Hunting and Exploiting Recursive MMIO Flaws in QEMU/KVM

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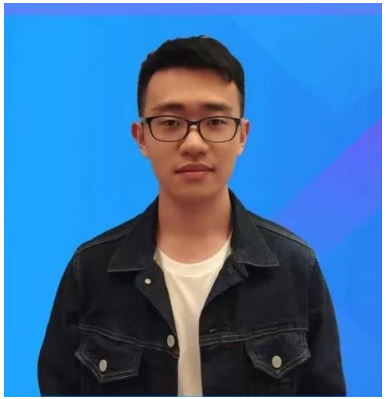
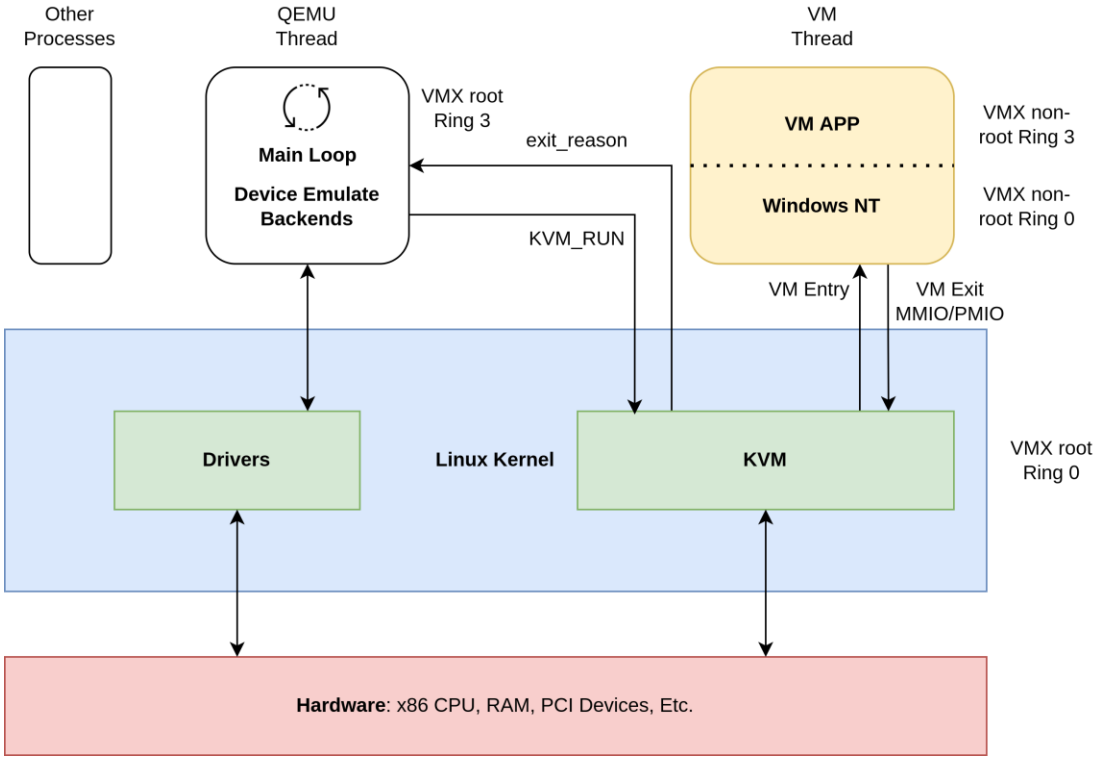


Outline

1. **Introduction**
2. Root Causes
3. Hunting Flaws
4. Case Study
5. Exploitation
6. Mitigations
7. Thoughts

QEMU/KVM Architecture



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Recursive MMIO

MMIO: EPT Misconfig

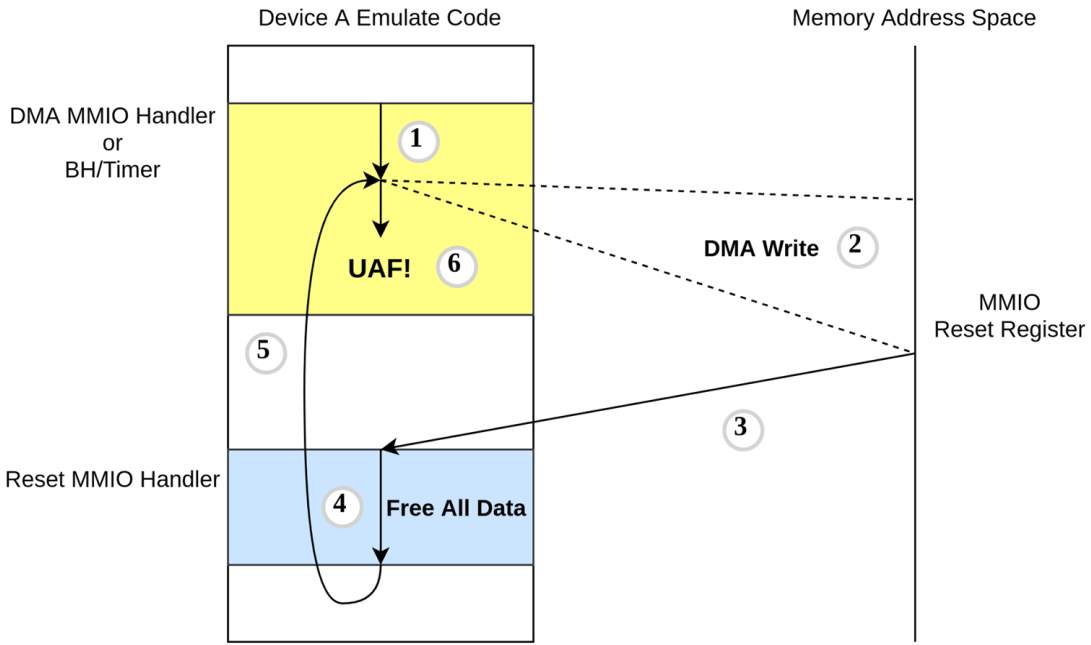
DMA: memcpy()

Device →Device

E.g. P2PDMA

A → B ✓

A → A ✗



Recursive MMIO

MMIO: EPT Misconfig

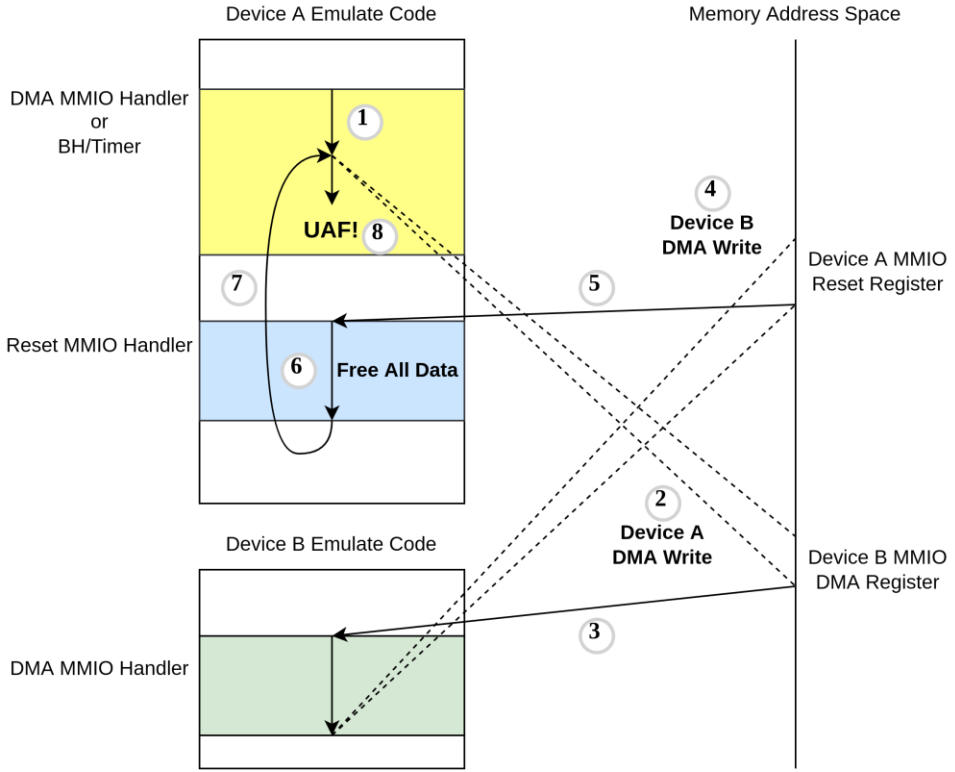
DMA: memcpy()

Device →Device

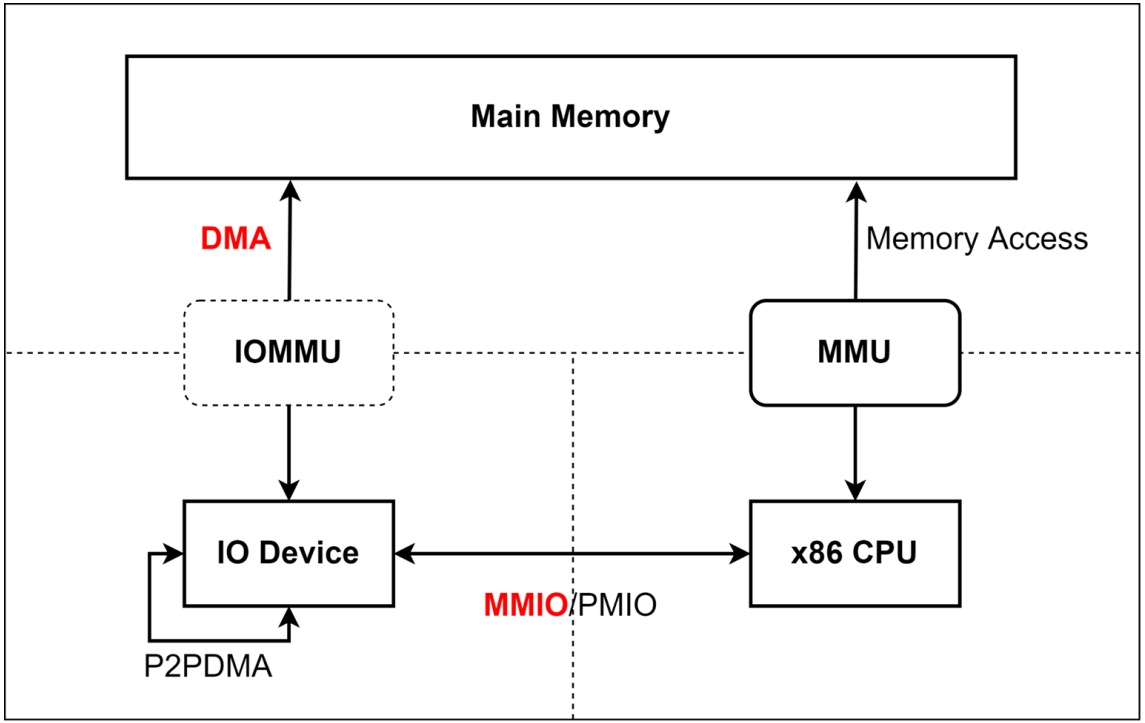
E.g. P2PDMA

A → B → C ✓

A → B → A ✗



Recursive MMIO



Common Consequences

Break device’s state machine:

1. **MMIO Reset Register → Free Data → Use Freed Data.**

2. Corrupt structures like transfer size and data index in global buffer.

3. Endless recursive call (stack overflow).

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Things on VirtualBox

In VirtualBox, most write-to-physical-address primitives, like PDMDevHlpPCIPhysWrite(), PDMDevHlpPhysWrite(), dmaR3WriteMemory(), Etc. are end to call PGMPhysWrite() -- it will call all the access handlers of the destination. So VirtualBox is also vulnerable to the recursive MMIO flaws in theory.

To verify our guess, we attached gdb to the VirtualBoxVM process and changed the GCPhys (physical address, controlled by the guest) to 0xf02000cc (in MMIO region of the pcnet device), successfully triggered a recursive MMIO.

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Recursive Paths

1. **MMIO Handler** → Write-to-Phys-Address API (DMA) → **MMIO Handler**

2. **BH/Timer Callback** → Write-to-Phys-Address API (DMA) → **MMIO Handler**

Recursive Paths

MMIO Write Handler

```
struct MemoryRegionOps {
    /* Read from the memory region. @addr is relative to @mr; @size is
     * in bytes. */
    uint64_t (*read)(void *opaque,
                     hwaddr addr,
                     unsigned size);
    /* Write to the memory region. @addr is relative to @mr; @size is
     * in bytes. */
    void (*write)(void *opaque,
                  hwaddr addr,
                  uint64_t data,
                  unsigned size);
    /* ..... */
```

Recursive Paths

MMIO Handler CodeQL

```
class MMIOFn extends Function {
  MMIOFn() {
    exists(GlobalVariable gv |
      gv.getFile().getAbsolutePath().regexpMatch(".*qemu-6.1.0/hw/.*") and
      gv.getType().getName().regexpMatch(".*MemoryRegionOps.*") and
      gv.getName().regexpMatch(".*mmio.*") and
      gv.getInitializer().getExpr().getChild(1).toString() = this.toString()
    )
  }
}
```

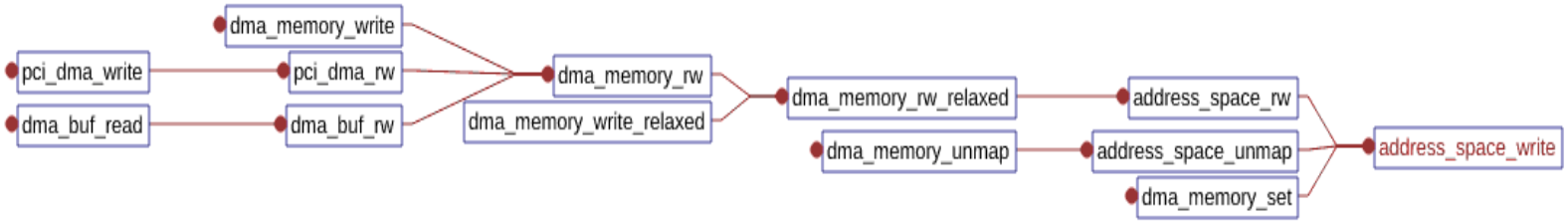
Recursive Paths

BH/Timer Callback CodeQL

```
class BHTFn extends Function {
  BHTFn() {
    exists(FunctionCall fc |
      fc.getTarget().getName().regexpMatch("qemu_bh_new_full|timer_new_ns") and
      fc.getFile().getAbsolutePath().regexpMatch(".*qemu-6.1.0/hw/.*") and
      (fc.getChild(0).toString() = this.toString() or fc.getChild(1).toString() = this.toString())
    )
  }
}
```

Recursive Paths

Write-to-Phys-Address Gadgets Relationship



docs/devel/loads-stores.rst

Recursive Paths

Write-to-Phys-Address Gadgets CodeQL

```
class ReentryFn extends Function {
  ReentryFn() {
    this.getName()

.regexpMatch("address_space_write|dma_memory_write|stb_dma|stl_be_dma|stl_le_dm
a|stq_be_dma|stq_le_dma|stw_be_dma|stw_le_dma|pci_dma_write|dma_buf_read|...")
  }
}
```

Recursive Paths

Nodes + Edges

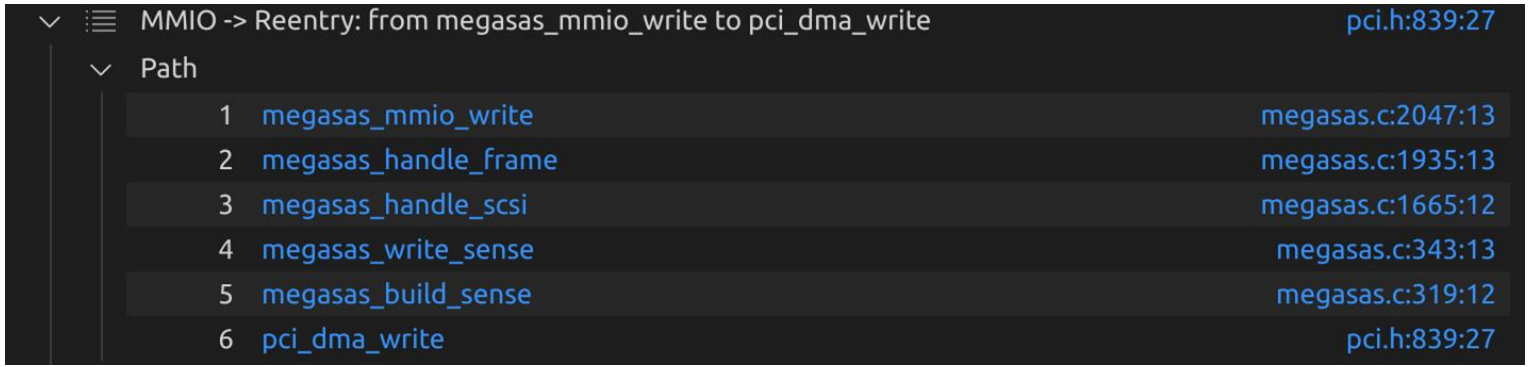
```
/**
 * @kind path-problem
 */

query predicate edges(Function a, Function b) { a.calls(b) }

from MMIOFn entry_fn, ReentryFn end_fn
where edges+(entry_fn, end_fn)
select end_fn, entry_fn, end_fn, "MMIO -> Reentry: from " + entry_fn.getName() + " to " +
end_fn.getName()
```

CodeQL: Creating path queries, Recursion

Recursive Paths



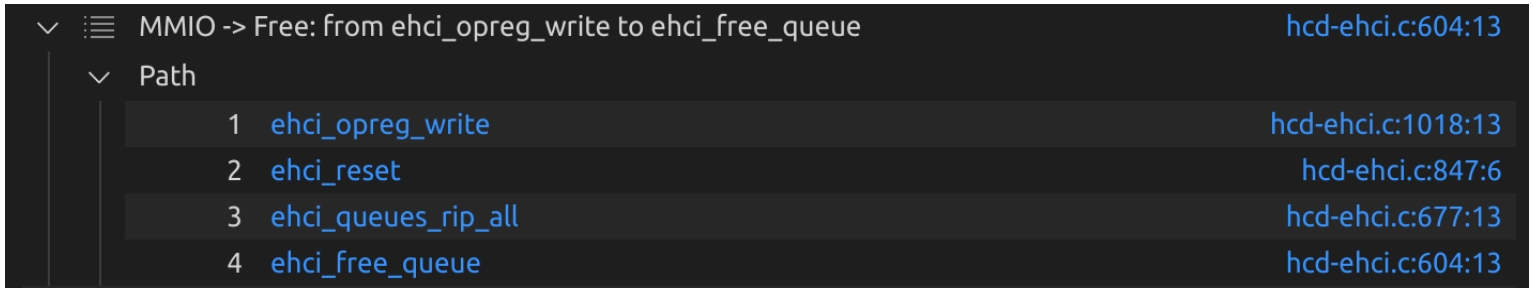
MMIO to pci_dma_write in MegaRAID SAS 8708EM2

Free Primitives

MMIO write handler -> reset/free gadget

```
class FreeFn extends Function {
  FreeFn() {
    exists(FunctionCall fc |
      fc.getTarget().getName().matches("g_free") and
      fc.getEnclosingFunction() = this and
      not this.getName().regexpMatch(".*shutdown.*") and
      not this.getFile()
          .getRelativePath()
          .regexpMatch(".*error.*|.*test.*|.*replay.*|.*translate-all.*|.*xen.*|.*qapi-visit.*")
    )
  }
}
```

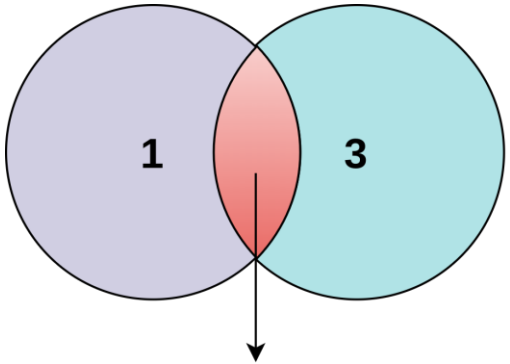
Free Primitives

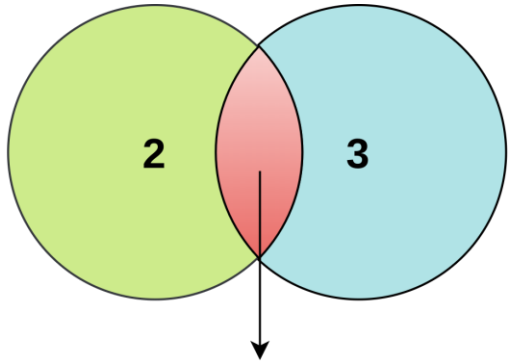


MMIO to Free in EHCI Controller

UAF Bugs

- 1. MMIO handler → Write-to-Phys-Address API (DMA)
- 2. BH/Timer callback → Write-to-Phys-Address API (DMA)
- 3. MMIO write handler → reset/free gadget





Possible Malloc Primitives

1. After the control flow returns from the MMIO reset handler, a malloc that allocates chunk the same size as freed chunk will be called.

2. We can write to another device's MMIO in which a chunk will be allocated, then we return to the vulnerable device to use the freed but occupied chunk. Since scatter-gather DMA is common in devices, it's easy to find vulnerable devices that do multiple write-to-physical-address actions.

Malloc Pattern

1. There should be a free() before the allocate call, or the guest keep allocating chunks and crash the hypervisor.
2. The allocated chunk is composed of multiple smaller units (predefined structures, constant size), so we can control the whole chunk's size to occupy the freed chunk.
3. There should be a read-from-physical-address action after the malloc call, so we can control the content of the allocated chunk.
4. The parameter of free(), read_from_guest(), and the return value of malloc() should be the same pointer.

*g_free(**buf**) → **buf** = g_malloc(**constant** * nonconstant) → read_from_guest(**buf**)*

Malloc Pattern

1. g_free(buf)
2. buf = g_malloc(constant * nonconstant)

Malloc Primitive in Intel HDA Device

Malloc Primitive in Intel HDA

```
static void intel_hda_parse_bdl(IntelHDAState *d, IntelHDAStream *st)
{
    hwaddr addr;
    uint8_t buf[16];
    uint32_t i;
    addr = intel_hda_addr(st->bdlp_lbase, st->bdlp_ubase);
    st->bentries = st->lvi +1;
    g_free(st->bpl); // There are 8 streams so we can malloc 1~8 chunks
    st->bpl = g_malloc(sizeof(bpl) * st->bentries); // 16n
    for (i = 0; i < st->bentries; i++, addr += 16) {
        pci_dma_read(&d->pci, addr, buf, 16);
        st->bpl[i].addr  = le64_to_cpu(*(uint64_t *)buf);
        st->bpl[i].len   = le32_to_cpu(*(uint32_t *)(buf + 8));
        st->bpl[i].flags = le32_to_cpu(*(uint32_t *)(buf + 12));
    }
    /* ..... */
```

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NVMe: CVE-2021-3929

```
static void nvme_ctrl_reset(NvmeCtrl *n)
{
    /* ..... */
    for (i = 0; i < n->params.max_ioqpairs + 1; i++) {
        if (n->cq[i] != NULL) {
            nvme_free_cq(n->cq[i], n); // cq->timer is freed
    /* ..... */
}

static void nvme_enqueue_req_completion(NvmeCQueue *cq, NvmeRequest *req)
{
    /* ..... */
    timer_mod(cq->timer, qemu_clock_get_ns(QEMU_CLOCK_VIRTUAL) + 500);
}
```


https://qiuhao.org/VD_QEMU_NVME_CWE-416.txt

NVMe: CVE-2021-3947

```
static uint16_t nvme_changed_nslist(NvmeCtrl *n, uint8_t rae, uint32_t buf_len,
                                    uint64_t off, NvmeRequest *req)
{
    uint32_t nslist[1024];
    uint32_t trans_len;
    int i = 0;
    uint32_t nsid;
    memset(nslist, 0x0, sizeof(nslist));
    // sizeof(nslist) = 4096, integer underflow!
    trans_len = MIN(sizeof(nslist) - off, buf_len);
    /* ..... */
    // transmit data to the guest, stack overflow!
    return nvme_c2h(n, ((uint8_t *)nslist) + off, trans_len, req);
}
```

https://t.me/learningnets https://qiuhao.org/VD_QEMU_NVME_CWE-191-125.txt

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Plan: Hijack the callback in cq->timer

1. In the guest OS, we **construct a fake timer and prepare a buffer for the MMIO write operations later**.

2. By leveraging CVE-2021-3947, we can **leak the virtual address of system@plt** and the **virtual address of the guest's RAM** in the VM.

3. Since CVE-2021-3929 and CVE-2021-3947 both are on the path of processing the Changed Namespace List command, and the content of the MMIO write operations in CVE-2021-3929 is from the buffer (nslist) in CVE-2021-3947, we can **make the source of MMIO write operations from a buffer in the guest's RAM (step 1).**

4. By leveraging CVE-2021-3929 and CVE-2021-3947, we trigger scatter-gather DMA operations to MMIO regions, and the first MMIO write is to the malloc primitive in the HDA device, allocating three chunks the same size as the QEMU's timer, **thus cleaning the tcache of the main thread.**

Plan (cont.)

5. In the same DMA context, the second recursive MMIO write is to the reset register of the NVMe controller, **releasing the cq structure (put on the main thread's tcache).**

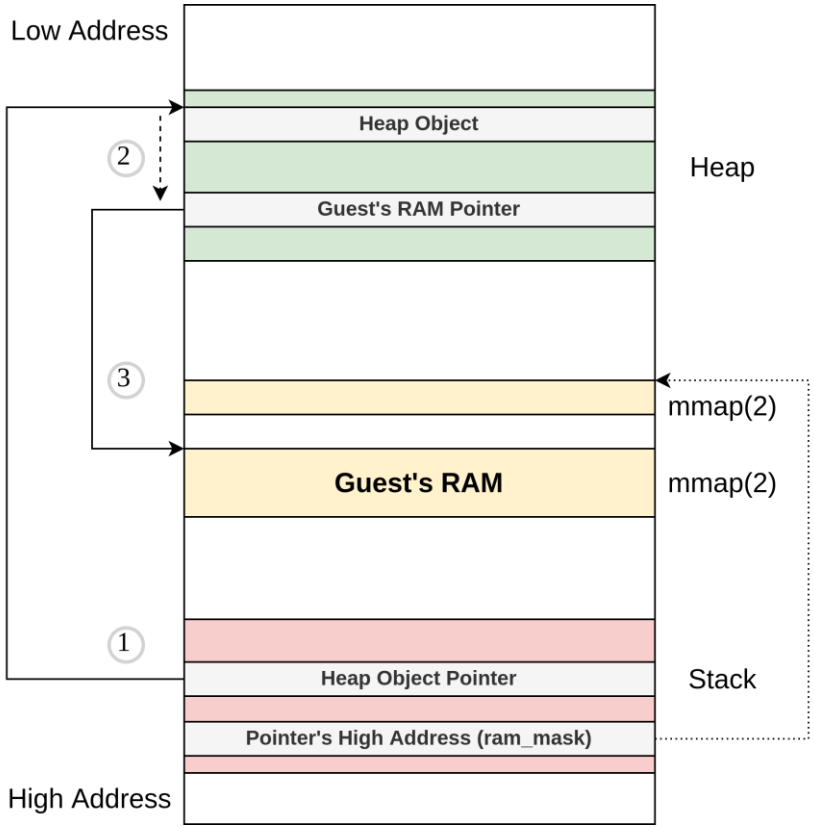
6. In the same DMA context, the last MMIO write is to the malloc primitive in the HDA device, **thus occupying the timer pointer in the freed cq structure and the timer pointer in cq now points to the fake timer we constructed before.**

7. When timer_mod() in nvme_enqueue_req_completion() is called after MMIO operations are finished. **The callback in the fake timer will be called. Since we control the callback and its parameters**, a control flow hijack can be achieved (VM escape).

Bypass ASLR: CVE-2021-3947

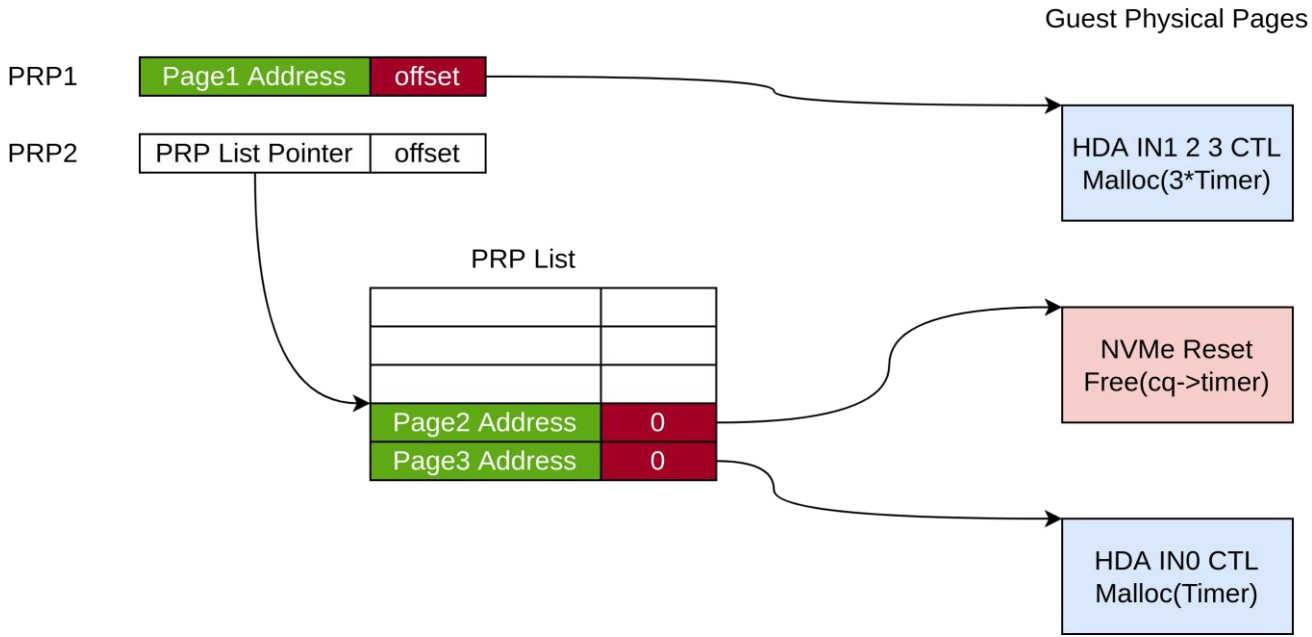
Leak Guest's RAM

```
Search Patterns:
uint64_t tmp = *(heap + search_index);
(tmp & 0x1fffff) /* 0xe00000 */ == 0;
(tmp & ~0x00007fffffffffff) == 0;
(tmp & ram_mask) == ram_mask;
```



Hijack Control Flow: CVE-2021-3929

PRP Structure

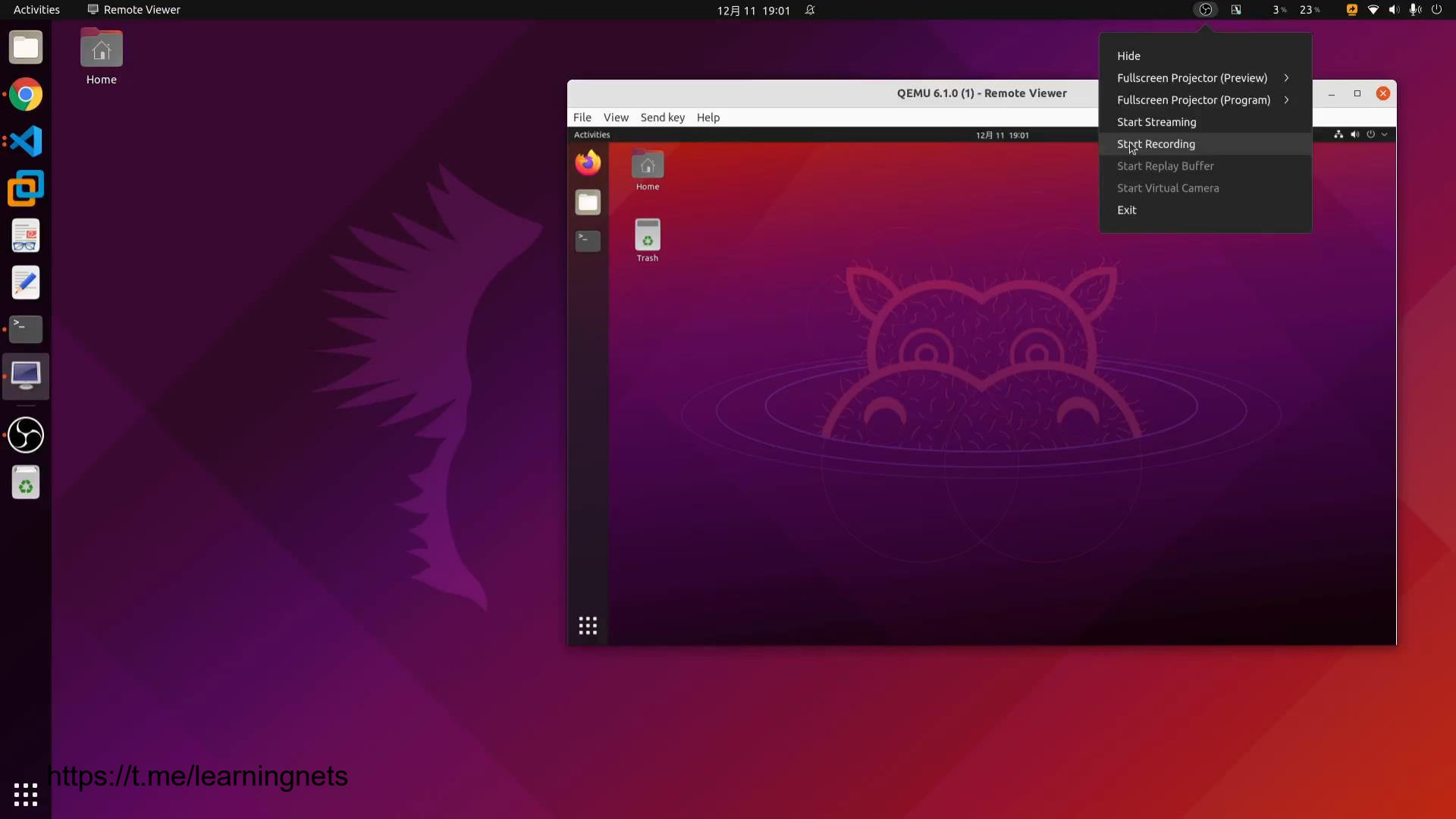


Hijack Control Flow: CVE-2021-3929

Fake TimerList Callback

```
struct QEMUTimer {
    int64_t expire_time;
    QEMUTimerList *timer_list;
    QEMUTimerCB *cb;
    void *opaque;
    QEMUTimer *next;
    int attributes;
    int scale;
};
```

```
void timerlist_notify(QEMUTimerList *timer_list)
{
    if (timer_list->notify_cb) {
        timer_list->notify_cb(timer_list->notify_opaque, timer_list->clock->type);
    } else {
        qemu_notify_event();
    }
}
```



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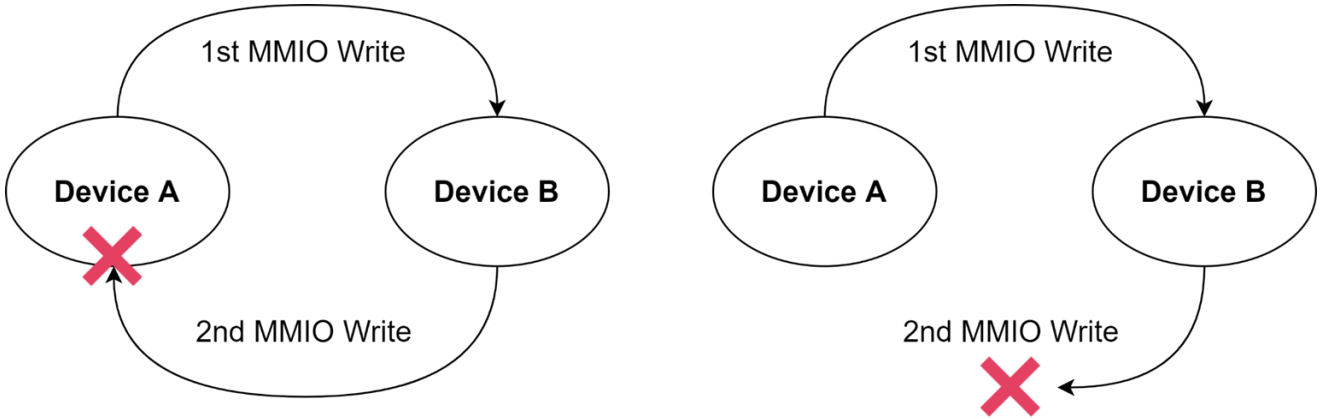
Check in Device or Log on Bus



[RFC PATCH] memory: Fix dma-reentrancy issues at the MMIO level

[RFC PATCH v3 0/3] physmem: Have flaview API check bus permission

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Thoughts

1. This design flaw has a large impact and should be fixed ASAP. Any virtual **device that can perform DMA at a controlled address and has an MMIO region may be affected.**

2. The device reentry / recursive MMIO defect has existed in QEMU for at least ten years, or more than one year just considering the large-scale appearance. For these bugs, all communication is public except CVE-2021-3929 -- **if you are a malicious hacker, a fast way to attack an open-source software might be checking its bug tracker instead of finding vulnerability by yourself :)**

3. When auditing the hypervisors, we should **pay attention to the different behaviors between virtualization software and real hardware.**

Thank You

We will release the **white paper** and **PoC** on May 20 at:

https://github.com/QiuhaoLi/CVE-2021-3929-3947