A journey of fuzzing Nvidia graphic driver leading to LPE exploitation

Quarkslab

/HEXACON/

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Thierry Doré

Motivation

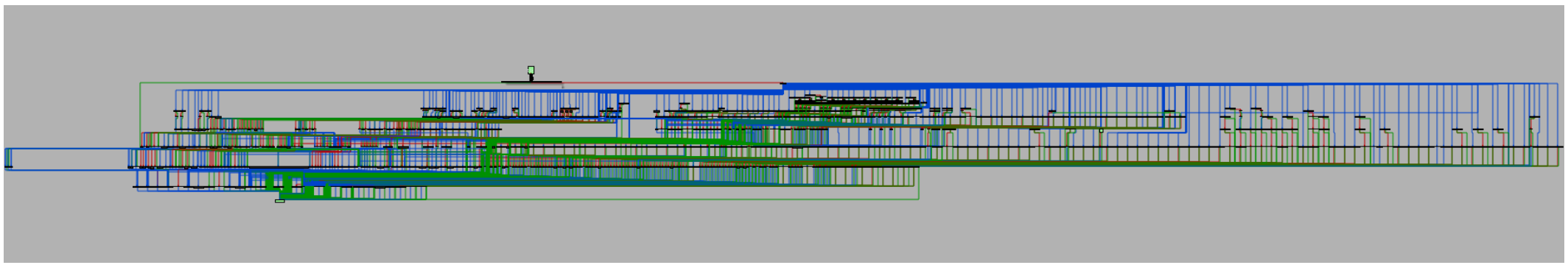
- Two fuzzing projects released in 2021: **WTF** & **Rewind**
- Both offer to easily target kernel components
- Wanted to get familiar with both of them
- Needed a target
  - Tried various ~~victims~~ candidates
  - Decided to go for the graphical driver developed by Nvidia

Why Nvidia Graphic Driver?

- Simple entry point...

```
NTSTATUS DxgkddiEscape(
         IN_CONST_HANDLE hAdapter,
         IN_CONST_PDXGKARG_ESCAPE pEscape
        )
```

- With an interesting attack surface



Previous Works

- Attacking the Windows NVIDIA Driver

  Blogpost 2017, Project Zero
- Evolutionary Kernel Fuzzing

  BlackHat 2017, Richard Johnson
- Direct X – Direct way to Microsoft Windows Kernel

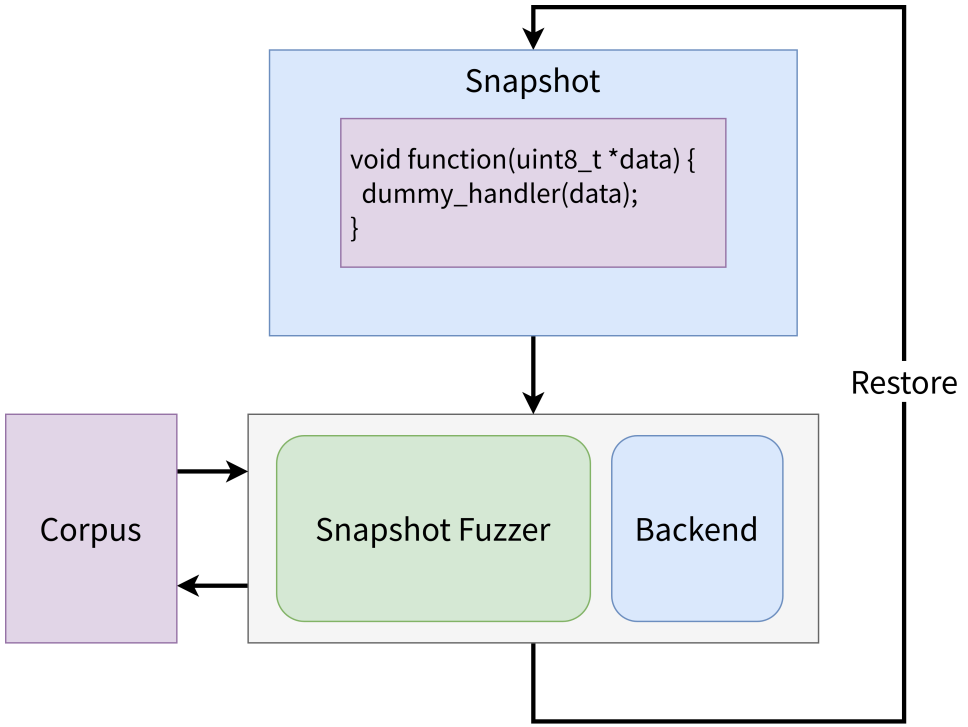
  Zeronights 2011, Nikita Tarakanov

Snapshot Fuzzing

WTF
- By 0vercl0k
- https://github.com/0vercl0k/wtf

Rewind
- By Erynian
- https://github.com/quarkslab/rewind

- Both use Hyper-V, BochsCPU and KVM backend



DxgkDdiEscape Interface

```
NTSTATUS DxgkddiEscape(
        IN_CONST_HANDLE hAdapter,
        IN_CONST_PDXGKARG_ESCAPE pEscape
        )
```

- Entry point arguments
  - `hAdapter`: adapter handle
  - `pEscape`: documented structure
    - Contains the message sent to the interface (`pPrivateDriverData`)
    - The format is constructor specific!

DxgkDdiEscape Escape Structure

```
typedef struct _DXGKARG_ESCAPE {
    [in]     HANDLE             hDevice;
    [in]     D3DDDI_ESCAPEFLAGS Flags;
    [in/out] VOID               *pPrivateDriverData;
    [in/out] UINT               PrivateDriverDataSize;
    [in]     HANDLE             hContext;
    HANDLE             hKmdProcessHandle;
} DXGKARG_ESCAPE;
```

- The handles are optional except for hDevice
- The command message is constructor dependant

First Fuzzing Iteration

Corpus Generation

- Record the command messages sent to the graphic driver
- Generate activities using a benchmarking tool

Result

- Barely 40% of the driver handlers covered

We have to build a better corpus

Corpus Generation

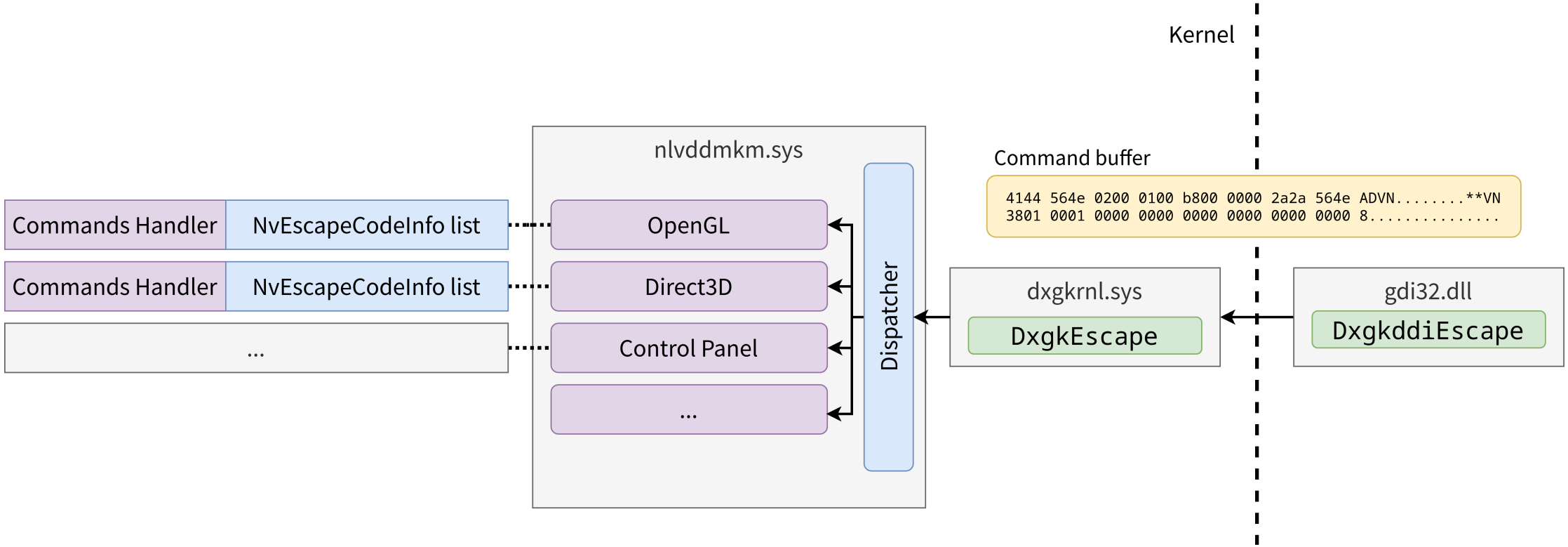
Private Buffer Format

- Starts with a generic header
- Followed by the actual content
  - Specific format for each functionality

```
// sizeof(NvPrivateDataHeader) == 0x10
struct NvPrivateDataHeader {
    DWORD magic_tag;
    WORD major_version;
    WORD minor_version;
    DWORD private_data_size;
    DWORD caller_tag;
}

struct NvPrivateData {
    UINT EscapeCode;
    ...
}
```

Driver Architecture



Generic Attribute Validation

```
typedef struct _NvEscapeCodeInfo {
    UINT EscapeCode;
    UINT Size;
    BYTE Unk_2[0x8];
    UINT AdminPrivRequired;
    UINT Flags_1;
    ...
    PVOID ValidationFunction;
} NvEscapeCodeInfo;
```

- The `Flag_1` value gives information about the handle(s) to provide
  - `0x1`: A device handle is required
  - `0x2`: Device and context handles are required

Specific Message Callbacks

- Callbacks may give interesting information about the format

```
bool validation_function_1000151(DXGKARG_ESCAPE Escape, /* ... */) {
    PrivateData1000151 *msg = Escape->pPrivateDriverData;
    if (RtlCompareMemory(msg->guid_1, GUID_E7A07B48, sizeof(GUID)) ||
        RtlCompareMemory(msg->guid_2, GUID_7F03FC51, sizeof(GUID)) ||
        RtlCompareMemory(msg->guid_3, GUID_C50F93EF, sizeof(GUID))) {
      return true;
    }
    return false;
}
```

Inputs Generation

- IDA scripting
  - Parsing NvEscapeCodeInfo structures to generate message header

```
00000000: 0000 0000 0000 0000 4144 564e 0200 0100  ........ADVN....
00000010: 4001 0000 2a2a 564e 0300 0001 0000 0000  @...**VN........
00000020: 0000 0000 0000 0000 0000 0000 0000 0000  ................
00000030: 0000 0000 0000 0000 0000 0000 0000 0000  ................
```

Inputs Generation

- IDA scripting
  - Parsing NvEscapeCodeInfo structures to generate message header
- Dynamic Symbolic Execution
  - Generate inputs that pass the validation

```
00000000: 0000 0000 0000 0000 4144 564e 0200 0100  ........ADVN....
00000010: 4001 0000 2a2a 564e 0300 0001 0000 0000  @...**VN........
00000020: 0000 0000 0000 0000 0000 0000 0000 0000  ................
00000030: 0000 0000 0000 0000 0000 0000 0000 0000  ................
```

- **Triton - https://github.com/JonathanSalwan/Triton**
  - Dynamic binary analysis library with Python bindings
  - Allows to easily cover all the edges of a function

Inputs Generation

- Most of the time, only the first argument is used
- Both `DXGKARG_ESCAPE.Flags` and `DXGKARG_ESCAPE.PrivateDataBuffer` are symbolized
- Cover all the edges of the function
  - For each jump instruction, we look for a symbolized value that inverts it

```
{'isTaken': False,
 'srcAddr': 5382793397, 'dstAddr': 5382793426,
 'constraint': (((~(ref_724) & 0x1) & (~(ref_728) & 0x1)) == 0x1)}

New inputs: {52: SymVar_52:8 = 0x0, 53: SymVar_53:8 = 0x0, 55: SymVar_55:8 = 0x4,
             54: SymVar_54:8 = 0x0}
```

Inputs Generation

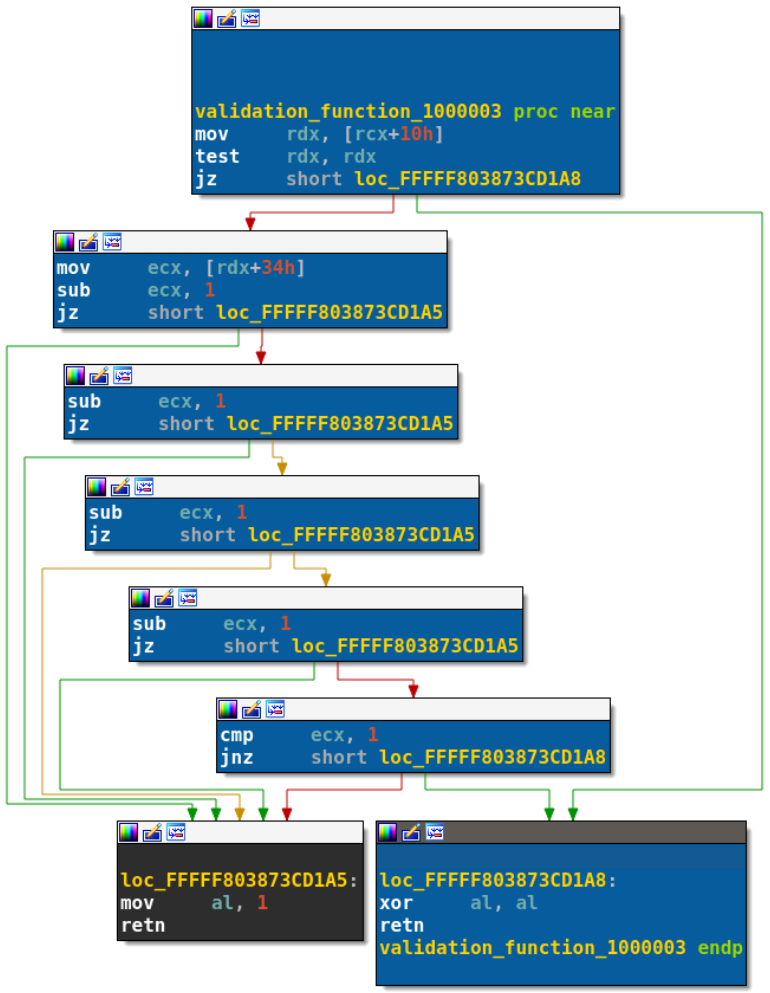
- At the end of the function
  - Try to resolve the symbolic value of rax with it equal to `TRUE` as a constraint

```
rax = (((((((0x1 == 0x1) and not (((~(ref_724) & 0x1) & (~(ref_728) & 0x1)) == 0x1))
       and not (((~(ref_733) & 0x1) & (~(ref_737) & 0x1)) == 0x1))
       and not (((~(ref_742) & 0x1) & (~(ref_746) & 0x1)) == 0x1))
       and not (((~(ref_751) & 0x1) & (~(ref_755) & 0x1)) == 0x1))
       and not (ref_760 == 0x0)) and (0x1 == 0x1))

Valid escape buffer:
    ...
    00000040: 00 00 00 00 00 00 00 00  00 00 00 00 01 00 00 00  ................
    00000050: 00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
    ...
```

- Input generated by the IDA script

```
00000000: 0000 0000 0000 0000 4144 564e 0200 0100  ........ADVN....
00000010: 4001 0000 2a2a 564e 0300 0001 0000 0000  @...**VN........
00000020: 0000 0000 0000 0000 0000 0000 0000 0000  ................
00000030: 0000 0000 0000 0000 0000 0000 0000 0000  ................
```



- Input generated by the IDA script

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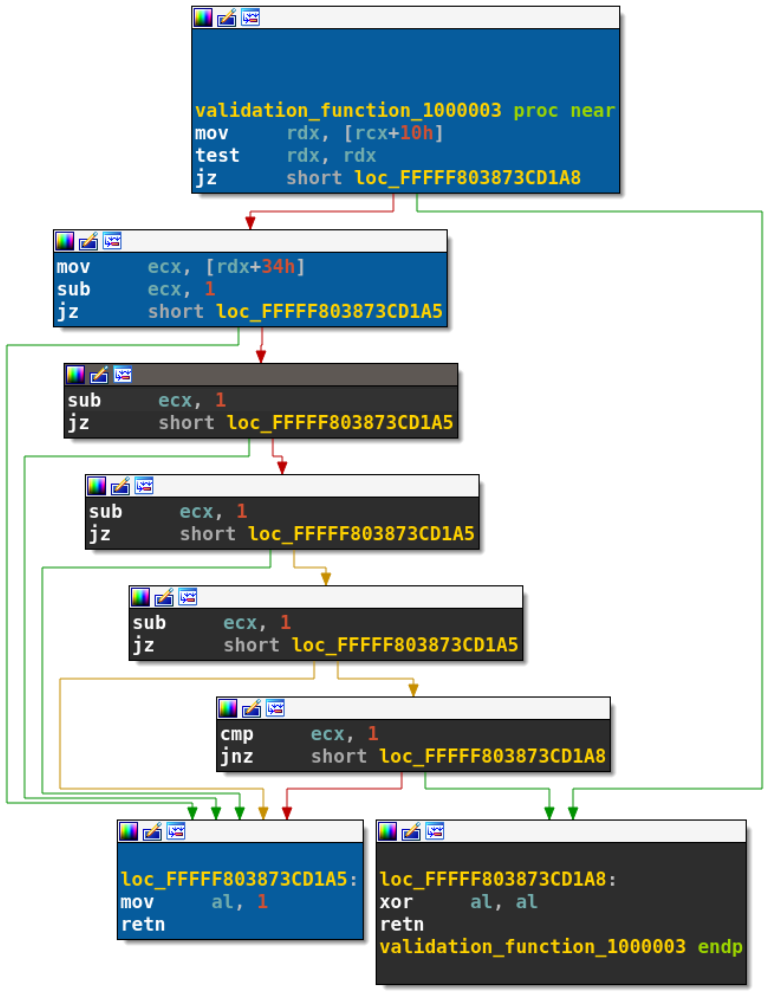

- First valid file generated with DSE

```
00000000: 0000 0000 0000 0000 4144 564e 0200 0100  ........ADVN....
00000010: 4001 0000 2a2a 564e 0300 0001 0000 0000  @...**VN........
00000020: 0000 0000 0000 0000 0000 0000 0000 0000  ................
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- Second valid file generated with DSE

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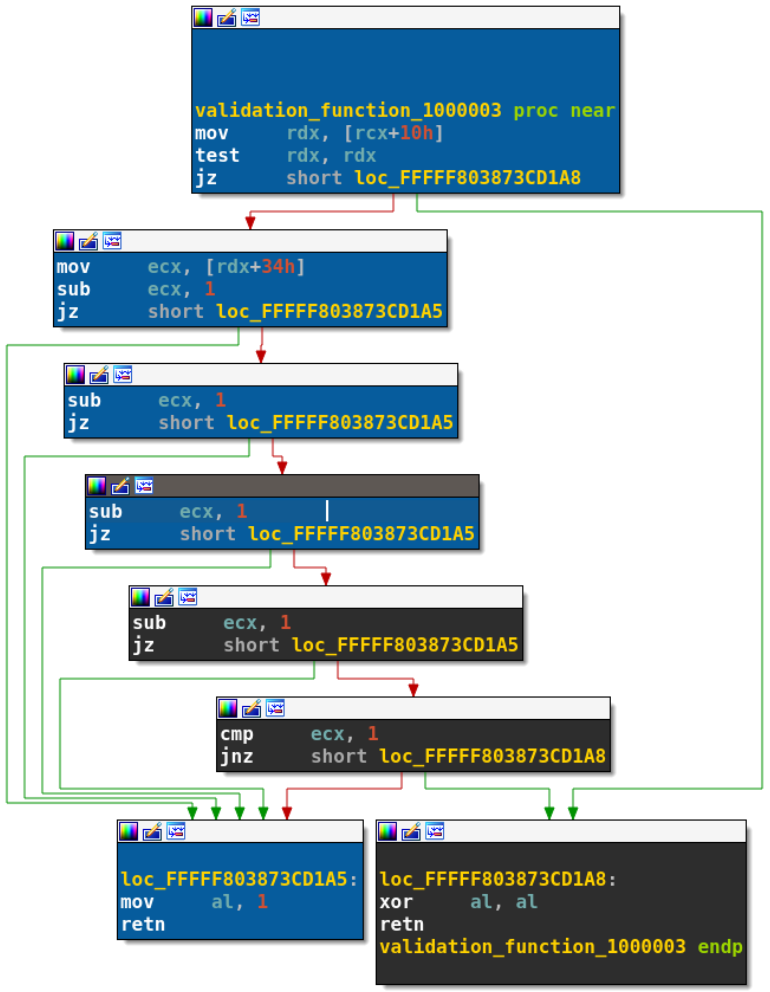


- Third valid file generated with DSE

```
00000000: 0000 0000 0000 0000 4144 564e 0200 0100  ........ADVN....
00000010: 4001 0000 2a2a 564e 0300 0001 0000 0000  @...**VN........
00000020: 0000 0000 0000 0000 0000 0000 0000 0000  ................
00000030: 0000 0000 0000 0000 0000 0000 0300 0000  ................
```

New Corpus and Coverage

- Coverage with the new corpus: 40% -> 80%

Limitation

- Some callbacks access objects in memory and cannot be emulated
  - Need a way to link the script with the memory dump

Fuzzing Harness

- Quite simple harness
- Implementation of 2 functions:
  - `Init`: setup stop addresses
  - `InsertTestcase`: called at every iteration
    - Allows to set up the test case files
- Discards invalid buffers
  - When important data (MagicCode, size, etc.) is corrupted

> We remove all the mutation strategies in WTF that could impact the buffer size

Fuzzing Results

Identified Bugs

Command ID	Bug	Description
0x1000083	**Out of bounds write**	**Out of bound write in the Adapter object leading to a privilege escalation vulnerability**
0x100006b	**Out of bounds read**	**Out of bound read in the data section**
0x100002f	Out of bounds read	Out of bound read bug. *Not exploitable.*
0x7000013		
0x700010b		

0x100006b: Out of Bounds Read

- Offset read without any check and used in a memory copy

```
uint32_t offset = EscapeBuffer->Offset;
data_size = 0x2FC - offset;
if (data_size > 0x1DC) {
    data_size = 0x1DC;
}
src_ptr = DataSectionArray + offset;
memcpy(EscapeBuffer->OutputData, src_ptr, data_size);
```

- Allows to copy 476 bytes after an array stored in the `.data` section
- Function pointer and stack cookie present in this section
  - Can help to bypass KASLR or to exploit a stack buffer overflow (if any)

0x1000083: Out of Bounds Write

- Access to an array located in the Adapter object with an untrusted index
  - 32-bit value retrieved from the private escape buffer

```
uint8_t oob_write(void *p_adapter, /*...*/, uint32_t val_3, uint32_t index) {
    // ...
    if(val_3 & 0x3000) {
        pAdapter->UnkByte_1 = val_1;
        pAdapter->UnkByte_2 = val_2;
        pAdapter->ArrayOffset4E94[index] = val_3;
    }
    // ...
}
```

0x1000083: Limitations

- Allows to write a partially controlled value in the 4GB of memory after the array stored in the Adapter object

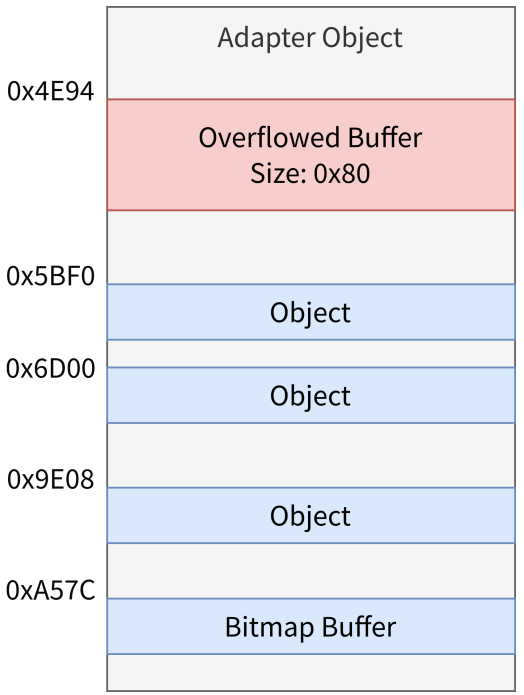
- Presence of an annoying cache
  - Registration of the Userland process PID
  - Vulnerable code skipped if the same process calls the escape feature twice
  - No simple way to remove the PID from the cache without administrative rights

- Create a new process each time we want to corrupt

- Some limitation on the corrupted value
  - Setting the 12th and 13th bits changes the execution path

Adapter Object Layout

```
> !pool ffff9d0f220eb000
ffff9d0f220eb000 : large page allocation, tag is NvDI, size is 0x14000 bytes
```



- Several objects can be corrupted
- Gaining a R/W primitive is possible
  - But no CFG protection
  - Corrupting pointers is easier
- Corruption of 32-bit at a time
  - Need to trigger the bug twice
  - Choose something not heavily used by the driver

Tracing Memory Access

- Leverage the fuzzer corpus to follow memory accesses and find our target
- Bochscpu allows to easily add callbacks on the execution
  - `BOCHSCPU_HOOK_MEM_EXECUTE`
  - `BOCHSCPU_HOOK_MEM_READ`
  - `BOCHSCPU_HOOK_MEM_RW`
  - `BOCHSCPU_HOOK_MEM_WRITE`
- `bochscpu_backend.cc` modification to trace memory accesses

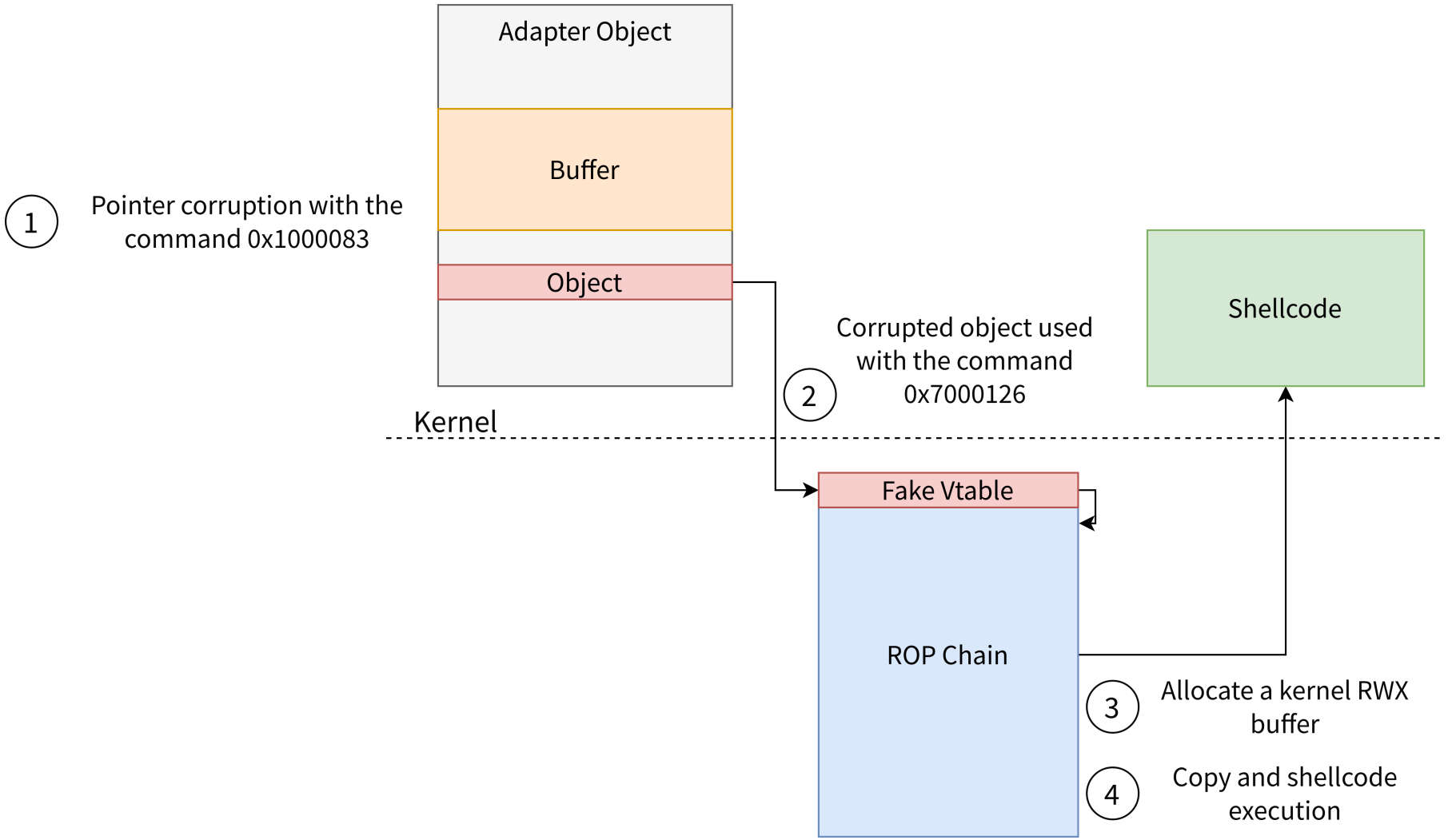
Finding a Pointer to Corrupt

- Looking for a specific pattern:
  - 8-byte read access in the Adapter object memory that can be controlled
  - Followed by another access to the value that has been read previously

```
Read 0xffff8083c4535000 at offset: 0x9e08 (pc: 0xfffff803866678bf)
Access 0xffff8083c4535000 at 0xfffff80387174019

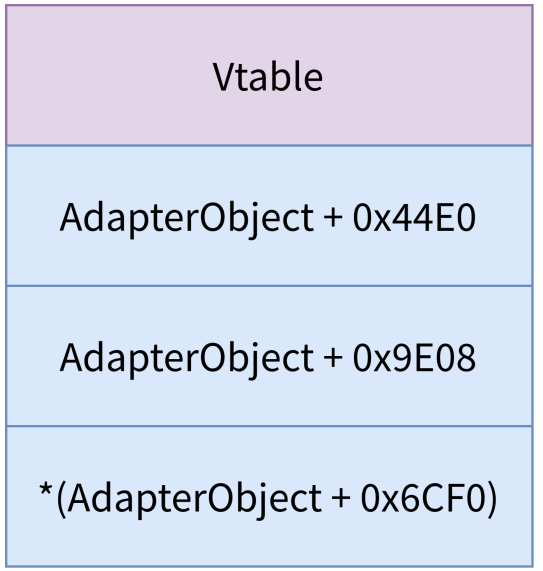
Read 0xffff8083c5d30fe0 at offset: 0x5bf0 (pc: 0xfffff80387173f5c)
Access 0xffff8083c5d30fe0 at 0xfffff80387173f63

Read 0xffff8083c2022000 at offset: 0x6cf0 (pc: 0xfffff803871009d0)
Access 0xffff8083c2022000 at 0xfffff803873a852d
```


Adapter Object
Buffer
Object
1
Pointer corruption with the command 0x1000083
2
Corrupted object used with the command 0x7000126
Shellcode
Kernel
Fake Vtable
ROP Chain
3
Allocate a kernel RWX buffer
4
Copy and shellcode execution

Restoring the Object

- Need to restore the corrupted object
  - Cannot leak the pointer before overwriting it :(
  - Need to reconstruct it
- Vtable pointer retrievable in an easy way
  - Driver base address is known
- Other fields require a leak of the Adapter object address



Transforming the Corruption into a Memory Leak

- Some Nvidia requests return data to the user
  - Leverage the Adapter object corruption to leak memory
- Bypass the validation by modifying the object before the data is copied in the output buffer
- Reuse of the memory tracing capability offered by Bochscpu backend
  - Record of every read access to the object followed by a copy in the output buffer

Transforming the Corruption into a Memory Leak

We are looking for this kind of pattern:

- Read memory access from the escape buffer
  - we can control something
- Read memory in the controlled part of the Adapter object
- Write memory access in the escape buffer
  - something is returned to the user

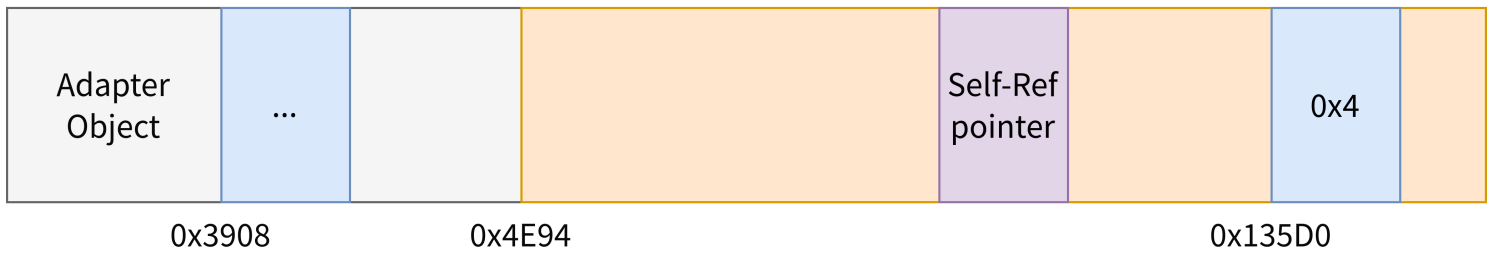
```
Adapter Read 0x00000004 to GVA 0xffff8083c20575d0 (Offset: 0x135d0)

PrivateBuffer Read 0x00000002 to GVA 0xffffd70b83110030 at 0xfffff803870fa488
PrivateBuffer Read 0x00000002 to GVA 0xffffd70b83110030 at 0xfffff803870fa490

Adapter Read 0x000000009ac31d0a to GVA 0xffff8083c204c9b0 (Offset: 0x89b0)
PrivateBuffer Write 8 bytes to GVA 0xffffd70b83110034 at 0xfffff803870fa4b5
```

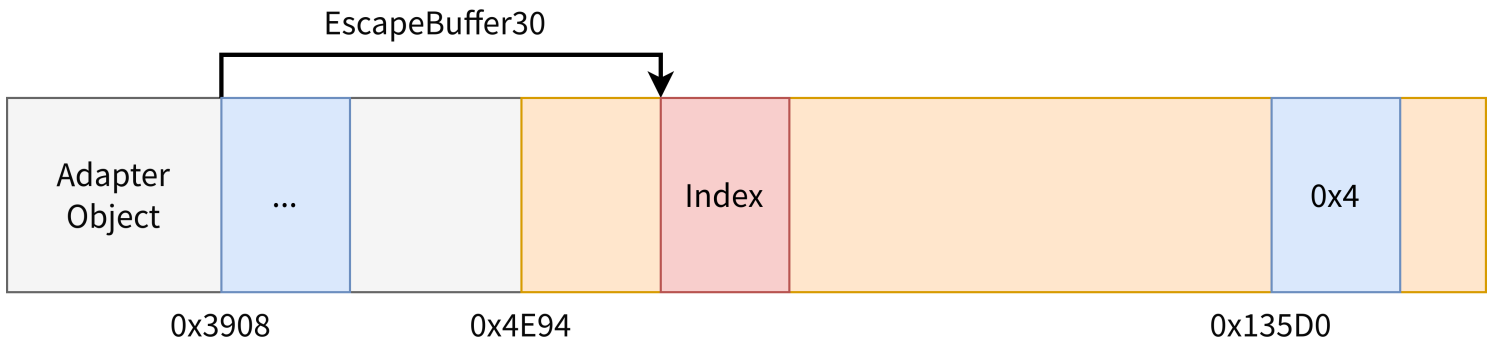
Transforming the Corruption into a Memory Leak

```
// Private Escape Code 0x2000041
uint32_t EscapeBuffer30 = EscapeBuffer->index;
if (EscapeBuffer30 <= AdapterObject->Offset135D0MaxIndex) {
    uint32_t index = AdapterObject->Offset3908Array[EscapeBuffer30];
    uint32_t value = AdapterObject->Offset89B0Array[index * 0x18];
    // ...
    EscapeBuffer->OutputValue = value;
    // ...
```



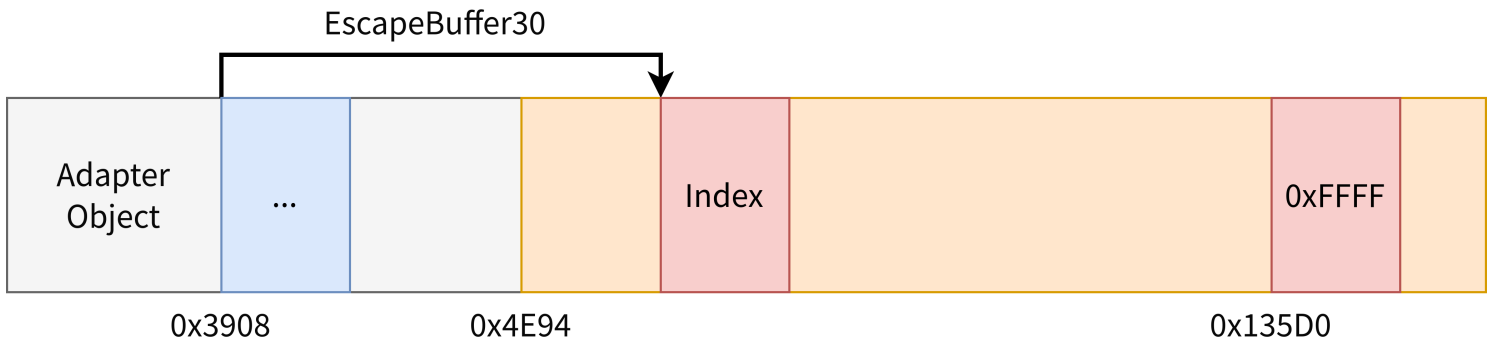
Transforming the Corruption into a Memory Leak

```
// Private Escape Code 0x2000041
uint32_t EscapeBuffer30 = EscapeBuffer->index;
if (EscapeBuffer30 <= AdapterObject->Offset135D0MaxIndex) {
    uint32_t index = AdapterObject->Offset3908Array[EscapeBuffer30];
    uint32_t value = AdapterObject->Offset89B0Array[index * 0x18];
    // ...
    EscapeBuffer->OutputValue = value;
    // ...
```



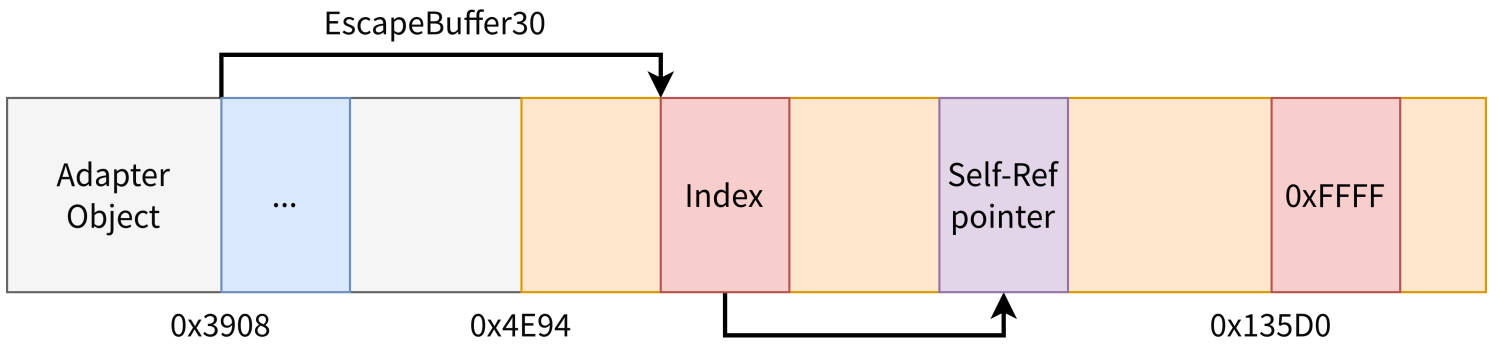
Transforming the Corruption into a Memory Leak

```
// Private Escape Code 0x2000041
uint32_t EscapeBuffer30 = EscapeBuffer->index;
if (EscapeBuffer30 <= AdapterObject->Offset135D0MaxIndex) {
    uint32_t index = AdapterObject->Offset3908Array[EscapeBuffer30];
    uint32_t value = AdapterObject->Offset89B0Array[index * 0x18];
    // ...
    EscapeBuffer->OutputValue = value;
    // ...
```

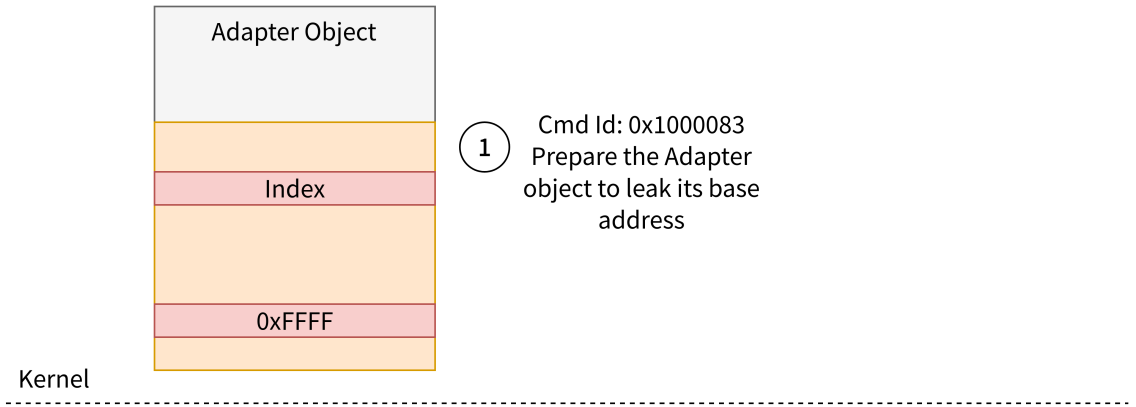


Transforming the Corruption into a Memory Leak

```
// Private Escape Code 0x2000041
uint32_t EscapeBuffer30 = EscapeBuffer->index;
if (EscapeBuffer30 <= AdapterObject->Offset135D0MaxIndex) {
    uint32_t index = AdapterObject->Offset3908Array[EscapeBuffer30];
    uint32_t value = AdapterObject->Offset89B0Array[index * 0x18];
    // ...
    EscapeBuffer->OutputValue = value;
    // ...
```



Final Exploitation Step



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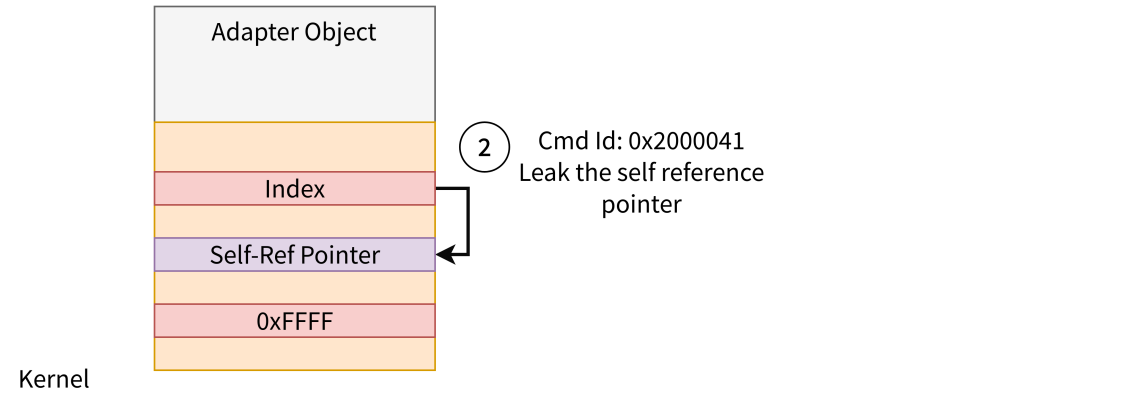

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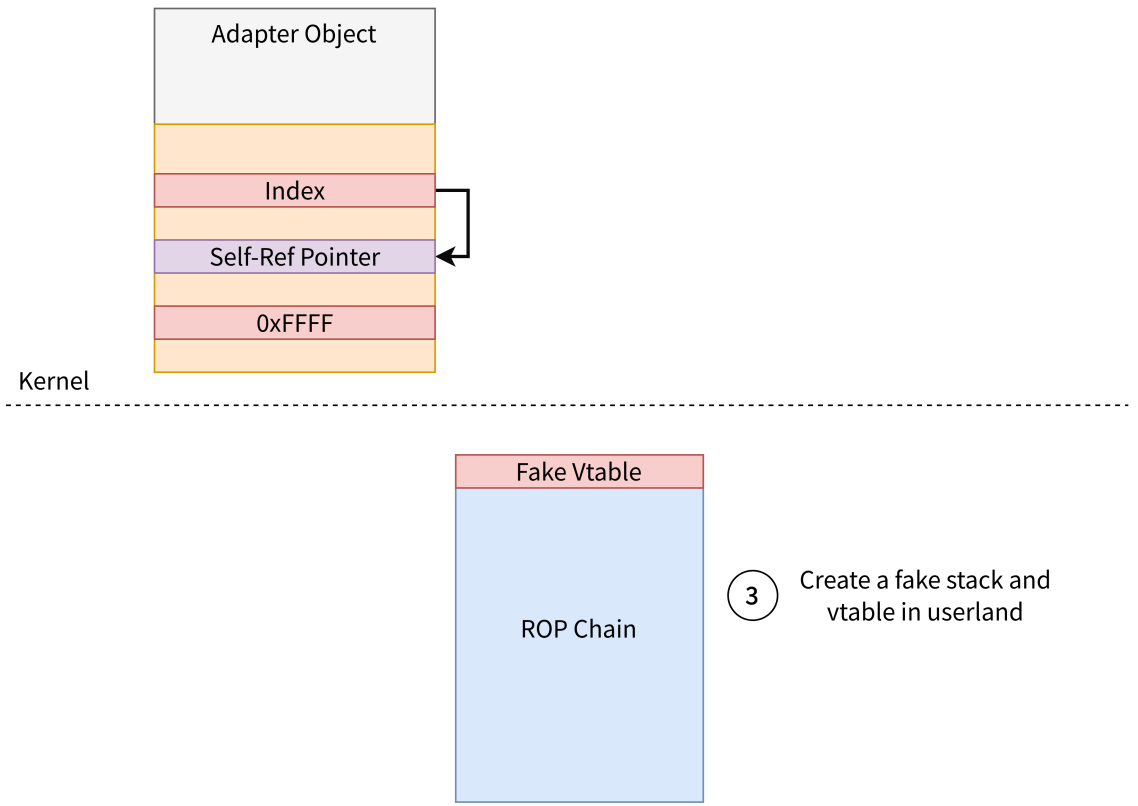

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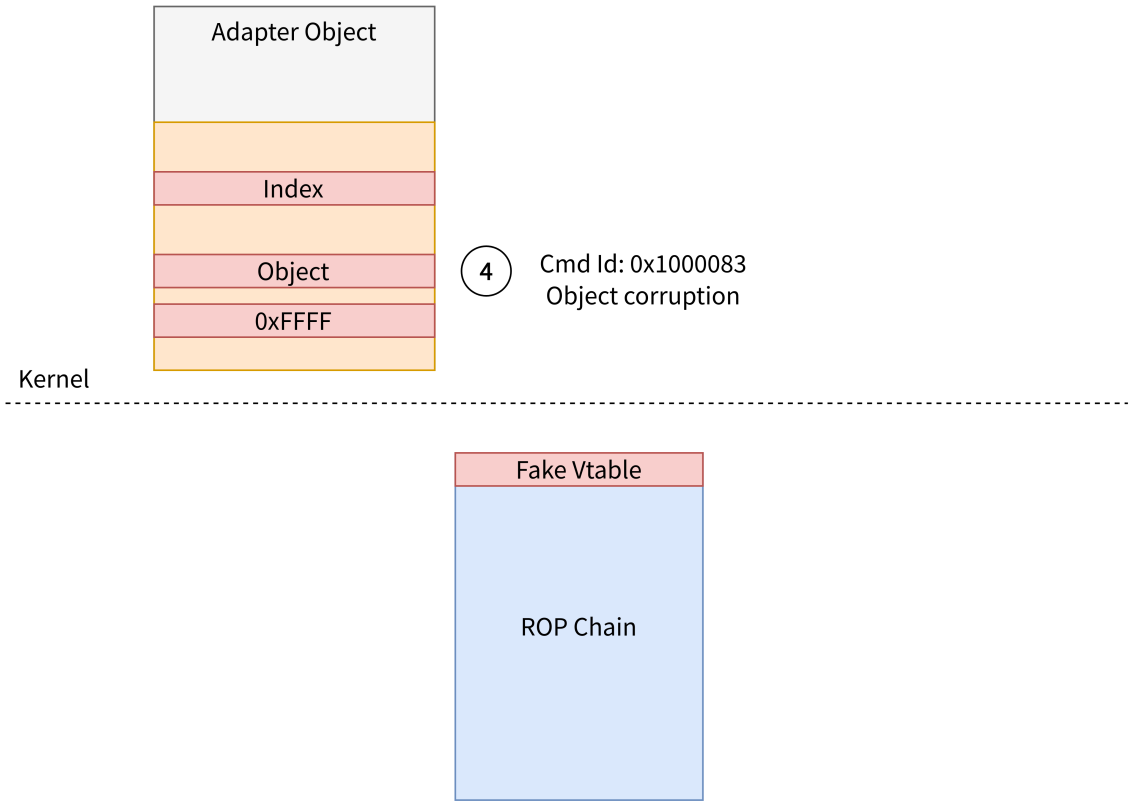

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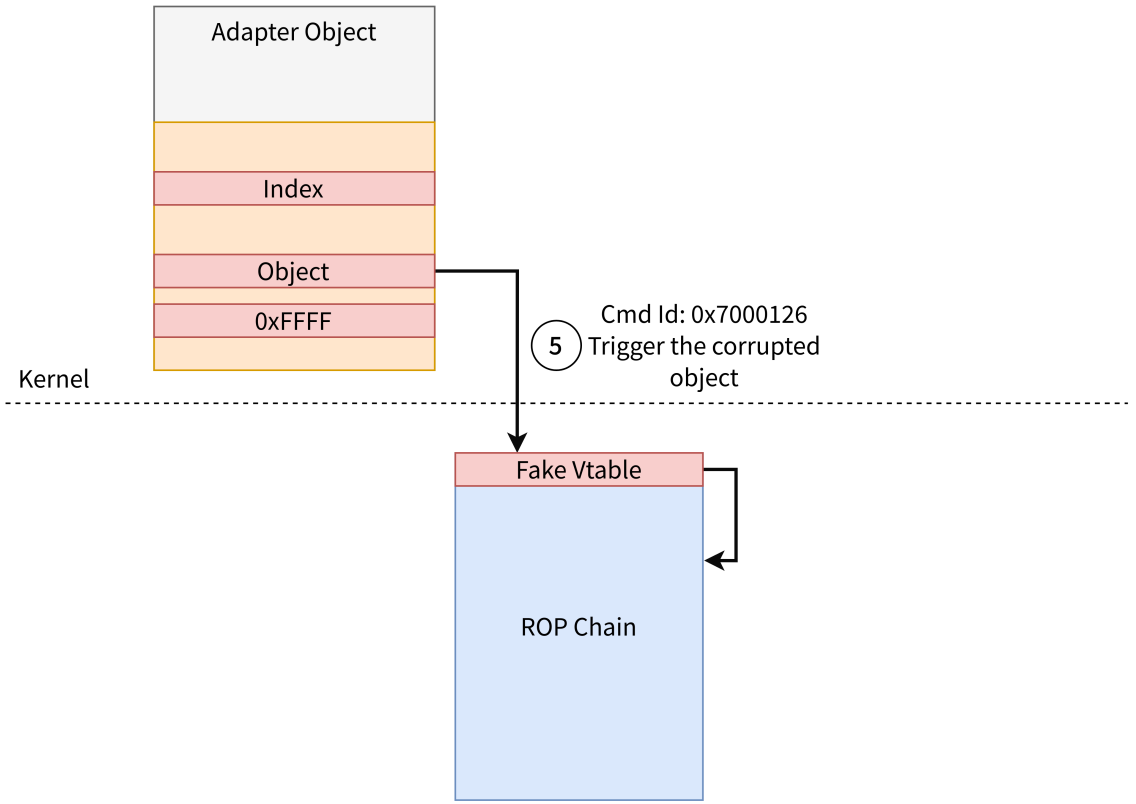

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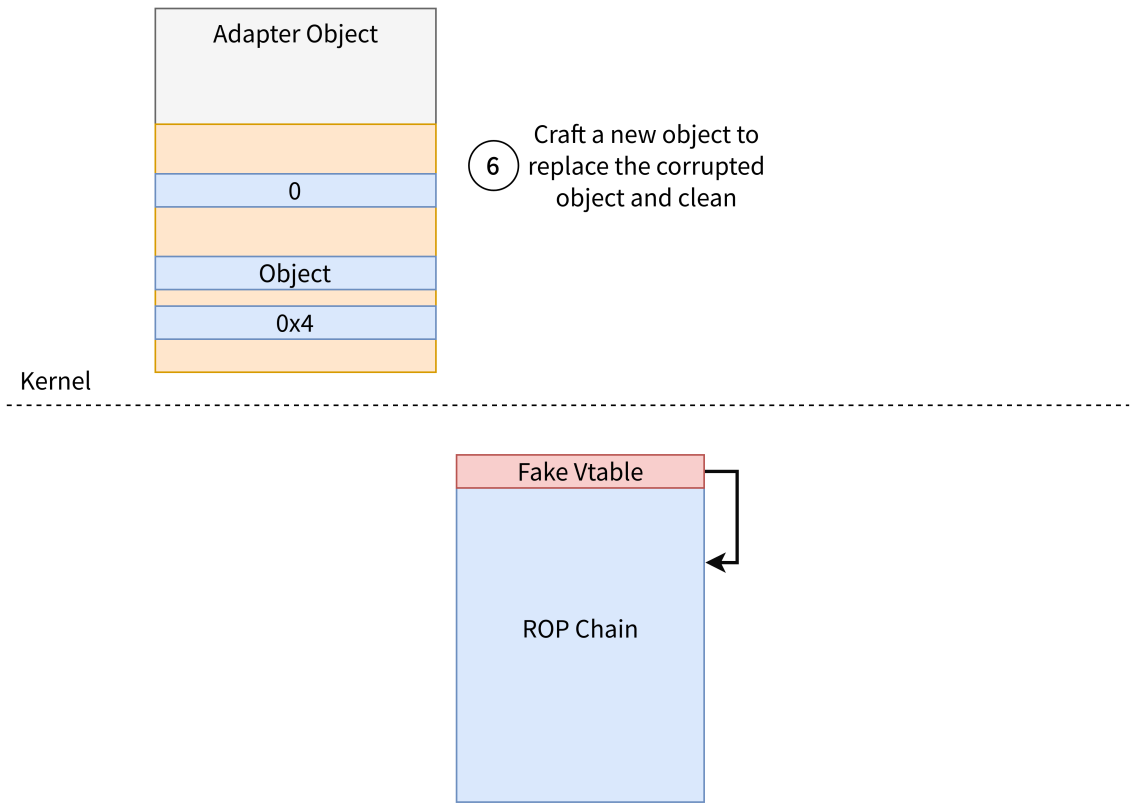

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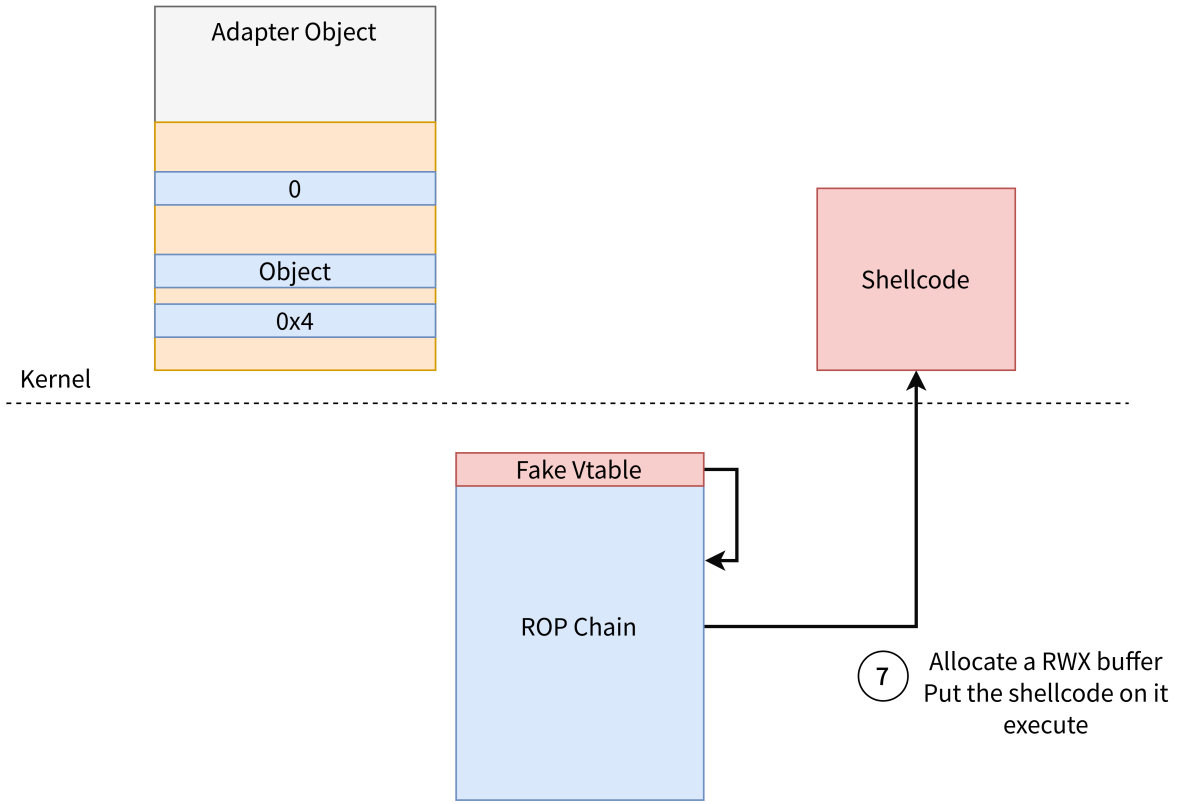

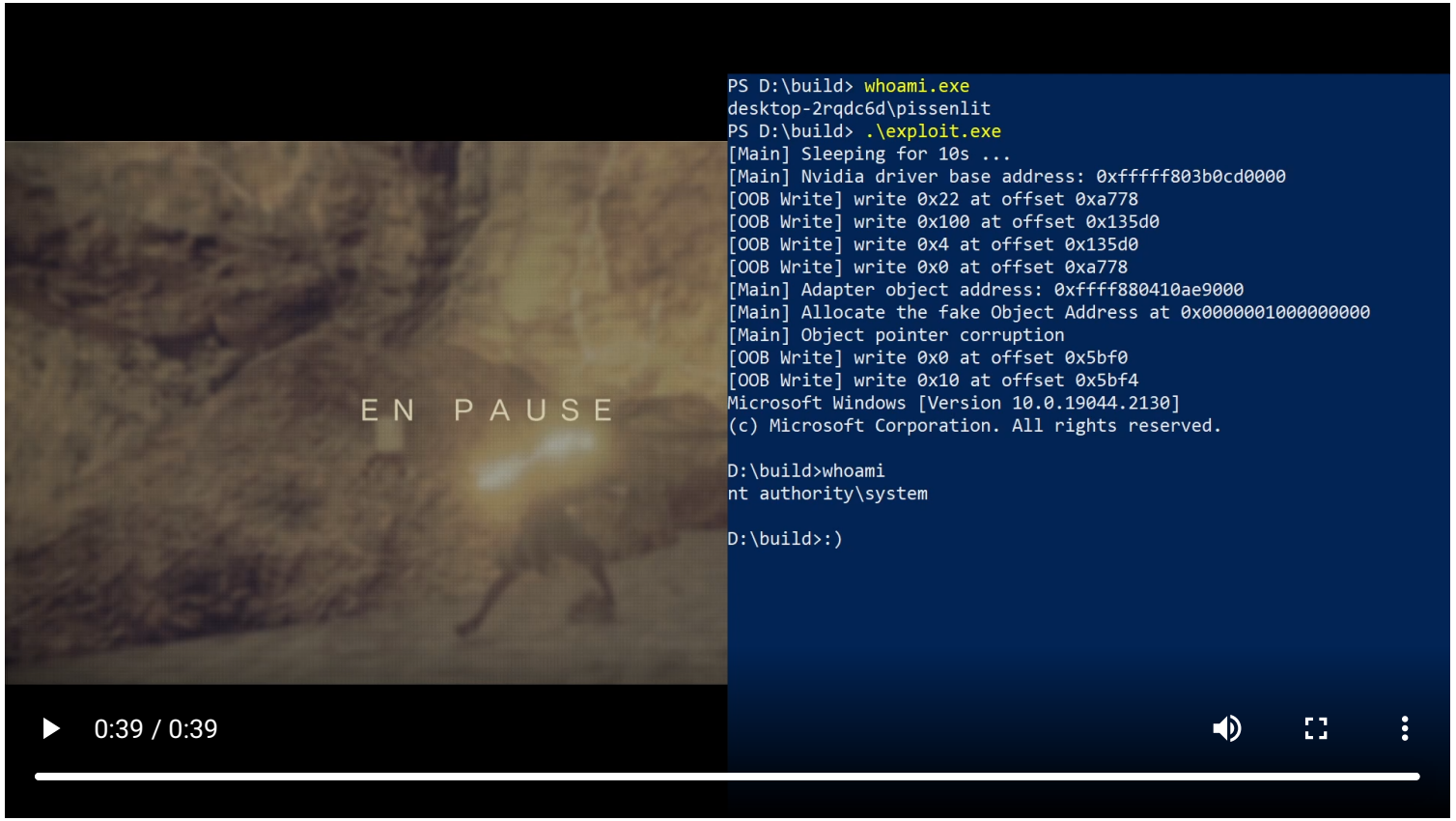
EN PAUSE
0:39 / 0:39
PS D:\build> whoami.exe
desktop-2rqdc6d\pissenlit
PS D:\build> .\exploit.exe
[Main] Sleeping for 10s ...
[Main] Nvidia driver base address: 0xfffff803b0cd0000
[OOB Write] write 0x22 at offset 0xa778
[OOB Write] write 0x100 at offset 0x135d0
[OOB Write] write 0x4 at offset 0x135d0
[OOB Write] write 0x0 at offset 0xa778
[Main] Adapter object address: 0xffff880410ae9000
[Main] Allocate the fake Object Address at 0x0000001000000000
[Main] Object pointer corruption
[OOB Write] write 0x0 at offset 0x5bf0
[OOB Write] write 0x10 at offset 0x5bf4
Microsoft Windows [Version 10.0.19044.2130]
(c) Microsoft Corporation. All rights reserved.
D:\build>whoami
nt authority\system
D:\build>:)

Timeline

- 3 May 2022: Disclose the vulnerabilities to Nvidia
- 17 May 2022: Notice us that they manage to validate the findings and plan to release a patch in August
- 2 August 2022: All the bugs disclosed have been patched (CVE-2022-31606, CVE-2022-31612, CVE-2022-31616, and CVE-2022-31617)

> **Security Bulletin: NVIDIA GPU Display Driver - August 2022**
>
> https://nvidia.custhelp.com/app/answers/detail/a_id/5383

Questions?

Quarkslab

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