

Hyntrospect: A Fuzzer for Hyper-V Devices

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Whoami?

- Security Engineer at Google
- 20% with Project Zero
- Passionate about vulnerability research on systems
- 🄰 @0xdidu

Why Hyper-V?

• Project Zero mission: aims to reduce harm caused by targeted attacks on the Internet

• Hyper-V

- Hypervisor running Azure, Microsoft Cloud
- Modern versions of Windows run it (Virtualization-based security)
- Possibly a high impact if there are 0-days in the wild
- ... and because virtualization is a fun topic
 - Spans multiple layers from hardware to high level software
 - Some complex implementations



Goals

- Instrumenting Hyper-V for vulnerability research
 - A fuzzer called Hyntrospect was developed and open sourced <u>https://github.com/googleprojectzero/Hyntrospect</u>
 - Coverage-guided
 - On closed-source binaries
 - Pragmatic approach, using existing Hyper-V features and Windows tools
 - In a real execution environment
 - Its internals and current results (coverage...) are presented
- Finding vulnerabilities and reporting them to Microsoft

Agenda

- Background on Hyper-V
- The Research Target
- Hyntrospect fuzzer
- Current results
- Future endeavours





Background on Hyper-V

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Microsoft

Hyper-V

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Hyper-V Architecture Overview



Hyper-V High Level Architecture

What is a "Guest to Host Escape"?

- Gaining code execution on one of the hypervisor layers from a virtual machine
- On Hyper-V: ambiguous
 - Hypervisor layer
 - Root partition (kernel / userland)
- Other type of attack: **host denial of service**



The Hypervisors' Attack Surface

• As defined by Alisa Esage (Zer0Con 2020):



... and in practice



Hyper-V Attack Surface

- Hypervisor
 - Hypercall handlers
 - Faults
 - Instruction emulation
 - Intercepts
 - Register access (MSRs...)
- Root partition kernel attack surface
 - VMBus
- Root partition userland attack surface
 - Emulated devices
 - Integration components
- ... and this list is not exhaustive
- MSRC: <u>first-steps-in-hyper-v-research</u>

State of the Art on the Research

- MSRC and Microsoft publish on Hyper-V
 - Blog posts to help vulnerability researchers
 - e.g. First Steps in Hyper-V research
 - Posts on Hyper-V components
 - Several presentations at conferences on vulnerabilities found internally
 - e.g. Breaking VSM by Attacking SecureKernel at BlackHatUSA 2020
 - Symbols provided for some key components
- Active external contributors
 - @gerhart_x and his dedicated blog
 - @alisaesage
 - Presentation by Damien Aumaitre on whyp at SSTIC 2020
- And many more (a list can be found on GitHub/gerhart01/Hyper-V-Internals)

Load: 00007ffe`35600000 00007ffe`3567f000 Load: 00007ffe`13180000 00007ffe`131e5000 Load: 00007ffe`397e0000 00007ffe`39855000

The Research Target

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

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The Emulated Devices Controllers

- Examples: floppy disks, IDE, PS2
- Called "virtual devices" or "VDEVs" at Microsoft
- Emulation of hardware controller by the hypervisor
 - Real hardware controllers use and access control
 - Resources shared
 - Guest operating systems unmodified
- Implemented for Hyper-V generation 1 VMs
 - Azure mostly uses this generation
- Userland of the root partition
- In DLLs loaded by the worker process



Why Choosing the Emulated Devices?

- Complex (state machines)
 - For example: enabling / disabling ports, updating a status register, waiting 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": input from I/O port in DX into EAX
 - "OUT DX, EAX": output in EAX to I/O port address in DX
 - More details and versions in Intel manuals
- Communication through the hypervisor, the VID, and callbacks
- More on MSRC blogpost "Attacking the VM worker process"
- Some VDEVs are more complex with MMIO handling for instance, or the use of the VMBus



Some Reverse Engineering

- DLL implementing the controllers
- Typical IO handlers
 - \$Device::NotifyIOPortRead
 - \$Device::NotifyIOPortWrite
- +: Symbols available, no particular difficulty (no obfuscation...)
- : Reversing C++ and its indirect calls
- Example with VmEmulatedStorage.dll

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Inspiration

- 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

- DynamoRIO
- Intel Pin
- Intel PT (though this is not a tool like previous two)
- Mesos
- QDBI for Windows
- Tinylnst

• Fuzzers

- WinAFL + DynamoRIO
- Jackalope
- whvp
- Memory Corruption Detection
 - PageHeap

So Why Another Toolchain?

- The target is a DLL
 - This disqualifies all the fuzzers that only apply to executables
- Emulating only the relevant functions is hard
 - All the VM context would be needed
- vmwp binary and the DLL cannot be restarted with instrumentation
 - That would mean restarting the whole VM for each run
- The runtime operations are specific
 - Injecting / mocking the injection of IOs
- 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
 - vSMB, or with some architectural changes the network stack...

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 (2)

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













• Block coverage



• Block coverage



• Block coverage



- Block coverage
 - Versus edge coverage: easier to implement but does not promote rare paths



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



- 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]
 - Record of legitimate traffic
- Corpus of "interesting files"
 - Corpus files = permanent residents
 - Input files = temporary residents to be tested
- Coverage increase -> truncated input file added to the corpus
 - Will influence future runs
- 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

- 2 levels of monitoring: debugger level + monitoring process
 - Tip: the monitoring process can track the VM uptime
 - -> avoid while(true)

-> avoid missing quick status change (up-down-up again) ... as if it was blinking

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

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Coverage visualization in IDA

• Optionally, using a helper and IDA+LightHouse



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Current Results

opl=0 TBD: flags

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

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Z Administrator: Windows PowerShell

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Local Runs

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

• Next goal: port the fuzzer to GCP

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

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

Future endeavours

cpla@ TBD: flags

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



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Design Limitations

- Restricted to the userland of the root partition
 - Limits the attack surface as parts of the virtualized stack are in the root partition kernel and hypervisor
- Not optimized for speed
 - More expensive in Cloud as more cycles are needed

Future Work

Development of the fuzzer internals

- Mutation strategy
- Userland vs kernel
- Speed-related updates: minimal debugger?

• Porting to GCP

- 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

lLoad: 00007ffe`35600000 00007ffe`3567f000 lLoad: 00007ffe`13180000 00007ffe`131e5000 lLoad: 00007ffe`397e0000 00007ffe`39855000 lLoad: 00007ffe`4174e000

Conclusion

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 T8D: flags

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 fs=8053
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3D Objects				
Desktop				
Documents				
Downloads				
h Music				
D Music	1.470 hotes			

PS cluserslibinithestraplyintroopect> .\Vain.ps1 Carting Obgshell with fuzzer-master parametered through config.json. cluserslibinithestoplout_ide\corpusiseed-1

Z Administrator: Windows PowerShell

Activate Windows Co to Settlegs to activate Window

https://github.com/googleprojectzero/Hyntrospect

