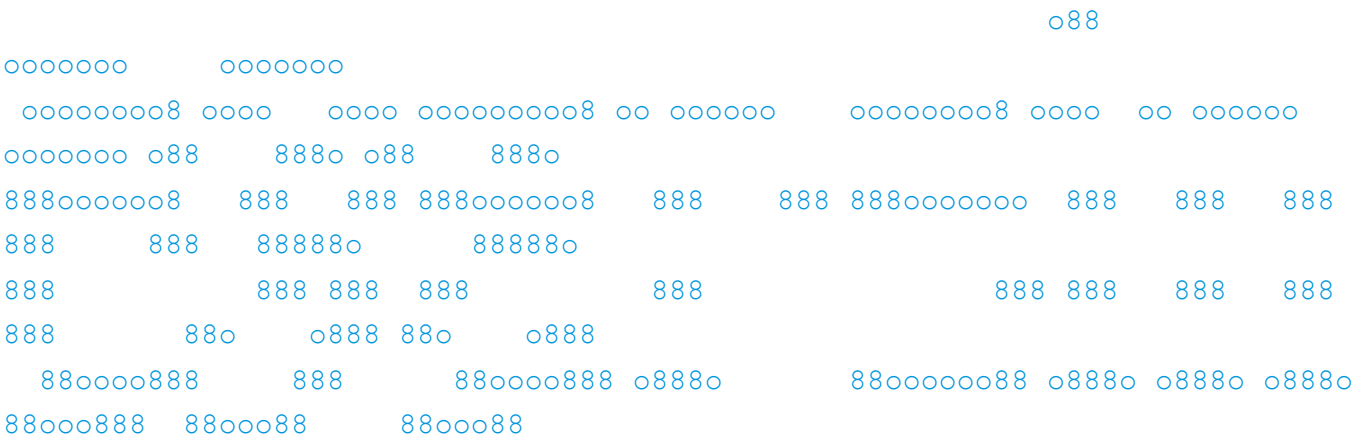
Driver Reverse Engineering 101



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A few months ago, while hunting for vulnerable drivers to abuse for BYOVD on operations, I stumbled upon a repository of 47GBs of signed Windows drivers. After fuzzing them with ioctlance, a symbolic execution based fuzzer, I was able to identify many previously unknown loldrivers. In this post I do not want to talk about exploiting drivers, but about how to approach reverse engineering of Windows WDM drivers. I often get asked questions on how to approach this, so I figured I might as well write it down once. The good news is: reversing IOCTL based WDM drivers (the most prevalent way drivers are developed) is very easy, as they always follow the same structure.

This is the dummy dummy explanation if your goal is to get reversing quickly. Of course I advise you to learn the basics of driver development, `IOCTL`s, `IRP`s and more, to really understand whats happening here. But at the end of this tutorial, you should be able to get going with simple driver reverse engineering of `IOCTL` communications using IDA.

WTF is WDM?

Windows Driver Model (WDM) is the "old school" way of writing drivers. A lot of newer drivers are written using the Kernel Mode Driver Framework (KMDF), which takes care of lots of boilerplate code for the developer and is generally recommended. Still, a lot of drivers you will encounter in the wild are based on WDM.

A driver in the end is just a regular PE that is loaded and executed with kernel privileges, usually by creating a service. The basic skeleton of a WDM driver looks as follows:

First, we have a driver entry, where we usually create a device object and a symbolic link to it. This symbolic link can then be used by usermode processes to get a handle to our driver (e.g. by calling `CreateFile` on `\??\BasicWdmLink`) and send messages (`IOCTL`s) to it to communicate (this is just one way for usermode to kernelmode communikation, albeit the most common one). As usual, error handling and some code hidden for brevity:

```
#include <ntddk.h>

PDEVICE_OBJECT g_DeviceObject = NULL;
UNICODE_STRING g_DeviceName =
RTL_CONSTANT_STRING(L"\\Device\\BasicWdmDevice");
UNICODE_STRING g_SymbolicLink = RTL_CONSTANT_STRING(L"\\??\\BasicWdmLink");

NTSTATUS
DriverEntry(
    _In_ PDRIVER_OBJECT DriverObject,
    _In_ PUNICODE_STRING RegistryPath
)
{
    // Create device
    status = IoCreateDevice(
        DriverObject,
        0,
        &g_DeviceName,
        FILE_DEVICE_UNKNOWN,
        0,
        FALSE,
        &g_DeviceObject
    );

    // Create symbolic link
    status = IoCreateSymbolicLink(&g_SymbolicLink, &g_DeviceName);
```

Usually, in this function the driver registers different dispatch routines. These describe what the driver does when its interacted with:

```
    // Set dispatch routines
    DriverObject->MajorFunction[IRP_MJ_CREATE] = DispatchCreate;
    DriverObject->MajorFunction[IRP_MJ_CLOSE] = DispatchClose;
    DriverObject->MajorFunction[IRP_MJ_DEVICE_CONTROL] = DispatchIoctl;
    DriverObject->DriverUnload = DriverUnload;
```

```
    return STATUS_SUCCESS;
}
```

These can be implemented as follows:

```
VOID
DriverUnload(
    _In_ PDRIVER_OBJECT DriverObject
)
{
    IoDeleteSymbolicLink(&g_SymbolicLink);
    IoDeleteDevice(DriverObject->DeviceObject);
}

NTSTATUS
DispatchCreate(
    _In_ PDEVICE_OBJECT DeviceObject,
    _Inout_ PIRP Irp
)
{
    Irp->IoStatus.Status = STATUS_SUCCESS;
    Irp->IoStatus.Information = 0;
    IoCompleteRequest(Irp, IO_NO_INCREMENT);
    return STATUS_SUCCESS;
}

NTSTATUS
DispatchClose(
    _In_ PDEVICE_OBJECT DeviceObject,
    _Inout_ PIRP Irp
)
{
    UNREFERENCED_PARAMETER(DeviceObject);
    Irp->IoStatus.Status = STATUS_SUCCESS;
    Irp->IoStatus.Information = 0;
    IoCompleteRequest(Irp, IO_NO_INCREMENT);
    return STATUS_SUCCESS;
}
```

Most interesting is usually the `IOCTL` dispatcher routine though, as this handles the calls from a usermode program that sends an `IOCTL` via `DeviceIoControl`. The macro `CTL_CODE` is used to build a unique 32-bit value to identify an `IOCTL`, based on some options. More on that later. For now all you need to know is that an `IOCTL` code to us reverse engineers looks like a random 32 bit value, that actually encodes some information (which can be decoded e.g. with OSR Ioctl Decoder) .

```
#define IOCTL_ECHO_DATA CTL_CODE(FILE_DEVICE_UNKNOWN, 0x800,
METHOD_BUFFERED, FILE_ANY_ACCESS)

NTSTATUS
DispatchIoctl(
    _In_ PDEVICE_OBJECT DeviceObject,
    _Inout_ PIRP Irp
)
{
    // Get IOCTL code sent to our driver
    PIO_STACK_LOCATION stack = IoGetCurrentIrpStackLocation(Irp);
    ULONG code = stack->Parameters.DeviceIoControl.IoControlCode;

    switch (code) {
    case IOCTL_ECHO_DATA:
    {
        // HANDLE THE DATA FROM USERMODE
        break;
    }
    default:
        status = STATUS_INVALID_DEVICE_REQUEST;
        break;
    }

    Irp->IoStatus.Status = status;
    Irp->IoStatus.Information = info;
    IoCompleteRequest(Irp, IO_NO_INCREMENT);
    return status;
}
```

A usermode program can now sent the `ECHO_DATA IOCTL` in our driver using the same `CTL_CODE`. In this case, we send a `TestMessage` string to our driver:

```
#define IOCTL_ECHO_DATA CTL_CODE(FILE_DEVICE_UNKNOWN, 0x800,
METHOD_BUFFERED, FILE_ANY_ACCESS)

int main() {
    HANDLE hDevice = CreateFileW(
        L"\\\\.\\BasicWdmLink",
        GENERIC_READ | GENERIC_WRITE,
        0,
        NULL,
        OPEN_EXISTING,
        FILE_ATTRIBUTE_NORMAL,
```

```
        NULL
    );

    const char input[] = "TestMessage";
    char output[64] = {0}; // buffer for the output, which the driver may
write into
    DWORD bytesReturned = 0;

    DeviceIoControl(
        hDevice,
        IOCTL_ECHO_DATA,
        (LPVOID)input,
        sizeof(input),
        output,
        sizeof(output),
        &bytesReturned,
        NULL
    );
}
```

There are different methods for `IOCTL` communication, here `METHOD_BUFFERED` is used (which again, is very common). This essentially means, that a buffer is shared for both input and output of the operation.

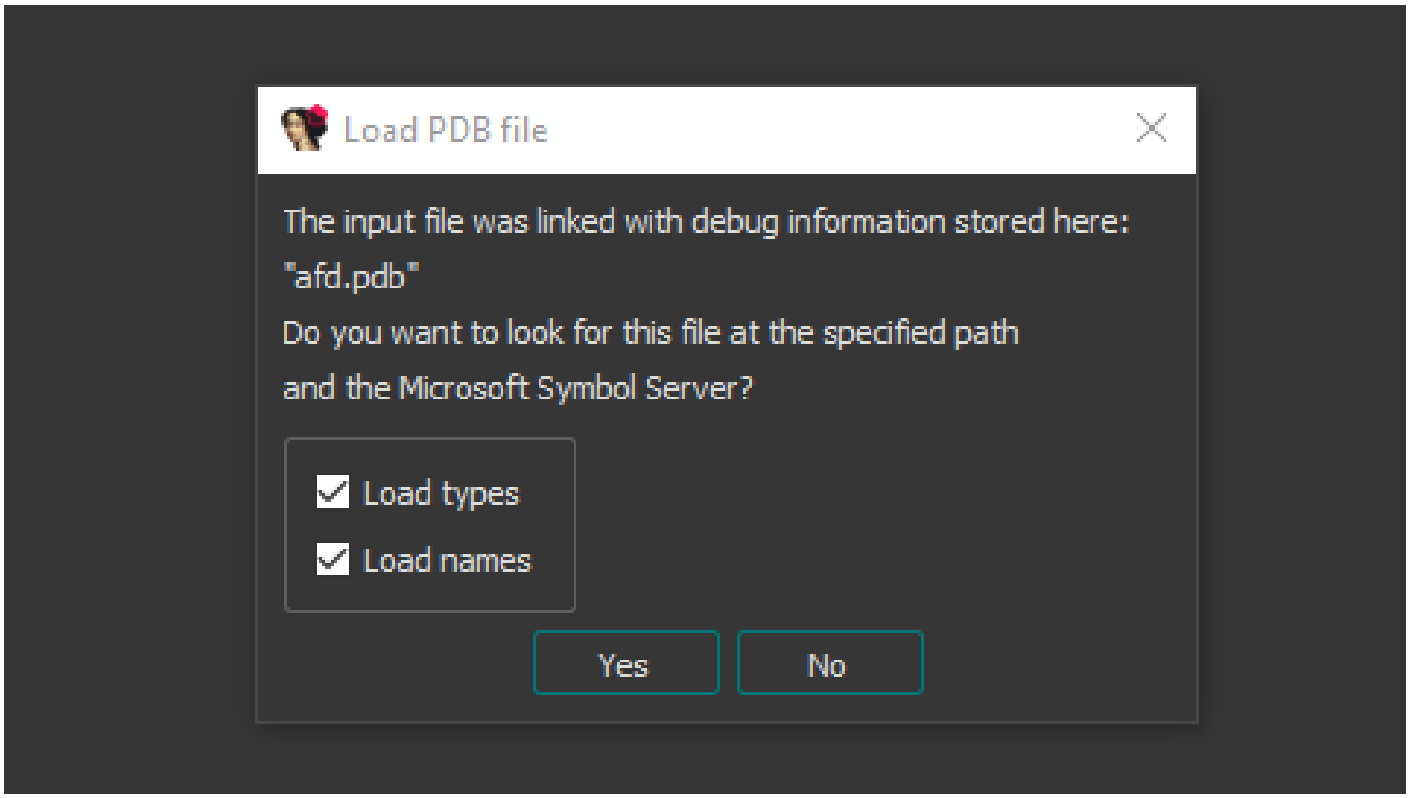
How can the driver access this? Through a huge union structure called `IRP`, which in turn contains another huge union, the `IO_STACK_LOCATION`. We will not dive deep here, but this will be important when reversing in IDA later, as we need to choose the right union depending on the method. See here and here for the struct definitions.

Essentially, this is enough knowledge to get going. So let's start disassembling a random driver:

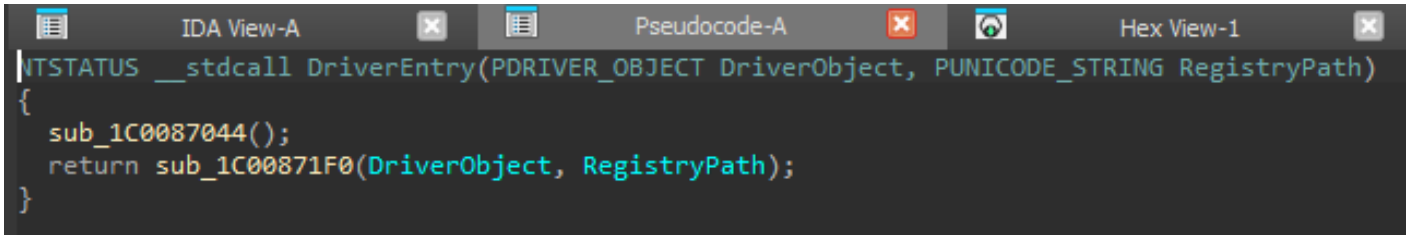
Static Reverse Engineering

We are going to use the driver `afd.sys`, since this one will be present on your Windows version as well, so you can follow along. I chose this deliberately, but if you are wondering, this is the driver that is used for socket communication - so malware can, instead of using the winsock API, talk to this driver directly via IOCTLs to create socket connections and send data.

Open `C:\Windows\system32\drivers\afd.sys` in IDA, and you will be asked if you want to resolve symbols from the MS Symbol Server:

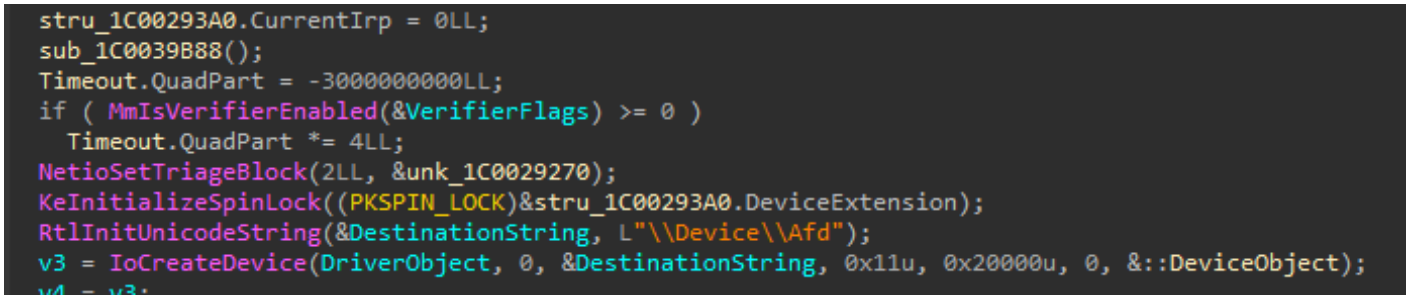


Usually, we would say yes, because this makes reverse engineering almost like reading source code, but since our goal is to get a methodology that works regardless of the presence of symbols, we are going to say no here. After some analysis time, you should be greeted with the `DriverEntry` (think `main`) function. If you do not see pseudocode but disassembly, press `F5`:

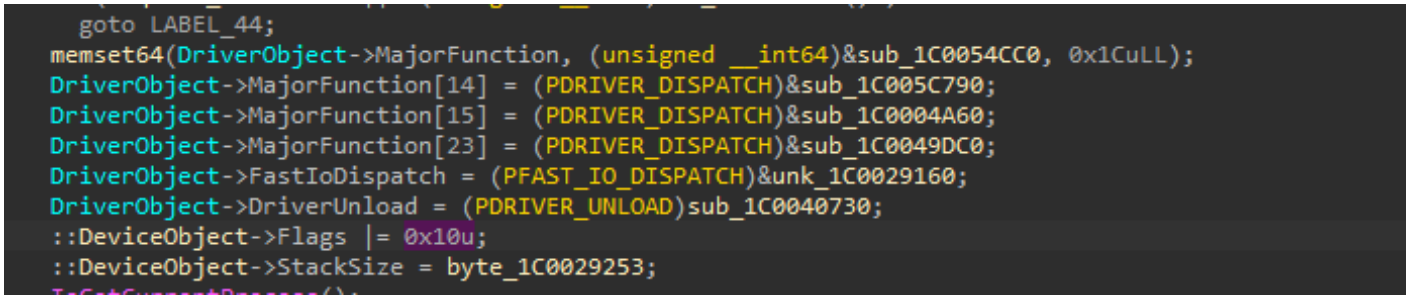


As you can see this is just some boilerplate wrapper to the actual main entry, which will be `sub_1C00871F0` in this case. You can see this, since the `DriverObject` and `RegistryPath` are passed to that function, and at least the `DriverObject` is needed for the initial setup of a classic `IOCTL` based driver.

If you double click this function and scroll down a little, you can see a call to the creation of a unicode string `\\Device\\Afd` and a call to `IoCreateDevice`. You can note down the device name, since this will be what we can open a handle to to send commands and potentially exploit our target driver:



If you scroll down a bit, you will usually at one point find a block of code that looks like the following:



This is essentially the equivalent of our code block in the beginning, where we registered our dispatch routines, except that IDA does not resolve the numbers to the enums automatically.

```
    // Set dispatch routines
    DriverObject->MajorFunction[IRP_MJ_CREATE] = DispatchCreate;
    DriverObject->MajorFunction[IRP_MJ_CLOSE] = DispatchClose;
    DriverObject->MajorFunction[IRP_MJ_DEVICE_CONTROL] = DispatchIoctl;
    DriverObject->DriverUnload = DriverUnload;
```

If you consult the following table, you should be able to spot the `IRP_MJ_DEVICE_CONTROL` (the "IOCTL Handler") in `afd.sys`. Tip: click on a number and press `h` to convert from decimal to hex and vice versa

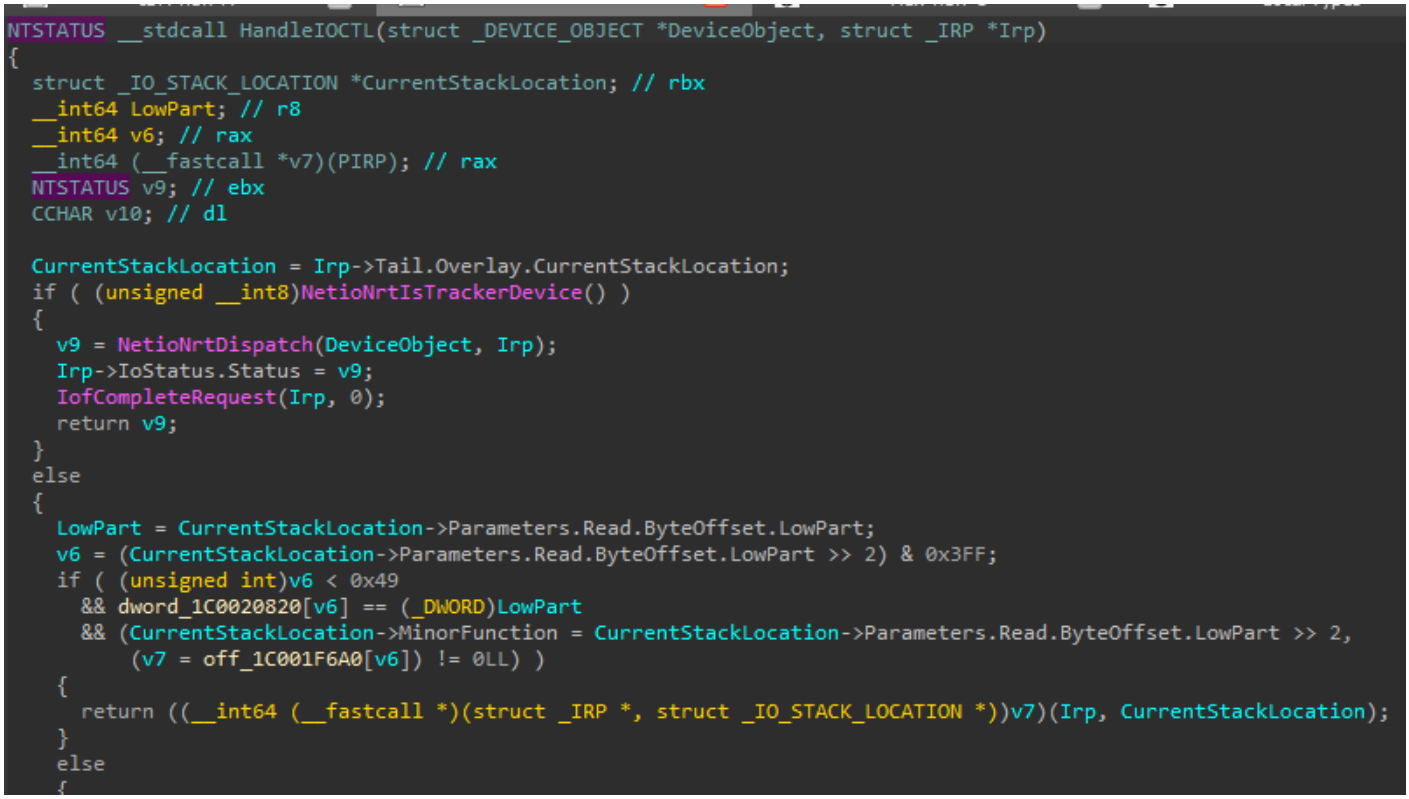
```
//
// Define the major function codes for IRPs.
//


#define IRP_MJ_CREATE                   0x00
#define IRP_MJ_CREATE_NAMED_PIPE        0x01
#define IRP_MJ_CLOSE                    0x02
#define IRP_MJ_READ                     0x03
#define IRP_MJ_WRITE                    0x04
#define IRP_MJ_QUERY_INFORMATION        0x05
#define IRP_MJ_SET_INFORMATION          0x06
#define IRP_MJ_QUERY_EA                 0x07
#define IRP_MJ_SET_EA                   0x08
#define IRP_MJ_FLUSH_BUFFERS            0x09
#define IRP_MJ_QUERY_VOLUME_INFORMATION 0x0a
#define IRP_MJ_SET_VOLUME_INFORMATION   0x0b
#define IRP_MJ_DIRECTORY_CONTROL        0x0c
#define IRP_MJ_FILE_SYSTEM_CONTROL      0x0d
#define IRP_MJ_DEVICE_CONTROL           0x0e
#define IRP_MJ_INTERNAL_DEVICE_CONTROL  0x0f
#define IRP_MJ_SHUTDOWN                 0x10
#define IRP_MJ_LOCK_CONTROL             0x11
#define IRP_MJ_CLEANUP                  0x12
#define IRP_MJ_CREATE_MAILSLOT          0x13
#define IRP_MJ_QUERY_SECURITY           0x14
#define IRP_MJ_SET_SECURITY             0x15
#define IRP_MJ_POWER                    0x16
#define IRP_MJ_SYSTEM_CONTROL           0x17
#define IRP_MJ_DEVICE_CHANGE            0x18
#define IRP_MJ_QUERY_QUOTA              0x19
#define IRP_MJ_SET_QUOTA                0x1a
#define IRP_MJ_PNP                      0x1b
#define IRP_MJ_PNP_POWER                IRP_MJ_PNP      // Obsolete....
#define IRP_MJ_MAXIMUM_FUNCTION         0x1b
```

Since `0x0e` resolves to 14 in decimal, our function of interest is `sub_1C005C790`. We can rename it to `HandleIOCTL` by pressing `n`. To add proper typing for parameters and return values, also cast it to `PDRIVER_DISPATCH` by pressing `y`:

```
  goto LABEL_44;
memset64(DriverObject->MajorFunction, (unsigned __int64)&sub_1C0054CC0, 0x1CuLL);
DriverObject->MajorFunction[0xE] = HandleIOCTL;
DriverObject->MajorFunction[15] = (PDRIVER_DISPATCH)&sub_1C0004A60;
DriverObject->MajorFunction[23] = (PDRIVER_DISPATCH)&sub_1C0049DC0;
DriverObject->FastIoDispatch = (PFAST_IO_DISPATCH)&unk_1C0029160;
DriverObject->DriverUnload = (PDRIVER_UNLOAD)sub_1C0040730;
::DeviceObject->Flags |= 0x10u;
::DeviceObject->StackSize = byte_1C0029253;
```

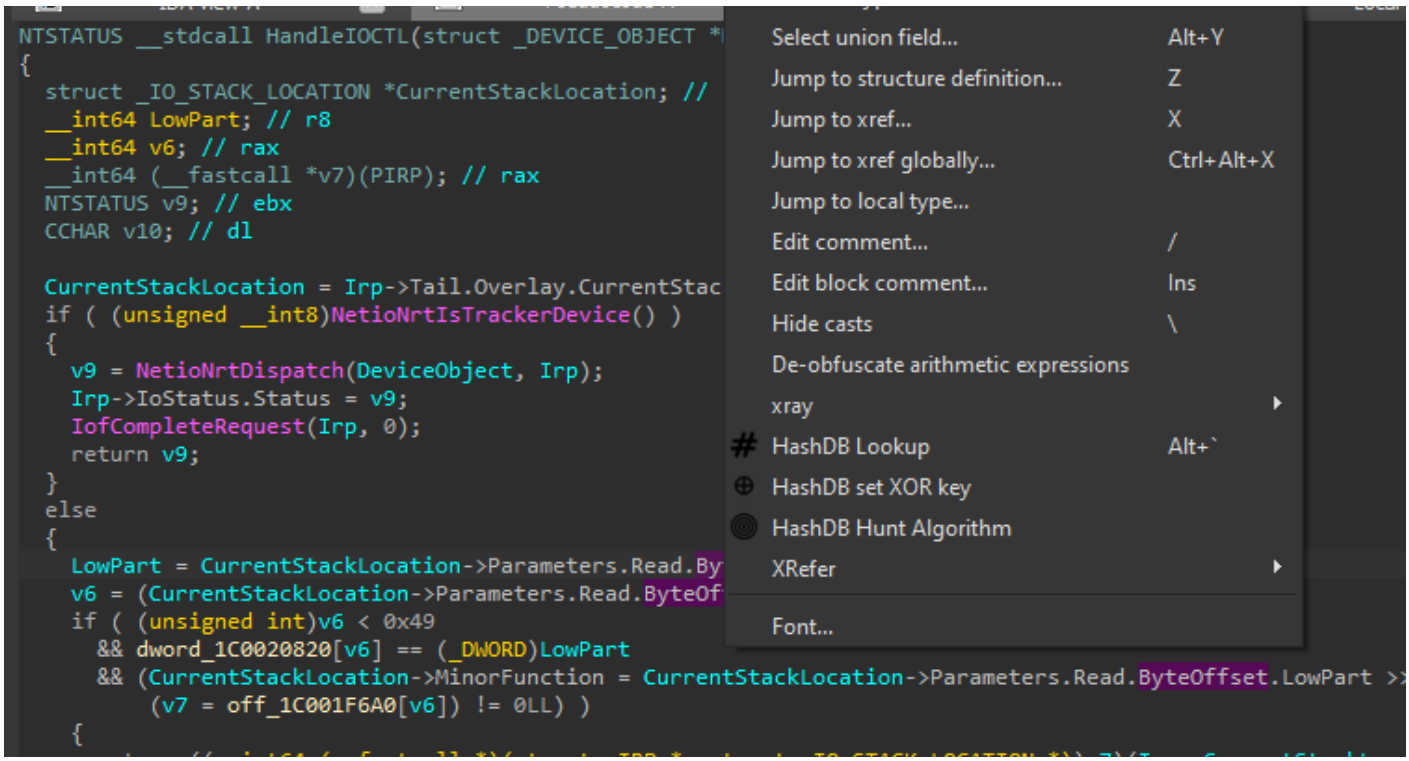
The call to `memset64` is something you will often see: this usually just sets all routines to a stub that signals an unsupported routine, so that if an operation is not supported, the driver does not crash.

As an exercise, you can try finding out what the other functions being registered do. For now let us jump into the handler:

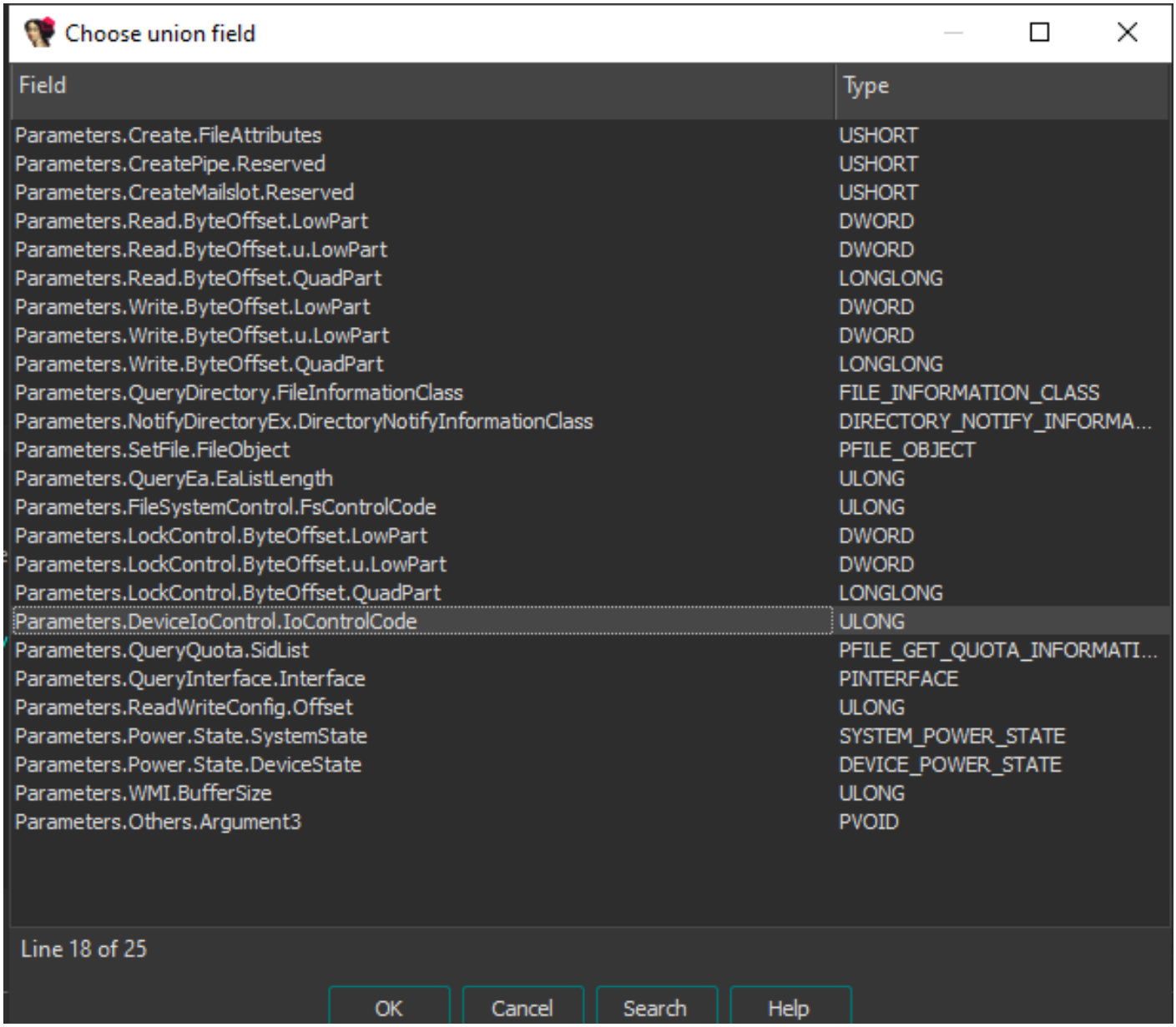


```
NTSTATUS __stdcall HandleIOCTL(struct _DEVICE_OBJECT *DeviceObject, struct _IRP *Irp)
{
  struct _IO_STACK_LOCATION *CurrentStackLocation; // rbx
  __int64 LowPart; // r8
  __int64 v6; // rax
  __int64 (__fastcall *v7)(PIRP); // rax
  NTSTATUS v9; // ebx
  CCHAR v10; // dl

  CurrentStackLocation = Irp->Tail.Overlay.CurrentStackLocation;
  if ( (unsigned __int8)NetioNrtIsTrackerDevice() )
  {
    v9 = NetioNrtDispatch(DeviceObject, Irp);
    Irp->IoStatus.Status = v9;
    IofCompleteRequest(Irp, 0);
    return v9;
  }
  else
  {
    LowPart = CurrentStackLocation->Parameters.Read.ByteOffset.LowPart;
    v6 = (CurrentStackLocation->Parameters.Read.ByteOffset.LowPart >> 2) & 0x3FF;
    if ( (unsigned int)v6 < 0x49
      && dword_1C0020820[v6] == (_DWORD)LowPart
      && (CurrentStackLocation->MinorFunction = CurrentStackLocation->Parameters.Read.ByteOffset.LowPart >> 2,
          (v7 = off_1C001F6A0[v6]) != 0LL) )
    {
      return ((__int64 (__fastcall *)(struct _IRP *, struct _IO_STACK_LOCATION *))v7)(Irp, CurrentStackLocation);
    }
    else
    {
```

Now this might seem intimidating at first, but there is one trick which makes this a lot more readable. Do you remember how I told you earlier that an `_IO_STACK_LOCATION` is a massive union? If you are aware of unions, essentially they mean that one type can mean different things. How can IDA choose the right union? It can not, which is why you usually need to select the correct one by right clicking or pressing `alt+y` to select a union field where `CurrentStackLocation`, the `_IO_STACK_LOCATION` member of the `IRP` is used:



Since we are an an IOCTL handler, it is likely that this field references the `IoControlCode`:



Now the pseudocode makes a lot more sense. I renamed variables and added comments to explain what it does:

```
{
  ioctl_code = CurrentStackLocation->Parameters.DeviceIoControl.IoControlCode;
  // Get function code from ioctl
  function_code = (CurrentStackLocation->Parameters.DeviceIoControl.IoControlCode >> 2) & 0x3FF;
  if ( (unsigned int)function_code < 0x49     // bounds check
    && expected_ioctl_list[function_code] == (_DWORD)ioctl_code// verify ioctl is as expected
    && (CurrentStackLocation->MinorFunction = CurrentStackLocation->Parameters.DeviceIoControl.IoControlCode >> 2,
        (v7 = ioctl_function_table[function_code]) != 0LL) )// call function from function table
  {
```

Essentially, it extracts the function code from the incoming `IOCTL`, verifies it is as expected by checking against a whitelist and finally calls a function from a function table. We can double click the function table you can see all the different functions (that can be called through this IOCTL handler) in an array:

```
.rdata:00000001C001F69F                   db    0
.rdata:00000001C001F6A0 ioctl_function_table dq offset sub_1C0033C20
.rdata:00000001C001F6A0                                           ; DATA XREF: HandleIOCTL+60↓r
.rdata:00000001C001F6A8                   dq offset sub_1C004E580
.rdata:00000001C001F6B0                   dq offset sub_1C005BD20
.rdata:00000001C001F6B8                   dq offset sub_1C005C5A0
.rdata:00000001C001F6C0                   dq offset sub_1C004D270
.rdata:00000001C001F6C8                   dq offset sub_1C0055E50
.rdata:00000001C001F6D0                   dq offset sub_1C0057CF0
.rdata:00000001C001F6D8                   dq offset sub_1C0056B60
.rdata:00000001C001F6E0                   dq offset sub_1C00752B0
.rdata:00000001C001F6E8                   dq offset sub_1C005CD50
.rdata:00000001C001F6F0                   dq offset sub_1C0010EC0
.rdata:00000001C001F6F8                   dq offset sub_1C00371F0
.rdata:00000001C001F700                   dq offset sub_1C0010EC0
.rdata:00000001C001F708                   dq offset sub_1C0010EC0
.rdata:00000001C001F710                   dq offset sub_1C0010EC0
.rdata:00000001C001F718                   dq offset sub_1C0010EC0
.rdata:00000001C001F720                   dq offset sub_1C0010EC0
.rdata:00000001C001F728                   dq offset sub_1C0010EC0
.rdata:00000001C001F730                   dq offset sub_1C0010EC0
.rdata:00000001C001F738                   dq offset sub_1C0010EC0
.rdata:00000001C001F740                   dq offset sub_1C0010EC0
.rdata:00000001C001F748                   dq offset sub_1C0010EC0
.rdata:00000001C001F750                   dq offset sub_1C0010EC0
.rdata:00000001C001F758                   dq offset sub_1C0010EC0
.rdata:00000001C001F760                   dq offset sub_1C0010EC0
.rdata:00000001C001F768                   dq offset sub_1C0010EC0
.rdata:00000001C001F770                   dq offset sub_1C0010EC0
.rdata:00000001C001F778                   dq offset sub_1C0010EC0
.rdata:00000001C001F780                   dq offset sub_1C0010EC0
```

Now theres two ways in which IOCTL functions are called from an IOCTL handler (of course there is endless possibilities, but those are the two you will encounter most often):

- The function code is extracted from the IOCTL and used as an index to a table of functions
- A huge switch statement

Let us look at an example of the latter as well. For this we open `mountmgr.sys` and follow the exact same steps to end up in the IOCTL handler which has an if/else/switch statement handling different codes:

```
  if ( ioctl <= 0x6D4020 )
  {
    switch ( ioctl )
    {
      case 0x6D4020u:
ABEL_54:
        PsDetachSiloFromCurrentThread(v13);
        goto LABEL_7;
      case 0x6D0008u:
        v5 = "IOCTL_MOUNTMGR_QUERY_POINTS";
        v4 = sub_1C0009730((int)DeviceExtension, (int)Irp);
        goto LABEL_54;
      case 0x6D0030u:
        v5 = "IOCTL_MOUNTMGR_QUERY_DOS_VOLUME_PATH";
        v4 = sub_1C00091D0(DeviceExtension, Irp);
        goto LABEL_54;
      case 0x6D0034u:
        v5 = "IOCTL_MOUNTMGR_QUERY_DOS_VOLUME_PATHS";
        v4 = sub_1C0009E90(DeviceExtension, Irp);
        goto LABEL_54;
      case 0x6D003Cu:
        v5 = "IOCTL_MOUNTMGR_QUERY_AUTO_MOUNT";
        v4 = sub_1C0011568(DeviceExtension, Irp);
        goto LABEL_54;
      case 0x6D4008u:
        v5 = "IOCTL_MOUNTMGR_QUERY_POINTS_ADMIN";
        v4 = sub_1C0009730((int)DeviceExtension, (int)Irp);
        goto LABEL_54;
    }
ABEL_53:
    v5 = "IOCTL UNKNOWN";
    v4 = -1073741808;
    goto LABEL_54;
  }
```

From here you can either follow the function calls and see if you find vulnerabilities in themselves, or if you found a vulnerable IOCTL through fuzzing, you now know how to find it from the `DriverEntry` on.

If we look into one example function of this driver, there is yet again the `IRP` that is used to pass on information to the function call. And again, it is important to select the correct union:

```
1  __int64 __fastcall sub_1C0011568(__int64 a1, PIRP a2, __int64 a3)
2  {
3    ULONG_PTR v4; // rbx
4    struct _IRP *MasterIrp; // rdx
5    unsigned int v6; // edi
6
7    v4 = 0LL;
8    MasterIrp = a2->AssociatedIrp.MasterIrp;
9    v6 = 0;
0    if ( a2->Tail.Overlay.CurrentStackLocation->Parameters.Read.Length >= 4 )
1    {
2      LOBYTE(v4) = *(_BYTE *)(a1 + 192) != 0;
3      *(_DWORD *)&MasterIrp->Type = v4;
4      v4 = 4LL;
5    }
6    else
7    {
8      v6 = -1073741811;
9      if ( off_1C0006000 != (PDEVICE_OBJECT)&off_1C0006000 && (HIDWORD(off_1C0006000->Timer) & 1)
0        sub_1C000234C(off_1C0006000->AttachedDevice, 339LL, a3);
1    }
2    a2->IoStatus.Information = v4;
3    return v6;
4  }
```

As you can see, IDA default selected `MasterIrp` in line 8, when accessing the `IRP`. However, this is usually not the right union. Most of the time, you would want to choose `SystemBuffer` here, which would be the buffer passed from userland and back when calling the IOCTL from userland:

```
1  __int64 __fastcall sub_1C0011568(__int64 deviceExtension, PIRP pIRP, __int64 a3)
2  {
3    ULONG_PTR v4; // rbx
4    _DWORD *SystemBuffer; // rdx
5    unsigned int v6; // edi
6
7    v4 = 0LL;
8    SystemBuffer = pIRP->AssociatedIrp.SystemBuffer;
9    v6 = 0;
0    if ( pIRP->Tail.Overlay.CurrentStackLocation->Parameters.DeviceIoControl.OutputBufferLength >=
1    {
2      LOBYTE(v4) = *(_BYTE *)(deviceExtension + 192) != 0;
3      *SystemBuffer = v4;
4      v4 = 4LL;
5    }
6    else
7    {
8      v6 = 0xC000000D;
9      if ( off_1C0006000 != (PDEVICE_OBJECT)&off_1C0006000 && (HIDWORD(off_1C0006000->Timer) & 1)
0        sub_1C000234C(off_1C0006000->AttachedDevice, 339LL, a3);
1    }
2    pIRP->IoStatus.Information = v4;
3    return v6;
4  }
```

You can try out different union members and see what makes sense or actually go methodological and parse the IOCTL number with a tool like `OSR Ioctl Decoder` and choose the right union based upon the `Method`:

Method (IoControlCode & 0x3)	IRP Union Member to Use
METHOD_BUFFERED (0)	Irp->AssociatedIrp.SystemBuffer
METHOD_IN_DIRECT (1)	Irp->AssociatedIrp.SystemBuffer (input), Irp->MdlAddress (output)
METHOD_OUT_DIRECT (2)	Irp->AssociatedIrp.SystemBuffer (input), Irp->MdlAddress (output)
METHOD_NEITHER (3)	Parameters.DeviceIoControl.Type3InputBuffer (input), Irp->UserBuffer (output)

Now this should be enough to get going.

If you want to actually learn exploiting drivers, I recommend playing around with HackSys Extreme Vulnerable Driver.

Going Dynamic

One fallacy that novice reverse engineers (including myself) fall to early in their learnings, is that reverse engineering is looking at pseudo-C in IDA (or worse, disassembly) and renaming variables until you are basically at source code level. But most of the time, dynamic analysis is much more important, after you figured out the basic structure of the binary through static reversing.

This is a whole different topic, but there are many guides on that already. Here is a no bullshit guide on how to setup remote kernel debugging.

What you want to do is essentially:

- Setup 2 VMs (One Debugger, One Debugee)
- Enable Kernel Debugging on the Debugee
- Configure it to do remote kernel debugging (ideally via network) and connect back to your debugger VMs IP
- Run WinDbg on your Debugger VM

I hope this little intro gave you some tips on how to get started!

Happy Hacking!

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