Windows Kernel (Driver) Development

An Introduction

Prerequisites

1. Download the VMs from:
   Hyper-V: https://symposium9.nyc3.digitaloceanspaces.com/vms.zip
   Vmware: https://symposium9.nyc3.digitaloceanspaces.com/vms_vmware.zip
2. A computer with Hyper-V
3. Enough resources to run two VMs

Agenda

1. Setting up a kernel development & debugging environment
2. Intro to kernel debugging
3. Kernel crash course
4. I/O & IRPs
5. IOCTLs
6. Kernel programming miscellany
7. So what?
8. References

BLUF it for me

1. The Windows kernel is vast and complicated
2. I am no expert
3. We won't even remove the dust from the surface, let alone scratch it
4. I will demo stuff, and give you time to experiment
5. You will probably bluescreen your system

1. Setting up a kernel development & debugging environment

HOST: Setting up the environment

Assuming we have a working Visual Studio 2019 install...

1. Make sure windows 10 SDKs are installed
2. Make sure Spectre-mitigation libraries are installed
3. Download and install the WDK
   https://docs.microsoft.com/en-us/windows-hardware/drivers/download-the-wdk

TARGET: Enabling kernel debugging (non-Hyper-V)

1. Modify debug print filtering:

```
reg add "HKLM\SYSTEM\CurrentControlSet\Control\Session Manager\Debug Print Filter"
reg add "HKLM\SYSTEM\CurrentControlSet\Control\Session Manager\Debug Print Filter" /v "DEFAULT" /t REG_DWORD /d 0xf
reg add "HKLM\SYSTEM\CurrentControlSet\Control\Session Manager\Debug Print Filter" /v "IHVDRIVER" /t REG_DWORD /d 0xf
```

2. Enable driver test signing:

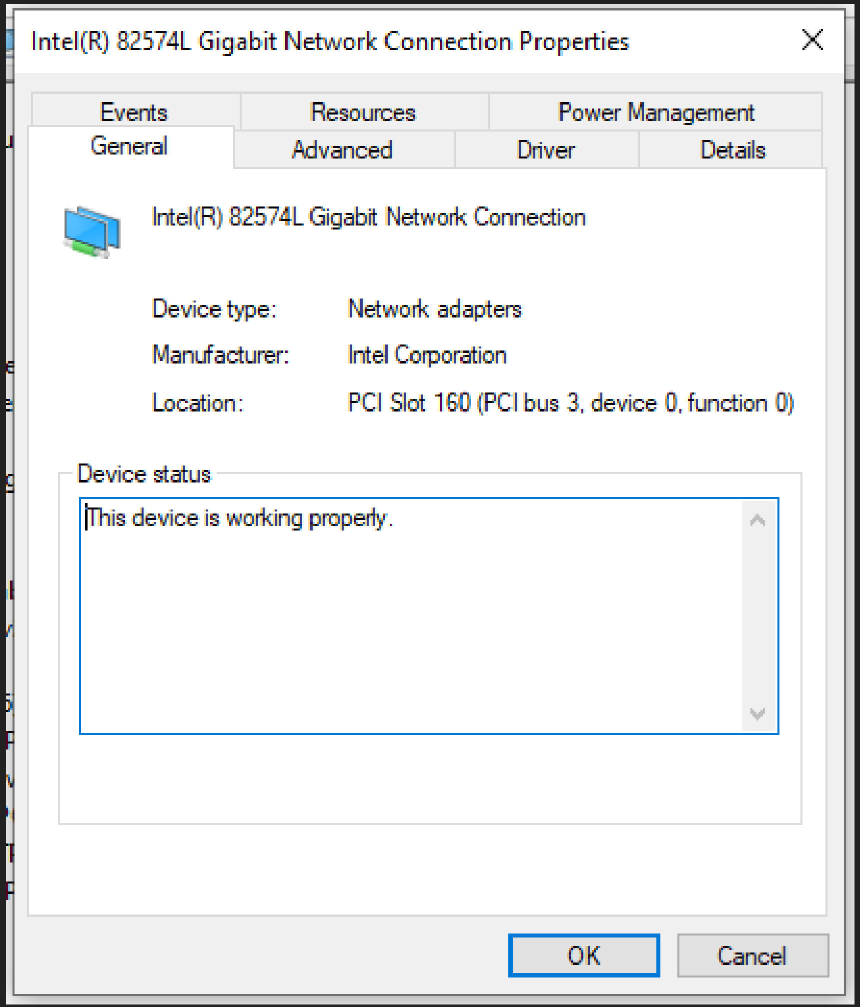
```
bcdedit /set testsigning on
```

3. Enable remote kernel debugging

```
bcdedit /debug on
bcdedit /dbgsettings net hostip:<HOST IP> port:50000
bcdedit /set "{dbgsettings}" busparams b.d.f
```

Make sure to replace "HOST IP" with the correct host ip address and b.d.f with the PCI bus settings for your NIC.

TARGET: Enabling kernel debugging (non-Hyper-V) (cont)



TARGET: Enabling kernel debugging

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```

2. Enable driver test signing:

```
bcdedit /set testsigning on
```

3. Enable remote kernel debugging

```
kdnet.exe <HOST-IP> 50000
```

Make sure to change HOST-IP and note the key returned!

Ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/debugger/setting-up-a-network-debugging-connection

Why testsigning?

- Starting with 64-bit Vista kernel-mode code must be digitally signed
- Starting with Windows 10 version 1607 all kernel-mode code must be cross-signed by Microsoft via the Dev Portal
- Signing requires an EV code-signing certificate
- http://wrogn.com/getting-a-kernel-mode-driver-signed-for-windows-10/

DigiCert Validation Request (Order #12464881)

Reciepts ×

DigiCert <validation@digicert.com> Tue, Dec 3, 2019, 10:48 AM

to me

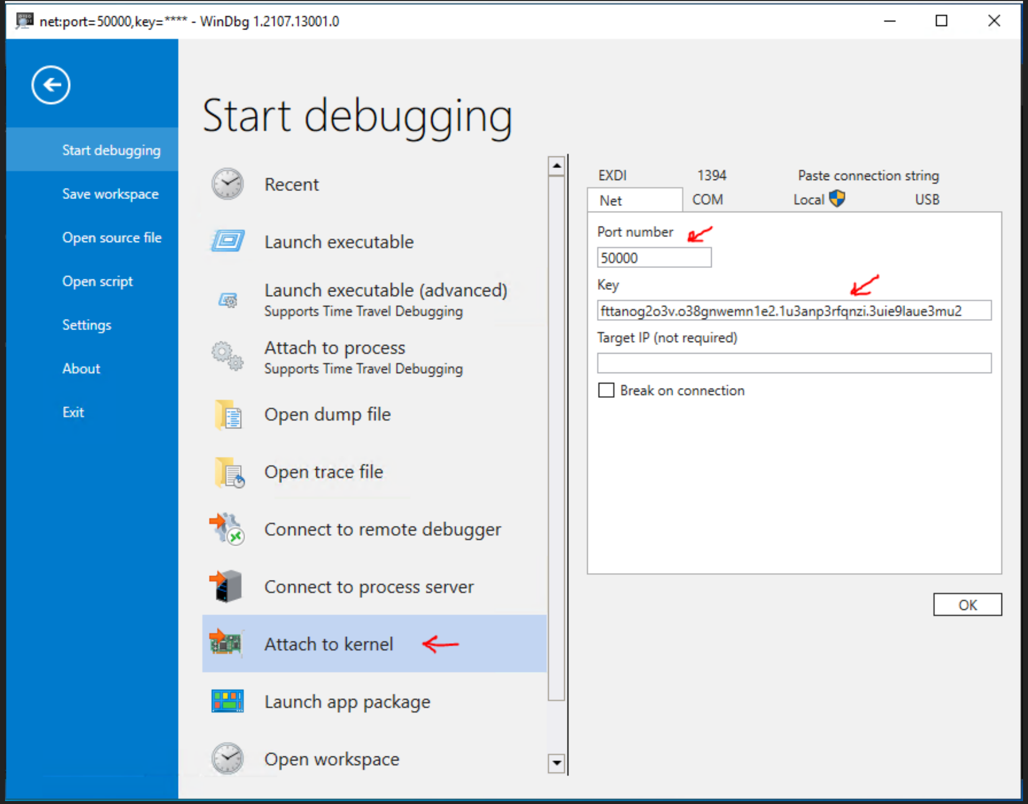
Hello Phillip,

I am trying to finish the validation of your certificate order and I need your help with just one thing:

I am trying to finish the validation of your company [redacted] - **Company ID #[redacted]**) so you can order SSL certificates for it, and I need your help with just one thing:

Please have a chartered/certified public accountant (CPA) or licensed attorney sign the attached opinion letter. An accountant must be a member of one of the associations listed at http://web.ifac.org/about/member-bodies

HOST: Connecting the debugger



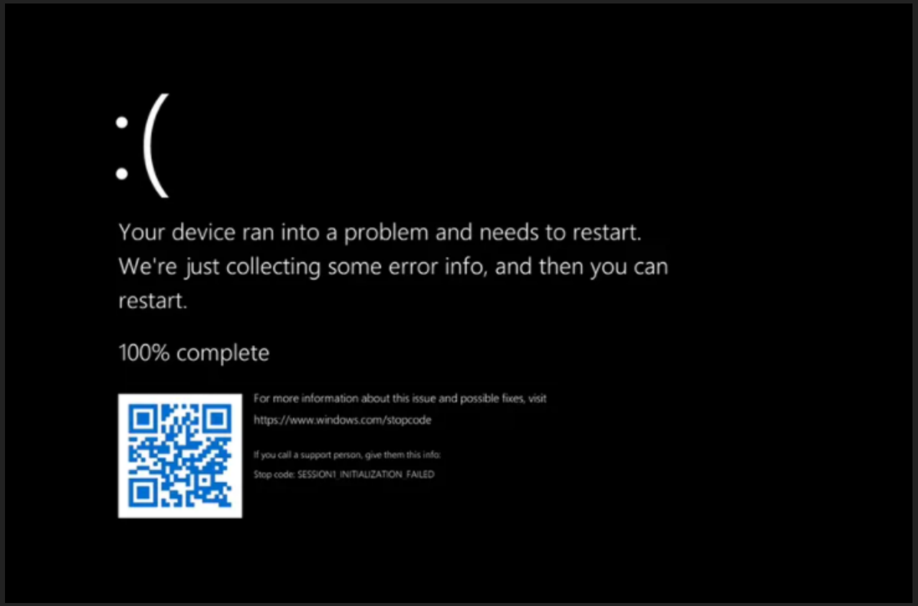
1. Connect WinDbg to the target system using the key you created earlier
2. Verify connection and the ability to break processing

2. Intro to kernel debugging

Handy WinDbg commands

<table>
<tr><th>Command</th><th>Purpose</th></tr>
<tr><td>version</td><td>show target version information</td></tr>
<tr><td>bl</td><td>list break points</td></tr>
<tr><td>bp <symbol>|<address></td><td>create a break point at a symbol or address</td></tr>
<tr><td>be | bd | bc <bp id></td><td>enable, delete, or clear a breakpoint</td></tr>
<tr><td>db/dw/dd/dq/dp <address></td><td>display byte, word, dword, qword, pointer at address</td></tr>
<tr><td>dt <address> <struct type></td><td>typecast address as a structure</td></tr>
<tr><td>x <symbol></td><td>display virtual address of symbol</td></tr>
<tr><td>r</td><td>r <register></td></tr>
</table>

WinDbg Demo



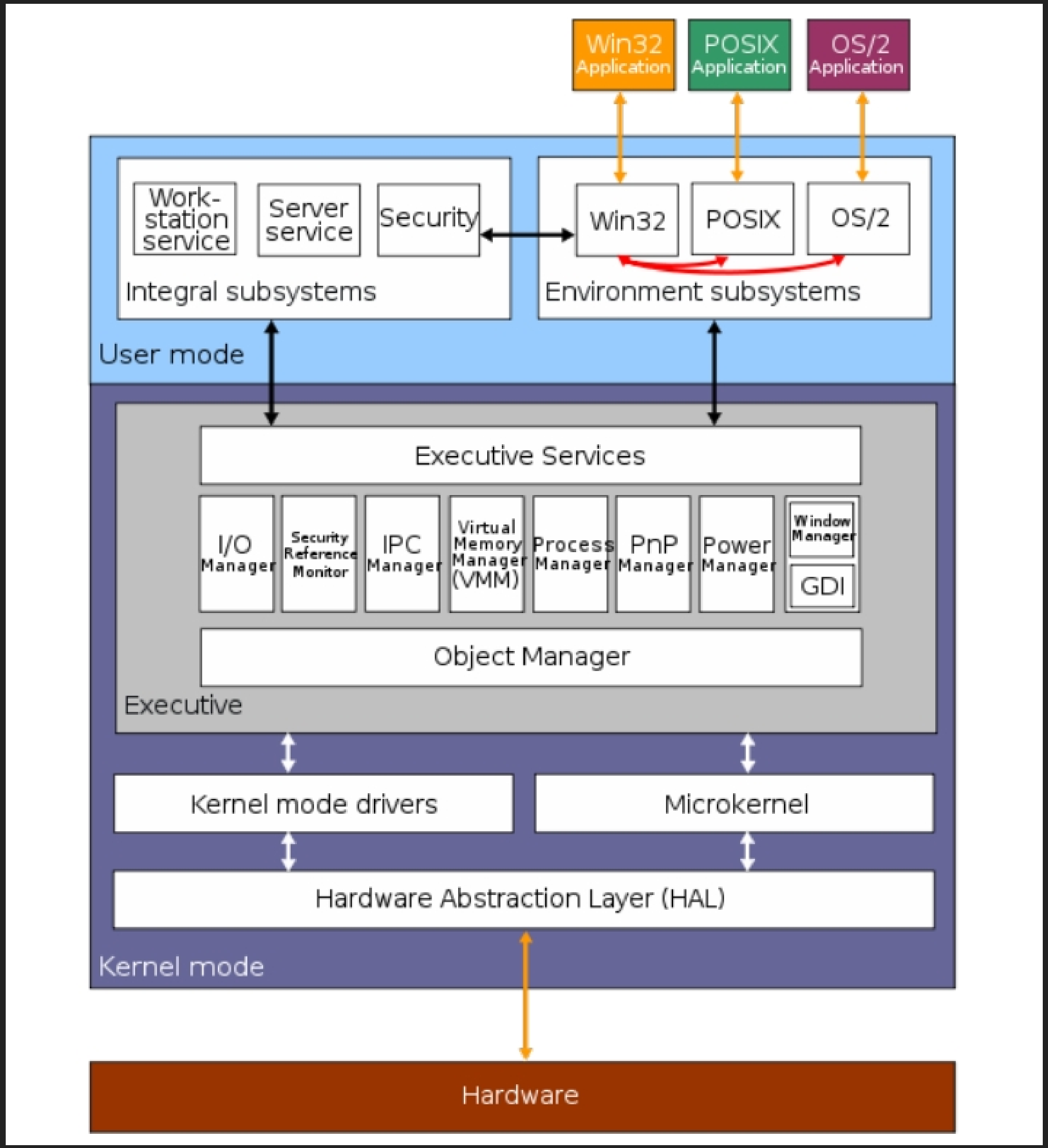
3. Kernel crash course

The executive

- "Upper" layer of the OS
- Provides generic OS functions and operations
- Operations like: memory management, process and thread management, I/O management
- Handles security, I/O, IPC

The kernel

- Microsoft defines a kernel as the core functionality that everything else in the OS depends upon
- The Windows kernel provides low-level operations like: scheduling threads, routing interrupts, etc.
- Implements processor dependent functions

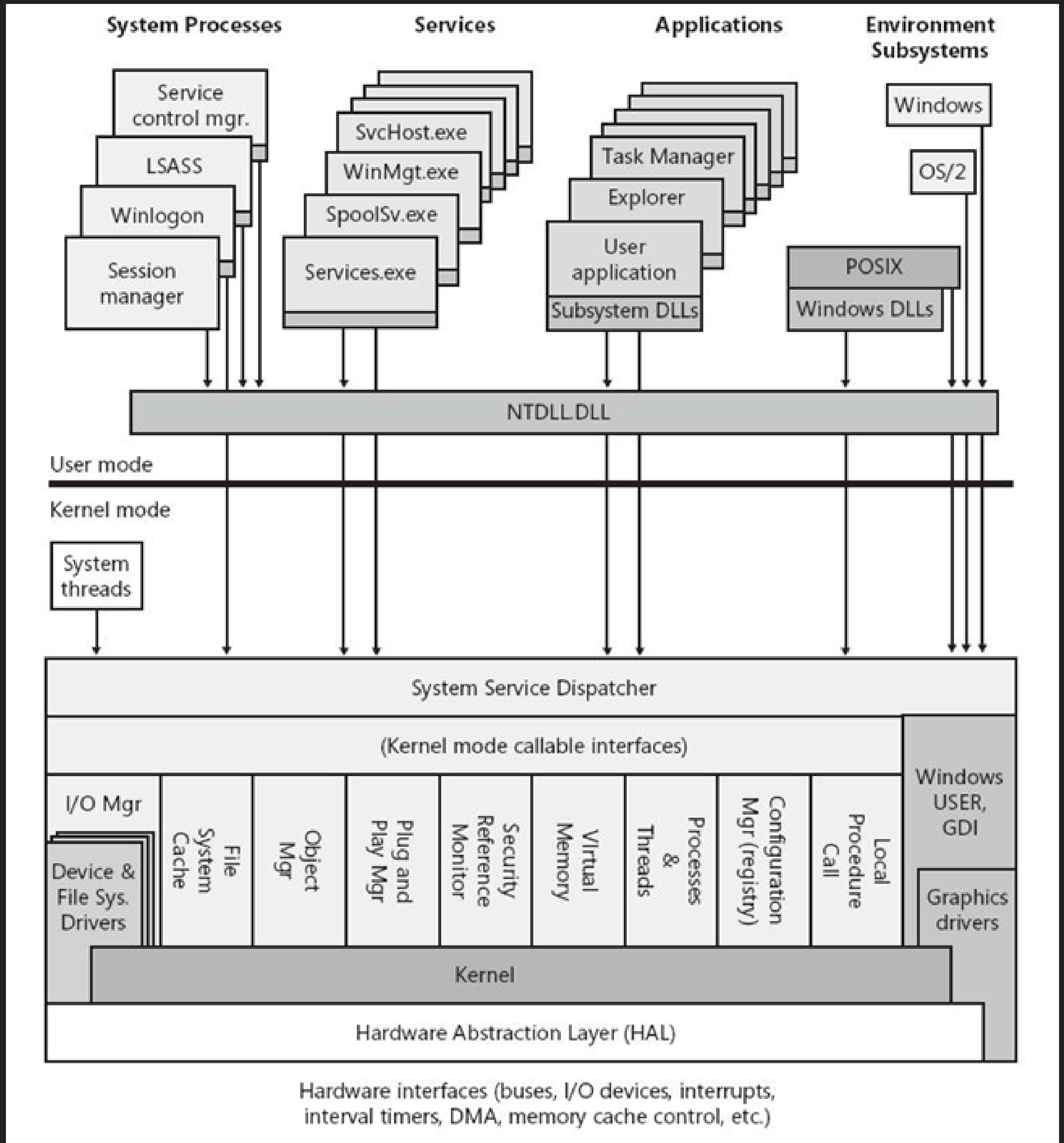


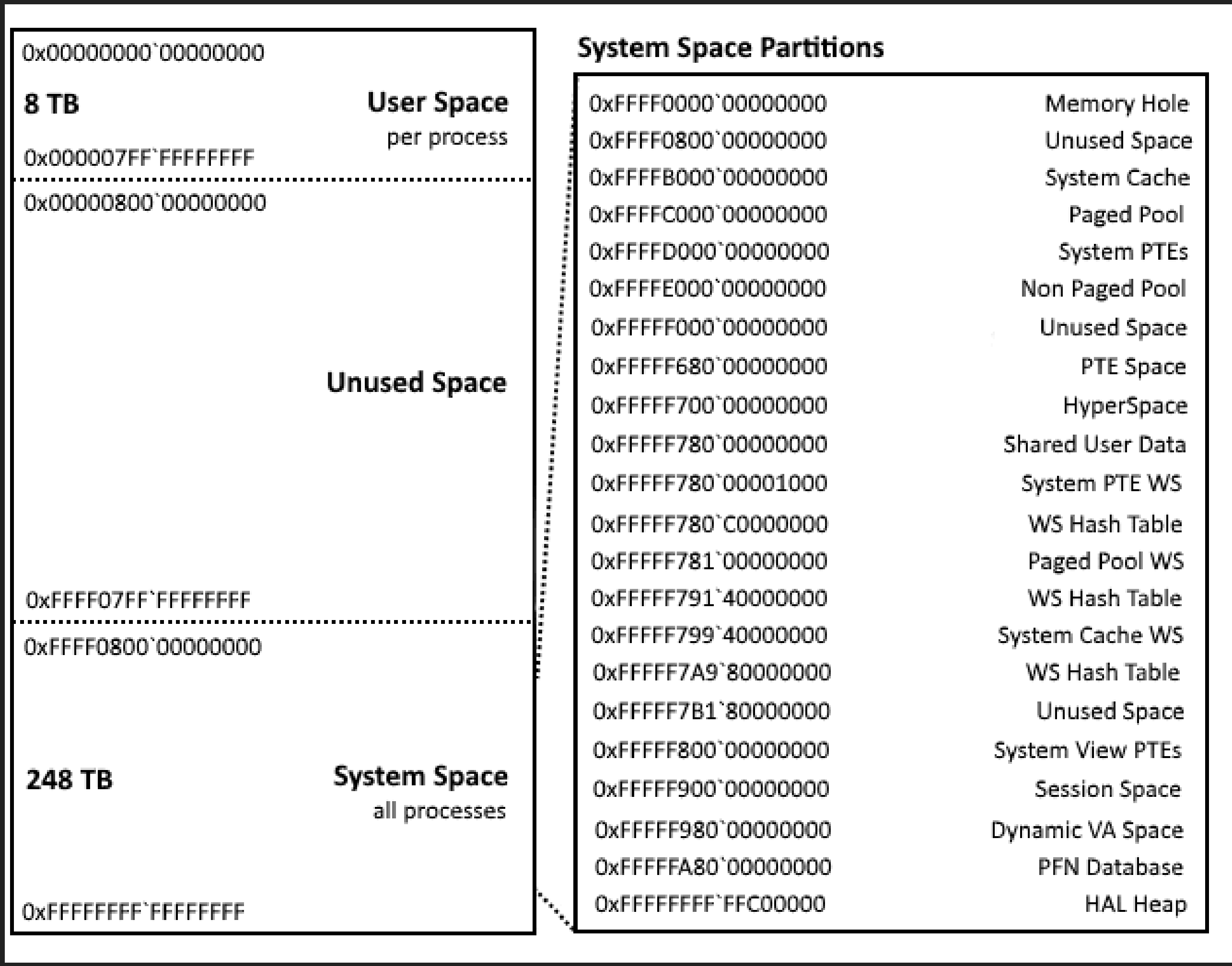
ref: http://cis2.oc.ctc.edu/oc_apps/Westlund/xbook/111_u04e/NT_arch.jpg

Differences between kernel and user programming

_	User	Kernel
unhandled exception	crash process	crash system (bluescreen)
process termination	leaked memory freed	leaked memory remains until reboot
return values	can be ignored	never ignored
IRQL	PASSIVE_LEVEL	can be DISPATCH_LEVEL or higher
debugging	done mostly local	done mostly remote
libraries	can be used	most can't be used
exceptions	c++ and seh	only seh
c++	good to go	nope

Yosifovich, Pavel. Windows Kernel Programming. CreateSpace Independent Publishing Platform, 2019.





ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/overview-of-windows-components

Windows driver models

Windows Driver Model (WDM)

- Older model
- Closely tied to the OS
- Limited checks by the OS (more trust)

Windows Driver Framework (WDF)

- Newer model, recommended by Microsoft
- Focus on driver requirements, framework does the rest

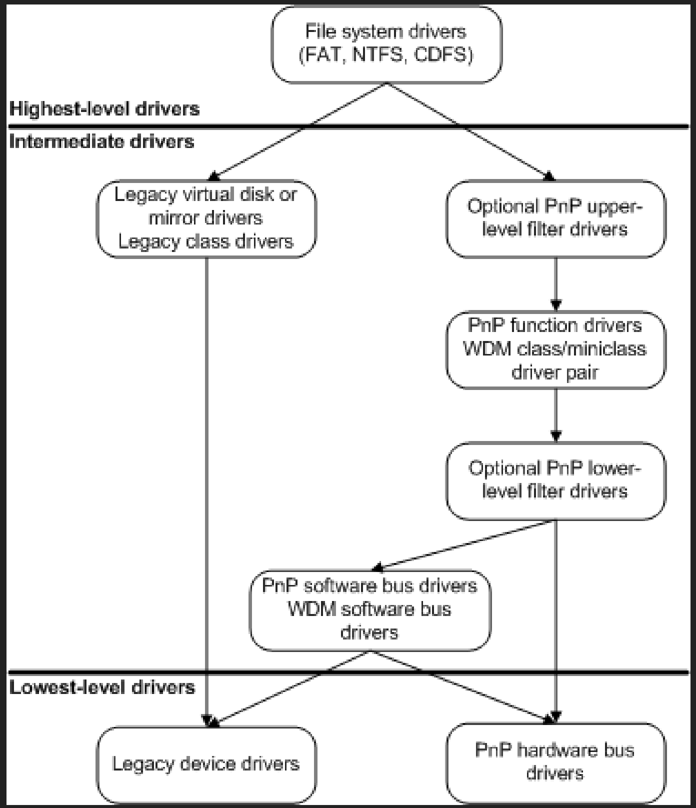
Driver types

User-mode Drivers

- Execute in user mode
- Typically interface between user apps and kernel-mode drivers

Kernel-mode Drivers

- Execute in kernel mode as part of the executive
- KMDs are layered from highest to lowest
- Pass data from layer to layer



ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/types-of-windows-drivers

WDM driver types

- bus driver -> drives an I/O bus
- function driver -> drives a device
- filter driver -> filters I/O for a device

ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/types-of-wdm-drivers

Driver goals

1. Portable
2. Configurable
3. Always preemptible and interruptible
4. Multiprocessor safe
5. Object-based
6. Packet driven I/O with reusable IRPs
7. Capable of async I/O

ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/design-goals-for-kernel-mode-drivers

Windows kernel components

- Object manager
- Memory manager
- Process & thread manager
- I/O manager
- PnP manager
- Configuration manager
- Kernel Transaction Manager
- …
- And many more!

ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/windows-kernel-mode-object-manager

Kernel API

Table 3-2: Common kernel API prefixes

Prefix	Meaning	Example
Ex	general executive functions	ExAllocatePool
Ke	general kernel functions	KeAcquireSpinLock
Mm	memory manager	MmProbeAndLockPages
Rtl	general runtime library	RtlInitUnicodeString
FsRtl	file system runtime library	FsRtlGetFileSize
Flt	file system mini-filter library	FltCreateFile
Ob	object manager	ObReferenceObject
Io	I/O manager	IoCompleteRequest
Se	security	SeAccessCheck
Ps	process structure	PsLookupProcessByProcessId
Po	power manager	PoSetSystemState
Wmi	Windows management instrumentation	WmiTraceMessage
Zw	native API wrappers	ZwCreateFile
Hal	hardware abstraction layer	HalExamineMBR
Cm	configuration manager (registry)	CmRegisterCallbackEx

https://docs.microsoft.com/en-us/windows-hardware/drivers/ddi/wdm/

Yosifovich, Pavel. Windows Kernel Programming. CreateSpace Independent Publishing Platform, 2019.

Standard driver routines

Required Stuff

- DriverEntry -> Initializes the driver and its driver object
- AddDevice -> Initializes devices and creates device objects (for PnP)
- Dispatch Routines -> Receive and process IRPs
- Unload -> Release resources acquired by the driver

ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/introduction-to-standard-driver-routines

Demo: Hello World Kernel Edition (hello_wdm & hello_kmdf)

Note: For future reference

In order to create and start a SCM managed driver you only need:

```
sc create blark binpath=c:\driver.sys type=kernel
sc start blark
sc stop blark
```

4. I/O & IRPs

Windows I/O model

- I/O to drivers is done via I/O Request Packets (IRP)
- I/O is layered and managed by the I/O manager
- The I/O manager establishes standard routines for drivers to support called **dispatch routines**
- Major function codes used to determine the correct dispatch routine

ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/overview-of-the-windows-i-o-model

IRPs

- I/O Request Packets (IRPs) are used to transfer data to and from drivers
- IRPs are self-contained kernel structures and may be be sent through multiple drivers
- Drivers in the stack of drivers can complete, queue, forward, etc. the IRP
- IRP structure: https://docs.microsoft.com/en-us/windows-hardware/drivers/ddi/wdm/ns-wdm-_irp

ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/different-ways-of-handling-irps-cheat-sheet

Dispatch Routines and major function codes

Dispatch routines are part of a driver object that handle the various functions of the driver.

Example major function codes:

- IRP_MJ_CLEANUP
- IRP_MJ_CLOSE
- IRP_MJ_CREATE
- IRP_MJ_DEVICE_CONTROL
- IRP_MJ_READ
- IPR_MJ_WRITE

ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/irp-major-function-codes

Dispatch Routines and major function codes (cont)

Dispatch routines are assigned to the DriverObject in the DriverEntry entrypoint.

```
NTSTATUS
DriverEntry(_In_ PDRIVER_OBJECT DriverObject, _In_ PUNICODE_STRING RegistryPath) {
    ...
    DriverObject->MajorFunction[IRP_MJ_CREATE] = DispatchCreateClose;
    ...
}
```

IRP handling

Drivers must do one of the following with an IRP:

1. For the IRP to another driver
    - can be done using **IoCallDriver** or **IoForwardIrpSynchronously**
    - can use a completion routine with **IoSetCompletionRoutineEx**
2. Complete the IRP
    - done with **IoCompleteRequest**
    - must set Irp->IoStatus.Status and Irp->IoStatus.Information
3. Hold the IRP for later processing
    - done with **IoMarkIrpPending**
    - queue the Irp internally within the driver
    - return STATUS_PENDING in the dispatch routine

IRP handling (cont)

Driver dispatch routines follow this general specification:

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

Accessing WDM drivers from user space

- Drivers supporting PnP use **IoRegisterDeviceInterface** and **AddDevice** to create an accessible interface
- Our simple drivers will use old school Dos Names

Creating a device object

- Before we can access our driver from user land we need to create a device object

```
PDEVICE_OBJECT DeviceObject = NULL;
UNICODE_STRING DeviceName;
RtlInitUnicodeString(&DeviceName, DEVICE_NAME);

Status = IoCreateDevice(
    DriverObject,       // driver object
    0,                  // device extension size
    &DeviceName,        // device name
    DEVICE_TYPE_CUSTOM, // device type (must be defined)
    0,                  // device characteristics
    FALSE,              // exclusive
    &DeviceObject);     // *DeviceObject

if (!NT_SUCCESS(Status)) {
    // uh-oh
}
```

refs: https://docs.microsoft.com/en-us/windows-hardware/drivers/ifs/creating-the-control-device-object | https://docs.microsoft.com/en-us/windows-hardware/drivers/ddi/wdm/nf-wdm-iocreatedevice

Creating a symbolic link

- Next we need to create a symbolic link for the user space application to open

```
UNICODE_STRING DeviceName;
UNICODE_STRING DeviceLink;

RtlInitUnicodeString(&DeviceName, DEVICE_NAME);
RtlInitUnicodeString(&DeviceLink, DEVICE_LINK);

status = IoCreateSymbolicLink(&DeviceLink, &DeviceName);
if (!NT_SUCCESS(status)) {
    // uh-oh
}
```

ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/introduction-to-ms-dos-device-names

Cleanup

- During driver cleanup, the device we created should be cleaned up

```
// cleanup symbolic link
RtlInitUnicodeString(&DeviceLink, DEVICE_LINK);
IoDeleteSymbolicLink(&DeviceLink);

// cleanup device
IoDeleteDevice(DriverObject->DeviceObject);
```

Opening a driver from user land

```
#define DEVICE_LINK L"\\\\.\\driver_name"
    ...
    HANDLE driver = INVALID_HANDLE_VALUE;
    driver = CreateFile(
        DEVICE_LINK,                        // filename
        GENERIC_READ | GENERIC_WRITE,       // desired access
        0,                                  // share mode
        NULL,                               // security attributes
        OPEN_EXISTING,                      // create disposition
        FILE_ATTRIBUTE_NORMAL,              // flags and attributes
        NULL);                              // template file
    ...
```

ref: https://docs.microsoft.com/en-us/windows/win32/api/fileapi/nf-fileapi-createfilea

Your mission: IRPs (irp_wdm)

- Your task is to use the provide irp_wdm template to create a driver that simply handles the open and close IRPs.
- Then use the template application to access the driver
- Relevant functions:
  - RtlInitUnicodeString
  - IoCreateDevice
  - IoCreateSymbolicLink
  - IoDeleteDevice
  - IoDeleteSymbolicLink
  - IoCompleteRequest

Demo: irp_wdm

5. IOCTLs

IOCTLs

- I/O Control Codes or IOCTLs are used for communications between user-mode applications and drivers
- Handled by the I/O manager using the **IRP_MJ_DEVICE_CONTROL** major function code
- Dispatch routine can handle the IOCTL or generate IRP for other drivers to handle
- Driver must use **IoGetCurrentStackLocation** on the incoming IOCTL IRP to get the IOCTL information

CTL_CODE

New IOCTLs can be defined using a handy macro provided by Microsoft

```
#define IOCTL_DOSTUFF CTL_CODE(
    DEVICE_TYPE_CUSTOM,  // device type
    0x0001,              // function
    METHOD_BUFFERED,     // method
    FILE_ALL_ACCESS)     // access
```

ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/defining-i-o-control-codes

Assigning the IOCTL dispatch routine

Nothing new here, assigning a new dispatch routine to handle IOCTLs is done the same as our previous CREATE and CLOSE routines

```
NTSTATUS
DriverEntry(_In_ PDRIVER_OBJECT DriverObject, _In_ PUNICODE_STRING RegistryPath)
{
    ...
    DriverObject->MajorFunction[IRP_MJ_DEVICE_CONTROL] = DispatchIoctl;
    ...
}
```

The IOCTL dispatch routine

- The routine for handling the IOCTL can be done in numerous ways. It is common to see IOCTLs handled with a switch statement.
- The dispatch routine must use **IoGetCurrentIrpStackLocation** to get the IRP and thus IOCTL parameters

```
NTSTATUS
DispatchIoctl(_In_ PDEVICE_OBJECT DeviceObject, _In_ PIRP Irp)
{
    ...
}
```

Driver stack location

- Checked with **IoGetCurrentStackLocation**
- https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/dispatch-routines-and-irqls

IoGetCurrentIrpStackLocation

- **IoGetCurrentIrpStackLocation** is used to get a pointer to the I/O stack location referenced in the IRP
- **IO_STACK_LOCATION** is a structure that contains the parameters from the IRP (among many other things)

```
IoStackLocation = IoGetCurrentIrpStackLocation(Irp);

switch (IoStackLocation->Parameters.DeviceIoControl.IoControlCode) {
    case IOCTL_DOSTUFF: {
        // stuff needs doing
        break;
    }
    default: {
        DbgPrint("ioctl_wdm: DispatchIoctl Unknown IOCTL\n");
        break;
    }
};
```

ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/ddi/wdm/nf-wdm-iogetcurrentirpstacklocation

Don't forget!

- The dispatch routine you use to handle the IOCTL IRP still MUST handle the IRP.
- That means doing one of the 3 things we mentioned earlier for handling IRPs.

Sending the IOCTL from user land

- Driver opening is the same as in our IRP example
- DeviceIoControl is the necessary function to control our driver
- We can use the same CTL_CODE macro to create our IOCTL

```
DeviceIoControl(
    driver,                 // driver handle
    IOCTL_DOSTUFF,          // io control code
    NULL,                   // in buffer
    0,                      // in buffer size
    NULL,                   // out buffer
    0,                      // out buffer size
    &BytesTransferred,      // bytes returned
    NULL);                  // overlapped
```

Your mission... IOCTLs

- Using the provide source code shell implement passing an IOCTL from a user application to your driver
- The source code shell has leading blanks to guide you along
- The soon to be re-discussed relevant functions are still relevant (hint!)
- Have your IOCTL dispatch handler do something simple like print a message to the kernel log
- A potential solution is provided in the source directory

IOCTL relevant functions (and macros)

1. **CTL_CODE** -> macro for defining new I/O control codes
2. **IoGetCurrentIrpStackLocation** -> gets a pointer to the **IO_STACK_LOCATION** structure with parameters important to the IRP
    - DeviceIoControl is particularly useful (IoControlCode)
3. **IoCompleteRequest** -> macro wrapping IofCompleteRequest that indicates an IRQ has been completed
4. **DeviceIoControl** -> used to send control codes from a user application to a driver

6. Kernel programming miscellany

Error handling

- Kernel drivers use SEH to catch and handle errors
- The syntax is familiar

```
try {
    ...
    /* Some totally sketchy code you know is gonna bluescreen
    the system again */
    ...
} except (EXCEPTION_EXECUTE_HANDLER) {
    /* pass... jk */
    ...
}
```

Async I/O

- When receiving an I/O request, a driver can handle it both synchronously and asynchronously
- Our toy demos all handle the request synchronously
- Asynchronous I/O can be completed by:
  - **IoMarkIrpPending** to indicate more work is needed
  - **IoBuildAsynchronousFsdRequest** to generate an IRP for lower drivers
  - **IoAllocateIrp** and **IoSetCompletionRoutine** to create an IRP and completion routine

ref: https://docs.microsoft.com/en-us/windows-hardware/drivers/kernel/different-ways-of-handling-irps-cheat-sheet

Kernel threading

- Threads are created with **PsCreateSystemThread**

```
NTSTATUS
DumbThread(PVOID context)
{...}

...
    HANDLE thread_handle;

    status = PsCreateSystemThread(
        &thread_handle,         // thread handle
        THREAD_ALL_ACCESS,      // desired access
        NULL,                   // object attributes
        NULL,                   // process handle
        NULL,                   // client id
        DumbThread,             // start routine
        NULL);                  // start context

    if (!NT_SUCCESS(status)) {
        // uh-oh
    }
```

Kernel threading (cont)

- **ObReferenceObjectByHandle** is used to maintained a reference to a running kernel thread

```
PVOID g_thread_object = NULL;

    ...
    status = ObReferenceObjectByHandle(
        thread_handle,            // handle
        THREAD_ALL_ACCESS,        // desired access
        NULL,                     // object type
        KernelMode,               // access mode
        &g_thread_object,         // object
        NULL);                    // handle information

    if (!NT_SUCCESS(status)) {
        // uh-oh
    }
```

Kernel threading (cont)

- **KeWaitForSingleObject** can be used to wait for a thread to finish
- **ObDereferenceObject** macro is used to decrement reference counter and allow thread cleanup

```
KeWaitForSingleObject(
    thread_object,  // object
    Executive,      // wait reason
    KernelMode,     // wait mode
    FALSE,          // alertable?
    NULL);          // timeout

ObDereferenceObject(thread_object);
```

7. So what?

Kernel drivers are scary!

- https://guidedhacking.com/threads/vulnerable-kernel-drivers-for-exploitation.15979/

Bad driver demo

8. References

Critical references

- https://docs.microsoft.com/en-us/windows-hardware/drivers/
- "Developing Drivers with the WDF" by Penny Orwick and Guy Smith
- "Windows Kernel Programming" by Pavel Yosifovich
- Classes by T.Roy (https://codemachine.com/)

Stuff we didn't even talk about...

- **Lots of stuff :(**
- DMA
- Interrupt Service Routines (ISR)s
- Message-Signaled Interrupts (MSI)s
- Plug and Play (PnP)
- Power Management
- Windows Management Instrumentation (WMI)