Xenpwn – Breaking Paravirtualized Devices

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#whoami

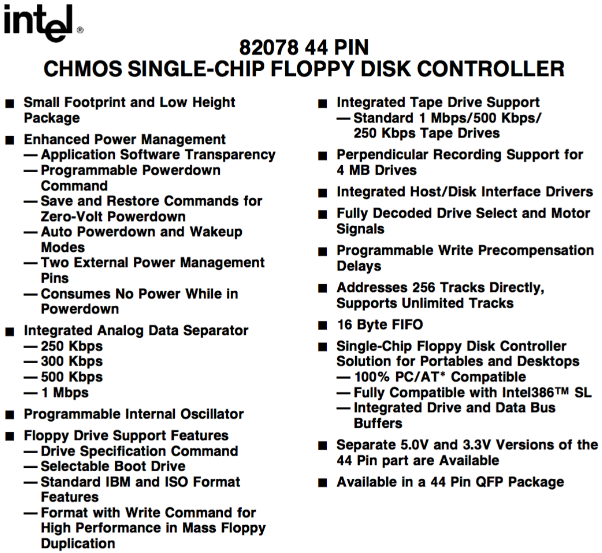
- Security Researcher @ ERNW Research
- Application and Virtualization Security
- Recent Research
    - Security Appliances (Palo Alto, FireEye)
    - Hypervisors
- @_fel1x on twitter

Agenda

- Device Virtualization & Paravirtualized Devices
- Double Fetch Vulnerabilities
- Xenpwn: Architecture and Design
- Results
- Case Study: Exploiting xen-pciback

Device Virtualization

- Virtualized systems need access to virtual devices
  - Disk, Network, Serial, …
- Traditionally: Device emulation
  - Emulate old and well supported hardware devices
  - Guest OS does not need special drivers
  - Installation with standard installation sources supported



intel®

82078 44 PIN
CHMOS SINGLE-CHIP FLOPPY DISK CONTROLLER

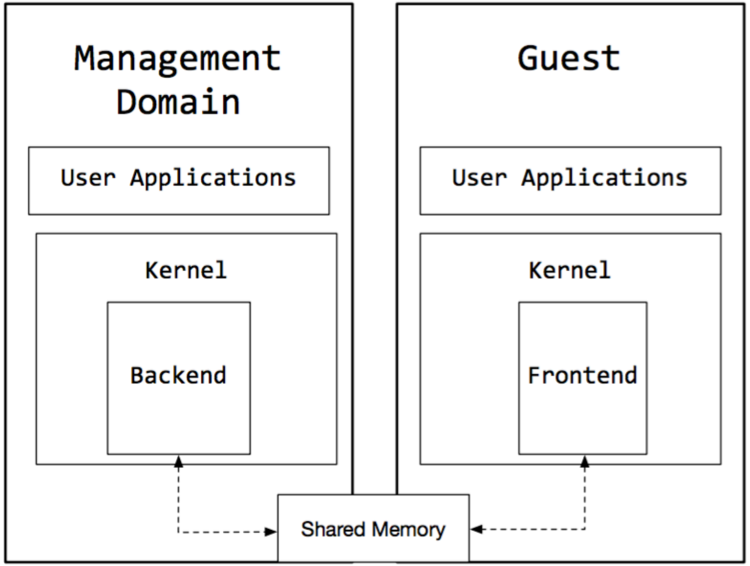
- Small Footprint and Low Height Package
- Enhanced Power Management
  - Application Software Transparency
  - Programmable Powerdown Command
  - Save and Restore Commands for Zero-Volt Powerdown
  - Auto Powerdown and Wakeup Modes
  - Two External Power Management Pins
  - Consumes No Power While in Powerdown
- Integrated Analog Data Separator
  - 250 Kbps
  - 300 Kbps
  - 500 Kbps
  - 1 Mbps
- Programmable Internal Oscillator
- Floppy Drive Support Features
  - Drive Specification Command
  - Selectable Boot Drive
  - Standard IBM and ISO Format Features
  - Format with Write Command for High Performance in Mass Floppy Duplication
- Integrated Tape Drive Support
  - Standard 1 Mbps/500 Kbps/ 250 Kbps Tape Drives
- Perpendicular Recording Support for 4 MB Drives
- Integrated Host/Disk Interface Drivers
- Fully Decoded Drive Select and Motor Signals
- Programmable Write Precompensation Delays
- Addresses 256 Tracks Directly, Supports Unlimited Tracks
- 16 Byte FIFO
- Single-Chip Floppy Disk Controller Solution for Portables and Desktops
  - 100% PC/AT* Compatible
  - Fully Compatible with Intel386™ SL
  - Integrated Drive and Data Bus Buffers
- Separate 5.0V and 3.3V Versions of the 44 Pin part are Available
- Available in a 44 Pin QFP Package

Paravirtualized Devices

- Most important downsides of emulated devices:
  - Hard to implement securely and correctly
  - Slow performance
  - No support for advanced features
- Solution: Paravirtualized Devices
  - Specialized device drivers for use in virtualized systems
  - Idea: Emulated devices are only used as fallback mechanism
  - Used by all major hypervisors
  - **Not the same as Xen paravirtualized domains!**

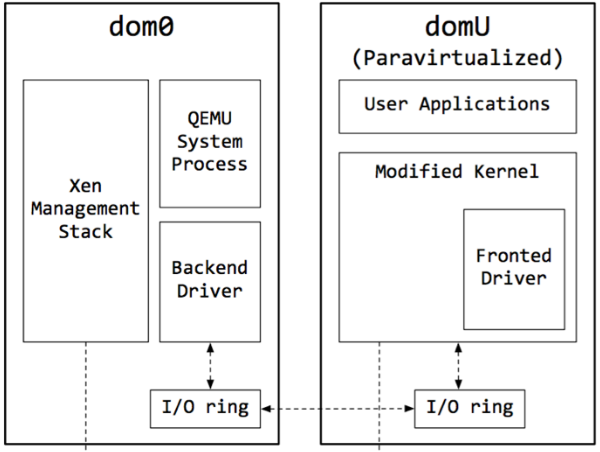
Paravirtualized Devices

- Split Driver Model
  - Frontend runs in Guest system
  - Backend in Host/Management domain
- Terminology differs between hypervisors
  - VSC / VSP in Hyper-V
  - Virtio devices and drivers
- Implementations are quite similar



Paravirtualized Devices

- PV devices are implemented on top of shared memory
  - Great Performance
  - Easy to implement
  - Zero copy algorithms possible
- Message protocols implemented on top
  - Xen, Hyper-V and KVM all use ring buffers
- Shared memory mappings can be constant or created on demand



Security of PV Devices

- Backend runs in privileged context ➔ Communication between frontend and backend is trust boundary
- Low level code + Protocol parsing ➔ Bugs
- Examples
  - Heap based buffer overflow in KVM disk backend (CVE-2011-1750)
  - Unspecified BO in Hyper-V storage backend (CVE-2015- 2361)
- Not as scrutinized as emulated devices
  - Device and hypervisor specific protocols
  - Harder to fuzz

Very Interesting Target

- Device **emulation** often done in user space ←→ PV backend often in kernel for higher performance
  - **Compromise of kernel backend is instant win ☺**
- PV devices are becoming more important
  - More device types (USB, PCI pass-through, touch screens, 3D acceleration)
  - More features, optimizations
- Future development: Removal of emulated devices
  - see Hyper-V Gen2 VMs

Research Goal

- ”Efficient vulnerability discovery in Paravirtualized Devices”
- Core Idea: No published research on the use of **shared memory** in the context of PV devices
- Bug class that only affect shared memory? ➔ Double fetches!

ERNW
providing security.

Double Fetch Vulnerabilities

- Special type of TOCTTOU bug affecting shared memory.
- Simple definition: Same memory address is accessed multiple times with validation of the accessed data missing on at least one access
- Can introduce all kinds of vulnerabilities
  - Arbitrary Write/Read
  - Buffer overflows
  - Direct RIP control ☺

Double Fetch Vulnerabilities

- Term "double fetch" was coined by Fermin J. Serna in 2008
  - But bug class was well known before that
- Some interesting research published in 2007/2008
  - Usenix 2007 "Exploiting Concurrency Vulnerabilities in System Call Wrappers" - Robert N. M. Watson
  - CCC 2007: "From RING 0 to UID 0" and Phrack #64 file 6 – twiz, sgrakkyu
- First example I could find is sendmsg() linux bug reported in 2005
  - Happy to hear about more ☺

Example:
sendmsg()

```
int cmsghdr_from_user_compat_to_kern(..)
{
  [...]
  while(ucmsg != NULL) {
        if(get_user(ucmlen, &ucmsg->cmsg_len))
                return -EFAULT;
        [...]
        tmp = ((ucmlen - CMSG_COMPAT_ALIGN(sizeof(*ucmsg))) +
               CMSG_ALIGN(sizeof(struct cmsghdr)));
        kcmlen += tmp;
        [...]
  }

  if(kcmlen > stackbuf_size)
        kcmsg_base = kcmsg = kmalloc(kcmlen, GFP_KERNEL);

  while(ucmsg != NULL) {
        __get_user(ucmlen, &ucmsg->cmsg_len);

        if(copy_from_user(CMSG_DATA(kcmsg),
                CMSG_COMPAT_DATA(ucmsg),
         (ucmlen - CMSG_COMPAT_ALIGN(sizeof(*ucmsg)))))
[...]
}
```

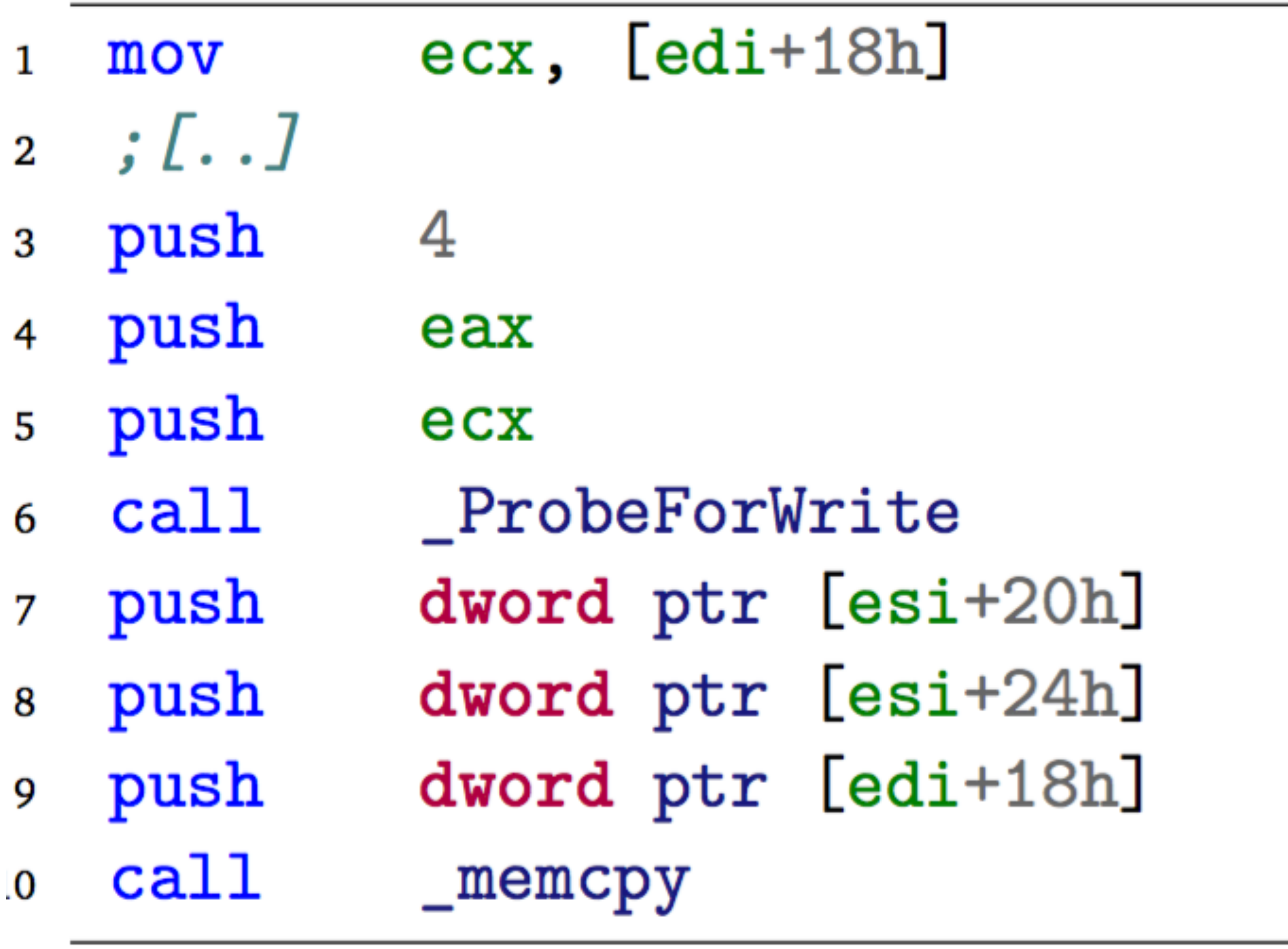
Bochspwn

- “Identifying and Exploiting Windows Kernel Race Conditions via Memory Access Patterns” (2013)
  - by j00ru and Gynvael Coldwind
- Uses extended version of Bochs CPU emulator to trace all memory access from kernel to user space.

bochs
think inside the bochs.

Bochspwn

- Resulted in significant number of Windows bugs (and a well deserved Pwnie)
  - but not much published follow-up research
- Whitepaper contains detailed analysis on exploitability of double fetches
  - On multi core system even extremely short races are exploitable
- Main inspiration for this research.

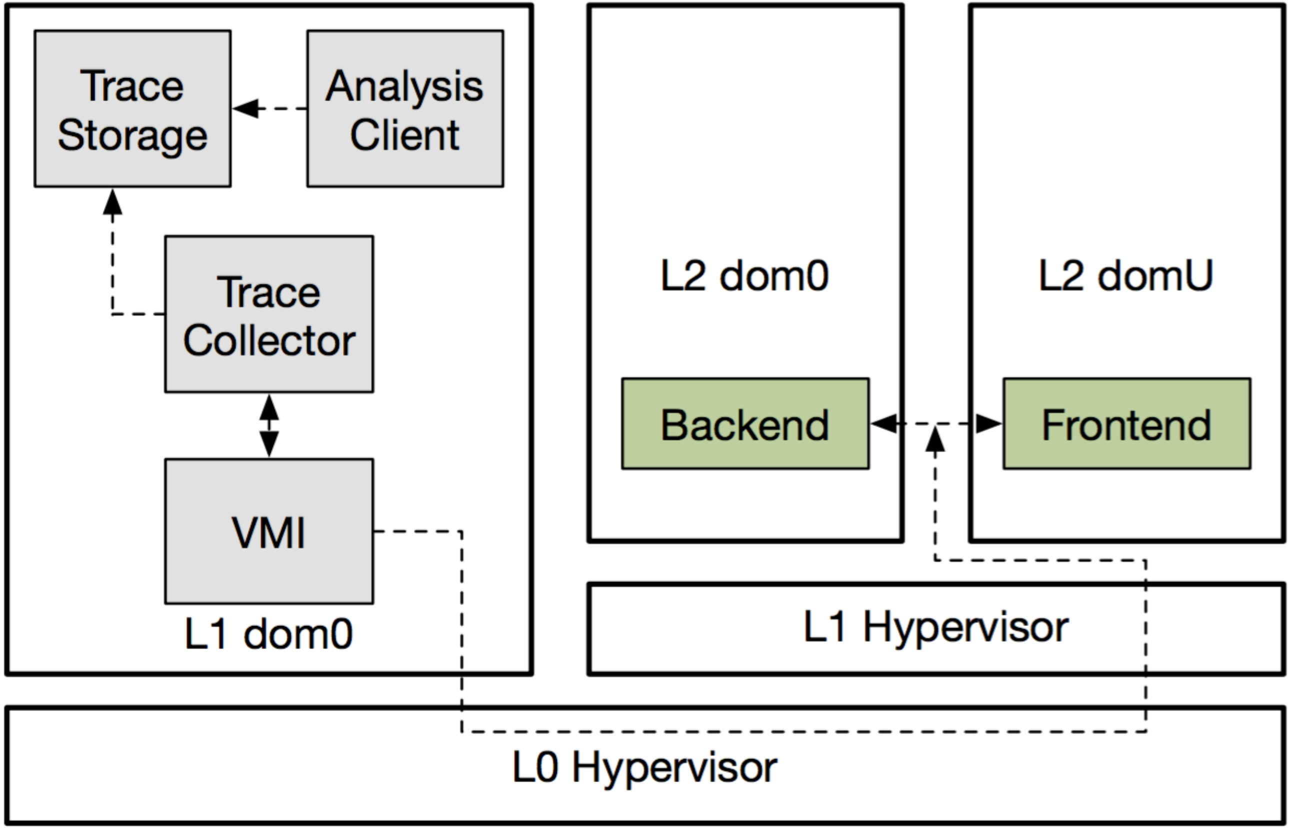


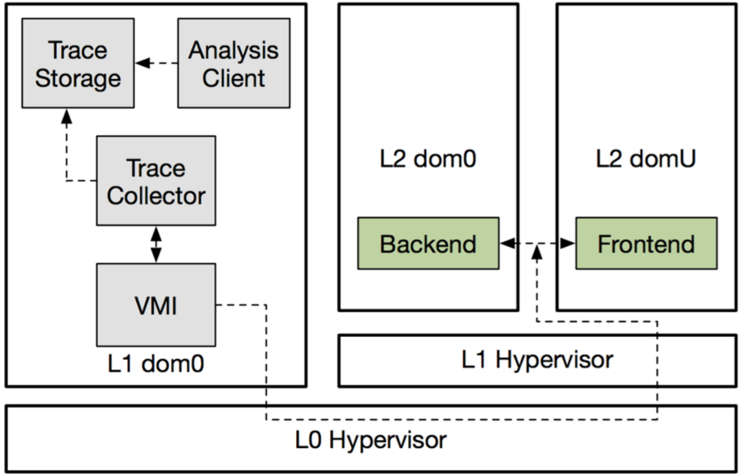
```
mov     ecx, [edi+18h]
;[..]
push    4
push    eax
push    ecx
call    _ProbeForWrite
push    dword ptr [esi+20h]
push    dword ptr [esi+24h]
push    dword ptr [edi+18h]
call    _memcpy
```

Example:
Bochspwn

Xenpwn

- Adapt memory access tracing approach used by Bochspwn for analyzing PV device communication.
- Why not simply use Bochspwn?
    - Extremely slow
    - Passive overhead (no targeted tracing)
    - Compatibility issues
    - Dumping traces to text files does not scale
- Idea: Implement memory access tracing on top of hardware assisted virtualization


Trace Storage
Analysis Client
Trace Collector
VMI
L1 dom0
L2 dom0
Backend
L2 domU
Frontend
L1 Hypervisor
L0 Hypervisor



Xenpwn Architecture

- Nested virtualization
  - Target hypervisor (L1) runs on top of base hypervisor (L0)
- Analysis components run in user space of L1 management domain.
  - No modification to hypervisor required
  - Bugs in these components do not crash whole system
- L0 hypervisor is Xen

libVMI

- Great library for virtual machine introspection (VMI)
  - Hypervisor agnostic (Xen and KVM)
  - User-space wrapper around hypervisor APIs
- Allows access to and manipulation of guest state (memory, CPU registers)
- Xen version supports memory events

LibVMI
Virtual Machine Introspection
Fast, Portable, Simple

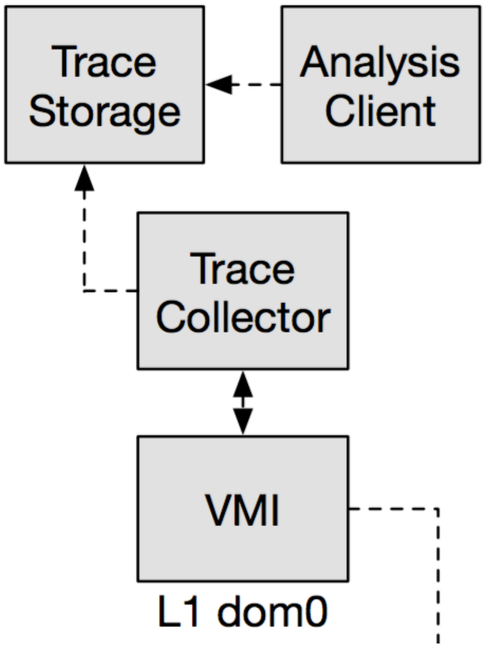
libVMI Memory Events

```
auto event = new vmi_event_t();
event->type = VMI_EVENT_MEMORY;
event->mem_event.physical_address = paddr;
event->mem_event.npages = 1;
event->mem_event.granularity = granularity;
event->mem_event.in_access = access;
event->callback = callback;

if (vmi_register_event(s->vmi, event) != VMI_SUCCESS)
 { /*... */}
```

- Trap on access to a guest physical address
- Implemented on top of Extended Page Tables (EPT)
  - Disallow access to GPA
  - Access triggers EPT violation and VM exit
  - VM exit is forwarded to libvmi handler

Memory Access Tracing with libvmi

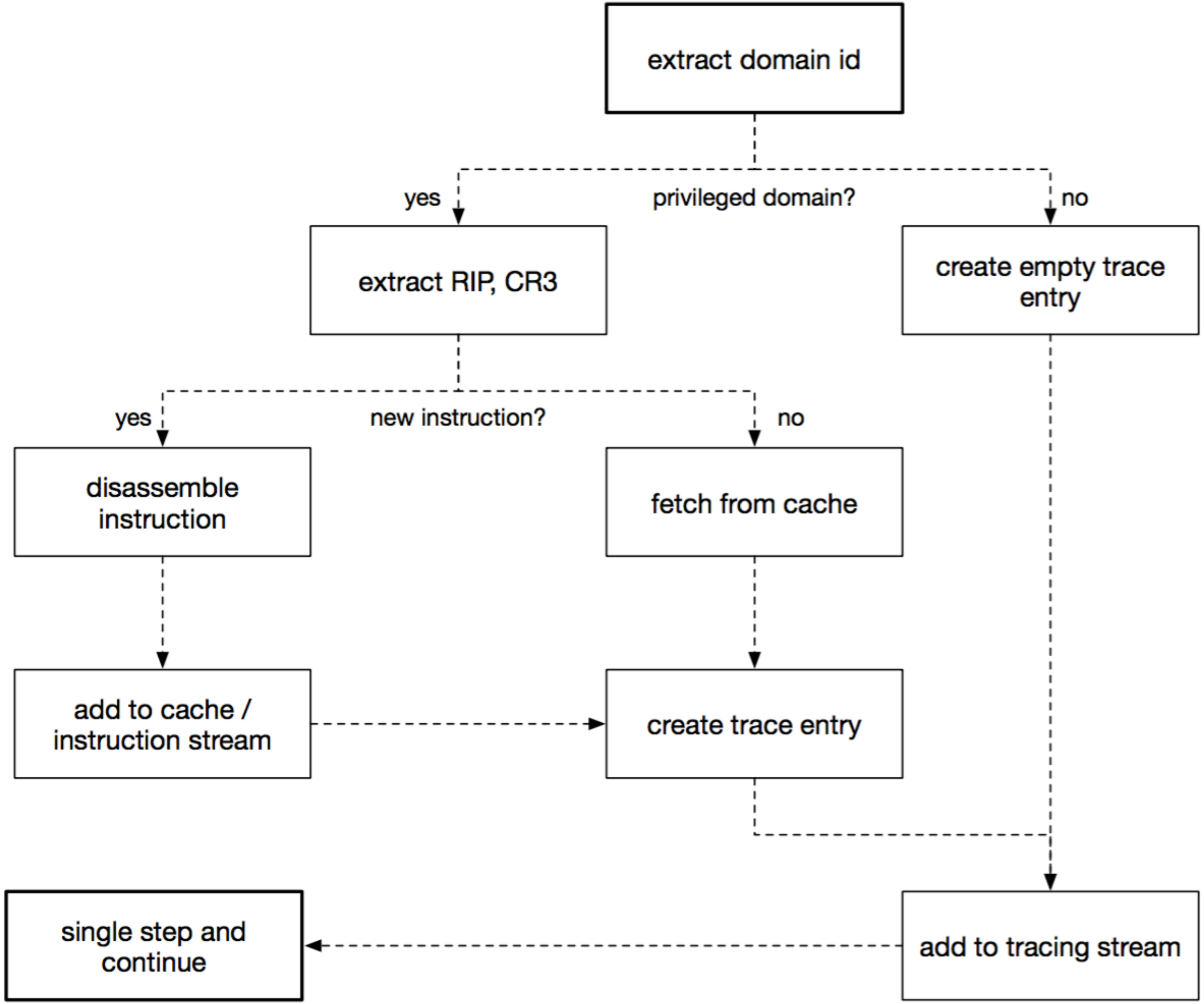
1. Find shared memory pages
2. Register memory event handlers
3. Analyze memory event, extract needed information and store in trace storage.
4. Run analysis algorithms (can happen much later)



Trace Collector

- Use libvmi to inspect memory and identify shared memory pages
  - Target specific code.
  - Identify data structures used by PV frontend/backend and addresses of shared pages
- Registers memory event handlers
- Main work is done in callback handler
  - Disassemble instructions using Capstone

Callback handler



Trace Storage

- Storage needs to be fast and persistent
  - Minimize tracing overhead
  - Allow for offline analysis
- Nice to have: Efficient compression
  - Allows for very long traces
- Tool that fulfills all these requirements: Simutrace
  - simutrace.org

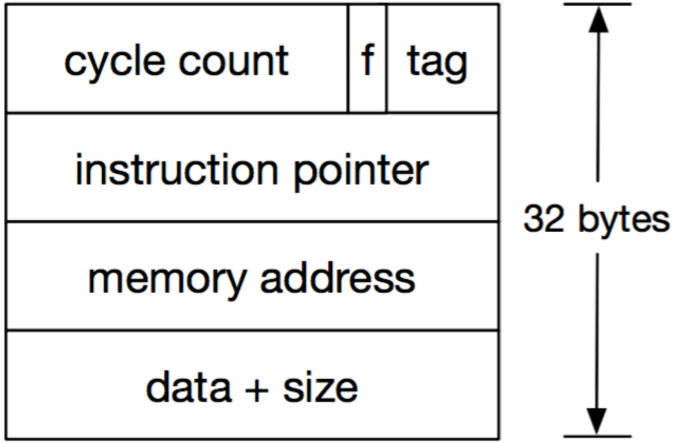
Simutrace

- Open source project by the Operation System Group at the Karlsruhe Institute of Technology
- Designed for full system memory tracing
  - All memory accesses including their content
- C++ daemon + client library
  - Highly efficient communication over shared memory pages
- Uses specialized compression algorithm optimized for memory traces
  - High compression rate + high speed
- Highly recommended!

Simutrace

Trace Entries

For every memory access:



cycle count | f | tag

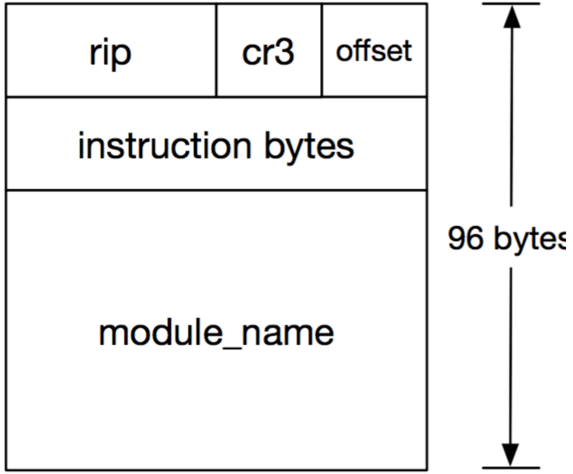
instruction pointer

memory address

data + size

32 bytes

For every unique instruction:



rip | cr3 | offset

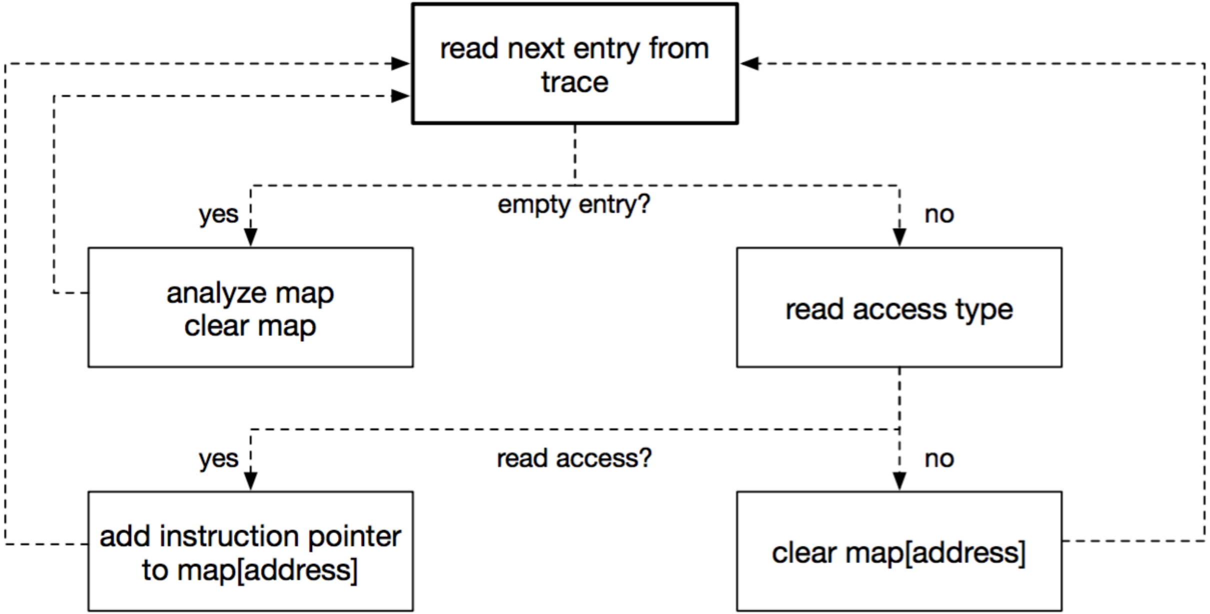
instruction bytes

module_name

96 bytes

Double Fetch Algorithm

Simplified version



Advantages & Limitations

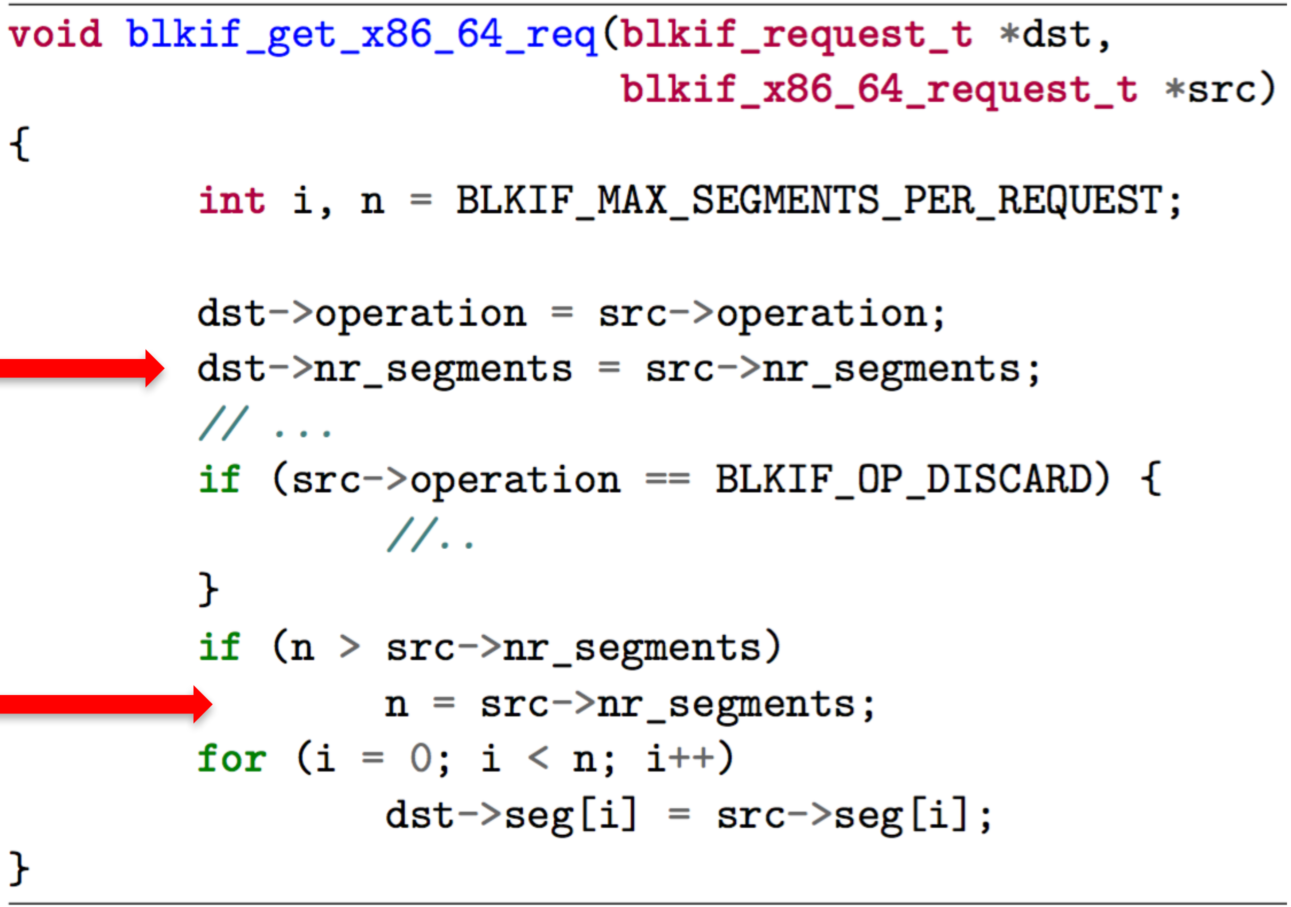
- Good:
  - Low passive overhead
  - Largely target independent
    - only Trace collector requires adaption
  - Easy to extend and develop
- Bad
  - High active overhead
    - VM exits are expensive
  - **Reliance on nested virtualization**

Nested Virtualization on Xen

- Xen Doku: *Nested HVM on Intel CPUs, as of Xen 4.4, is considered "tech preview". For many common cases, it should work reliably and with low overhead*
- Reality:
  - Xen on Xen works
  - KVM on Xen works (most of the time)
  - Hyper-V on Xen does not work ☹

Results

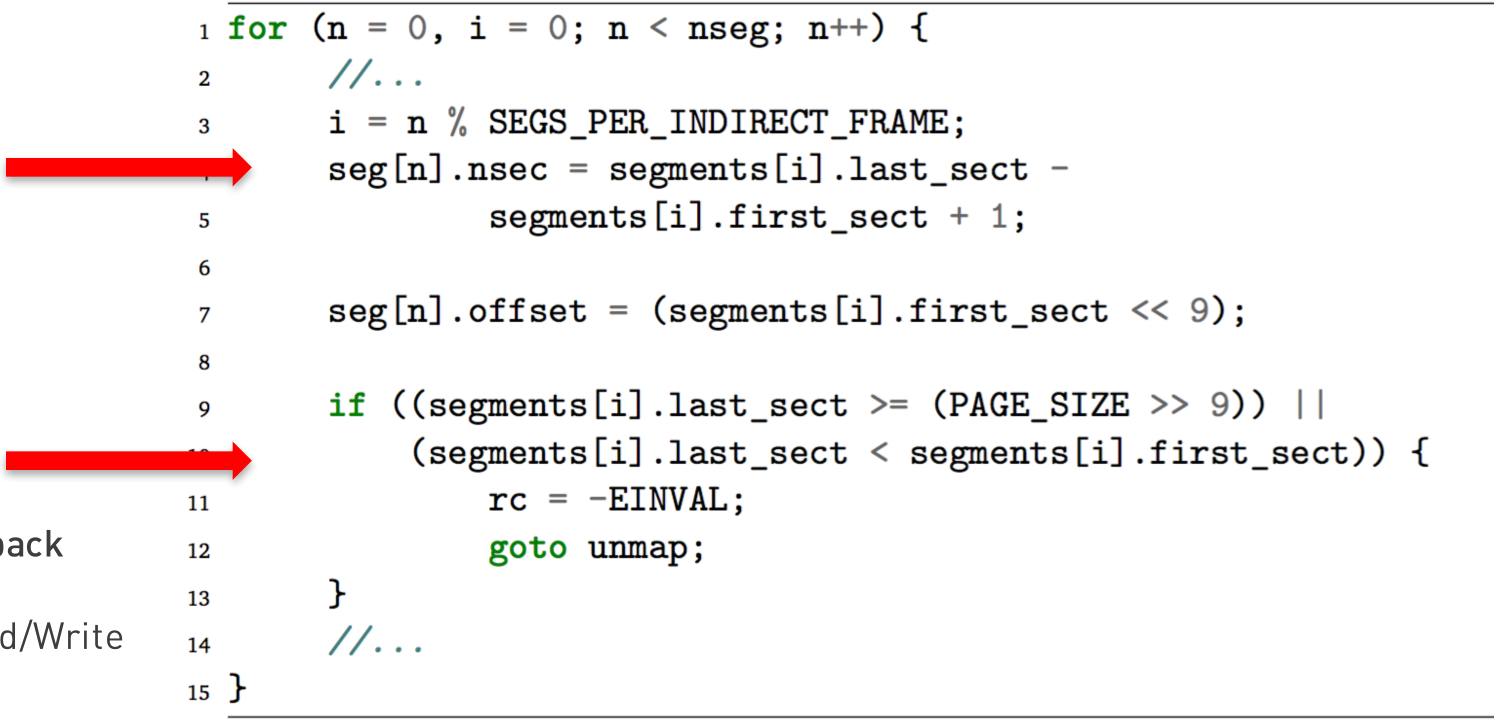
- KVM: no security critical double fetches
  - Main reason seems to be endian independent memory wrappers
  - .. but discovered other interesting issues while reading the virtio code ;)
- bhyve: one very interesting result
  - Ongoing disclosure process
- **Xen: Three interesting double fetches**



```
void blkif_get_x86_64_req(blkif_request_t *dst,
                          blkif_x86_64_request_t *src)
{
        int i, n = BLKIF_MAX_SEGMENTS_PER_REQUEST;

        dst->operation = src->operation;
        dst->nr_segments = src->nr_segments;
        // ...
        if (src->operation == BLKIF_OP_DISCARD) {
                //..
        }
        if (n > src->nr_segments)
                n = src->nr_segments;
        for (i = 0; i < n; i++)
                dst->seg[i] = src->seg[i];
}
```

QEMU xen_disk

Normally not exploitable thanks to compiler optimizations



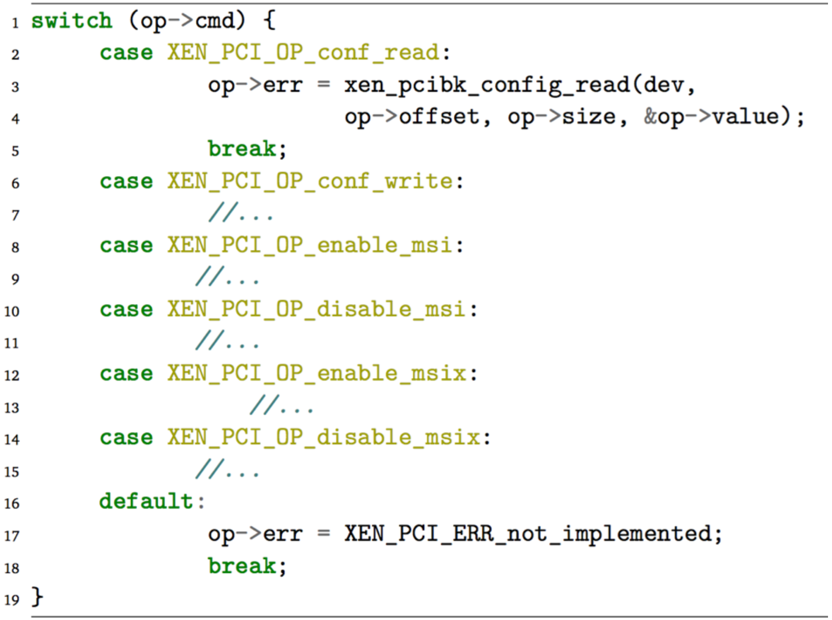
```
for (n = 0, i = 0; n < nseg; n++) {
        //...
        i = n % SEGS_PER_INDIRECT_FRAME;
        seg[n].nsec = segments[i].last_sect -
                segments[i].first_sect + 1;

        seg[n].offset = (segments[i].first_sect << 9);

        if ((segments[i].last_sect >= (PAGE_SIZE >> 9)) ||
            (segments[i].last_sect < segments[i].first_sect)) {
                rc = -EINVAL;
                goto unmap;
        }
        //...
}
```

xen-blkback

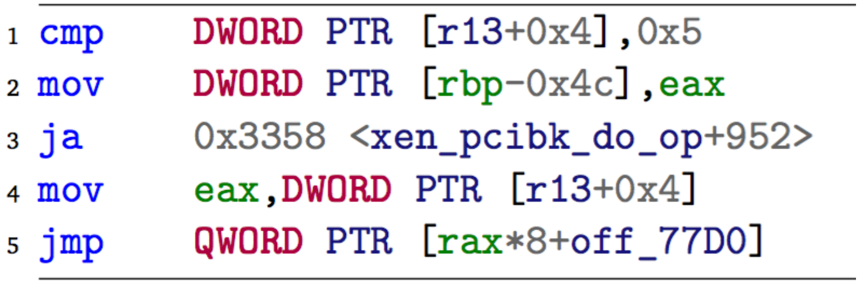
OOB Read/Write

xen-pciback

xen-pciback: xen_pcibk_do_op



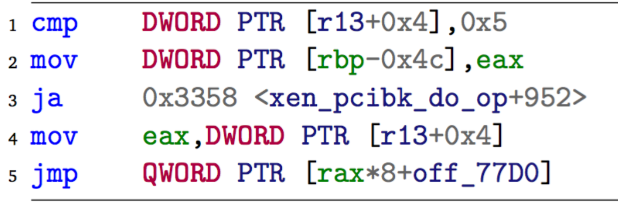
```c
switch (op->cmd) {
    case XEN_PCI_OP_conf_read:
        op->err = xen_pcibk_config_read(dev,
                  op->offset, op->size, &op->value);
        break;
    case XEN_PCI_OP_conf_write:
        //...
    case XEN_PCI_OP_enable_msi:
       //...
    case XEN_PCI_OP_disable_msi:
       //...
    case XEN_PCI_OP_enable_msix:
          //...
    case XEN_PCI_OP_disable_msix:
       //...
    default:
        op->err = XEN_PCI_ERR_not_implemented;
        break;
}
```



```
cmp    DWORD PTR [r13+0x4],0x5
mov    DWORD PTR [rbp-0x4c],eax
ja     0x3358 <xen_pcibk_do_op+952>
mov    eax,DWORD PTR [r13+0x4]
jmp    QWORD PTR [rax*8+off_77D0]
```

xen-pciback

- switch statement is compiled into jump table
- op->cmd == $r13+0x4
- Points into shared memory
- Range check and jump use two different memory accesses
- Valid compiler optimization
  - op is not marked as volatile



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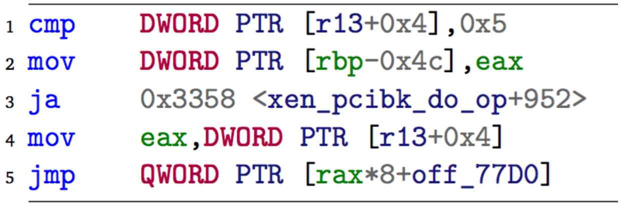
jmp     QWORD PTR [rax*8+off_77D0]
```

Exploiting pciback

- Race is very small: 2 Instructions
  - But can be reliably won if guest VM has multiple cores
- Lost race does not have any negative side effects
  - Infinite retries possible
- Simple to trigger
  - Send PCI requests while flipping value using XOR



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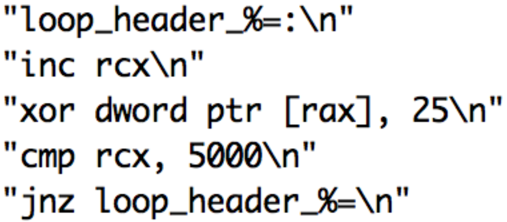
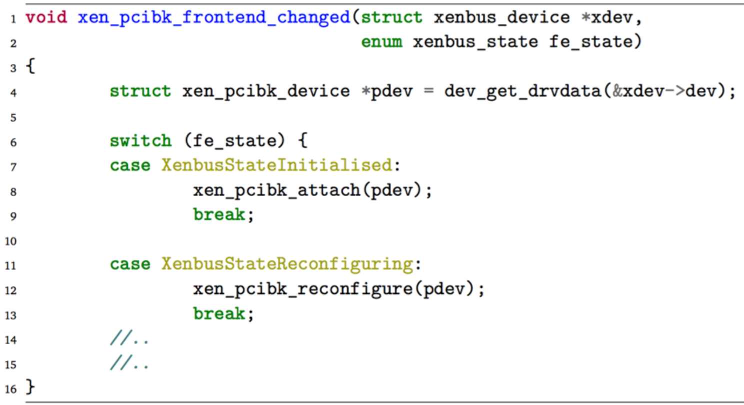


```
"loop_header_%=:\n"
"inc rcx\n"
"xor dword ptr [rax], 25\n"
"cmp rcx, 5000\n"
"jnz loop_header_%=\n"
```

Exploiting pciback

- Indirect jump ➔ No immediate RIP control
  - Need to find reliable offset to function pointer
- Load address of xen-pciback.ko is random
- Virtual address of backend mapping also not known
- A lot of similarities to a remote kernel exploit
- Chosen approach: Trigger type confusion to get write primitiv



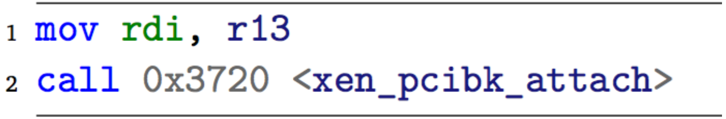
```c
void xen_pcibk_frontend_changed(struct xenbus_device *xdev,
                                enum xenbus_state fe_state)
{
        struct xen_pcibk_device *pdev = dev_get_drvdata(&xdev->dev);

        switch (fe_state) {
        case XenbusStateInitialised:
                xen_pcibk_attach(pdev);
                break;

        case XenbusStateReconfiguring:
                xen_pcibk_reconfigure(pdev);
                break;
        //..
        //..
}
```

Type Confusion

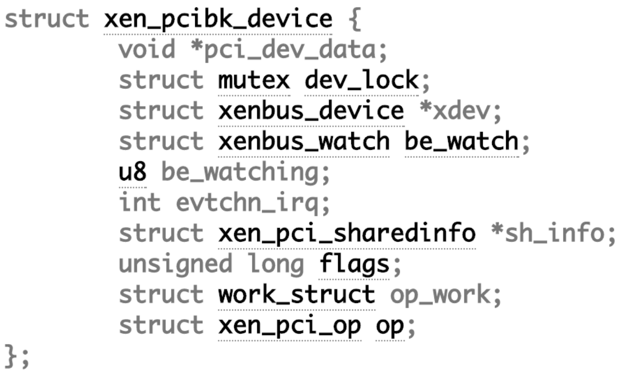
- Second jump table generated for xen-pciback
  - Almost directly behind the jump table generated for vulnerable function
- XenbusStateInitialized uses value of r13 register as first argument
  - Should be a pointer to a xen_pcibk_device structure
  - Is a pointer to the start of the shared memory page ☺



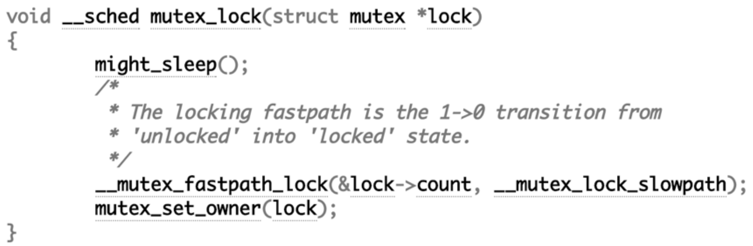
```
mov rdi, r13
call 0x3720 <xen_pcibk_attach>
```

Getting a write primitve

- xen_pcibk_attach first tries to lock the dev_lock mutex of referenced structure.
- Gives us the possibility to call mutex_lock with a fake mutex structure
- mutex_lock
  - Fastpath: Switch lock count from 1 -> 0
  - Slowpath: Triggered when lock count != 1

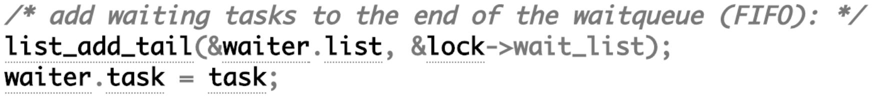


```
struct xen_pcibk_device {
        void *pci_dev_data;
        struct mutex dev_lock;
        struct xenbus_device *xdev;
        struct xenbus_watch be_watch;
        u8 be_watching;
        int evtchn_irq;
        struct xen_pci_sharedinfo *sh_info;
        unsigned long flags;
        struct work_struct op_work;
        struct xen_pci_op op;
};
```



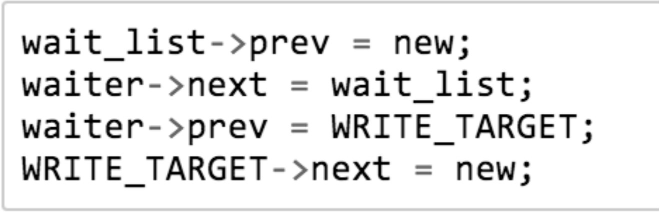
```
void __sched mutex_lock(struct mutex *lock)
{
        might_sleep();
        /*
         * The locking fastpath is the 1->0 transition from
         * 'unlocked' into 'locked' state.
         */
        __mutex_fastpath_lock(&lock->count, __mutex_lock_slowpath);
        mutex_set_owner(lock);
}
```

Getting a write primitive: mutex_lock slowpath



```
/* add waiting tasks to the end of the waitqueue (FIFO): */
list_add_tail(&waiter.list, &lock->wait_list);
waiter.task = task;
```

1. mutex_optimistic_spin needs to fail.
   - Can be achieved by setting lock->owner to a readable zero page
2. If lock count still not 1, mutex_waiter structure is created and stored on stack
3. mutex_waiter structure is added to lock->wait_list and kernel thread goes to sleep till wake up.

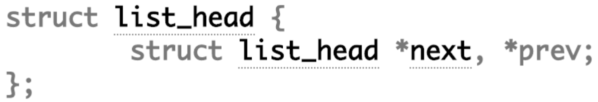


```
wait_list->prev = new;
waiter->next = wait_list;
waiter->prev = WRITE_TARGET;
WRITE_TARGET->next = new;
```

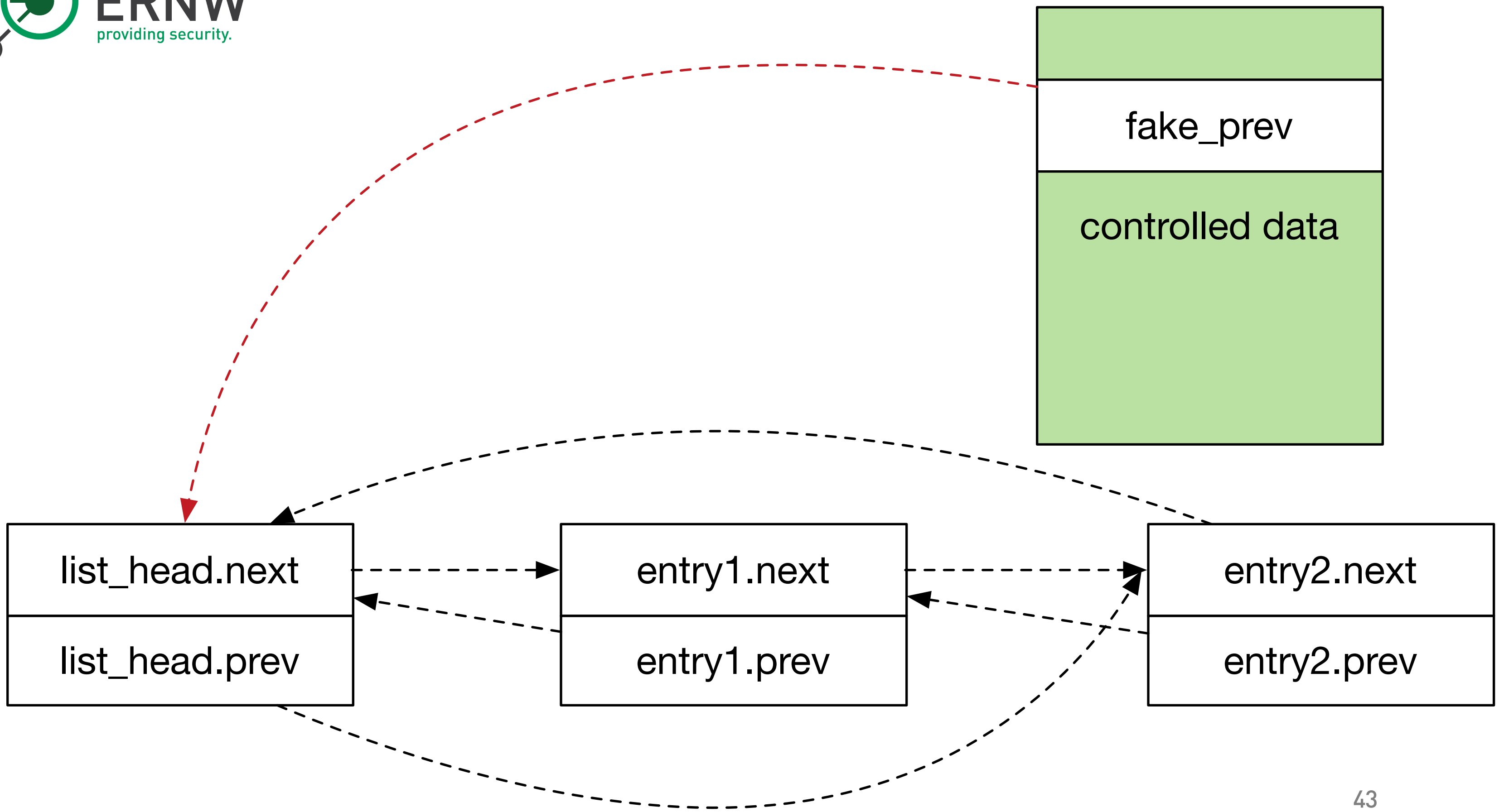
➔ Pointer to waiter is written to attacker controlled location.

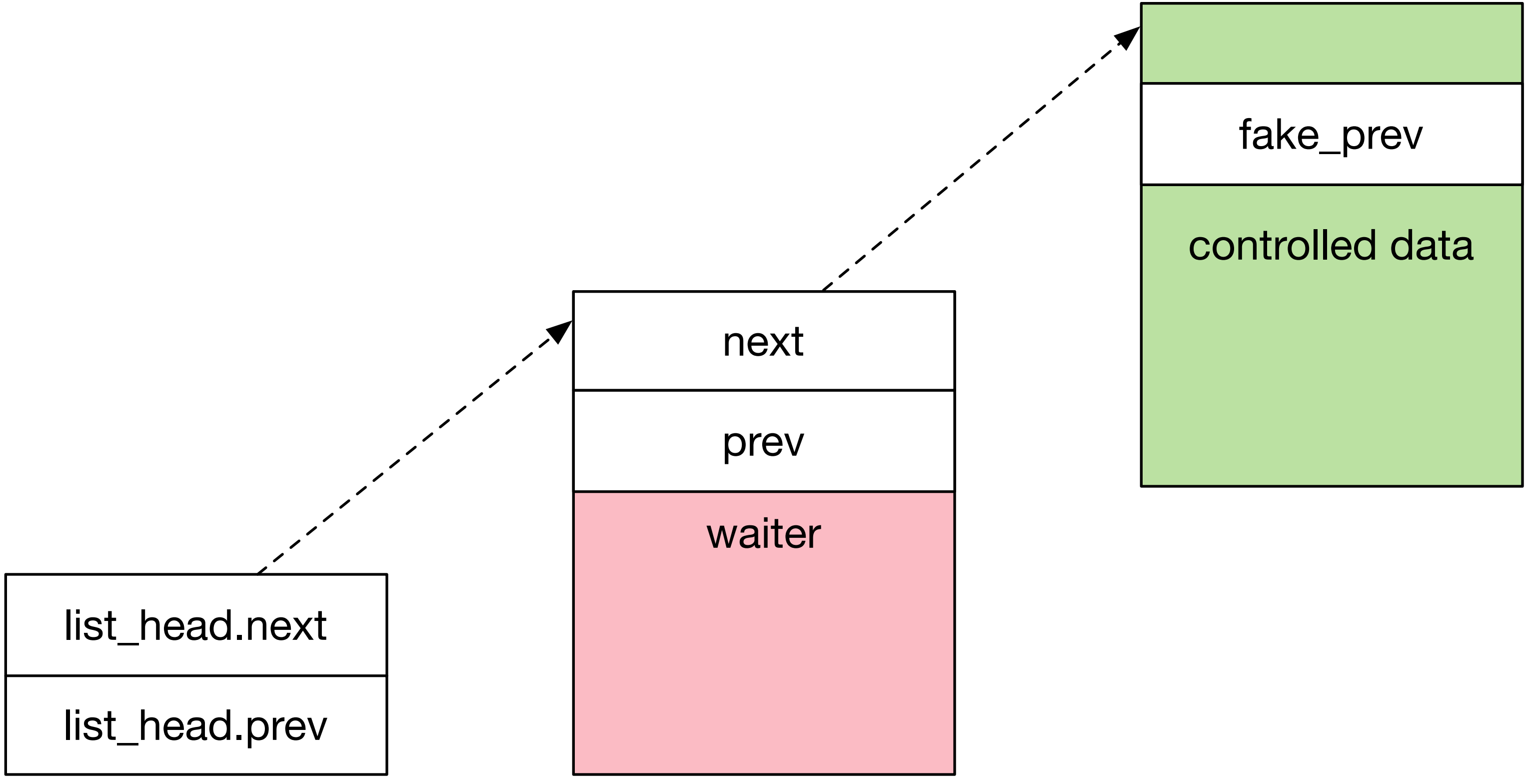
Write Primitive

- write-where but not write-what
  - Pointer to pointer to attacker controlled data
  - Can't simply overwrite function pointers
- One shot
  - pciback is locked due to xen_pcibk_do_op never returning
- Idea: Add faked entries to a global linked list.
  - Requires known kernel version + no KASLR or infoleak



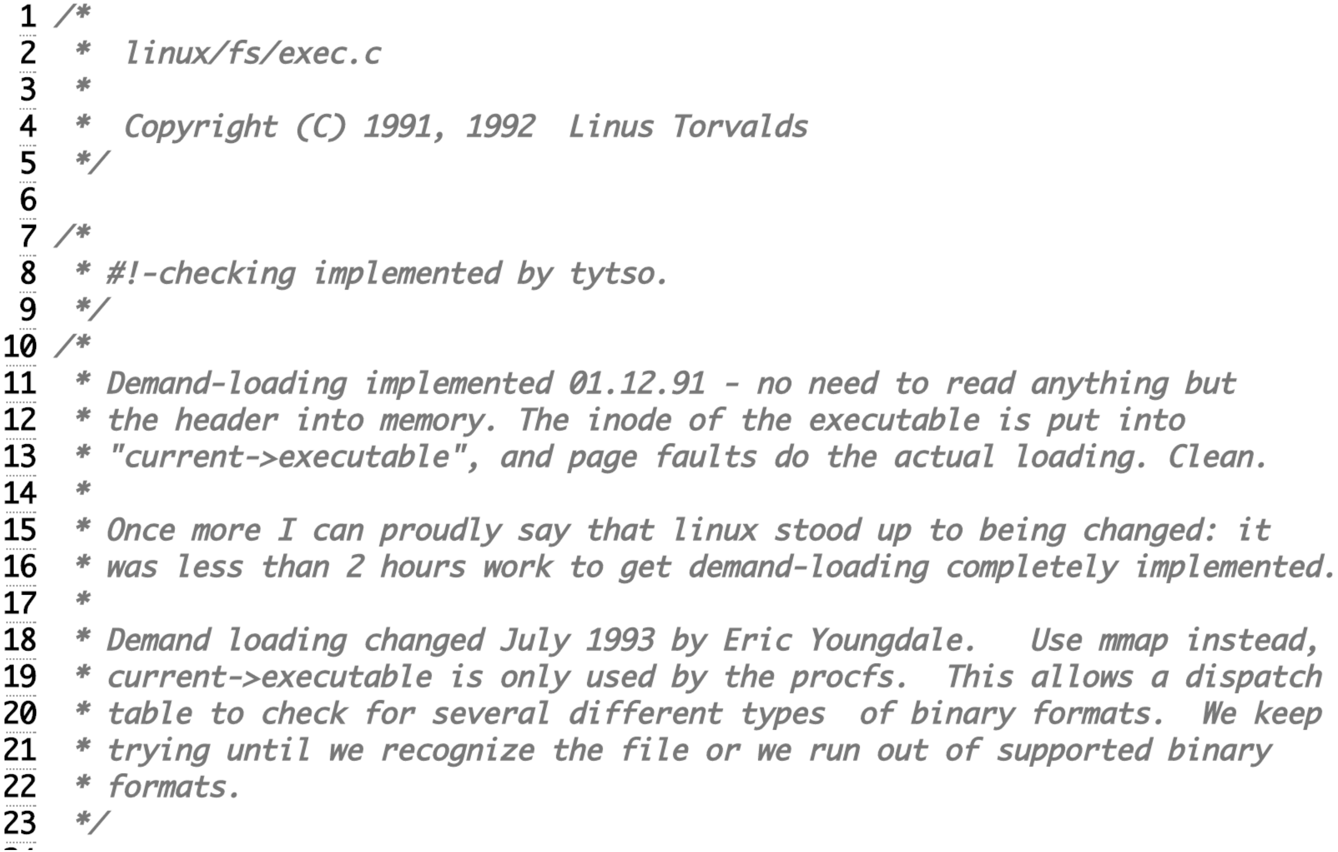
```
struct list_head {
        struct list_head *next, *prev;
};
```


fake_prev
controlled data
list_head.next
list_head.prev
entry1.next
entry1.prev
entry2.next
entry2.prev


fake_prev
controlled data
next
prev
waiter
list_head.next
list_head.prev

Overwrite target

- Global data structure
  - Need to know address of list_head
- No new elements should be attached during run time
  - list_head.prev is not changed, new entry might be added directly behind list_head
- Needs to survive one "junk" entry
  - No full control over waiter structure / stack frame



```
/*
 *  linux/fs/exec.c
 *
 *  Copyright (C) 1991, 1992  Linus Torvalds
 */

/*
 * #!-checking implemented by tytso.
 */
/*
 * Demand-loading implemented 01.12.91 - no need to read anything but
 * the header into memory. The inode of the executable is put into
 * "current->executable", and page faults do the actual loading. Clean.
 *
 * Once more I can proudly say that linux stood up to being changed: it
 * was less than 2 hours work to get demand-loading completely implemented.
 *
 * Demand loading changed July 1993 by Eric Youngdale.   Use mmap instead,
 * current->executable is only used by the procfs.  This allows a dispatch
 * table to check for several different types  of binary formats.  We keep
 * trying until we recognize the file or we run out of supported binary
 * formats.
 */
```

fs/exec.c: formats

- **formats** linked list contains entries for different file formats supported by exec
  - ELF
  - #! shell scripts
  - a.out format
- Walked every time exec* syscall is called to load input file.
- waiter entry is skipped because try_module_get function fails

Getting Code Execution

- Set address of load_binary pointer to stack pivot
- ROP chain to allocate executable memory and copy shellcode
  - vmalloc_exec + memcpy
- Restore original formats list
- $shellcode
- Return to user space

ERNW
providing security.

Demo

Open Source

- Xenpwn open source release:
    - https://github.com/felixwilhelm/xenpwn
- Whitepaper contains a lot more technical details
    - Implementation details
    - Performance evaluation
    - ...

Future Work

- Use Xenpwn against Hyper-V and VMWare
  - Requires improved support for nested virtualization
- Identify and analyze other shared memory trust boundaries
  - Sandboxes?
- What types of bugs can we find with full memory traces?

Thanks for your Attention!

Q&A