Acquisition and Analysis of Compromised Firmware Using Memory Forensics

By

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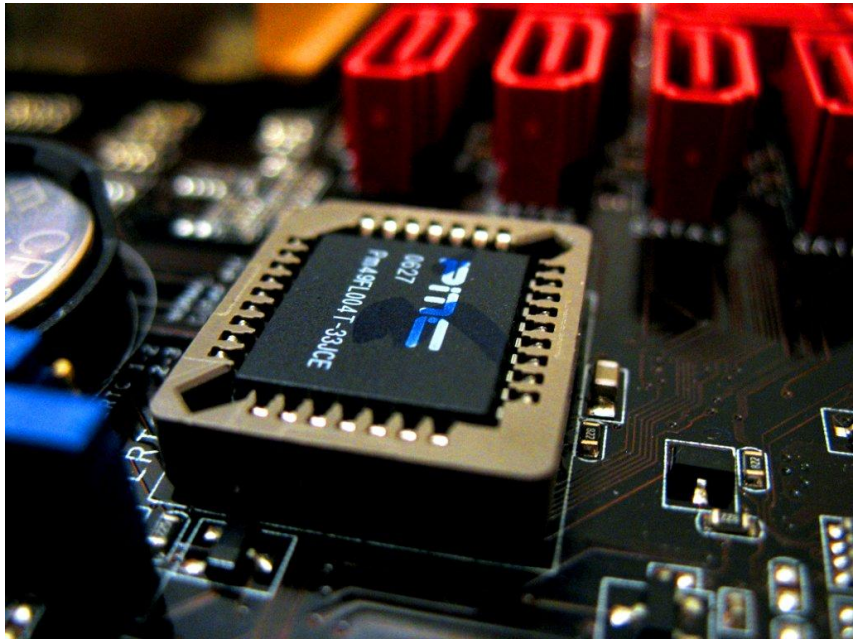
Problem Statement

Discover and acquire firmware code on x86 systems using memory forensics:

- Enumerate firmware memory in the physical address space
- Acquire firmware code and data via the memory bus



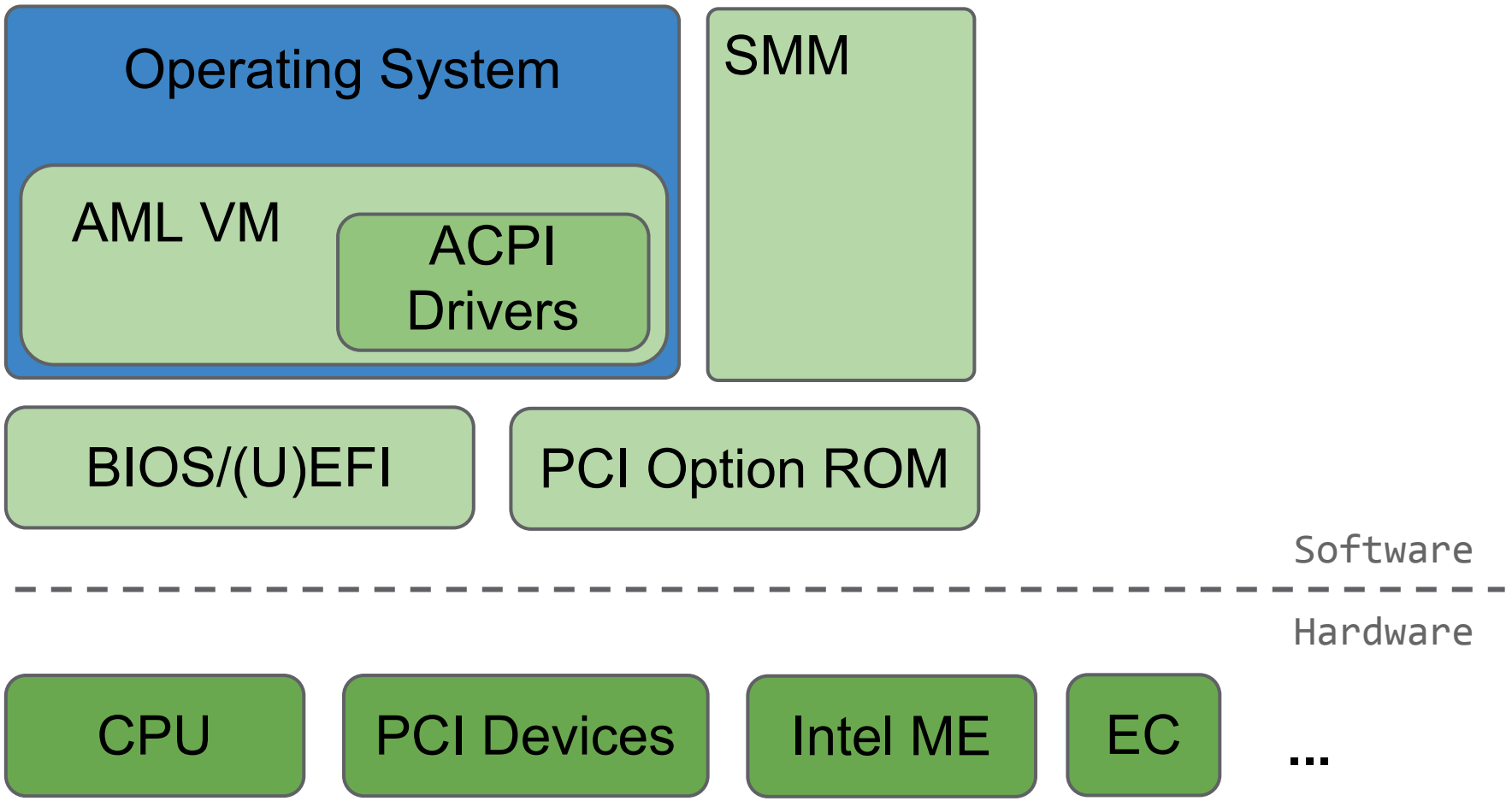
Related: Butterworth John, Xeno Kovah. *"Copernicus 2: SENTER the dragon"* CanSecWest (2014)

- Use Intel TXT and TPM to acquire firmware ROM
- Read firmware directly from SPI bus

Outline

- X86 Firmware Technologies
- Malicious Firmware Techniques
  - BIOS/(U)EFI
  - PCI Option ROM
  - ACPI
- Acquiring Firmware Code Using Memory Forensics
  - Locating Firmware in Memory
  - Accessing Firmware Memory
- Firmware Analysis
- Challenges

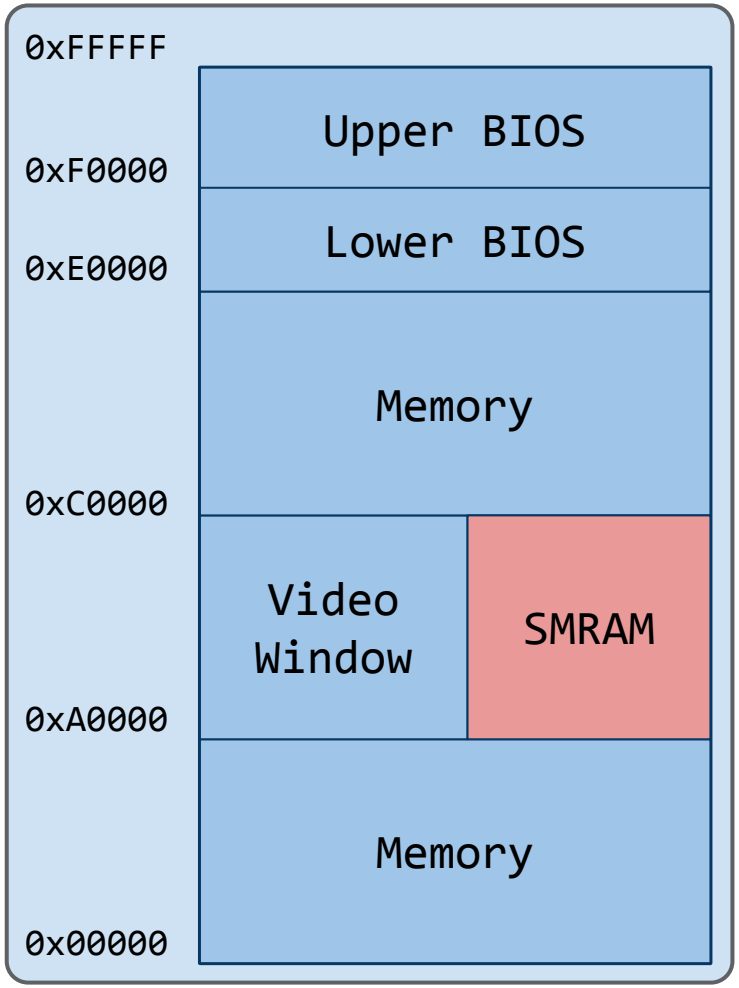
X86 Firmware Stack



BIOS / (U)EFI

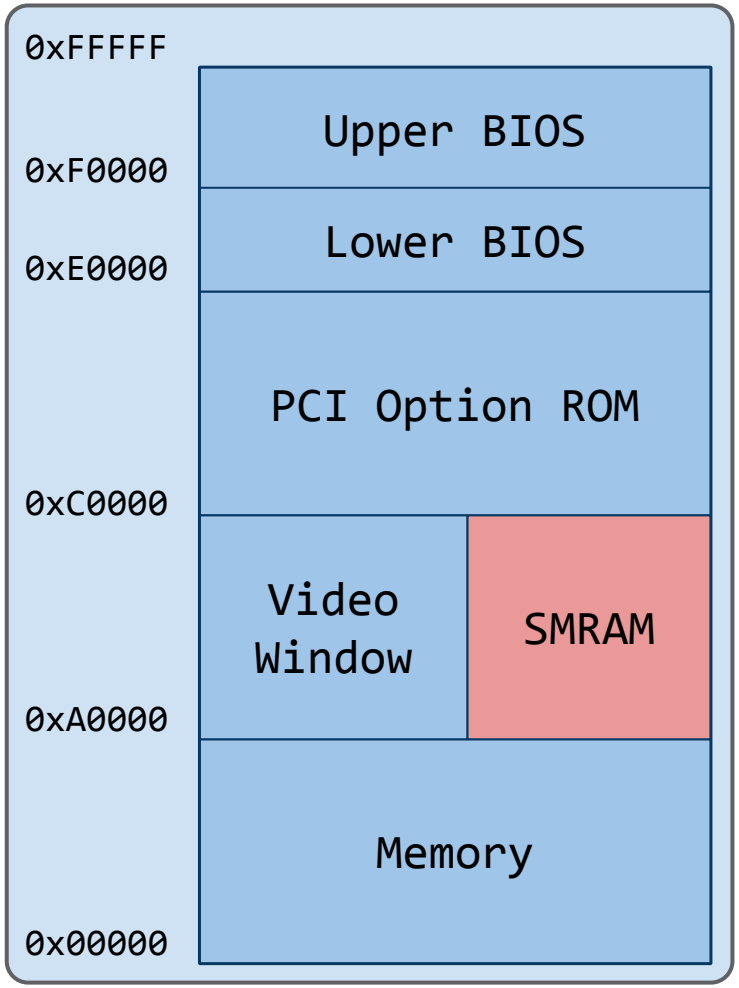
- BIOS code is stored on ROM chip
  - connected to southbridge via SPI
  - Mapped to `0xF0000 - 0xFFFFF` and `0xFFFF0000 - 0xFFFFFFFF`
- x86 CPU will load first instruction from `0xFFFFFFF0` when reset line is de-asserted (Reset Vector)
- Firmware initializes memory and migrates into RAM by modifying Programmable Attribute Map (PAM) registers

Note: (U)EFI has a different execution environment and driver model, the basic properties remain the same (Reset Vector, Mapped ROM, Migration to RAM)



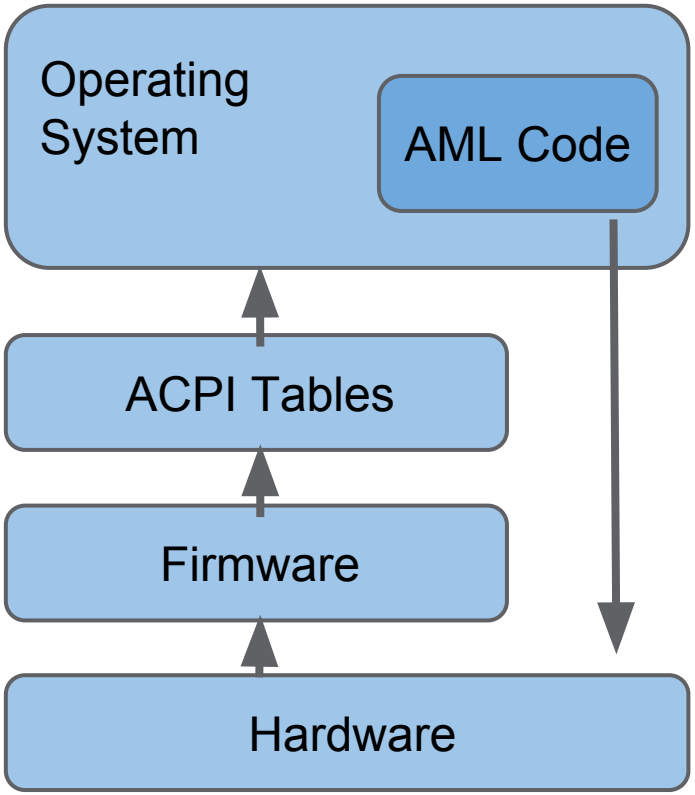
PCI Option ROM

- PCI devices require device specific initialization unknown to the firmware
- Initialization code stored in option ROM on the device
- Firmware maps ROM into physical address space and stores address of mapping in `XROMBAR` register in the devices PCI configuration space
- Firmware copies code from ROM into RAM (`0xC0000 - 0xE0000`)
- Initialization code is executed in firmware context with full privileges



ACPI

- ACPI Provides an abstract interface to platform configuration and power management
- ACPI code is written in ACPI Source Language (ASL) and compiled to bytecode called ACPI Machine Language (AML)
- Operating systems provide an implementation of an AML virtual machine
- Firmware provides information on ACPI registers and AML code in ACPI tables
- AML code runs in OS context



BIOS/EFI Rootkits

- Many BIOS implementations do not enforce code signing
- Already BIOS malware in the wild (Mebromi, 2011)
- (U)EFI and some BIOS implementations require signed updates
- ROM chip is replaceable/flashable with physical access
  - Brossard, Jonathan. *"Hardware Backdooring is practical."* BlackHat, Las Vegas*, USA* (2012).
- Signature implementations have bugs
  - Kallenberg, Corey, et al. *"Extreme Privilege Escalation On Windows 8/UEFI Systems."* Black Hat (2014).
- CRTM secure boot with TPM is flawed
  - Butterworth, John, et al. *"Bios chronomancy: Fixing the core root of trust for measurement."* ACM SIGSAC (2013).
  - Trust firmware to submit measurements to TPM
  - Firmware can be patched to still submit correct measurements
- Firmware updates are frequently ignored, so vulnerabilities remain unpatched for years
  - Corey Kallenberg, et al. *“How Many Million BIOSes Would you Like to Infect?”* CanSecWest 2015

PCI Option ROM Rootkits

- Patch option ROM on existing devices
  - Heasman, J. *"Implementing and detecting a PCI rootkit."* Black Hat USA (2006)
- Or connect a new device with a malicious option ROM
  - Loukas, K. *"De Mysteriis Dom Jobsivs–Mac EFI Rootkits."* Black Hat USA (2012)

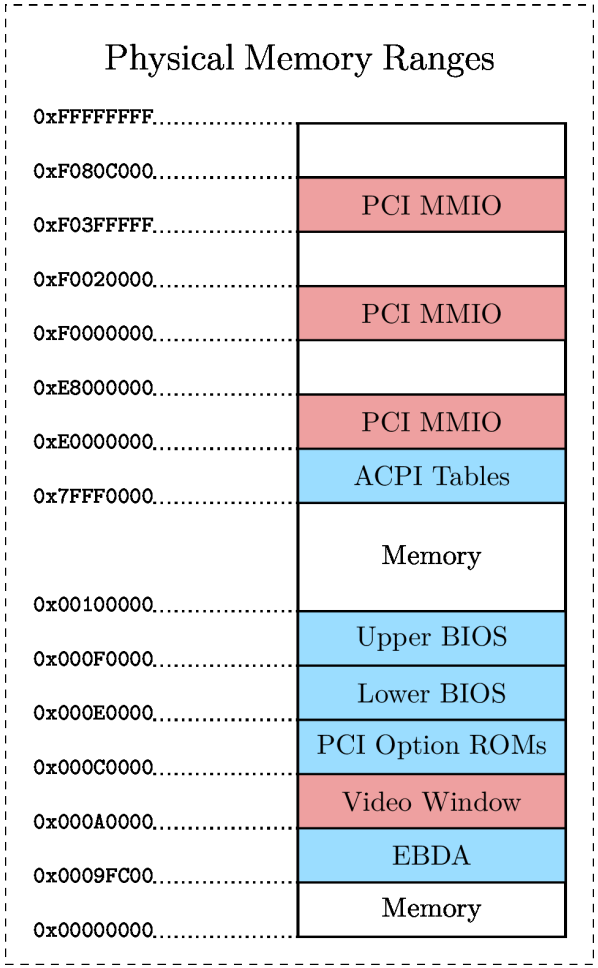
picture: http://ho.ax/De_Mysteriis_Dom_Jobsivs_Black_Hat_Paper.pdf

ACPI Rootkits

- BIOS copies ACPI code into RAM
- OS scans for “magic” signature
- OS executes AML code in AML VM in kernel mode
- Attacker can:
  - Patch BIOS to provide malicious ACPI tables
  - Put malicious ACPI code in memory in front of benign ACPI tables, because the OS will use first tables it can find
- ACPI code can read/write arbitrary kernel memory
- Heasman, John. *"Implementing and detecting an ACPI bios rootkit."* Black Hat Europe (2006).

Firmware Acquisition Using Memory Forensics

- All relevant firmware code and data regions are memory resident at runtime
- We can expand the memory acquisition process to acquire not only OS memory, but firmware memory as well
- We need to solve two problems:
  - Make sure not to access MMIO regions, as this can destabilize the system.
  - Avoid kernel APIs when mapping memory, as they were not intended for this and can fail.



Scope of Current Acquisition Tools

- Current tools only acquire memory marked as RAM by the OS
  - Prevent problems from accidentally reading device memory
- Major OS like Windows, Linux and OSX don't consider firmware regions to be RAM

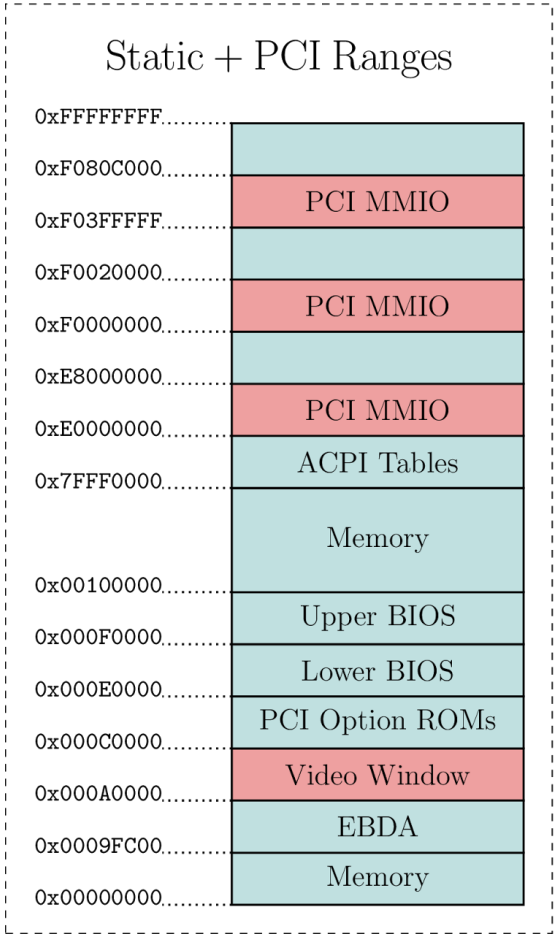
```
#define LIME_RAMSTR "System RAM"
...
for (p = iomem_resource.child; p ; p = p->sibling) {
                if (strcmp(p->name, LIME_RAMSTR))
                        continue;
                ...
}
```

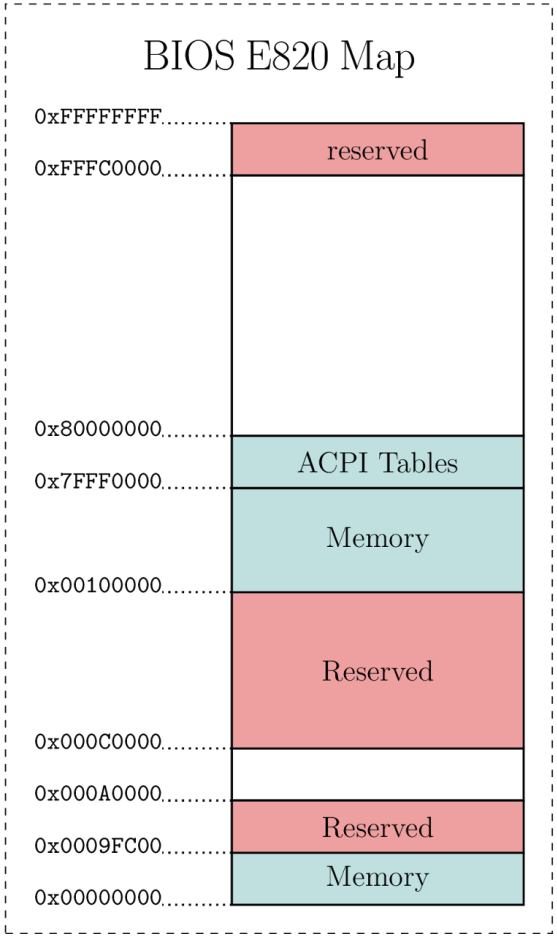
```
00000000-00000fff : reserved
00001000-0008efff : System RAM
0008f000-0008ffff : ACPI NV
00090000-0009ffff : System RAM
000a0000-000bffff : PCI Bus 00
000c0000-000c7fff : Video ROM
000c8000-000cbfff : pnp 00:00
000cc000-000cffff : pnp 00:00
000d0000-000d3fff : pnp 00:00
000d4000-000d7fff : pnp 00:00
000d8000-000dbfff : pnp 00:00
000dc000-000dffff : pnp 00:00
000e0000-000e3fff : pnp 00:00
000e4000-000e7fff : pnp 00:00
000e8000-000ebfff : pnp 00:00
000ec000-000effff : pnp 00:00
000f0000-000fffff : System ROM
00100000-da99efff : System RAM
...
```

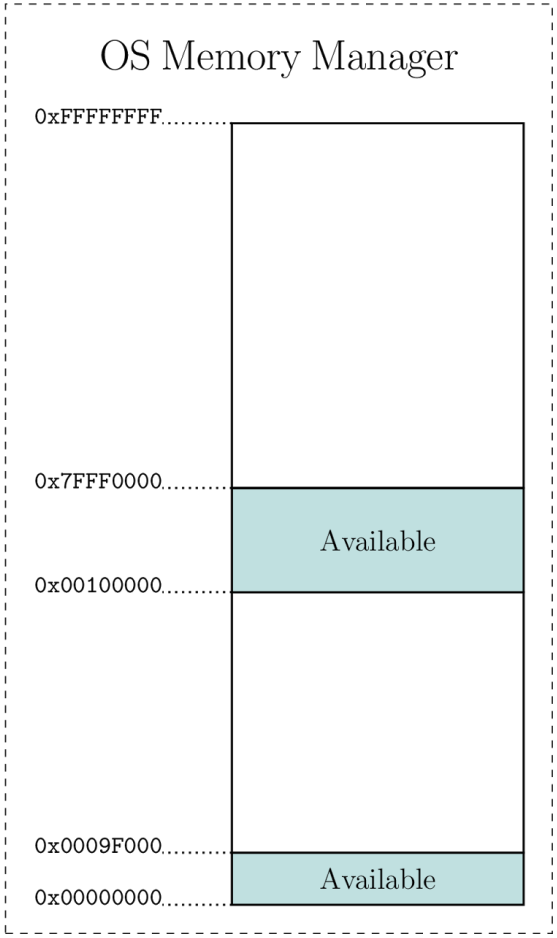
Enumerating Memory with PCI Introspection

- PCI Devices implement a configuration data structure
- It can be accessed via I/O ports `CONFIG_ADDRESS` (`0xCF8`) and `CONFIG_DATA` (`0xCFC`)
- Firmware configures MMIO for the device by writing the address of mapped regions to the BARs in configuration space for a device
- We can enumerate all MMIO regions by parsing the configuration space of all PCI devices
- We can safely read all memory (including firmware) by just skipping these regions

Completing the View on the Physical Address Space

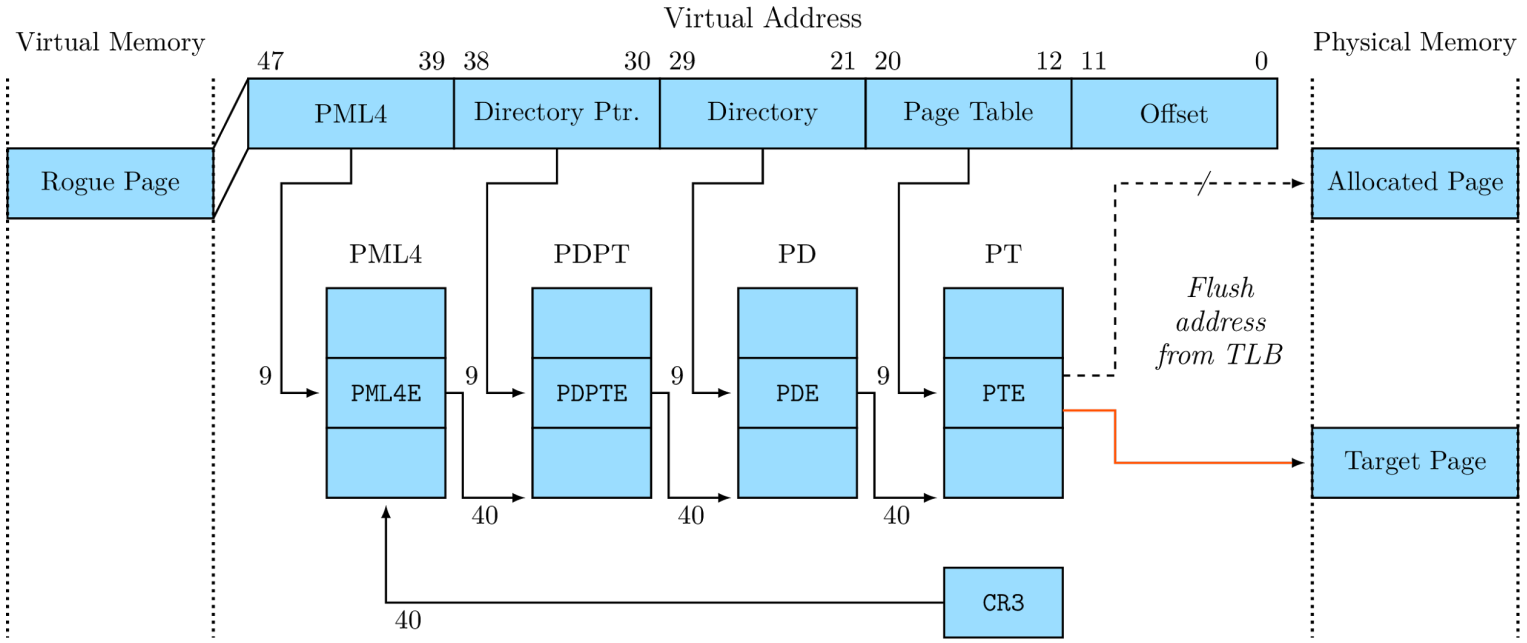






Mapping Firmware Memory

- We avoid OS APIs to prevent failure due to multiple mappings with different cache attributes
- Remap page in drivers data segment manually by editing the page tables and then flushing the page from the TLB (`invlpg`)



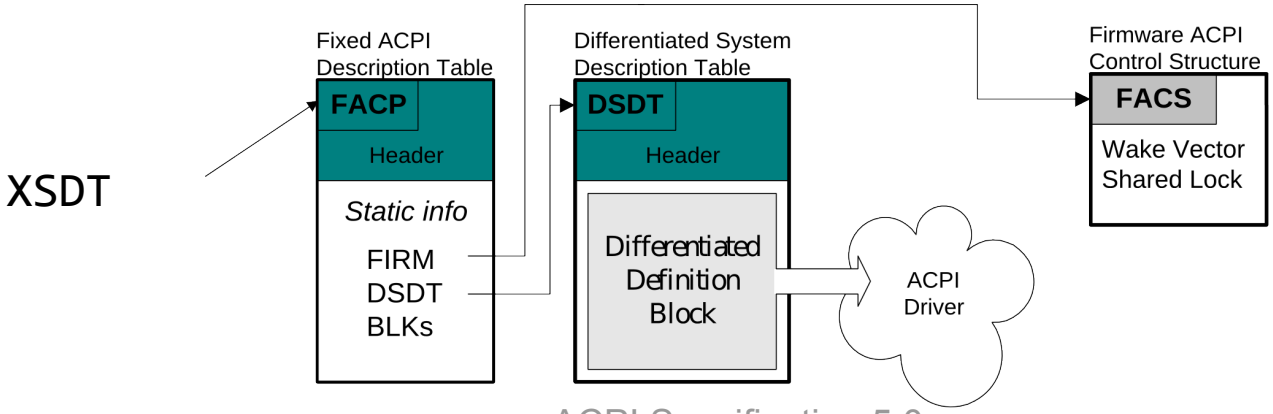
Implementation

- Technique is already implemented in Winpmem since version 1.5.2
- We have also ported it to Linux, not released yet
- In our evaluation, these two implementations were the only ones who could acquire firmware memory without crashing the system

Acquisition Tool	Firmware Acquired
Memoryze	✗
FTK Imager	✗
Moonsols DumpIt	✗
WinPmem	✗
WinPmem (pci)	✓
WindowsMemoryReader	✗
LiMe	✗
Pmem	✗
Pmem (pci)	✓

Firmware Analysis

- BIOS, (U)EFI and PCI Option ROMs can be dumped from the memory image for analysis with specialized software, as they reside in well defined regions in the physical address space
- The location of ACPI tables is not defined
  - OS finds them by scanning for a signature
- We have replicated this algorithm in a Volatility plugin
  - Dumps all ACPI tables to the file system



source: ACPI Specification 5.0

Operation Regions

- AML uses a construct called *Operating Regions* to access physical memory
- We have created an ACPI table scanner which analyzes all operating regions and flags references to kernel memory
- The scanner helps to focus on analyzing the relevant parts of the code

	Correctly Classified	Falsely Classified	$\sum$
Malicious	13.0%	16.4%	29.4%
Benign	61.9%		61.9%
Unknown	8.7%		8.7%
$\sum$	83.6%	16.4%	100%

Challenges

- SMRAM is only accessible in SMM
  - Restriction is enforced by memory controller
  - Set up by BIOS/(U)EFI before boot
  - Embleton, Shawn, Sherri Sparks, and Cliff C. Zou. *"SMM rootkit: a new breed of OS independent malware."* Security and Communication Networks 6.12 (2013): 1590-1605.
- Management Engine runs on separate CPU (ARC4, 32-bit RISC)
  - Full RAM access
  - Dedicated interrupt line to NIC
  - Dedicated RAM inacessible by CPU (ME-UMA)
  - Tereshkin, Alexander, and Rafal Wojtczuk. *"Introducing ring-3 rootkits."* Black Hat USA (2009).
- Embedded Controller exists in many modern laptops
  - Separate CPU
  - Separate Memory
  - Runs even when CPU is turned off
  - Weinmann, Ralf-Philipp. *“The Hidden Nemesis: Backdooring Embedded Controllers”* Chaos Communication Congress (2010)

Conclusion

- Malicious firmware is a real threat
- There are many memory regions containing firmware artifacts
  - Ignored by most current memory forensic tools
  - Can be acquired using PCI and MMU assisted methods
- We developed tools to acquire firmware on Windows and Linux
  - Extract firmware from memory images
  - Find indicators of compromise in ACPI tables

Questions?

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