

Windows Kernel Graphics Driver Attack Surface

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Who Am I ?

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- Pen test
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Outline/Agenda

- What's this talk about ?
- Windows graphics drivers
- WDDM kmd Driver
 - Synchronization
 - Entrypoints
- Full userland program to talk about this stuff
- Sniffing/snooping private data
- Putting it all together
 - Fuzzing
 - Reverse engineering

What's This Talk About ?

- Windows® WDDM drivers
 - Implementation security
 - Kernel driver part
- Audience
 - Auditors (what to look for)
 - Graphics drivers developers (what not to do, and where to pay close attention)
 - Curious people that like to poke around in driver internals
- Knowledge
 - Some basic knowledge of Windows drivers (IRP's, probing, capturing, ...)

Windows Graphics Drivers

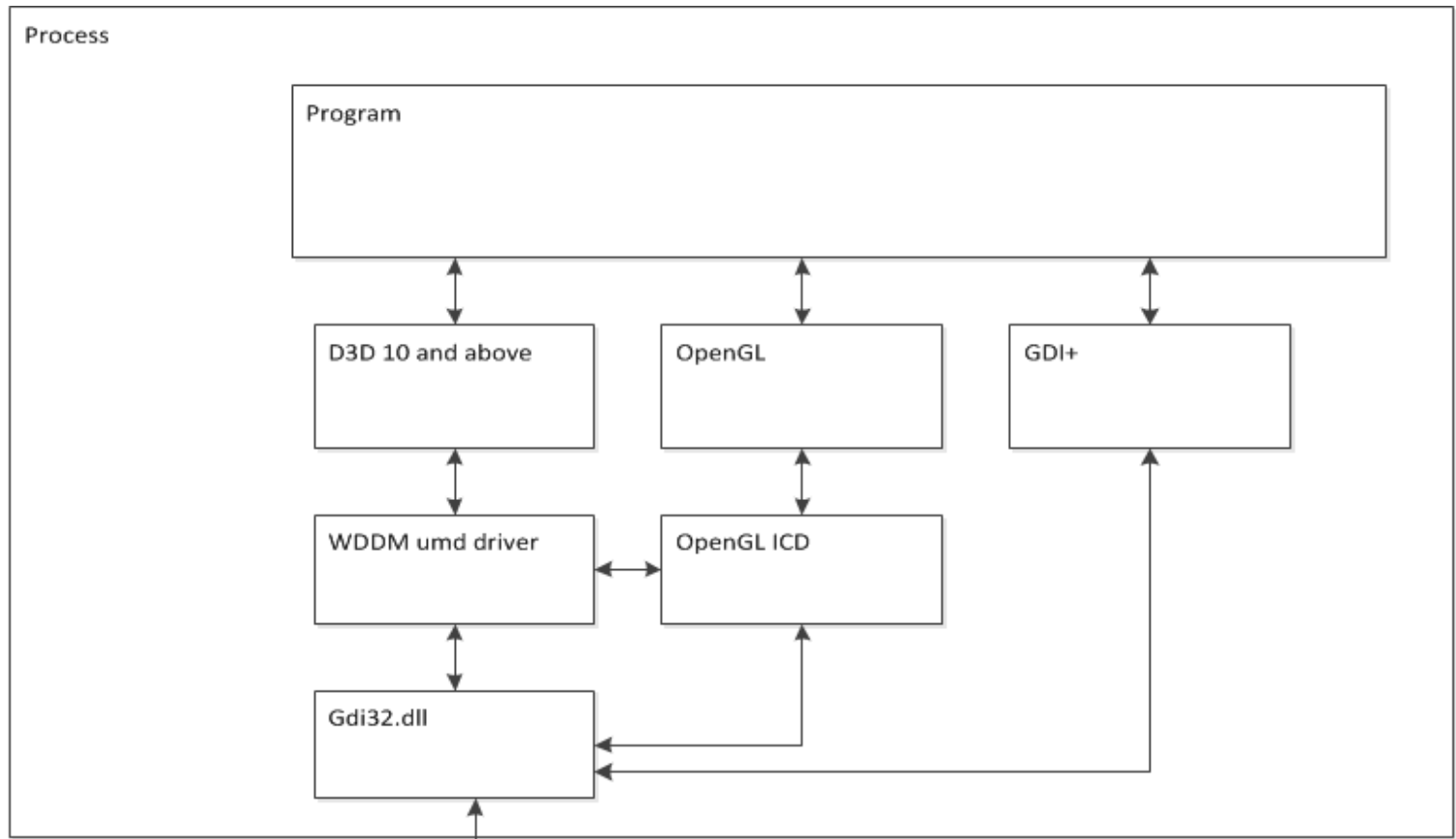
- Old Model
 - XDDM /XPDM
 - Windows 2000/XP
 - No longer supported as of Windows 8
 - Not covered in this presentation
- WDDM (Windows Display Driver Model)
 - New Vista model
 - v1 – vista
 - v1.1 – win 7
 - v1.2 – win 8
 - V1.3 – win 8.1
 - Will only describe interesting parts from a security perspective

Windows Graphics Drivers

- So who makes these things and why ?
 - IHV's (Intel, NVIDIA, AMD, Qualcomm, PowerVR, VIA, Matrox, ...)
 - Very rich drivers
 - Basic fallback (basic render, basic display)
 - Implements the bare minimum
 - Virtualization (VMware, Virtual Box, Parallels guest drivers)
 - Specific special purpose driver
 - Remote desktop scenario's (XenDesktop, RDP, ...)
 - Specific special purpose driver
 - Virtual display (intelligraphics, extramon, ...)
 - Specific special purpose driver

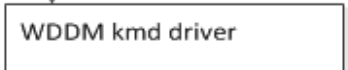
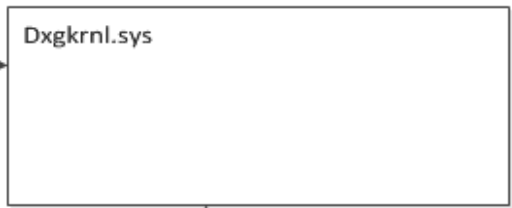
Windows Graphics Drivers

- WDDM model is split between user mode and kernel mode
- Move to user was done for stability and reliability
 - A large chunk of all blue screen prior to vista were due to graphics drivers (from MSDN): *“In Windows XP, display drivers, which are large and complex, can be a major source of system instability. These drivers execute entirely in kernel mode (i.e., deep in the system code) and hence a single problem in the driver will often force the entire system to reboot. According to the **crash analysis** data collected during the **Windows XP timeframe**, display drivers are responsible for **up to 20 percent of all blue screens.**”*
- User mode part runs as part of a dll in most processes
 - Still has interesting attack surface
 - Encoders / decoders
 - Binary planting
 - Some API's might be partially (and indirectly) exposed to remote attack surface (e.g. WebGL)
- Will not cover user mode part, only kernel mode.



User mode

Kernel mode



WDDM kmd Driver

- So what does a WDDM kmd driver look like?

```
NTSTATUS DriverEntry( IN PDRIVER_OBJECT DriverObject,  
                    IN PUNICODE_STRING RegistryPath )  
{  
    ...  
    DRIVER_INITIALIZATION_DATA DriverInitializationData;  
    ...  
    DriverInitializationData.DxgkDdiEscape = DDIEscape;  
    ...  
    Status = DxgkInitialize(DriverObject,  
                            RegistryPath,  
                            &DriverInitializationData);  
    ...  
}
```

WDDM kmd Driver

- DriverEntry() is the main entry point for any kernel driver
- Fill in DRIVER_INITIALIZATION_DATA struct
 - Contains a large set of callback functions
 - ‘dynamic’ struct
 - Bigger on win7 (vs vista)
 - Even bigger on win8
 - Grown even more for win 8.1
 - All later elements appended at the end
- Call DxgkInitialize()
 - Tells dxgkernel about this driver and all its callbacks
- No IRP's, no IOCTL's, nothing like WDM. You don't pass the IoManager.

WDDM kmd Driver

- Very similar variant of this
- Calls DxgkInitializeDisplayOnlyDriver() iso DxgkInitialize() instead
- Uses PKMDDOD_INITIALIZATION_DATA structure
- Much like the previous, but for use by a kernel mode display only driver

WDDM kmd Driver

- DRIVER_INITIALIZATION_DATA contains all sorts of callbacks
- From an attack surface perspective, we can roughly divide them into three groups:
 - Those where an attacker has no or very little control
 - Those where an attacker has some (indirect) control
 - Those where an attacker has significant input into the callback
- We're obviously mainly concerned with the latter

WDDM kmd Driver – Synchronization

- WDDM has a threading model for these callbacks which basically consists of four levels (where each callback belongs to one of these):
- Three
 - Only a single thread may enter
 - GPU Has to be idle
 - No DMA buffers being processed
 - Video memory is evicted to host CPU memory
- Two
 - Same as three except for video memory eviction

WDDM kmd Driver – Synchronization

- One
 - Calls are categorized into classes. Only one thread of each class is allowed to call into callback simultaneously
- Zero
 - Completely reentrant
- If concurrency is allowed, no two concurrent threads may belong to the same process.
- This is important to know, since you need to keep this in mind when looking for potential race conditions scenarios.

WDDM kmd Driver Entrypoints

- A fairly small number of the callbacks take significant input from userland:
 - Escape
 - Render
 - Allocation
 - QueryAdapter
- Before we can get to them, we need to perform proper driver initialization
 - Look at this first
- Then look at the callbacks

WDDM kmd Driver Entrypoints – Initialization

- Need to initialize the device before entry points can be reached from userland
- Assume we come from the GDI world and we have an HDC
- Succinctly, this involves three steps:
 - Convert HDC to WDDM adapter handle
 - Get a WDDM device handle out of the adapter handle
 - Create a context for the device

WDDM kmd Driver Entrypoints – Initialization

- Convert HDC to adapter handle
- Fill in the D3DKMT_OPENADAPTERFROMHDC data structure
- Call D3DKMTOpenAdapterFromHdc

```
D3DKMT_OPENADAPTERFROMHDC  
oafh;  
memset(&oafh, 0x00, sizeof(oafh));  
oafh.hDc = GetDC(NULL);  
D3DKMTOpenAdapterFromHdc(&oafh);
```

WDDM kmd Driver Entrypoints – Initialization

- Get a device handle out of the adapter handle
- Fill in D3DKMT_CREATEDEVICE data structure
- Call D3DKMTCreateDevice

```
D3DKMT_CREATEDEVICE cdev;  
memset(&cdev, 0x00, sizeof(cctx));  
cdev.hAdapter = oafh.hAdapter;  
D3DKMTCreateDevice(&cdev);
```

WDDM kmd Driver Entrypoints – Initialization

- Create a context for the device
- The previously obtained device handle is the handle that gets passed to most userland API's to talk to WDDM drivers.
- In order to do anything, you'll need to create a device context for the device
 - Sets up stuff like command buffers that can be passed off to a WDDM driver
 - There is some attack surface here. Allows passing arbitrary userland data (**pPrivateDriverData**) (with associated length, **PrivateDriverDataSize**) to WDDM driver.
 - It may or may not look at it. This is completely driver dependent.

WDDM kmd Driver Entrypoints – Initialization

- Create a context for the device
- Fill in D3DKMT_CREATECONTEXT data structure
- Call D3DKMTCreateContext

```
D3DKMT_CREATECONTEXT  
cctx;  
memset(&cctx, 0x00,  
sizeof(cctx));  
cctx.hDevice = cdev.hDevice;  
r =  
pfnKTCreateContext(&cctx);
```

- DxgkDdiCreateContext kernel entry point

```
typedef struct _D3DKMT_CREATECONTEXT {  
    D3DKMT_HANDLE      hDevice;  
    UINT               NodeOrdinal;  
    UINT               EngineAffinity;  
    D3DDDI_CREATECONTEXTFLAGS Flags;  
    VOID               *pPrivateDriverData;  
    UINT               PrivateDriverDataSize;  
    D3DKMT_CLIENTHINT   ClientHint;  
    D3DKMT_HANDLE      hContext;  
    VOID               *pCommandBuffer;  
    UINT               CommandBufferSize;  
    D3DDDI_ALLOCATIONLIST *pAllocationList;  
    UINT               AllocationListSize;  
    D3DDDI_PATCHLOCATIONLIST *pPatchLocationList;  
    UINT               PatchLocationListSize;  
    D3DGPU_VIRTUAL_ADDRESS CommandBuffer;  
} D3DKMT_CREATECONTEXT;
```


WDDM kmd Driver Entrypoints – Initialization

- Create a context for the device
- Some interesting output elements in struct
- Both command buffer and patchlocationlist get allocated on your behalf by WDDM
- In usermode. Used to talk to WDDM driver.

```
typedef struct _D3DKMT_CREATECONTEXT {
    D3DKMT_HANDLE      hDevice;
    UINT               NodeOrdinal;
    UINT               EngineAffinity;
    D3DDDI_CREATECONTEXTFLAGS Flags;
    VOID               *pPrivateDriverData;
    UINT               PrivateDriverDataSize;
    D3DKMT_CLIENTHINT   ClientHint;
    D3DKMT_HANDLE      hContext;
    VOID               *pCommandBuffer;
    UINT               CommandBufferSize;
    D3DDDI_ALLOCATIONLIST *pAllocationList;
    UINT               AllocationListSize;
    D3DDDI_PATCHLOCATIONLIST *pPatchLocationList;
    UINT               PatchLocationListSize;
    D3DGPU_VIRTUAL_ADDRESS CommandBuffer;
} D3DKMT_CREATECONTEXT;
```

WDDM kmd Driver Entrypoints – Escape

- DxgkDdiEscape
- This is the IOCTL of graphics drivers.
- Very much like the ‘old’ extEscape
- However, no escape function is passed.
- Just a pointer to private data and a length value
- MSDN describes it as “The *DxgkDdiEscape* function shares information with the user-mode display driver.”
- Driver is free to implement this any way it sees fit.
- Data isn’t structured in any standardized way.
 - Can and will vary wildly from driver to driver.
- Threading level 2

WDDM kmd Driver Entrypoints – Escape

- What does DxgkDdiEscape look like?

```
NTSTATUS APIENTRY  
DxgkDdiEscape(  
    __in const HANDLE hAdapter,  
    __in const DXGKARG_ESCAPE  
    *pEscape  
)  
{ ... }
```

```
typedef struct  
_DXGKARG_ESCAPE {  
    HANDLE          hDevice;  
    D3DDDI_ESCAPEFLAGS Flags;  
    VOID  
    *pPrivateDriverData;  
    UINT  
    PrivateDriverDataSize;  
    HANDLE          hContext;  
} DXGKARG_ESCAPE;
```

WDDM kmd Driver Entrypoints – Escape

- pPrivateDriverData is probed and captured
- No length restrictions (e.g. could be ~4 gigs)
- Userland has complete control of its content
- Any embedded pointers in it need to be probed and only used under a try/except

WDDM kmd Driver Entrypoints – Escape

- How do you talk to this from userland?

```
NTSTATUS D3DKMTEscape(  
_In_ const D3DKMT_ESCAPE  
*pData );
```

```
typedef struct _D3DKMT_ESCAPE {  
D3DKMT_HANDLE      hAdapter;  
D3DKMT_HANDLE      hDevice;  
D3DKMT_ESCAPE_TYPE Type;  
D3DDDI_ESCAPEFLAGS Flags;  
VOID                *pPrivateDriverData;  
UINT                PrivateDriverDataSize  
; D3DKMT_HANDLE      hContext;  
} D3DKMT_ESCAPE;
```

- Publicly documented function. Basically exposes a system call.

WDDM kmd Driver Entrypoints – Escape

```
.text:000000001800014A0 ; Exported entry 1131. D3DKMTEscape
.text:000000001800014A0
.text:000000001800014A0 ; ===== S U B R O U T I N E =====
.text:000000001800014A0
.text:000000001800014A0
.text:000000001800014A0
.text:000000001800014A0
.text:000000001800014A0
.text:000000001800014A0 ZwGdiDdDDIEscape proc near ; DATA XREF: .text:off_180027984↓o
.text:000000001800014A0 ; .pdata:0000000018012036C↓o ...
.text:000000001800014A0
.text:000000001800014A0 mov r10, rcx
.text:000000001800014A3 mov eax, 11B0h
.text:000000001800014A8 syscall
.text:000000001800014AA retn
.text:000000001800014AA ZwGdiDdDDIEscape endp
.text:000000001800014AA
.text:000000001800014AA ; -----
```


WDDM kmd Driver Entrypoints – Render

- DxgkDdiRender
- This callback is at the heart of rendering.
- Allows usermode to tell GPU to render from a command buffer
 - Will generate DMA buffer from command buffer

WDDM kmd Driver Entrypoints – Render

- What does DxgkDdiRender look like?

```
NTSTATUS APIENTRY
DxgkDdiRender(
    _In_    const HANDLE hContext,
    _Inout_ DXGKARG_RENDER
    *pRender
)
{ ... }
```

```
typedef struct _DXGKARG_RENDER {
    const VOID CONST      *pCommand;
    const UINT            CommandLength;
    VOID                  *pDmaBuffer;
    UINT                  DmaSize;
    VOID                  *pDmaBufferPrivateData;
    UINT                  DmaBufferPrivateDataSize;
    DXGK_ALLOCATIONLIST    *pAllocationList;
    UINT                  AllocationListSize;
    D3DDDI_PATCHLOCATIONLIST *pPatchLocationListIn;
    UINT                  PatchLocationListInSize;
    D3DDDI_PATCHLOCATIONLIST *pPatchLocationListOut;
    UINT                  PatchLocationListOutSize;
    UINT                  MultipassOffset;
    UINT                  DmaBufferSegmentId;
    PHYSICAL_ADDRESS      DmaBufferPhysicalAddress;
} DXGKARG_RENDER;
```

WDDM kmd Driver Entrypoints – Render

- pCommand buffer is a pointer that comes from userland
- pPatchLocationListIn is a pointer that comes from userland
- MSDN says the following about these:
“Both the command buffer **pCommand** and the input patch-location list **pPatchLocationListIn** that the user-mode display driver generates are allocated from the user-mode address space and are passed to the display miniport driver untouched. The display miniport driver must use __try/__except code on any access to the buffer and list and must validate the content of the buffer and list before copying the content to the respective kernel buffers.”
- It goes on to give a validation sample.

WDDM kmd Driver Entrypoints – Render

```
__try
{
    for (Index = 0; Index < AllocationListInSize; AllocationTable++,
        AllocationListIn++, AllocationListOut++, Index++)
    {
        D3DKMT_HANDLE AllocationHandle = AllocationListIn->hAllocation;
        ...
    }
}
__except(EXCEPTION_EXECUTE_HANDLER)
{
    Status = STATUS_INVALID_PARAMETER;
    SAMPLE_LOG_ERROR( "Exception occurred accessing ... Status=0x%l64x", Status);
    goto cleanup;
}
```

WDDM kmd Driver Entrypoints – Render

- Userland doesn't actually get to specify the command buffer and patch list addresses.
- Dxgkernel allocates them on your behalf when you call D3DKMTCreateContext, but does map it in userland.
- So you can unmap it (VirtualFree), behind the drivers back.
- Hence, why the try/except is needed.
- Given that both command and patch list addresses are in userland you need to watch out for double fetches.
 - Fetch one: dereference and validate
 - Userland changes data
 - Fetch two: dereference and use, double fetch bug, invalidates previous validation

WDDM kmd Driver Entrypoints – Render

- Example of missing try /except

```
static NTSTATUS APIENTRY DxgkDdiRenderNew( CONST HANDLE hContext, DXGKARG_RENDER *pRender) {
    if (pRender->CommandLength < sizeof (VBOXWDDM_DMA_PRIVATEDATA_BASEHDR))
    {
        return STATUS_INVALID_PARAMETER;
    }

    PVBOXWDDM_DMA_PRIVATEDATA_BASEHDR pInputHdr = (PVBOXWDDM_DMA_PRIVATEDATA_BASEHDR)pRender-
    >pCommand;
    NTSTATUS Status = STATUS_SUCCESS;
    VBOXCMDVBVA_HDR* pCmd = (VBOXCMDVBVA_HDR*)pRender->pDmaBufferPrivateData;
    switch (pInputHdr->enmCmd) ← no try/except.
    {
        ...
    }
    ...
    return STATUS_SUCCESS;
}
```


WDDM kmd Driver Entrypoints – Render

- Example of double fetch

```
static NTSTATUS APIENTRY DxgkDdiRenderNew( CONST HANDLE hContext, DXGKARG_RENDER *pRender) {  
...  
    PVBOXWDDM_DMA_PRIVATEDATA_BASEHDR pInputHdr =  
(PVBOXWDDM_DMA_PRIVATEDATA_BASEHDR)pRender->pCommand;  
...  
    PVBOXWDDM_DMA_PRIVATEDATA_UM_CHROMIUM_CMD pUmCmd = pInputHdr;  
...  
    PVBOXWDDM_UHGSMI_BUFFER_UI_SUBMIT_INFO pSubmUmInfo = pUmCmd->aBufInfos;  
...  
    if (pSubmUmInfo->offData >= pAlloc->AllocData.SurfDesc.cbSize  
        || pSubmUmInfo->cbData > pAlloc->AllocData.SurfDesc.cbSize  
        || pSubmUmInfo->offData + pSubmUmInfo->cbData > pAlloc->AllocData.SurfDesc.cbSize)  
    {  
        WARN(("invalid data"));  
        return STATUS_INVALID_PARAMETER;  
    }  
...  
    pSubmInfo->cbBuffer = pSubmUmInfo->cbData;  
...  
    return STATUS_SUCCESS;  
}
```

Validate

Use

ctive

WDDM kmd Driver Entrypoints – Render

- How do you talk to this from userland?

```
NTSTATUS APIENTRY  
D3DKMTRender(  
_Inout_ D3DKMT_RENDER *pData );
```

```
typedef struct _D3DKMT_RENDER {  
    union {  
        D3DKMT_HANDLE hDevice;  
        D3DKMT_HANDLE hContext;  
    };  
    UINT                CommandOffset;  
    UINT                CommandLength;  
    UINT                AllocationCount;  
    UINT                PatchLocationCount;  
    VOID                *pNewCommandBuffer;  
    UINT                NewCommandBufferSize;  
    D3DDDI_ALLOCATIONLIST *pNewAllocationList;  
    UINT                NewAllocationListSize;  
    D3DDDI_PATCHLOCATIONLIST *pNewPatchLocationList;  
    UINT                NewPatchLocationListSize;  
    D3DKMT_RENDERFLAGS  Flags;  
    ULONGLONG           PresentHistoryToken;  
    ULONG               BroadcastContextCount;  
    D3DKMT_HANDLE  
    BroadcastContext[D3DDDI_MAX_BROADCAST_CONTEXT];  
    ULONG               QueuedBufferCount;  
    D3DGPU_VIRTUAL_ADDRESS NewCommandBuffer;  
    VOID                *pPrivateDriverData;  
    UINT                PrivateDriverDataSize;  
} D3DKMT_RENDER;
```

WDDM kmd Driver Entrypoints – Render



```
.text:000007FF7FD713F0 ; Exported entry 1151. D3DKMTRender
.text:000007FF7FD713F0
.text:000007FF7FD713F0 ; ===== S U B R O U T I N E =====
.text:000007FF7FD713F0
.text:000007FF7FD713F0
.text:000007FF7FD713F0 public ZwGdiDdDDIRender
.text:000007FF7FD713F0 ZwGdiDdDDIRender proc near ; DATA XREF: .rdata:off_7FF7FDC24B8↓o
.text:000007FF7FD713F0 ; .pdata:000007FF7FDCE090↓o ...
.text:000007FF7FD713F0 mov r10, rcx
.text:000007FF7FD713F3 mov eax, 1187h
.text:000007FF7FD713F8 syscall
.text:000007FF7FD713FA retn
.text:000007FF7FD713FA ZwGdiDdDDIRender endp
.text:000007FF7FD713FA
.text:000007FF7FD713FA ; -----
```

WDDM kmd Driver Entrypoints – Allocation

- DxgkDdiCreateAllocation
- Dxgkernel calls this callback on userland's behalf to allocate memory.
- It will allocate either system or video memory, depending on flags.

WDDM kmd Driver Entrypoints – Allocation

- What does DxgkDdiCreateAllocation look like?

```
NTSTATUS APIENTRY DxgkDdiCreateAllocation(  
    const HANDLE hAdapter,  
    DXGKARG_CREATEALLOCATION  
    *pCreateAllocation  
)  
{ ... }
```

```
typedef struct  
_DXGKARG_CREATEALLOCATION {  
    const VOID          *pPrivateDriverData;  
    UINT                PrivateDriverDataSize;  
    UINT                NumAllocations;  
    DXGK_ALLOCATIONINFO  
    *pAllocationInfo;  
    HANDLE              hResource;  
    DXGK_CREATEALLOCATIONFLAGS  
    Flags;  
} DXGKARG_CREATEALLOCATION;
```

WDDM kmd Driver Entrypoints – Allocation

- What does DxgkDdiCreateAllocation look like ? (cont.)

```
typedef struct _DXGK_ALLOCATIONINFO {  
    VOID                *pPrivateDriverData;  
    UINT                PrivateDriverDataSize;  
    UINT                Alignment;  
    SIZE_T              Size;  
    SIZE_T              PitchAlignedSize;  
    DXGK_SEGMENTBANKPREFERENCE HintedBank;  
    DXGK_SEGMENTPREFERENCE PreferredSegment;  
    UINT                SupportedReadSegmentSet;  
    UINT                SupportedWriteSegmentSet;  
    UINT                EvictionSegmentSet;  
    UINT                MaximumRenamingListLength;  
    HANDLE              hAllocation;  
    DXGK_ALLOCATIONINFOFLAGS Flags;  
    DXGK_ALLOCATIONUSAGEHINT *pAllocationUsageHint;  
    UINT                AllocationPriority;  
} DXGK_ALLOCATIONINFO;
```


WDDM kmd Driver Entrypoints – Allocation

- Private driver data is captured from user to kernel.
- There are NumAllocations DXGK_ALLOCATIONINFO structures that userland gets to pass.
- DXGK_ALLOCATIONINFO's private driver data is also captured from user to kernel.
- DxgkDdiOpenAllocation can't be directly called from userland, but its private driver data is the same as provided here.

WDDM kmd Driver Entrypoints – Allocation

- How do you talk to this from userland ?

```
NTSTATUS APIENTRY  
D3DKMTCreateAllocation(  
    D3DKMT_CREATEALLOCATION  
    *pData  
);
```

```
typedef struct _D3DKMT_CREATEALLOCATION {  
    D3DKMT_HANDLE          hDevice;  
    D3DKMT_HANDLE          hResource;  
    D3DKMT_HANDLE          hGlobalShare;  
    const VOID              *pPrivateRuntimeData;  
    UINT                   PrivateRuntimeDataSize;  
    const VOID              *pPrivateDriverData;  
    UINT                   PrivateDriverDataSize;  
    UINT                   NumAllocations;  
    D3DDDI_ALLOCATIONINFO    *pAllocationInfo;  
    D3DKMT_CREATEALLOCATIONFLAGS Flags;  
    HANDLE  
    hPrivateRuntimeResourceHandle;  
} D3DKMT_CREATEALLOCATION;
```

WDDM kmd Driver Entrypoints – Allocation



```
.text:000007FF7FD74C20 ; Exported entry 1106. D3DKMTCreateAllocation2
.text:000007FF7FD74C20
.text:000007FF7FD74C20 ; ===== S U B R O U T I N E =====
.text:000007FF7FD74C20
.text:000007FF7FD74C20
.text:000007FF7FD74C20 public NtGdiDdDDICreateAllocation
.text:000007FF7FD74C20 NtGdiDdDDICreateAllocation proc near ; CODE XREF: D3DKMTCreateAllocation+B5↑p
.text:000007FF7FD74C20 ; DATA XREF: .rdata:off_7FF7FDC24B8↓o
.text:000007FF7FD74C20 mov r10, rcx
.text:000007FF7FD74C23 mov eax, 115Dh
.text:000007FF7FD74C28 syscall
.text:000007FF7FD74C2A retn
.text:000007FF7FD74C2A NtGdiDdDDICreateAllocation endp
.text:000007FF7FD74C2A
.text:000007FF7FD74C2A : -----
```



WDDM kmd Driver Entrypoints – queryadapter

- The actual type nr in user and driver different
- Dxgkernel does some kind of translation
- All have well defined format
- With well defined length
- Except for
DXGKQAITYPE_UMDRIVERPRIVATE
- Driver can implement that one any way it wants

```
typedef enum _DXGK_QUERYADAPTERINFOTYPE {  
    DXGKQAITYPE_UMDRIVERPRIVATE        = 0,  
    DXGKQAITYPE_DRIVERCAPS              = 1,  
    DXGKQAITYPE_QUERYSEGMENT            = 2,  
    #if (DXGKDDI_INTERFACE_VERSION >= DXGKDDI_INTERFACE_VERSION_WIN7)  
    DXGKQAITYPE_ALLOCATIONGROUP           = 3,  
    DXGKQAITYPE_QUERYSEGMENT2           = 4,  
    #endif  
    #if (DXGKDDI_INTERFACE_VERSION >= DXGKDDI_INTERFACE_VERSION_WIN8)  
    DXGKQAITYPE_QUERYSEGMENT3           = 5,  
    DXGKQAITYPE_NUMPOWERCOMPONENTS      = 6,  
    DXGKQAITYPE_POWERCOMPONENTINFO      = 7,  
    DXGKQAITYPE_PREFERREDGPUNODE        = 8,  
    #endif  
    #if (DXGKDDI_INTERFACE_VERSION >= DXGKDDI_INTERFACE_VERSION_WDDM1_3)  
    DXGKQAITYPE_POWERCOMPONENTPSTATEINFO = 9,  
    DXGKQAITYPE_HISTORYBUFFERPRECISION  = 10  
    #endif  
} DXGK_QUERYADAPTERINFOTYPE;
```

WDDM kmd Driver Entrypoints – queryadapter

- What does DxgkDdiQueryAdapterInfo look like?

```
NTSTATUS APIENTRY  
DxgkDdiQueryAdapterInfo(  
    HANDLE hAdapter,  
    DXGKARG_QUERYADAPTERINFO  
    *pQueryAdapterInfo )  
{ ... }
```

```
typedef struct  
_DXGKARG_QUERYADAPTERINFO {  
    DXGK_QUERYADAPTERINFOTYP  
    E Type; VOID *pInputData;  
    UINT InputDataSize;  
    VOID *pOutputData;  
    UINT OutputDataSize;  
} DXGKARG_QUERYADAPTERINFO;
```

WDDM kmd Driver Entrypoints – queryadapter

- Has interesting entry- and exit points
- Entry points:
 - Data being passed in from userland.
 - Most interesting type for this is `DXGKQAITYPE_UMDRIVERPRIVATE`.
- Exit points:
 - With Query API's that return large structures from kernel to user, there is the risk of information leaks.
 - Usually happens when a struct is on the stack/heap, no memset is done, and part of one or more members is not initialized (e.g. fixed character buffer that holds a 0-terminated string).

WDDM kmd Driver Entrypoints – queryadapter

- How do you talk to this from userland ?

```
NTSTATUS  
D3DKMTQueryAdapterInfo(  
    D3DKMT_QUERYADAPTERINFO  
    *pData  
);
```

```
typedef struct  
_D3DKMT_QUERYADAPTERINFO {  
    D3DKMT_HANDLE      hAdapter;  
    KMTQUERYADAPTERINFOTYPE Type;  
    VOID                *pPrivateDriverData;  
    UINT                PrivateDriverDataSize;  
} D3DKMT_QUERYADAPTERINFO;
```

WDDM kmd Driver Entrypoints – queryadapter

```
.text:000007FF7FD789E0 ; Exported entry 1145. D3DKMTQueryAdapterInfo
.text:000007FF7FD789E0
.text:000007FF7FD789E0 ; ===== S U B R O U T I N E =====
.text:000007FF7FD789E0
.text:000007FF7FD789E0
.text:000007FF7FD789E0 public NtGdiDdDDIQueryAdapterInfo
.text:000007FF7FD789E0 NtGdiDdDDIQueryAdapterInfo proc near ; DATA XREF: .rdata:off_7FF7FDC24B8↓o
.text:000007FF7FD789E0 mov r10, rcx
.text:000007FF7FD789E3 mov eax, 1181h
.text:000007FF7FD789E8 syscall
.text:000007FF7FD789EA retn
.text:000007FF7FD789EA NtGdiDdDDIQueryAdapterInfo endp
.text:000007FF7FD789EA
.text:000007FF7FD789EA ; -----
```

WDDM kmd Driver Entrypoints – Best Practices

- Out of bound read ← very common
 - This means bluescreen in kernel
 - Could happen, even for a single byte out of bound read
- Don't ship debug code
 - Remove DbgPrint calls
 - And surrounding code (e.g. data that will be printed by formatstring)
 - Ends up in binary otherwise. Could contains exploitable bugs.
 - #ifdef debug
- Use kernel safe integer library routines (e.g. RtlUIntAdd)
 - Please don't roll your own ...

Full userland Program to Talk to this Stuff

- Slightly more difficult than it looks.
- The API's are documented on msdn, and exported from gdi32.dll.
- The data structures are documented on msdn.
- Meant for OpenGL ICD (Installable client driver) drivers
 - No headers for this stuff:
 - Need to LoadLibrary/GetProcAddress
 - There is a devkit for this, but, ..., MSDN says: “**Note** To obtain a license for the OpenGL ICD Development Kit, contact the [OpenGL Issues](#) team.”
 - Given that it is documented, getting a (partially) working implementation is pretty easy.
 - Or you could use the COM APIs. ☺

Sniffing/snooping Private Data

- Since data send from umd to kmd is not structured in any way, we need to see what gets send to kmd under normal conditions.
- To get an idea of what the protocol looks like for any given driver
- Hook APIs:
 - D3DKMTEscape
 - D3DKMTRender
 - D3DKMTCreateAllocation
 - D3DKMTQueryAdapterInfo

Sniffing/snooping Private Data

- Tool/demo
- Release!
- Running against PowerPoint seems to give pretty good results.

Putting It all Together

- Fuzzing
- Reverse engineering

Putting It all Together – Fuzzing

- Mutating fuzzer
- Starting off with sniffed data (template per driver)
- Mutate data
- Loop
- Combine this with reversing
 - If (embedded_len != PrivateDataSize) bail;
 - Checksums
- ➔ Bugs!

Putting It all Together – Reverse Engineering

"If the process of reverse engineering Windows drivers could be modeled as a discrete task, 90% would be understanding how Windows works and 10% would be understanding assembly code." – Bruce Dang

WDDM kmd Driver – Reverse Engineering

- As shown before, all the driver does as part of it's initialization is call DxgkInitialize() or DxgkInitializeDisplayOnlyDriver().
- And pass it a callback table (DRIVER_INITIALIZATION_DATA)
- When looking at the driver in a disassembler no call to these functions is observed.
- These functions are inlined

WDDM kmd Driver – Reverse Engineering

- So what does it look like? (with symbols)

```
00406000 ; int __stdcall DriverEntry(_DRIVER_OBJECT *pDriverObject, _UNICODE_STRING *pRegistryPath)
00406000 _DriverEntry@8 proc near ; CODE XREF: GsDriverEntry(x,x)+B↑j
00406000
00406000 InitialData = _KMDDOD_INITIALIZATION_DATA ptr -0A4h
00406000 pDriverObject = dword ptr 8
00406000 pRegistryPath = dword ptr 0Ch
00406000
00406000 push ebp
00406001 mov ebp, esp
00406003 sub esp, 0A4h
00406009 push 0A0h ; size_t
0040600E lea eax, [ebp+InitialData.DxgkDdiAddDevice]
00406014 push 0 ; int
00406016 push eax ; void *
00406017 call _memset
0040601C add esp, 0Ch
0040601F mov [ebp+InitialData.Version], 4002h
....
00406104 mov [ebp+InitialData.DxgkDdiSystemDisplayEnable], offset ?BddDdiSystemDisplayEnable@@YGJPAXIPAU_DXGKARG_SYSTEM_DI
0040610B mov [ebp+InitialData.DxgkDdiSystemDisplayWrite], offset ?BddDdiSystemDisplayWrite@@YGXPAX0IIIII@Z ; BddDdiSystemD
00406112 call _DxgkInitializeDisplayOnlyDriver@12 ; DxgkInitializeDisplayOnlyDriver(x,x,x)
00406117 mov esp, ebp
00406119 pop ebp
0040611A retn 8
0040611A DriverEntry@8 endp
```

```

int __stdcall DxgkInitializeDisplayOnlyDriver(_DRIVER_OBJECT *DriverObject, _UNICODE_STRING *RegistryPath, _KMDDOD_INITIALIZATION_DATA *InitData)
{
    char v3; // b1@1
    _KMDDOD_INITIALIZATION_DATA *v4; // edi@3
    unsigned int v5; // eax@4
    int result; // eax@8
    int v7; // esi@9
    int (__stdcall *DpiInitialize)(_DRIVER_OBJECT *, _UNICODE_STRING *, _KMDDOD_INITIALIZATION_DATA *); // [sp+8h] [bp-Ch]@1
    void *FileObject; // [sp+Ch] [bp-8h]@1
    _DEVICE_OBJECT *DxgDeviceObject; // [sp+10h] [bp-4h]@1

    v3 = 0;
    FileObject = 0;
    DxgDeviceObject = 0;
    DpiInitialize = 0;
    if ( DriverObject && RegistryPath && (v4 = InitData) != 0 )
    {
        v5 = InitData->Version;
        if ( InitData->Version == 4178 || v5 == 4179 || v5 == 8197 || v5 >= 0x300E )
        {
            v7 = DlpLoadDxgkrnl((_FILE_OBJECT **)&FileObject, &DxgDeviceObject);
            if ( v7 >= 0 || v7 == -1073741554 )
            {
                v3 = v7 != -1073741554;
                v7 = DlpCallSyncDeviceIoControl(
                    DxgDeviceObject,
                    0x230043u,
                    1,
                    0,
                    0,
                    &DpiInitialize,
                    4u,
                    (unsigned int *)&InitData);
            }
            if ( FileObject )
                ObfDereferenceObject();
            if ( v7 < 0 )
            {
                if ( v3 )
                    DlpUnloadDxgkrnl();
            }
            else
            {
                MiniportStartDevice = (int)v4->DxgkDdiStartDevice;
                v4->DxgkDdiStartDevice = DlpStartDevice;
                v7 = DpiInitialize(DriverObject, RegistryPath, v4);
            }
            result = v7;
        }
        else
        {
            result = -1073741735;
        }
    }
    else
    {
        result = -1073741811;
    }
    return result;
}

```


WDDM kmd Driver – Reverse Engineering

```
int __stdcall DlpLoadDxgkrnl(_FILE_OBJECT **FileObject, _DEVICE_OBJECT **DeviceObject)
{
    const wchar_t *u2; // eax@1
    void *u3; // edi@1
    int u4; // esi@2
    char u5; // bl@5
    _UNICODE_STRING DeviceName; // [sp+8h] [bp-1Ch]@5
    _UNICODE_STRING DriverServiceName; // [sp+10h] [bp-14h]@3
    signed __int64 DelayDuration; // [sp+18h] [bp-Ch]@8
    int v10; // [sp+20h] [bp-4h]@1

    v10 = 10;
    u2 = DlpGetServiceNameInSystemSpace();
    u3 = (void *)u2;
    if ( u2 )
    {
        RtlInitUnicodeString(&DriverServiceName, u2);
        u4 = ZwLoadDriver(&DriverServiceName);
        ExFreePoolWithTag(u3, 0);
        if ( u4 >= 0 || u4 == -1073741554 )
        {
            u5 = u4 != -1073741554;
            RtlInitUnicodeString(&DeviceName, L"\\Device\\Dxgkrnl");
            while ( 1 )
            {
                u4 = IoGetDeviceObjectPointer(&DeviceName, 0xC0000000u, FileObject, DeviceObject);
                if ( u4 >= 0 )
                    break;
                if ( u5 )
                {
                    DlpUnloadDxgkrnl();
                    return u4;
                }
                DelayDuration = -50000i64;
                KeDelayExecutionThread(0, 0, (PLARGE_INTEGER)&DelayDuration);
                --v10;
                if ( !v10 )
                    return u4;
            }
            if ( !u5 )
                u4 = -1073741554;
        }
    }
    else
    {
        u4 = -1073741801;
    }
    return u4;
}
```

```
const wchar_t *__stdcall DlpGetServiceNameInSystemSpace()
{
    const wchar_t *result; // eax@1

    result = (const wchar_t *)ExAllocatePoolWithTag(PagedPool, 0x78u, 0x706D6C44u);
    if ( result )
        memcpy((void *)result, L"\\Registry\\Machine\\System\\CurrentControlSet\\Services\\DXGKrnl", 0x78u);
    return result;
}
```

WDDM kmd Driver – Reverse Engineering

- Loads Dxgkrnl.sys (it should already be loaded)
- Gets a pointer to it's device object
- Issues ioctl 0x230043 on it (video device, function 10, method neither, FILE_ANY_ACCESS)
- Hands back a function pointer to be used to register the callback
- Call that function pointer with DRIVER_INITIALIZATION_DATA or PKMDDOD_INITIALIZATION_DATA struct as argument

WDDM kmd Driver – Reverse Engineering

- The table itself can be created/stored several different ways
 - tabled stored globally
 - Created on the stack
 - Specific function fills in DRIVER_INITIALIZATION_DATA
- Or filled out in a local stack buffer right before calling DxgkInitialize()
- Finding the code that does this is usually pretty simple. It'll happen early on, usually in DriverEntry() or some function it calls.
- Tends to look like this:

WDDM kmd Driver – Reverse Engineering

```
lea    ecx, [ebp+var_A4]
push   ecx
push   edx
push   eax
mov     [ebp+var_A4], 300Eh
mov     [ebp+var_A0], offset sub_402C80
mov     [ebp+var_9C], offset sub_402D50
mov     [ebp+var_98], offset sub_403250
mov     [ebp+var_94], offset sub_4032C0
mov     [ebp+var_90], offset sub_4032E0
mov     [ebp+var_8C], offset sub_4032F0
mov     [ebp+var_88], offset sub_4036F0
mov     [ebp+var_84], offset sub_4037E0
mov     [ebp+var_80], offset sub_403840
mov     [ebp+var_7C], offset sub_4038B0
mov     [ebp+var_78], offset sub_4038C0
mov     [ebp+var_74], offset sub_4038D0
mov     [ebp+var_70], offset nullsub_1
mov     [ebp+var_6C], offset sub_4038F0
mov     [ebp+var_68], offset sub_403930
mov     [ebp+var_64], offset nullsub_2
mov     [ebp+var_60], offset sub_403950
mov     [ebp+var_5C], offset sub_4051C0
mov     [ebp+var_58], offset sub_405550
mov     [ebp+var_54], offset sub_405650
mov     [ebp+var_50], offset sub_405720
mov     [ebp+var_4C], offset sub_4061A0
mov     [ebp+var_48], offset sub_406250
mov     [ebp+var_44], offset sub_406320
mov     [ebp+var_40], offset sub_4065B0
mov     [ebp+var_3C], offset sub_4066E0
mov     [ebp+var_38], offset sub_408BA0
mov     [ebp+var_34], offset sub_4067D0
mov     [ebp+var_30], offset sub_4067E0
mov     [ebp+var_2C], offset sub_4068E0
mov     [ebp+var_28], offset sub_408170
mov     [ebp+var_24], offset sub_408180
mov     [ebp+var_20], offset sub_4083E0
mov     [ebp+var_1C], offset sub_4083F0
mov     [ebp+var_18], offset nullsub_3
mov     [ebp+var_10], offset sub_406900
call    sub_42A64C
```

```
__int64 __fastcall sub_23870(__int64 a1)
{
    __int64 result; // rax@1

    *(_DWORD *)a1 = 0x3008;
    *(_QWORD *)(a1 + 8) = DxgkDdiAddDevice;
    *(_QWORD *)(a1 + 16) = DxgkDdiStartDevice;
    *(_QWORD *)(a1 + 24) = sub_50DE0;
    *(_QWORD *)(a1 + 32) = sub_50590;
    *(_QWORD *)(a1 + 40) = sub_1C3A0;
    *(_QWORD *)(a1 + 48) = sub_1C460;
    *(_QWORD *)(a1 + 56) = sub_1C350;
    *(_QWORD *)(a1 + 64) = sub_53260;
    *(_QWORD *)(a1 + 72) = sub_53340;
    *(_QWORD *)(a1 + 80) = sub_535A0;
    *(_QWORD *)(a1 + 88) = sub_25030;
    *(_QWORD *)(a1 + 104) = sub_1C550;
    *(_QWORD *)(a1 + 112) = sub_510C0;
    *(_QWORD *)(a1 + 136) = sub_529C0;
    *(_QWORD *)(a1 + 152) = sub_1A2B0;
    *(_QWORD *)(a1 + 160) = sub_1A560;
    *(_QWORD *)(a1 + 168) = sub_197A0;
    *(_QWORD *)(a1 + 176) = sub_51080;
    *(_QWORD *)(a1 + 184) = sub_53E80;
    *(_QWORD *)(a1 + 192) = sub_53ED0;
    *(_QWORD *)(a1 + 200) = sub_53630;
    *(_QWORD *)(a1 + 208) = sub_545A0;
    *(_QWORD *)(a1 + 216) = sub_304B0;
    *(_QWORD *)(a1 + 224) = sub_31460;
    *(_QWORD *)(a1 + 232) = sub_544F0;
    *(_QWORD *)(a1 + 256) = sub_527D0;
    *(_QWORD *)(a1 + 264) = sub_1C5B0;
    result = a1;
    *(_QWORD *)(a1 + 248) = sub_30DB0;
    return result;
}
```

WDDM kmd Driver – Reverse Engineering

- Here's what the structure looks like in C:

```
typedef struct _DRIVER_INITIALIZATION_DATA {  
    ULONG                                     Version;  
    PDXGKDDI_ADD_DEVICE                      DxgkDdiAddDevice;  
    PDXGKDDI_START_DEVICE                    DxgkDdiStartDevice;  
    PDXGKDDI_STOP_DEVICE                     DxgkDdiStopDevice;  
    PDXGKDDI_REMOVE_DEVICE                   DxgkDdiRemoveDevice;  
    ...  
} DRIVER_INITIALIZATION_DATA, *PDRIVER_INITIALIZATION_DATA;
```

- Mapping this to IDA disassembly and renaming the functions to something meaningful is pretty easy

WDDM kmd Driver – Reverse Engineering

- Userland data passed in (PrivateData)
 - Driver gets to handle this any way it sees fit
 - Usually:
 - Feels like (simple) network protocol reverse engineering
 - Usually comes with a header
 - Type
 - Length
 - Value
 - Switch case or nested if/else to handle values for types

WDDM kmd Driver – Reverse Engineering

- Example of a typical case:

```
int __fastcall DxgkDdiEscape(PVOID hAdapter, __int64 pEscape)
{
    __int64 v2; // rbx@1
    PVOID v3; // rdi@1
    int result; // eax@3

    v2 = pEscape;
    v3 = hAdapter;
    DbgPrintEx(78164, 3164, qword_140015680, "Ud3dkAdapter::DxgkDdiEscape");
    if ( *(_DWORD *) (v2 + 24) < 4u )
    {
        LABEL_18:
        result = 0xC0000000;
    }
    else
    {
        switch ( **(_DWORD *) (v2 + 16) )
        {
            case 3:
                result = sub_14000E70(v3, v2);
                break;
            case 0:
                result = sub_14000C340(v3, v2);
                break;
            case 1:
                result = sub_14000C370(v3, v2);
                break;
            case 2:
                result = sub_14000C380(v3, v2);
                break;
            case 4:
                result = sub_14000FB20(v3);
                break;
            case 5:
                result = sub_14000D880(v3, v2);
                break;
            case 6:
                result = sub_14000CAC0(v3, v2);
                break;
            case 7:
                result = sub_14000CB20(v3, v2);
                break;
            case 8:
                result = sub_14000CB60(v3, v2);
                break;
            case 9:
                result = sub_14000C870(v3, v2);
                break;
            case 0xA:
                result = sub_14000C390(v3, v2);
                break;
            case 0xB:
                result = sub_14000CFE0(v3, v2);
                break;
            case 0xC:
                result = sub_14000ED50(v3, v2);
                break;
            case 0xD:
                result = sub_14000D800(v3, v2);
                break;
            case 0xE:
                result = sub_14000EDD0(v3, v2);
                break;
            default:
                goto LABEL_18;
        }
    }
    return result;
}
```


WDDM kmd Driver – Reverse Engineering

- Functions (e.g. DxgkDdiEscape) tend to return STATUS_INVALID_PARAMETER (0xc000000d) when userland provided data couldn't be parsed
 - Return value gets picked by driver
 - If you see this often/constantly during fuzzing, it's usually a sign you've hit some kind of validation/checksum.
 - Dig into assembly to figure out why, and adjust your fuzzer accordingly.

Q&A