 "Software attacks against Intel VT-d technology", Invisible Things Lab, Xen

Possible hardening directions

- Sandbox `qemu-kvm` (work underway well before this talk).
- Build `qemu-kvm` as PIE.
- Lazily `mmap`/`mprotect` guest RAM?
- XOR-encode key function pointers?
- More auditing and fuzzing of `qemu-kvm`.

Future research directions

- Fuzzing/auditing `kvm.ko` (That x86 emulator sketches me)
- Fingerprinting `qemu-kvm` versions
- Searching for infoleaks (Rosenbugs?)

It's demo time

Questions?

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