BLUEHAT

IL 2022

Hyntrospect: a Fuzzer for Hyper-V Devices

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Whoami

- Security Engineer at Google
- Research project done as a 20% with Project Zero

- Passionate about vulnerability research on systems
- Active member of Women in Security networks
- 🐦 @0xdidu

Why Hyper-V?

Microsoft
Hyper-V

- Project Zero mission
- Running on

Azure

- … and because virtualization is a fun topic
  - Multiple layers from hardware to high level software
  - Complex implementations

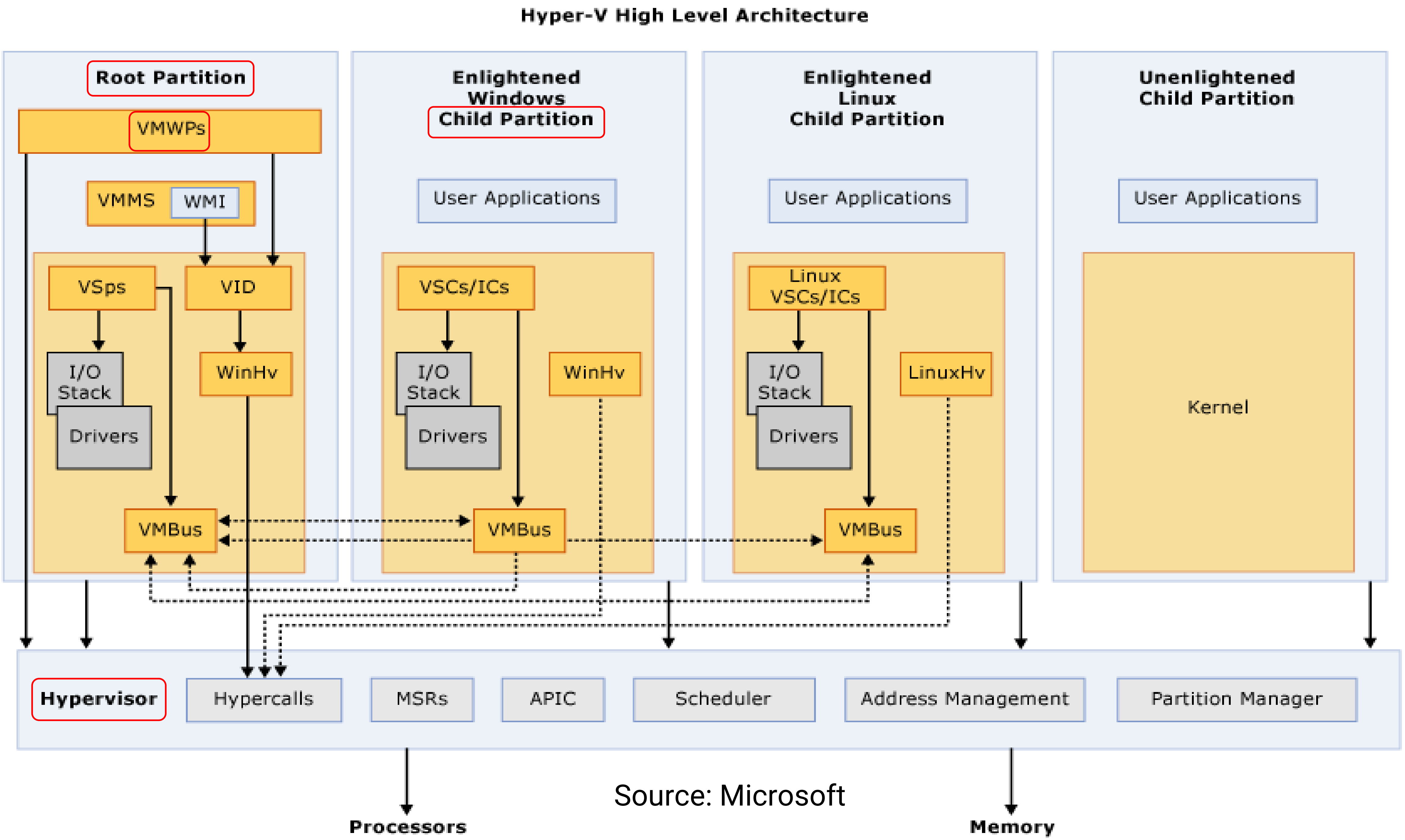
Goals

- Instrumenting Hyper-V for vulnerability research
  - Fuzzer called Hyntrospect: https://github.com/googleprojectzero/Hyntrospect
- Finding vulnerabilities and reporting them to Microsoft

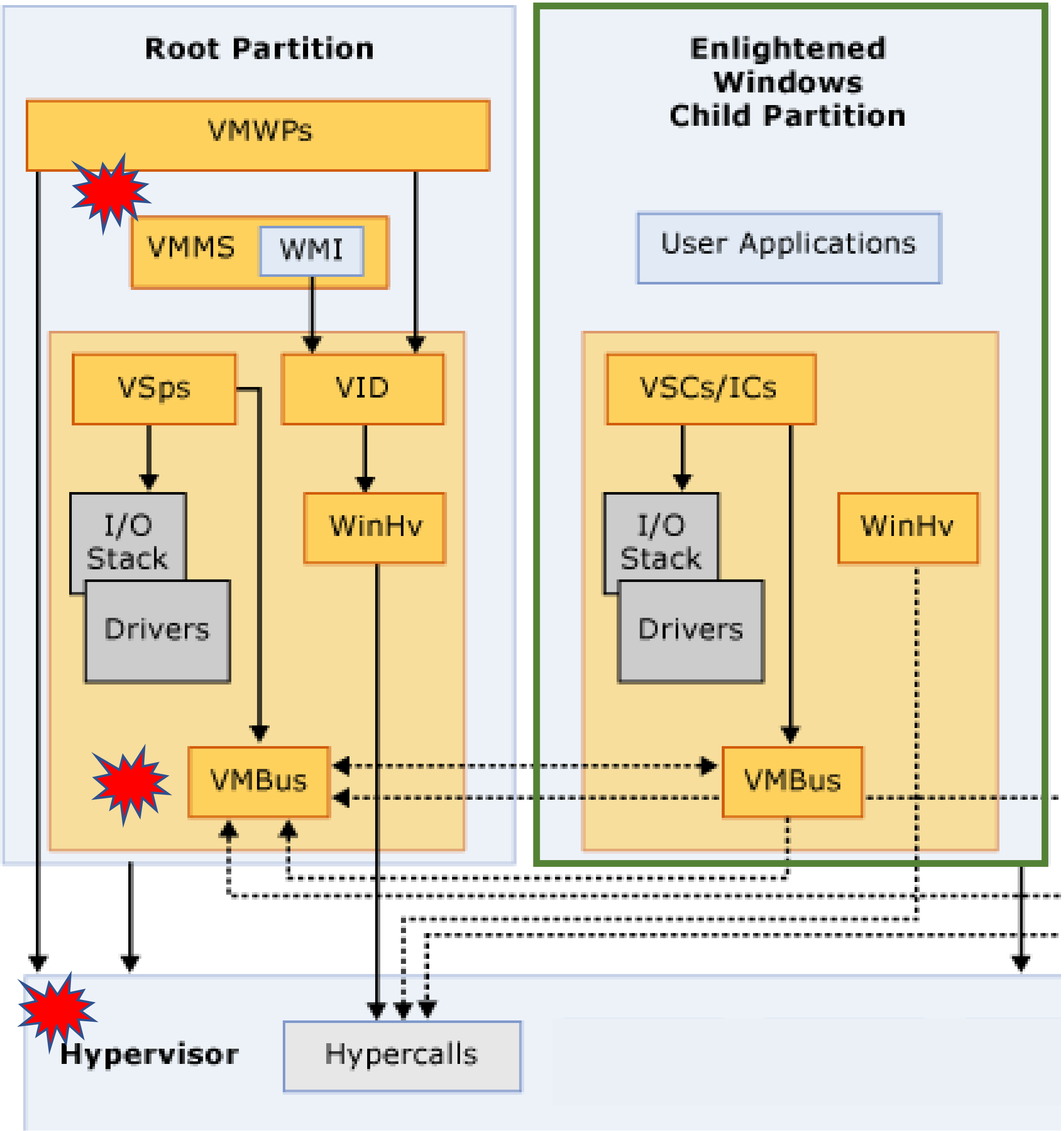
Agenda

- Background on Hyper-V
- The Research Target
- Hyntrospect Fuzzer
- Current Results
- Future Endeavors

Background on Hyper-V



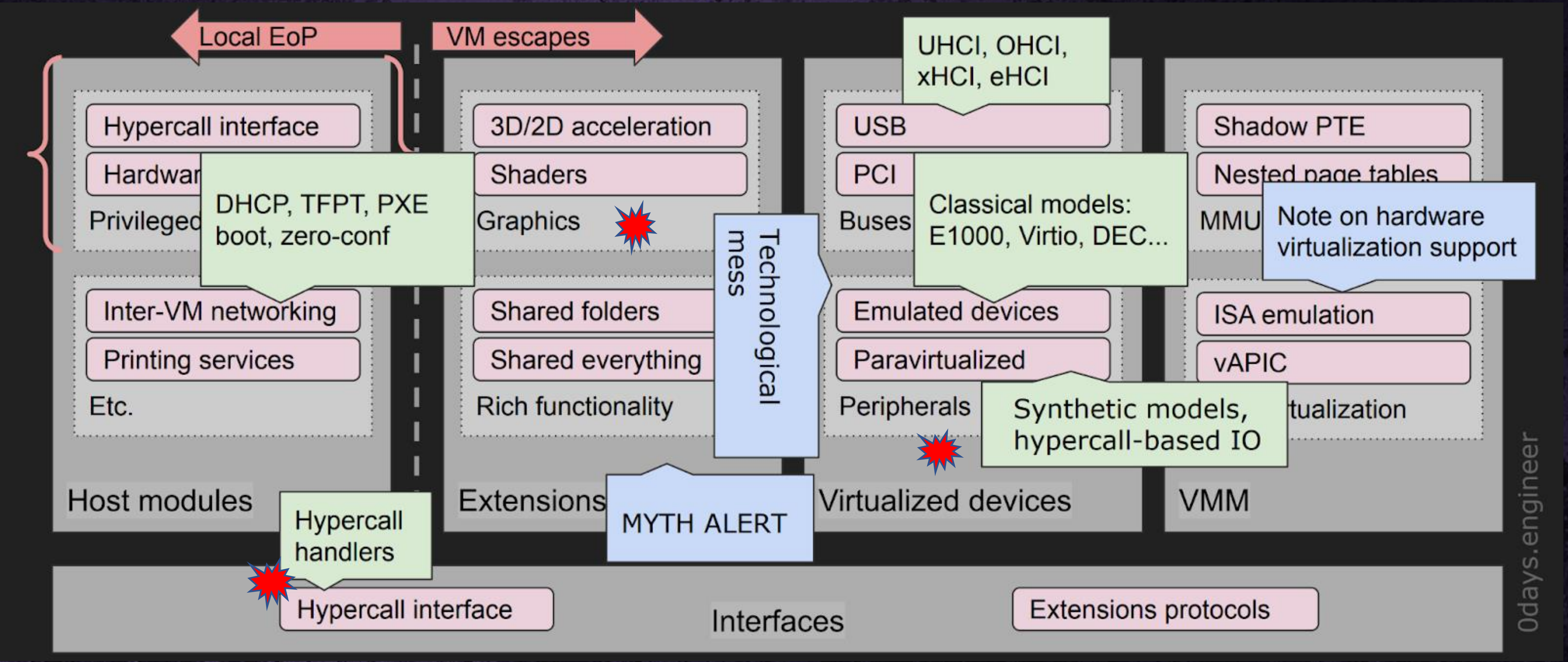
Source: Microsoft



What is a Guest to Host Escape?

- Gaining **code execution** on one of the **hypervisor layers from a virtual machine**
- On Hyper-V: several layers
- Also Host denial of service, leaks …

The Hypervisors’ Attack Surface



Local EoP

VM escapes

Host modules

Hypercall interface

Hardwar

Privileged

DHCP, TFPT, PXE boot, zero-conf

Inter-VM networking

Printing services

Etc.

Extensions

3D/2D acceleration

Shaders

Graphics

Shared folders

Shared everything

Rich functionality

Technological mess

MYTH ALERT

Virtualized devices

UHCI, OHCI, xHCI, eHCI

USB

PCI

Buses

Classical models: E1000, Virtio, DEC...

Emulated devices

Paravirtualized

Peripherals

Synthetic models, hypercall-based IO

VMM

Shadow PTE

Nested page tables

MMU

Note on hardware virtualization support

ISA emulation

vAPIC

tualization

Interfaces

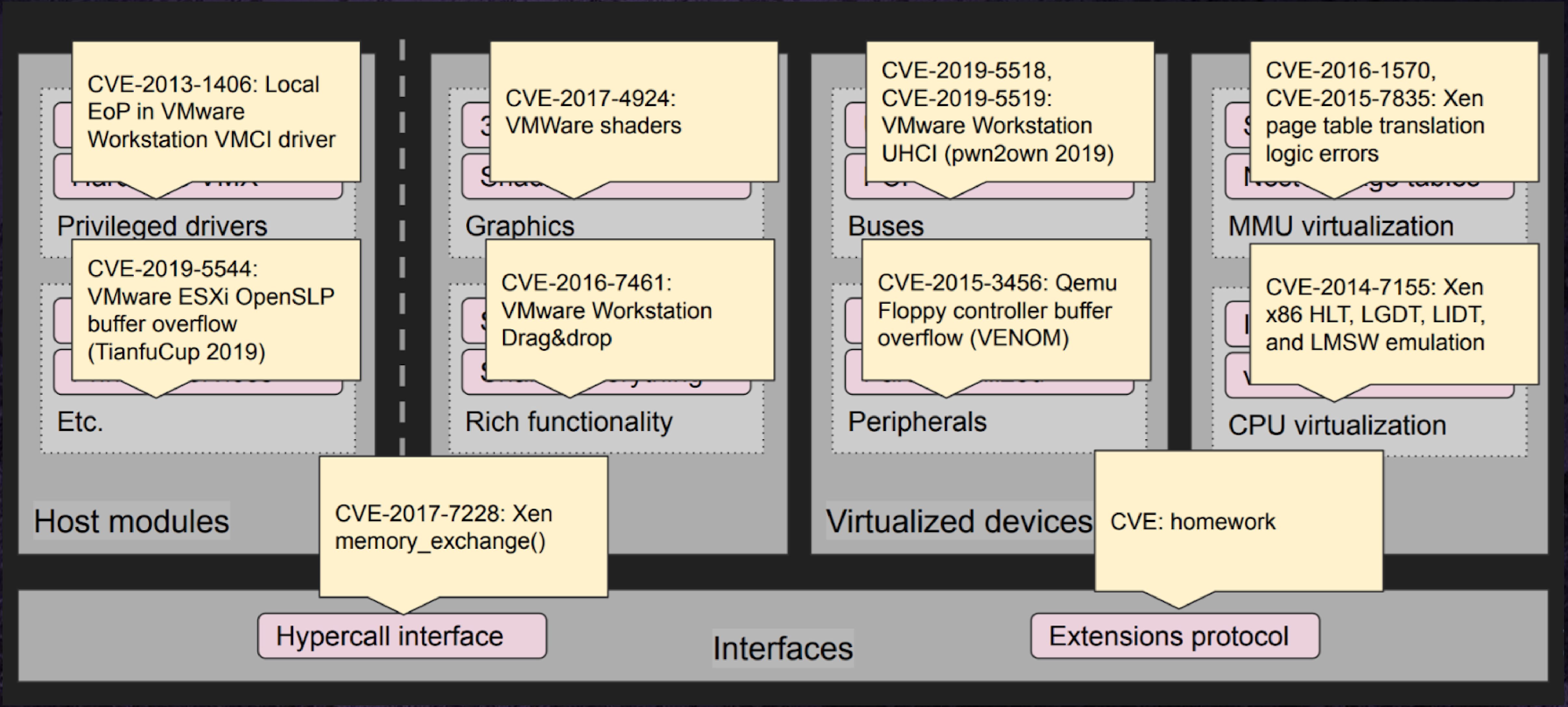
Hypercall handlers

Hypercall interface

Extensions protocols

As defined by Alisa Esage (Zer0Con 2020)

...and in practice



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

CVE-2017-4924: VMWare shaders

CVE-2019-5518, CVE-2019-5519: VMware Workstation UHCI (pwn2own 2019)

CVE-2016-1570, CVE-2015-7835: Xen page table translation logic errors

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

CVE-2016-7461: VMware Workstation Drag&drop

CVE-2015-3456: Qemu Floppy controller buffer overflow (VENOM)

CVE-2014-7155: Xen x86 HLT, LGDT, LIDT, and LMSW emulation

CVE-2017-7228: Xen memory_exchange()

CVE: homework

Hyper-V Attack Surface

Hypervisor

- Hypercall handlers
- Faults
- Instruction emulation
- Intercepts
- Register access (MSRs...)

Root partition

- Kernel
  - VMBus
  - Drivers (storage…)
- Userland
  - Emulated devices
  - Integration components

… and this list is not exhaustive

MSRC: first-steps-in-hyper-v-research

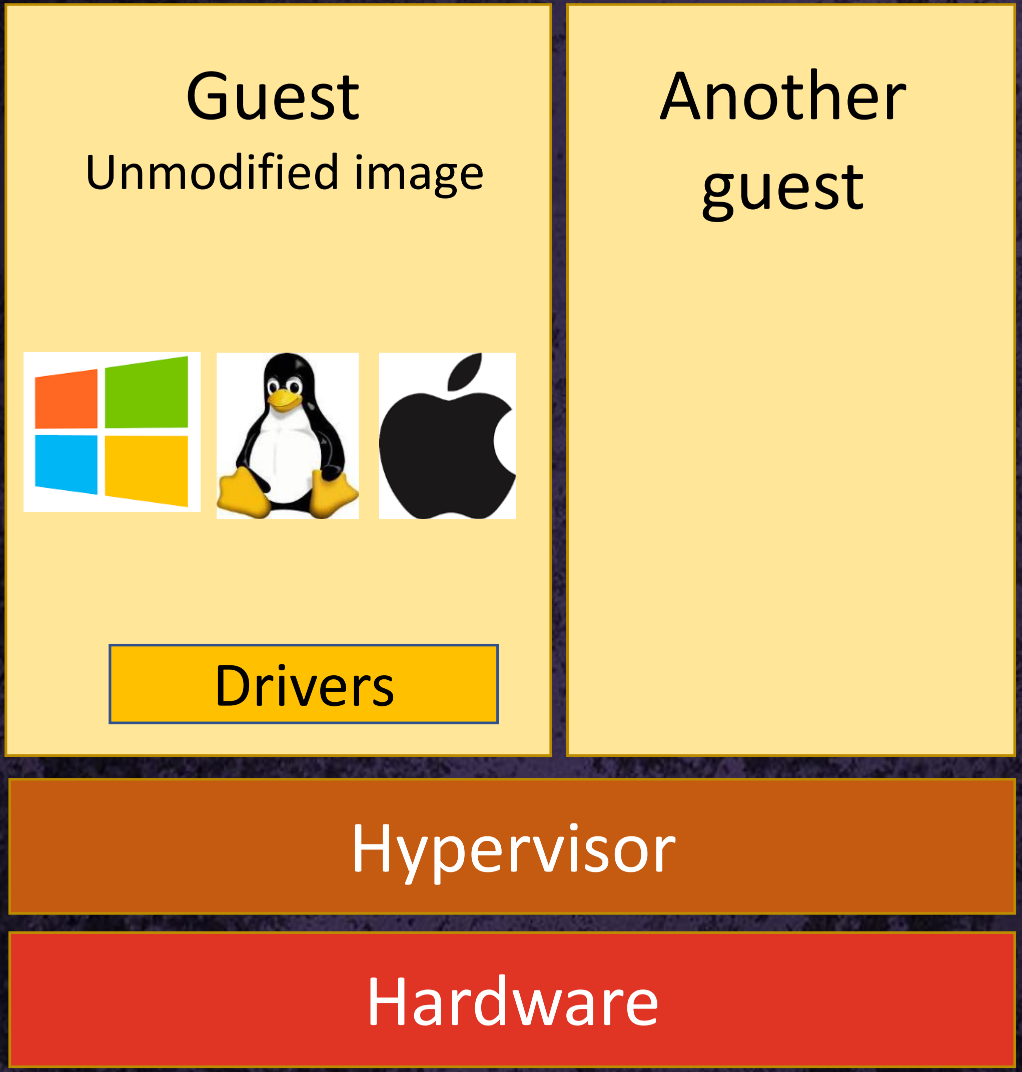
Research - State of the Art

- MSRC and Microsoft publish on Hyper-V
  - Security blog posts: e.g. First Steps in Hyper-V research
  - Posts on Hyper-V components
  - Talks on vulnerabilities found internally
    e.g. Breaking VSM by Attacking SecureKernel at BlackHatUSA 2020
  - Symbols for some key components

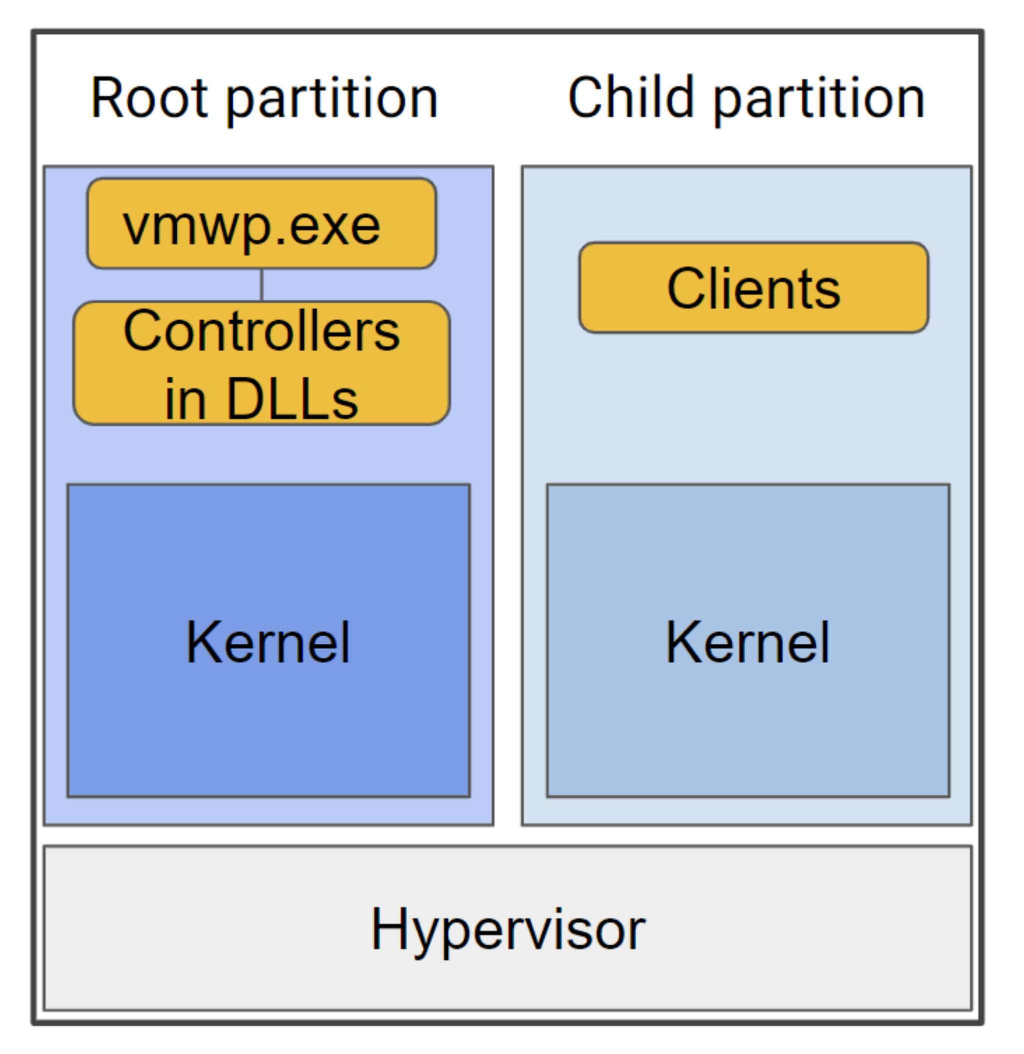
- Active external contributors: @gerhart_x, @alisaesage, @erynian…
  And many more (GitHub/gerhart01/Hyper-V-Internals)

The Research Target

The Emulated Devices Controllers



- Access by the VM to the hardware
- Emulation of hardware controller by the hypervisor
  - Hypervisor as a proxy
  - Guest operating systems unmodified
- Called “virtual devices” or “VDEVs” at Microsoft



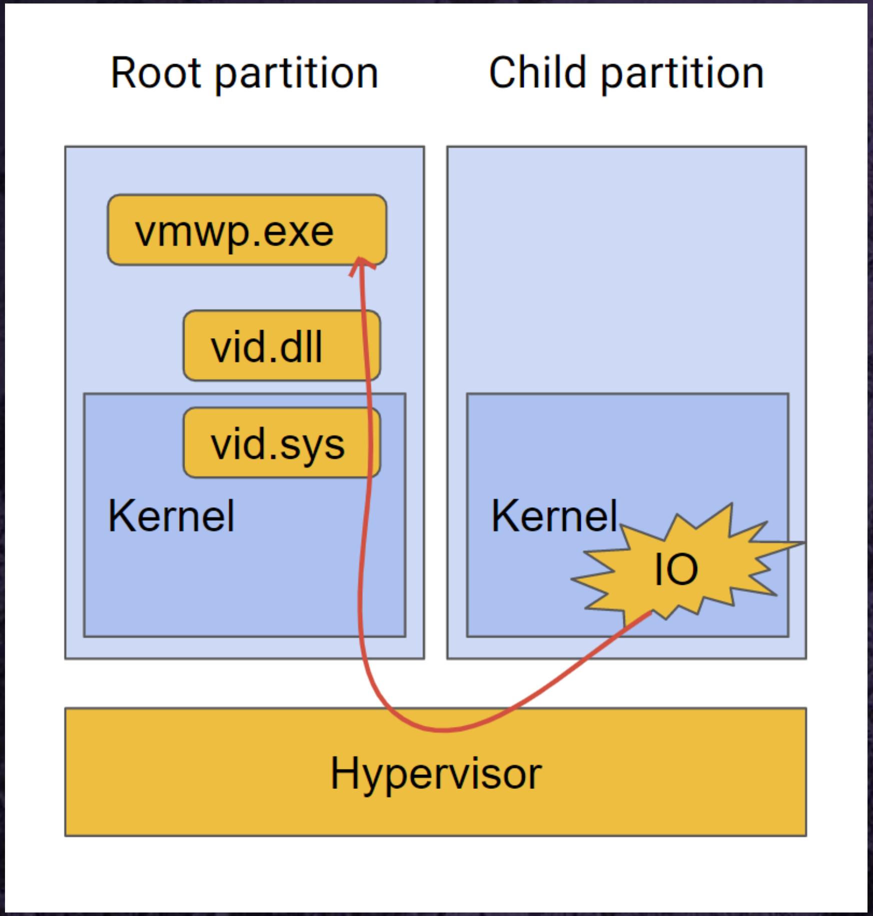
...on Hyper-V

- Generation 1 VMs
  - Azure mostly uses this generation
- Userland of the root partition
- DLLs loaded by the worker process

Why Choose the Emulated Devices

- Complex (state machines)
  - For example: enable / disable ports, update a status register, wait for a command
- Several bugs on several hypervisors
- Azure mostly uses Generation 1 VMs
- Hyper-V is developed in C++
- Potential “guest to root partition” escapes

Life of a Request



- Communication through IO ports
  - CPU instructions: IN / OUT
    - “IN EAX, DX”
    - “OUT DX, EAX”

- Communication through the hypervisor, the VID, and callbacks

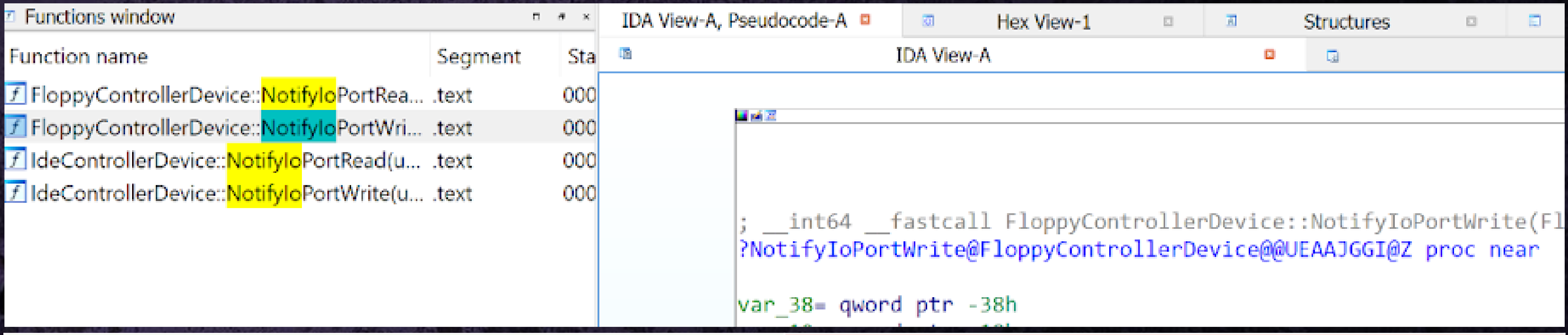
- Some VDEVs are more complex
  - MMIO handling
  - Use of the VMBus

- More on MSRC blogpost “Attacking the VM worker process”

Some Reverse Engineering

- DLL implementing the controllers
- Typical IO handlers
  - $Device::NotifyIOPortRead
  - $Device::NotifyIOPortWrite

Example: VmEmulatedStorage.dll



Function name	Segment	Sta
FloppyControllerDevice::NotifyIoPortRea...	.text	000
FloppyControllerDevice::NotifyIoPortWri...	.text	000
IdeControllerDevice::NotifyIoPortRead(u...	.text	000
IdeControllerDevice::NotifyIoPortWrite(u...	.text	000

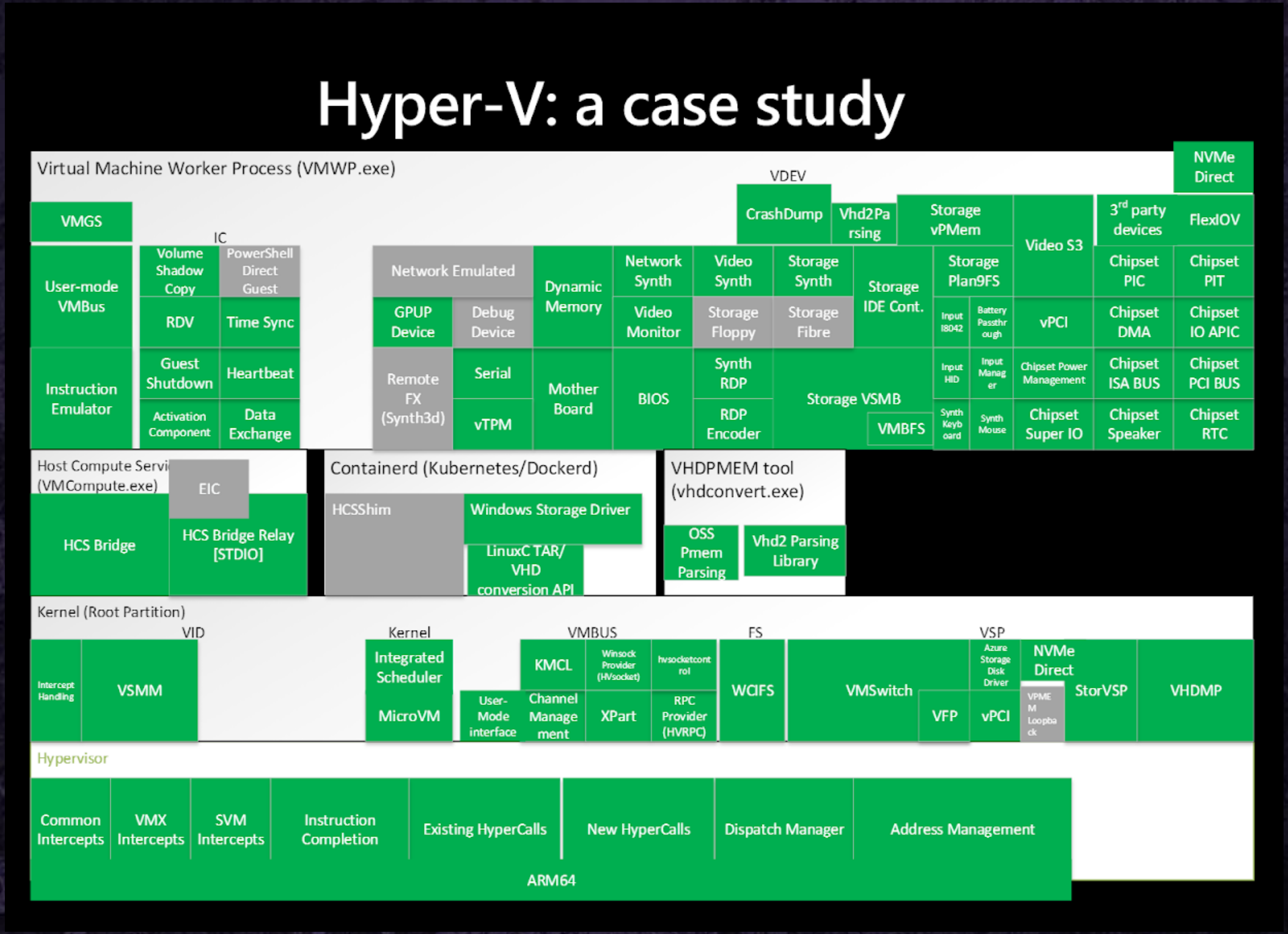
```
; __int64 __fastcall FloppyControllerDevice::NotifyIoPortWrite(Fl
?NotifyIoPortWrite@FloppyControllerDevice@@UEAAJGGI@Z proc near

var_38= qword ptr -38h
```

+	-
Symbols No particular difficulty (obfuscation…)	C++, indirect calls

Hyntrospect: A Fuzzer for the Emulated Devices

https://github.com/googleprojectzero/Hyntrospect

Inspiration


Hyper-V: a case study

- libFuzzer:
  Coverage-guided approach
- Microsoft publication on their coverage (Keeping Windows Secure - Bluehat IL 2019)
- CVE-2018-0959 + Dedicated MSRC blogpost

➡ How to do the same, closed source?

Existing Tools for Windows Binaries Fuzzing

Gathering Coverage	**Fuzzers**	**Memory Corruption Detection**
• DynamoRIO • Intel Pin • Intel PT • Mesos • QDBI for Windows • TinyInst	• WinAFL + DynamoRIO • Jackalope • whvp	PageHeap

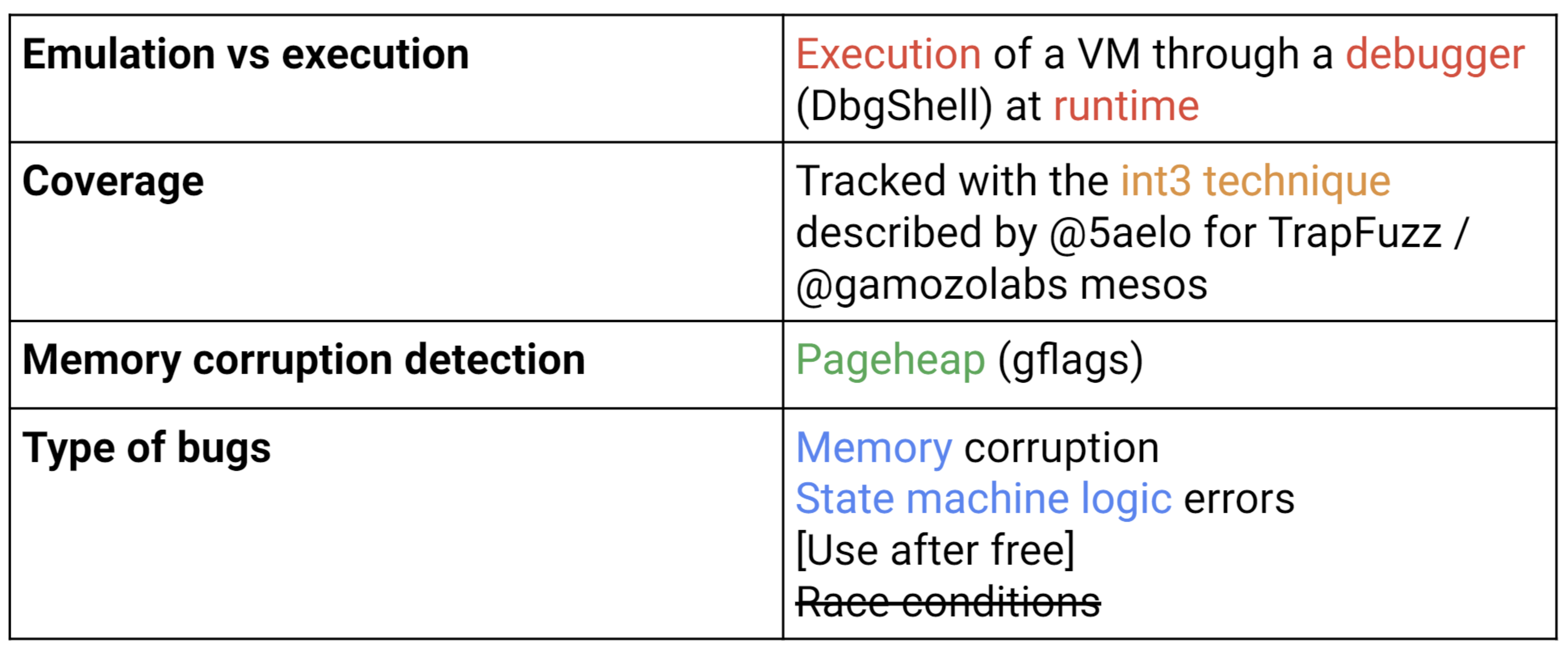
So Why Another Tool?

- The target is a DLL
- Emulating only the relevant functions is hard
- vmwp binary and the DLL cannot be restarted with instrumentation
- The runtime operations are specific: IOs injections
- Some tools were developed during Hyntrospect development
- Managing all the blocks with a minimal set of languages is hard
- The fuzzer will be ported to similar use cases

Scope

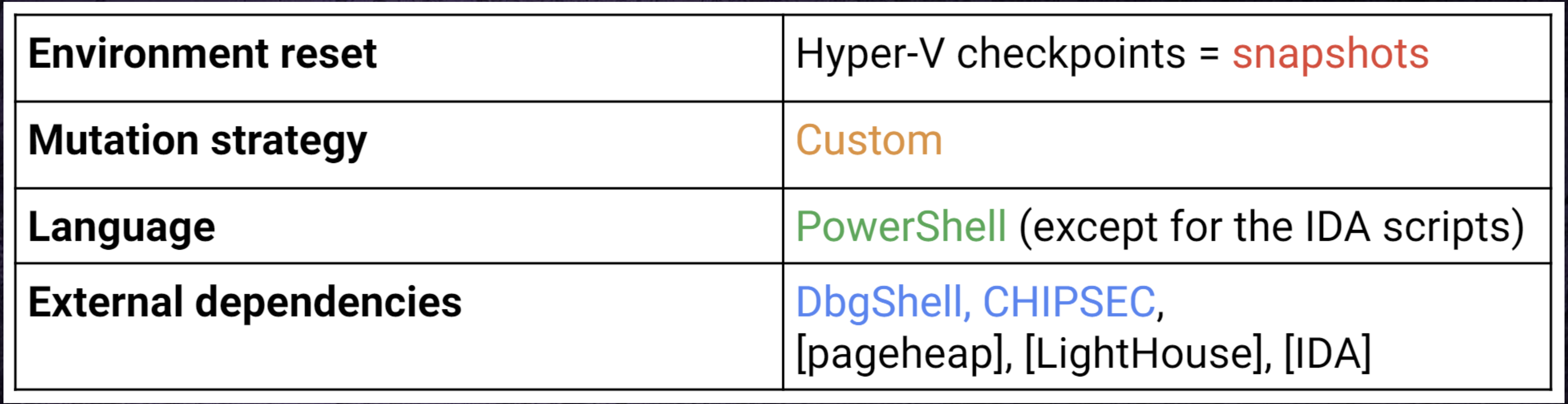
- Windows guest VM
- Intel CPU
- Generation 1VMs
- Binaries (DLLs/EXEs) in the userland of the root partition

Design Choices at a Glance



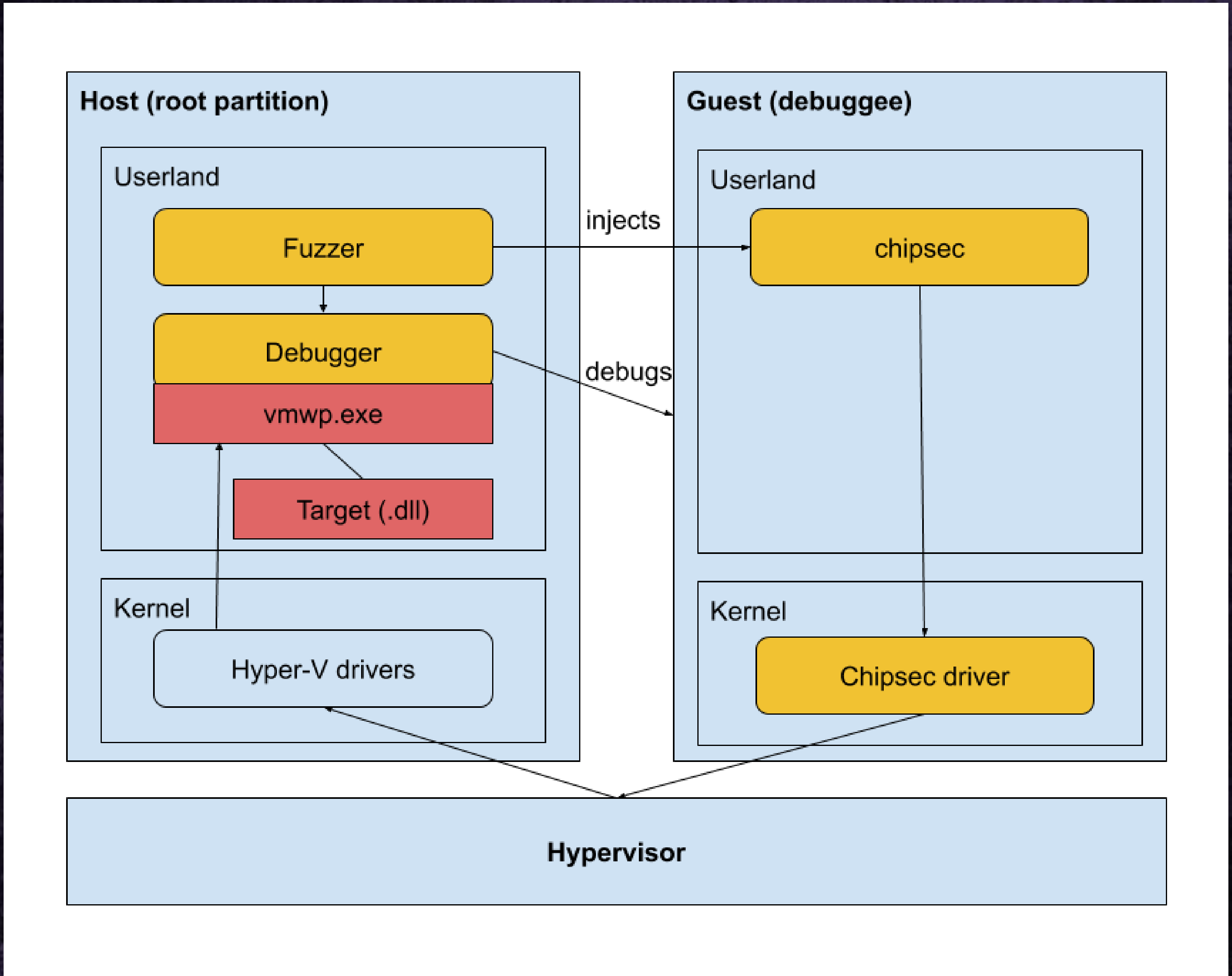
Emulation vs execution	Execution of a VM through a debugger (DbgShell) at runtime
Coverage	Tracked with the int3 technique described by @5aelo for TrapFuzz / @gamozolabs mesos
Memory corruption detection	Pageheap (gflags)
Type of bugs	Memory corruption State machine logic errors [Use after free] ~~Race conditions~~

Design Choices at a Glance

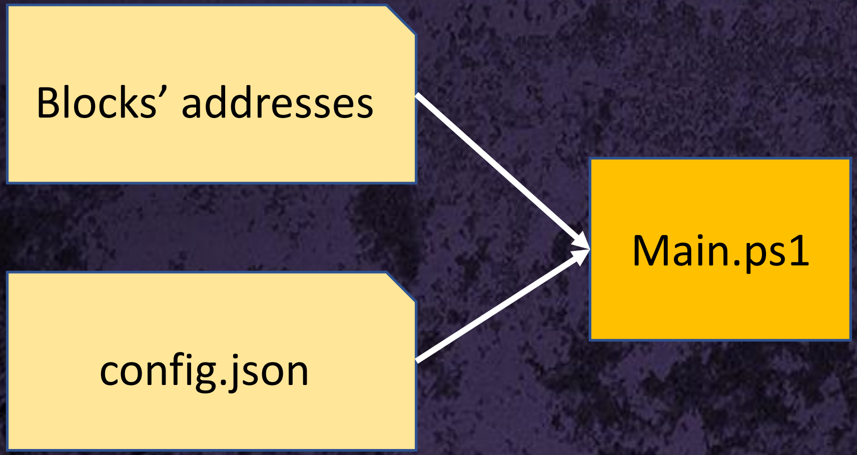


Environment reset	Hyper-V checkpoints = snapshots
Mutation strategy	Custom
Language	PowerShell (except for the IDA scripts)
External dependencies	DbgShell, CHIPSEC, [pageheap], [LightHouse], [IDA]

Overview of Hyntrospect



Workflow

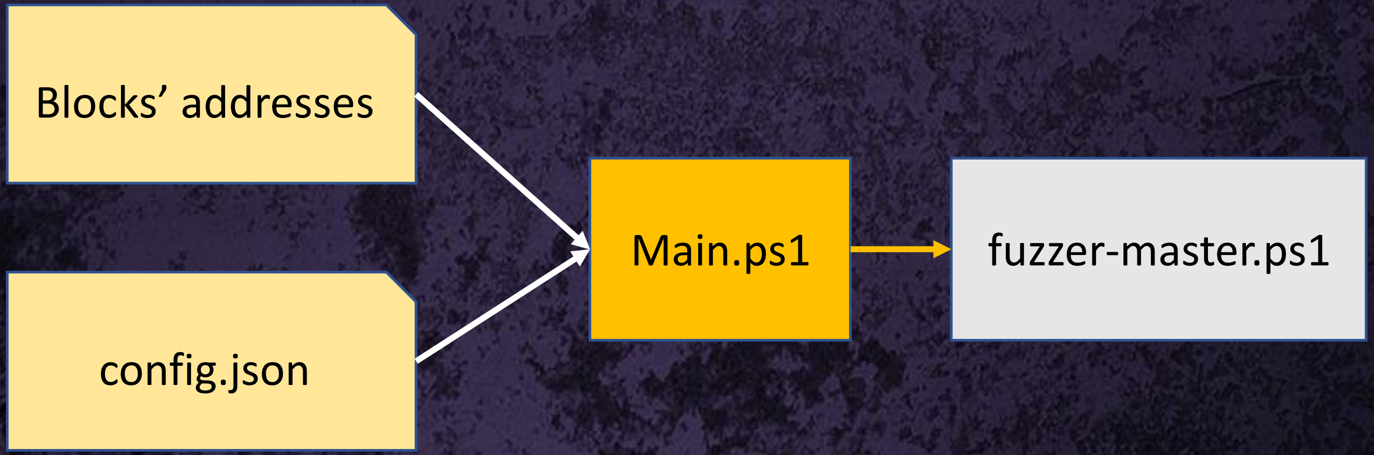


Blocks’ addresses

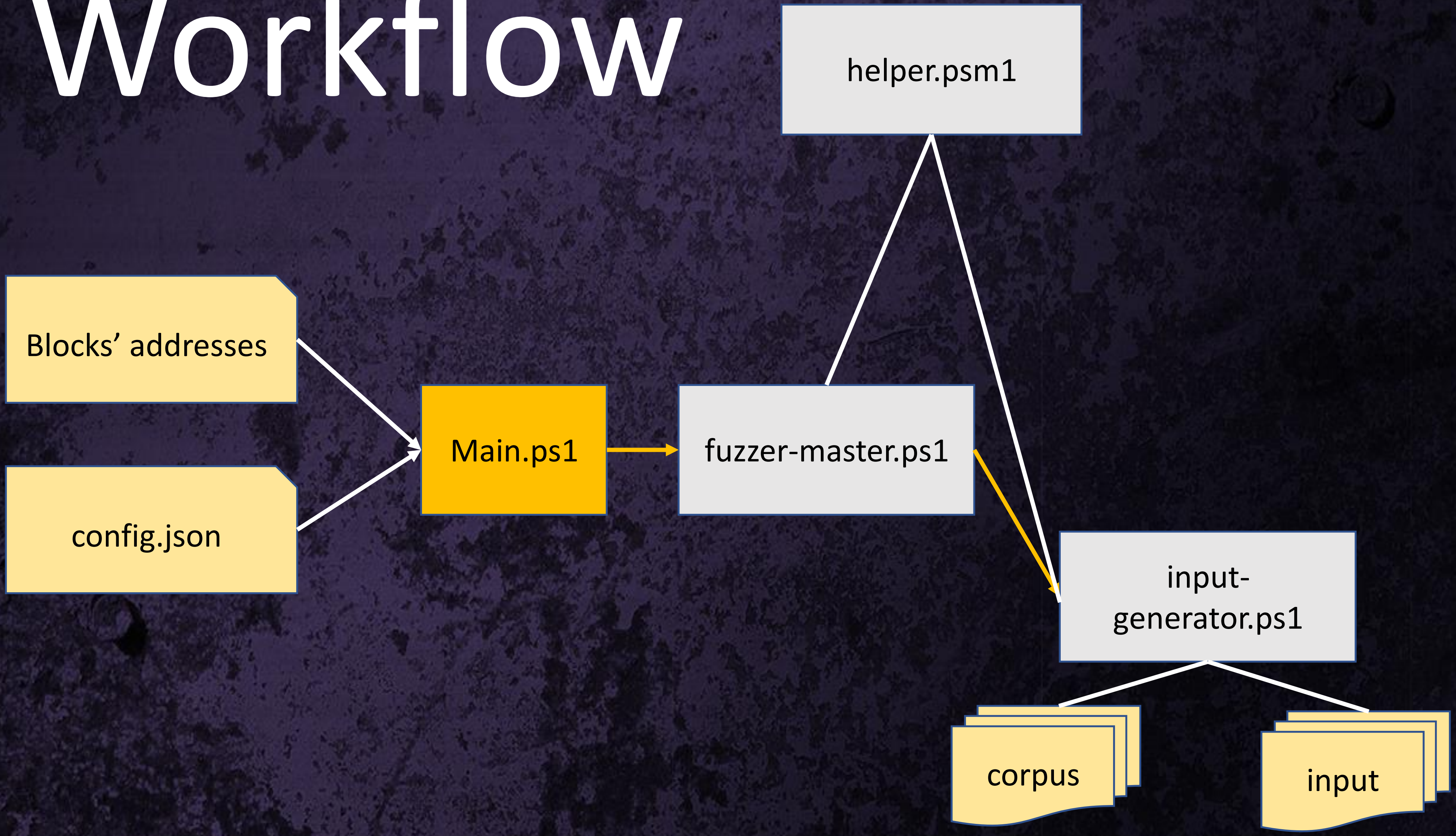
config.json

Main.ps1

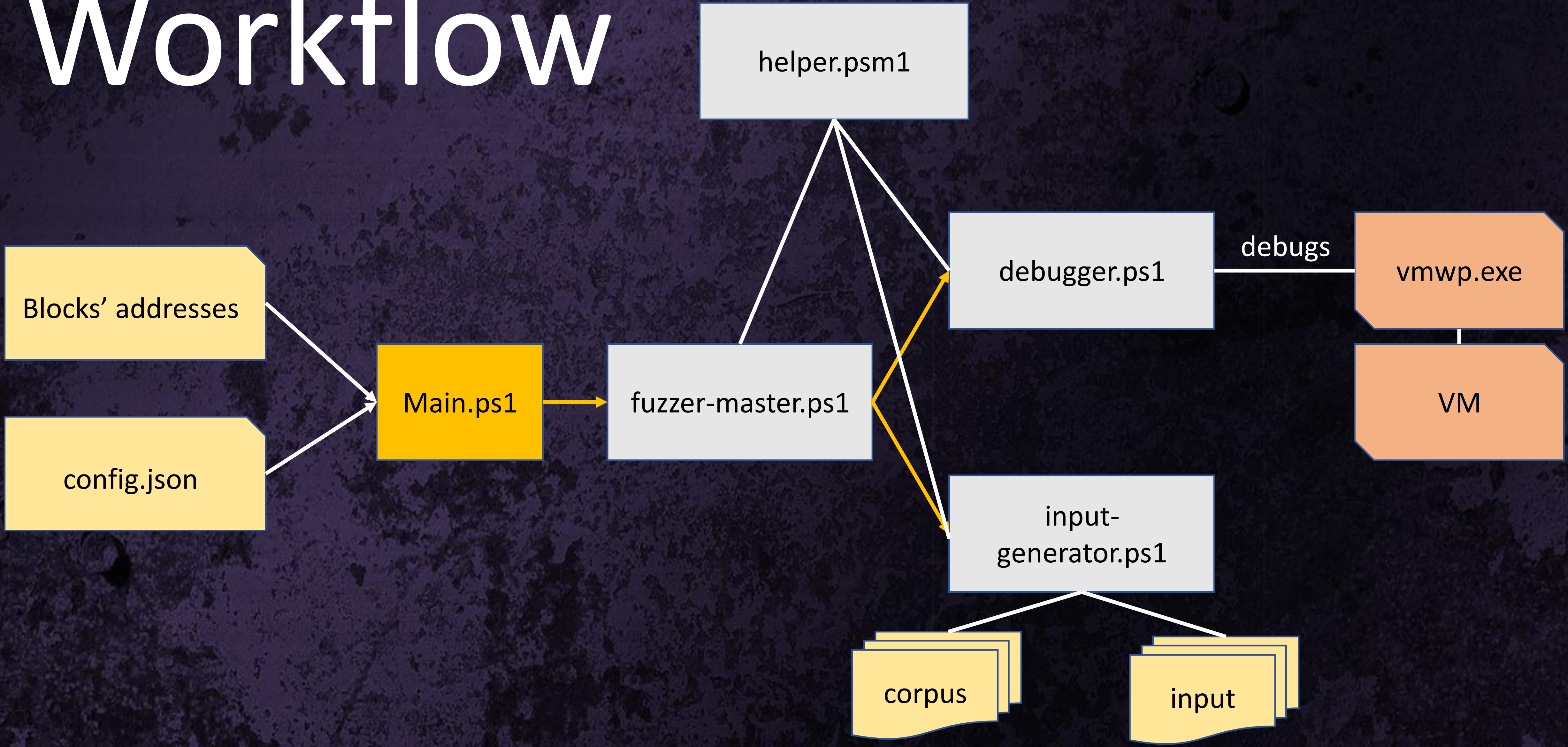
Workflow



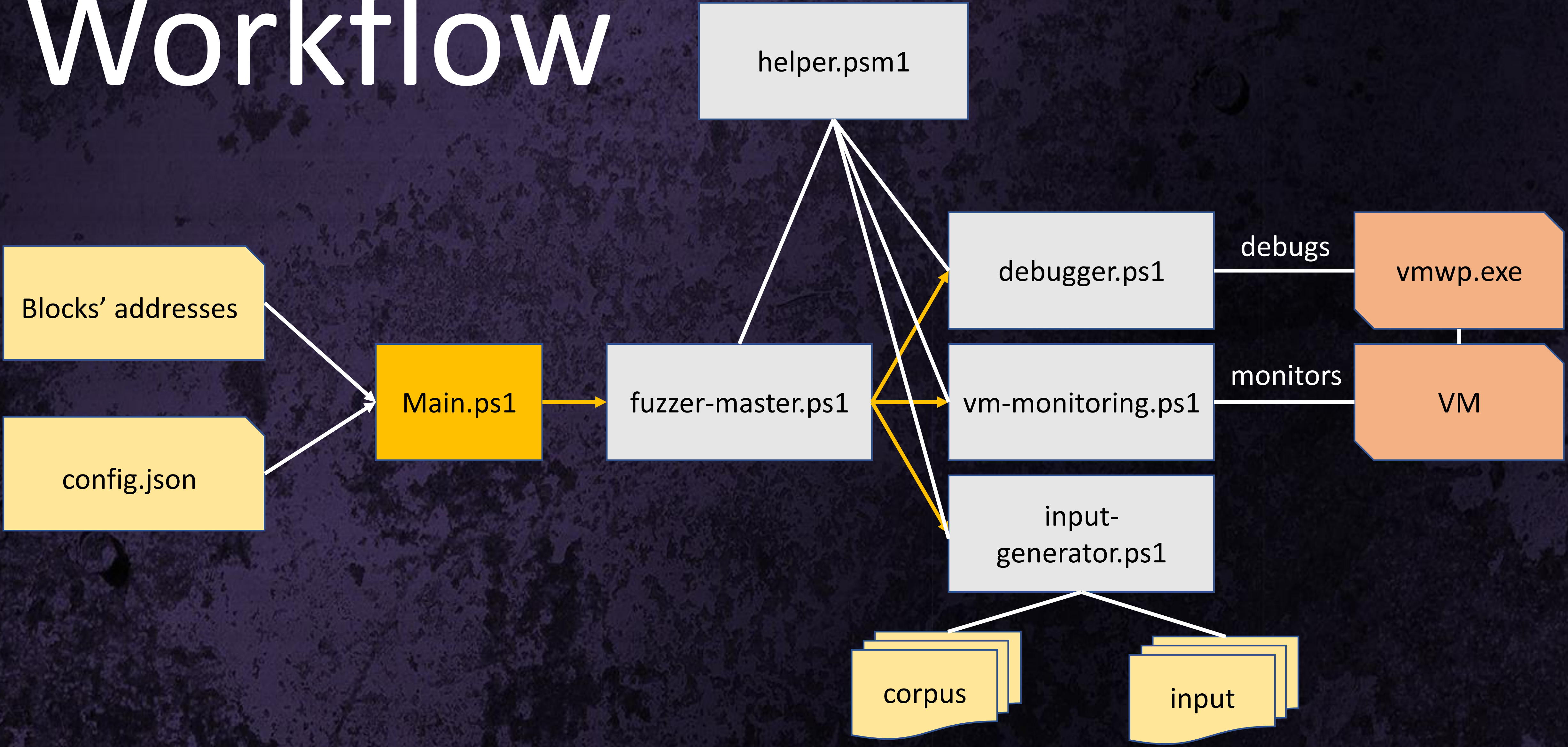
Workflow


helper.psm1
Blocks’ addresses
Main.ps1
fuzzer-master.ps1
config.json
input-generator.ps1
corpus
input

Workflow

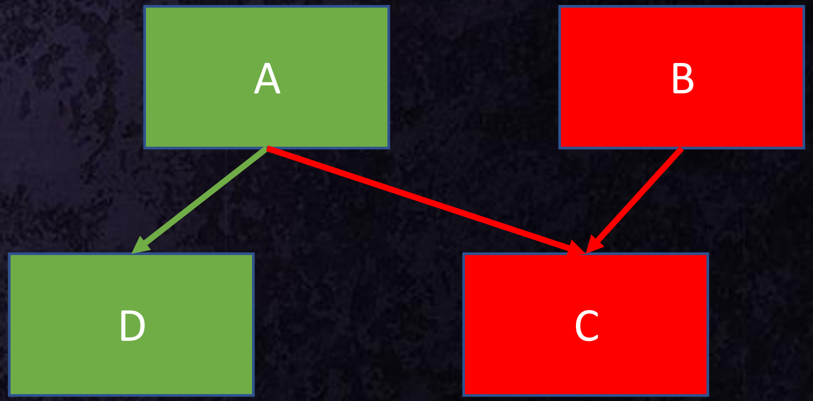

helper.psm1
Blocks' addresses
config.json
Main.ps1
fuzzer-master.ps1
debugger.ps1
debugs
vmwp.exe
VM
input-generator.ps1
corpus
input

Workflow


helper.psm1
Blocks’ addresses
config.json
Main.ps1
fuzzer-master.ps1
debugger.ps1
debugs
vmwp.exe
vm-monitoring.ps1
monitors
VM
input-generator.ps1
corpus
input

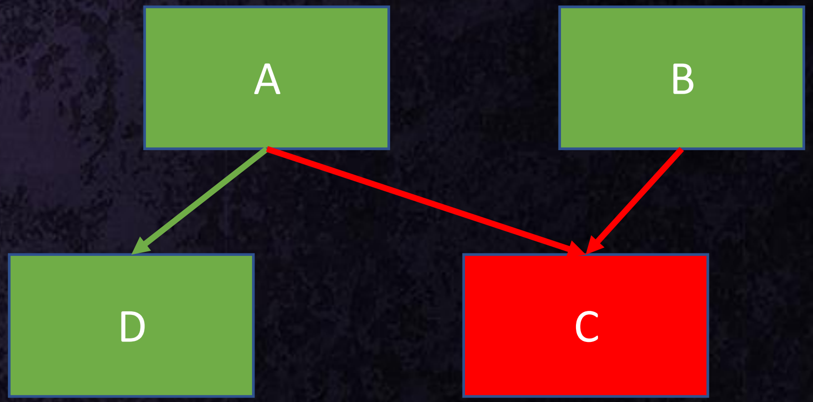
Coverage collection and guidance

- Block coverage



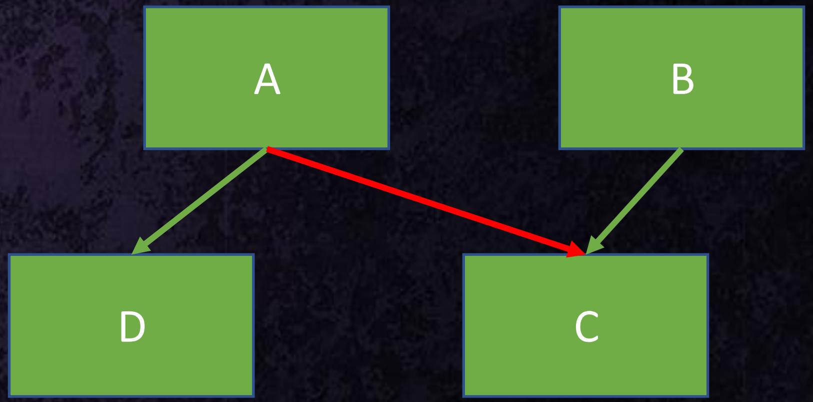
Coverage collection and guidance

- Block coverage



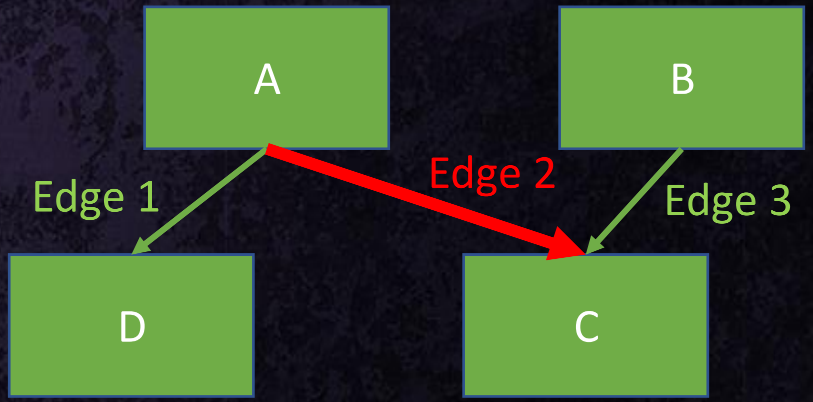
Coverage collection and guidance

- Block coverage



Coverage collection and guidance

- Block coverage
  - Versus edge coverage: easier to implement but does not promote rare paths
  - No counter



int3 technique

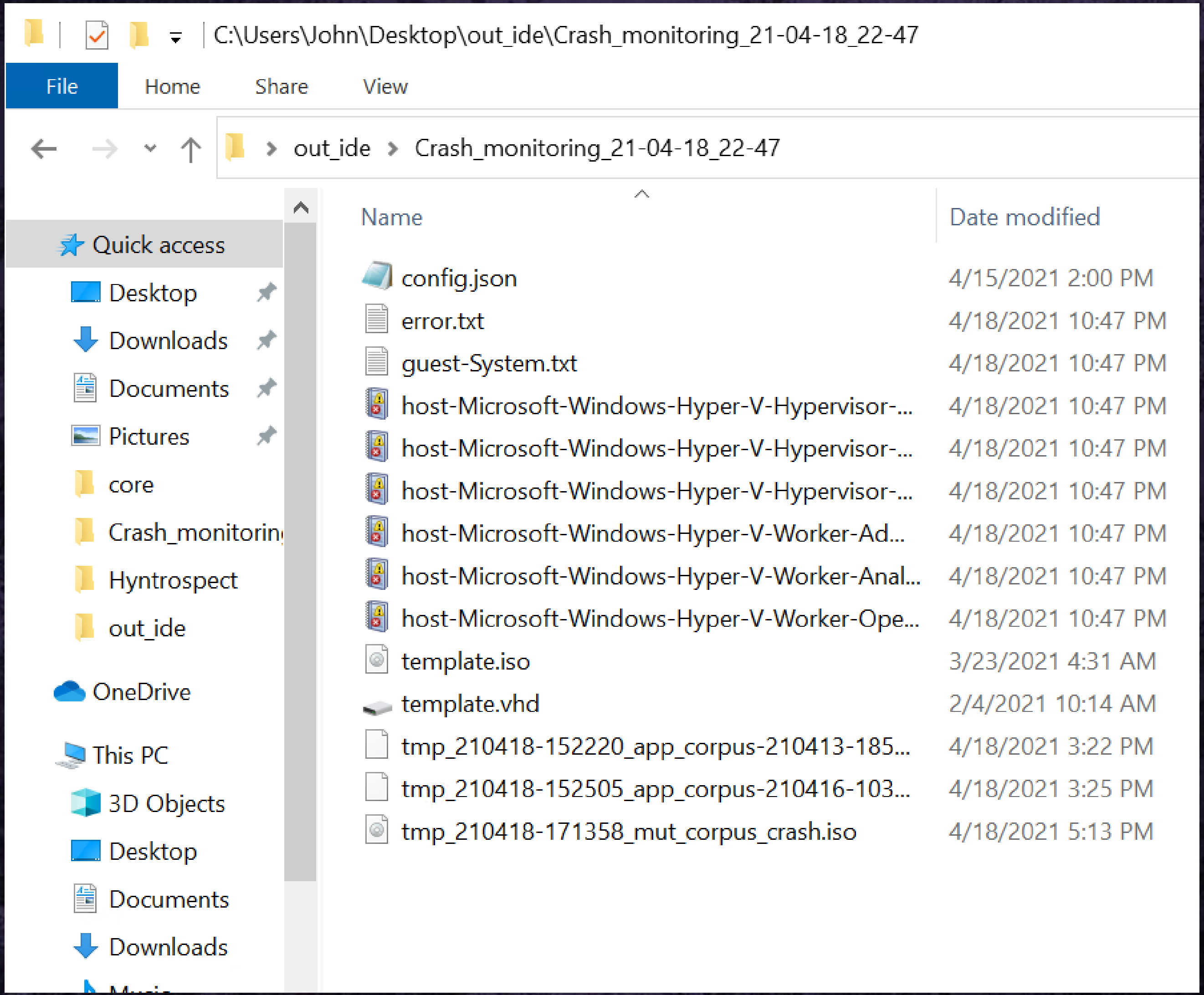
- Pre-compute the list of targeted blocks’ addresses
- Set int3 at the beginning of each block
- Each int3 reached = coverage increase
- The int3 is removed, input file handled, execution resumes
- Faster over time

Generation of the Input File

- Record of seeds at the beginning [optional]
- Corpus of "interesting files"
- Coverage increase -> truncated input file added to the corpus
- 3 strategies: mutate, append, generate randomly

- Format of input files
  - Byte 0 % 2 -> IN / OUT operation
  - Byte 1 % (number of ports) -> selected IO port
  - Byte 2 % 3 -> length
  - If OUT and based on length -> value

Crash Qualification



C:\Users\John\Desktop\out_ide\Crash_monitoring_21-04-18_22-47

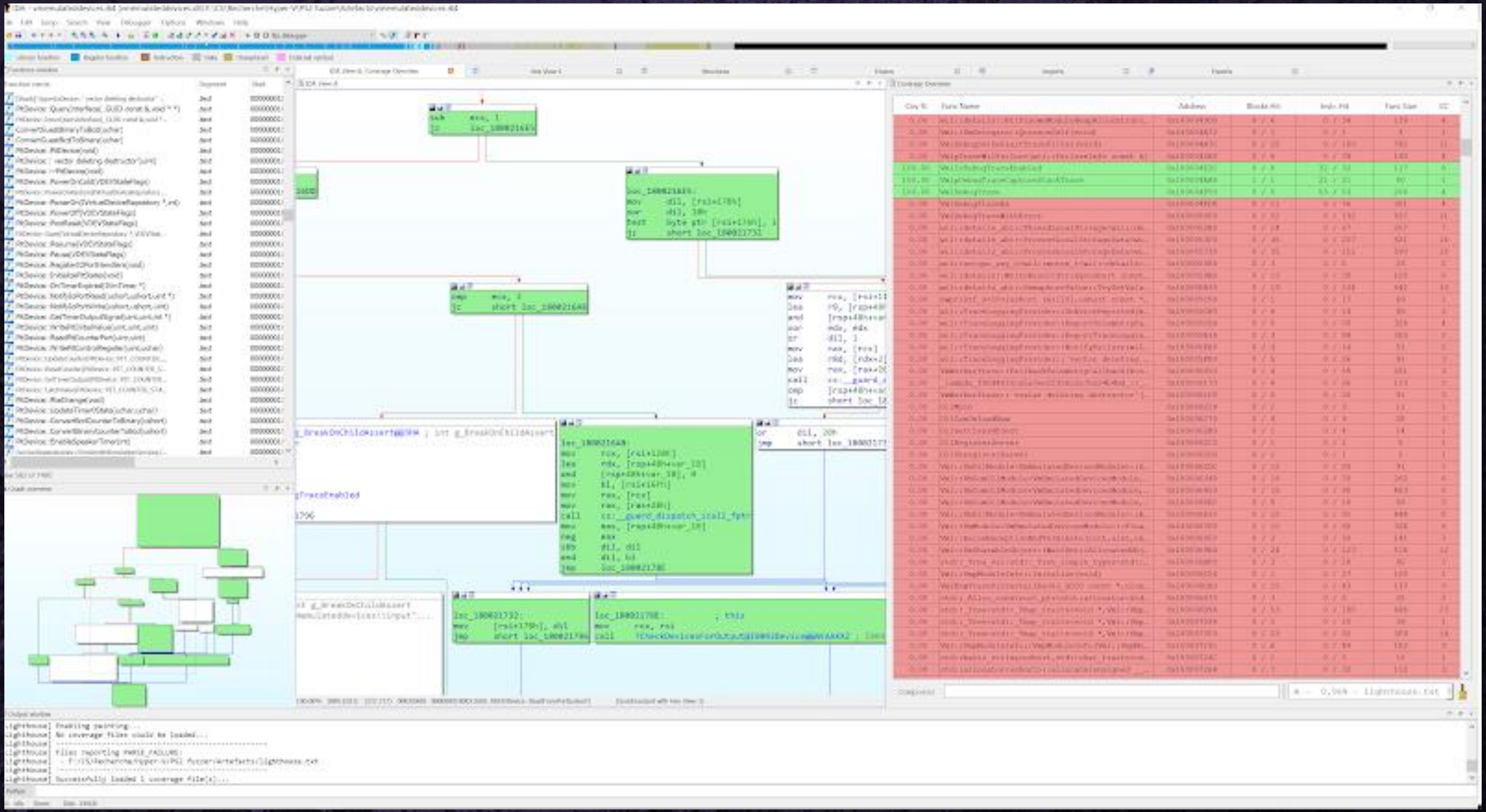
out_ide > Crash_monitoring_21-04-18_22-47

Name	Date modified
config.json	4/15/2021 2:00 PM
error.txt	4/18/2021 10:47 PM
guest-System.txt	4/18/2021 10:47 PM
host-Microsoft-Windows-Hyper-V-Hypervisor-...	4/18/2021 10:47 PM
host-Microsoft-Windows-Hyper-V-Hypervisor-...	4/18/2021 10:47 PM
host-Microsoft-Windows-Hyper-V-Hypervisor-...	4/18/2021 10:47 PM
host-Microsoft-Windows-Hyper-V-Worker-Ad...	4/18/2021 10:47 PM
host-Microsoft-Windows-Hyper-V-Worker-Anal...	4/18/2021 10:47 PM
host-Microsoft-Windows-Hyper-V-Worker-Ope...	4/18/2021 10:47 PM
template.iso	3/23/2021 4:31 AM
template.vhd	2/4/2021 10:14 AM
tmp_210418-152220_app_corpus-210413-185...	4/18/2021 3:22 PM
tmp_210418-152505_app_corpus-210416-103...	4/18/2021 3:25 PM
tmp_210418-171358_mut_corpus_crash.iso	4/18/2021 5:13 PM

- 2 levels of monitoring:
  - Debugger level
  - Monitoring process
- Tip: track the VM uptime

- Crash folder created with logs and artefacts to re-run the case

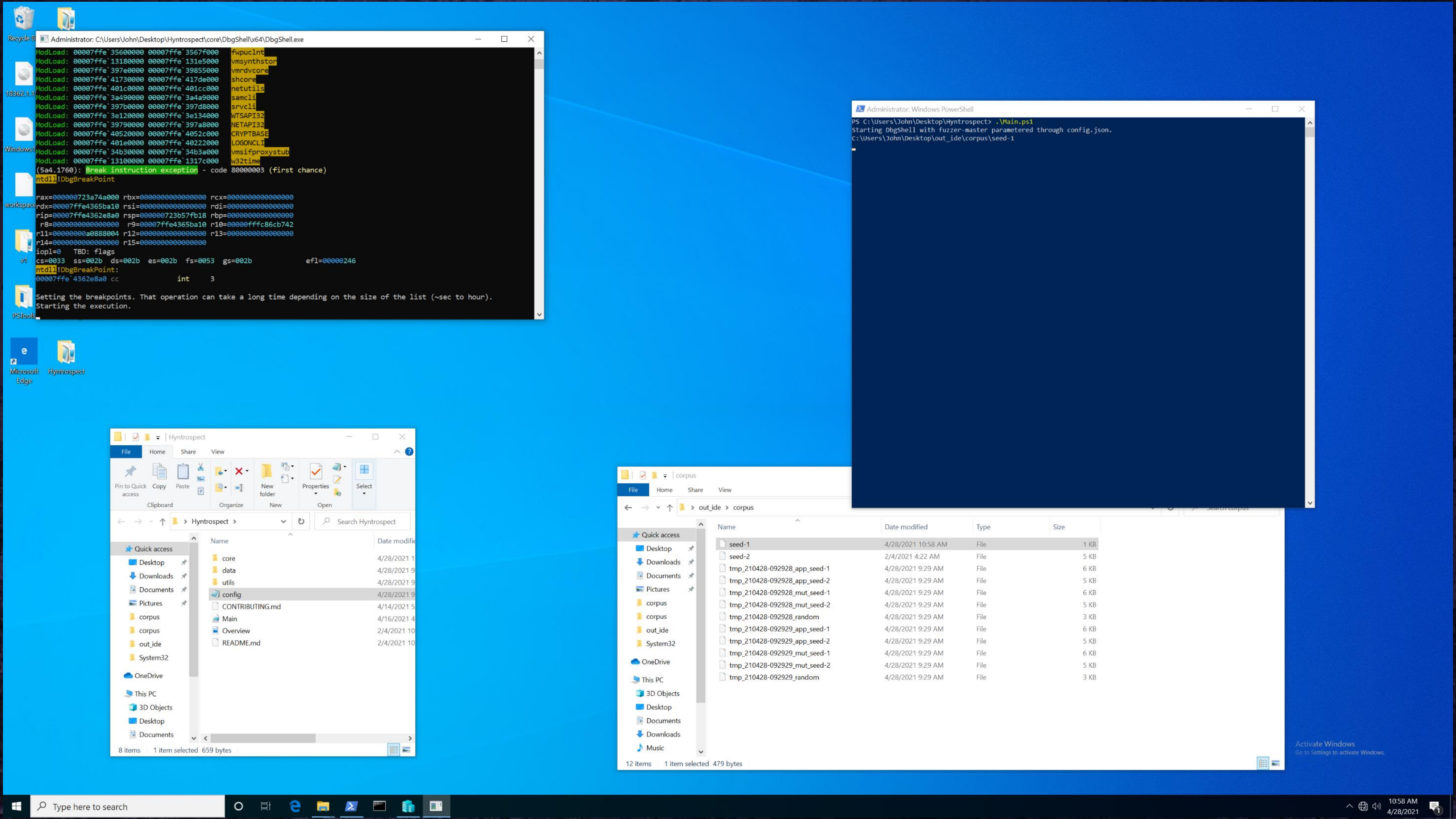
Coverage Visualization in IDA



```
[Lighthouse] Enabling painting...
[Lighthouse] No coverage files could be loaded...
[Lighthouse] ------------------------------------------------
[Lighthouse] Files reporting PARSE_FAILURE:
[Lighthouse]  - F:\IS\Recherche\Hyper-V\PS2 fuzzer\Artefacts\lighthouse.txt
[Lighthouse] ------------------------------------------------
[Lighthouse] Successfully loaded 1 coverage file(s)...
```

Optionally, using a helper and IDA

+ LightHouse



Administrator: C:\Users\John\Desktop\Hyntrospect\core\DbgShell\x64\DbgShell.exe

```
ModLoad: 00007ffe`35600000 00007ffe`3567f000   fwpuclnt
ModLoad: 00007ffe`13180000 00007ffe`131e5000   vmsynthstor
ModLoad: 00007ffe`397e0000 00007ffe`39855000   vmrdvcore
ModLoad: 00007ffe`41730000 00007ffe`417de000   shcore
ModLoad: 00007ffe`401c0000 00007ffe`401cc000   netutils
ModLoad: 00007ffe`3a490000 00007ffe`3a4a9000   samcli
ModLoad: 00007ffe`397b0000 00007ffe`397d8000   srvcli
ModLoad: 00007ffe`3e120000 00007ffe`3e134000   WTSAPI32
ModLoad: 00007ffe`39790000 00007ffe`397a8000   NETAPI32
ModLoad: 00007ffe`40520000 00007ffe`4052c000   CRYPTBASE
ModLoad: 00007ffe`401e0000 00007ffe`40222000   LOGONCLI
ModLoad: 00007ffe`34b30000 00007ffe`34b3a000   vmsifproxystub
ModLoad: 00007ffe`13100000 00007ffe`1317c000   w32time
(5a4.1760): Break instruction exception - code 80000003 (first chance)
ntdll!DbgBreakPoint

rax=000000723a74a000 rbx=0000000000000000 rcx=0000000000000000
rdx=00007ffe4365ba10 rsi=0000000000000000 rdi=0000000000000000
rip=00007ffe4362e8a0 rsp=000000723b57fb18 rbp=0000000000000000
 r8=0000000000000000  r9=00007ffe4365ba10 r10=00000fffc86cb742
r11=00000000a0888004 r12=0000000000000000 r13=0000000000000000
r14=0000000000000000 r15=0000000000000000
iopl=0   TBD: flags
cs=0033  ss=002b  ds=002b  es=002b  fs=0053  gs=002b             efl=00000246
ntdll!DbgBreakPoint:
00007ffe`4362e8a0 cc              int     3

Setting the breakpoints. That operation can take a long time depending on the size of the list (~sec to hour).
Starting the execution.
```

Administrator: Windows PowerShell

```
PS C:\Users\John\Desktop\Hyntrospect> .\Main.ps1
Starting DbgShell with fuzzer-master parametered through config.json.
C:\Users\John\Desktop\out_ide\corpus\seed-1
```

Hyntrospect

Hyntrospect ›

Name	Date modifie
core	4/28/2021 1
data	4/28/2021 9
utils	4/28/2021 9
config	4/28/2021 9
CONTRIBUTING.md	4/14/2021 5
Main	4/16/2021 4
Overview	2/4/2021 10
README.md	2/4/2021 10

8 items   1 item selected 659 bytes

corpus

› out_ide › corpus

Name	Date modified	Type	Size
seed-1	4/28/2021 10:58 AM	File	1 KB
seed-2	2/4/2021 4:22 AM	File	5 KB
tmp_210428-092928_app_seed-1	4/28/2021 9:29 AM	File	6 KB
tmp_210428-092928_app_seed-2	4/28/2021 9:29 AM	File	5 KB
tmp_210428-092928_mut_seed-1	4/28/2021 9:29 AM	File	6 KB
tmp_210428-092928_mut_seed-2	4/28/2021 9:29 AM	File	5 KB
tmp_210428-092928_random	4/28/2021 9:29 AM	File	3 KB
tmp_210428-092929_app_seed-1	4/28/2021 9:29 AM	File	6 KB
tmp_210428-092929_app_seed-2	4/28/2021 9:29 AM	File	5 KB
tmp_210428-092929_mut_seed-1	4/28/2021 9:29 AM	File	6 KB
tmp_210428-092929_mut_seed-2	4/28/2021 9:29 AM	File	5 KB
tmp_210428-092929_random	4/28/2021 9:29 AM	File	3 KB

12 items   1 item selected 479 bytes

Current results

Local runs

- First targets: i8042 (PS/2), videoS3, floppy, IDE
  - Example: I8042 device with IO ports 0x60, 0x61, 0x62, 0x64
- Local setup:
  - Dedicated workstation
  - 32 GB RAM and Intel Core i9 CPU
  - 8 GB per VM, 1 or 2 vCPUs
  - Windows 10
- Speed limitation
  - Main factor: number of breakpoints
  - Time to set them / update them in DbgShell
  - Not linear
- Next goal: port the fuzzer to GCP/Azure

Number of breakpoints	Time to set up the breakpoints in DbgShell at each iteration
150	immediate
500	6 seconds
1000	20 seconds
2000	1 minute 15 seconds

Coverage (3 days run)

vmemulateddevices.dll	Current coverage
VideoS3Device	42.7%
i8042Device	40%

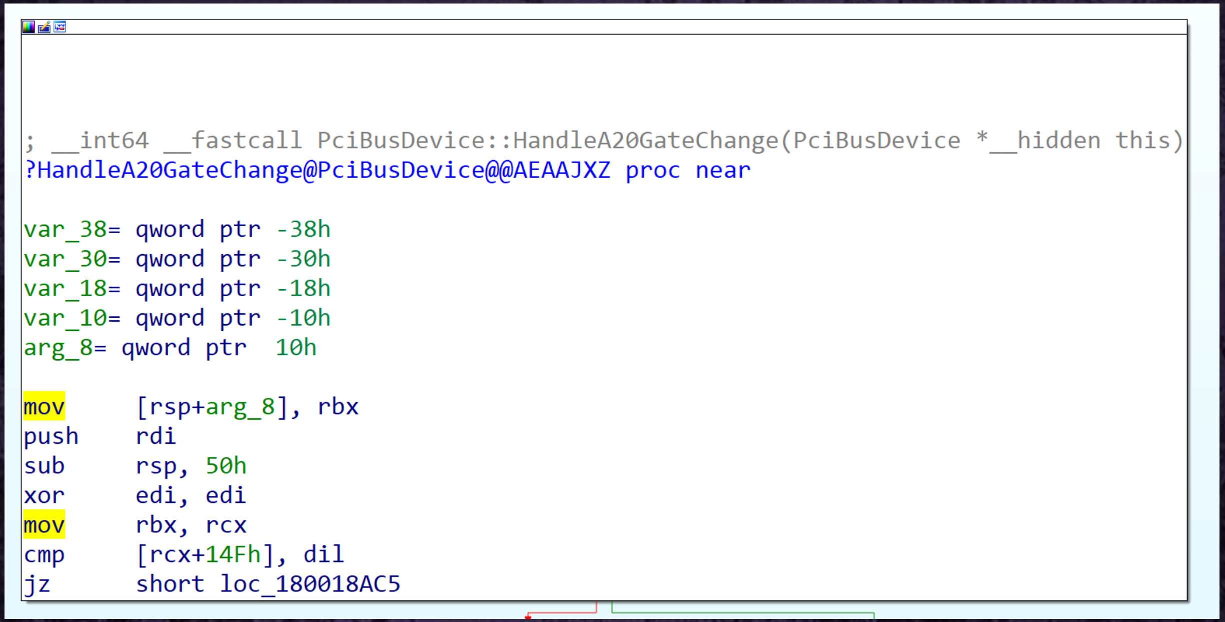
VmEmulatedStorage.dll	Current coverage
FloppyControllerDevice	43.3%
IdeControllerDevice	28.8%

- Start / init / stop functions not called
    - Attaching to a running VM
- Debug strings blocks skipped

Guest VM Crash found

- On i8042 device
- Reproducible
- BSOD of the VM with different error messages at each run
  - SYSTEM_SERVICE_EXCEPTION (0x3b)
  - PFN_LIST_CORRUPT (4e)
  - ATTEMPTED_WRITE_TO_READONLY_MEMORY (0xbe)
  - KERNEL_SECURITY_CHECK_FAILURE (0x139)
  - …
- Memory corruption error

Some more investigation



```
; __int64 __fastcall PciBusDevice::HandleA20GateChange(PciBusDevice *__hidden this)
?HandleA20GateChange@PciBusDevice@@AEAAJXZ proc near

var_38= qword ptr -38h
var_30= qword ptr -30h
var_18= qword ptr -18h
var_10= qword ptr -10h
arg_8= qword ptr  10h

mov     [rsp+arg_8], rbx
push    rdi
sub     rsp, 50h
xor     edi, edi
mov     rbx, rcx
cmp     [rcx+14Fh], dil
jz      short loc_180018AC5
```

- Narrowed down the case
  - Sequence of 2 OUT operations
  - State machine, path accessible in 2 steps
- PciBusDevice::HandleA20GateChange
  - Legacy A20 device
  - Updates the host memory mapping
  - … but the guest keeps the same mapping
- Question: possible compromise of VBS?

Follow-up

- In practice, impossible to exploit
- Not a security bug
- Shared with MSRC

- Validates the behavior of the fuzzer, crash handling and reproduction scripts
- Highlights that this surface has probably been well covered

Future Endeavours

Design Limitations

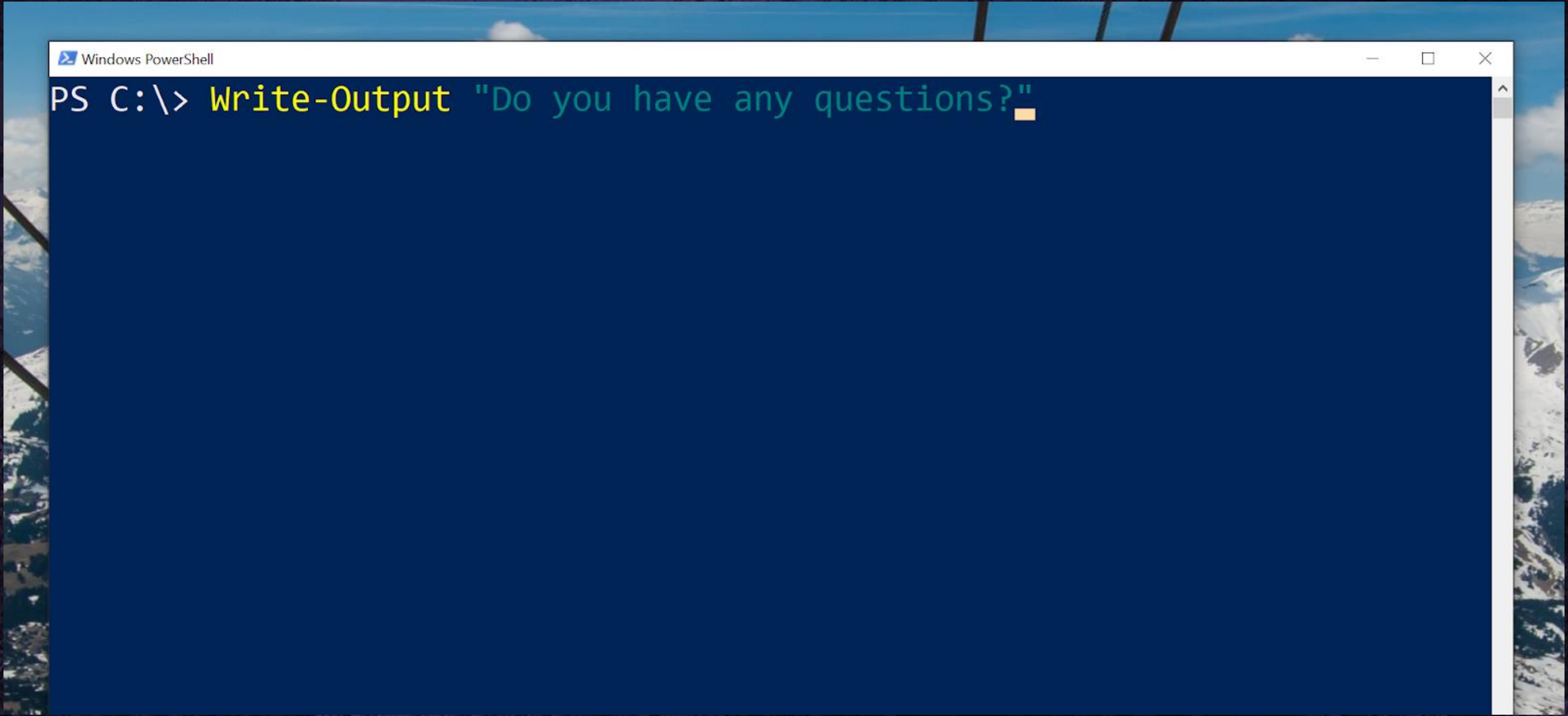
- Space: Restricted to the userland of the root partition
- Time: Not optimized for speed

Future Work

- Development of the fuzzer internals
  - Mutation strategy
  - Redevelop some parts in C++ or C# for performance
  - Speed-related updates: towards a minimal debugger?
  - [not prioritized] Userland vs kernel (or hAFL1?)
- Porting to GCP / Azure
  - Port to new devices
  - Run faster and longer
- Adapting to other root partition targets
  - Keeping the frame and “basic blocks”
  - Changing the commands and input consumption
  - Other interesting dlls loaded in vmwp.exe (generation 2).

Conclusion

https://github.com/googleprojectzero/Hyntrospect



```
PS C:\> Write-Output "Do you have any questions?"
```