CHIPSET BASED DETECTION AND REMOVAL OF VIRTUALIZATION MALWARE
a.k.a. DeepWatch

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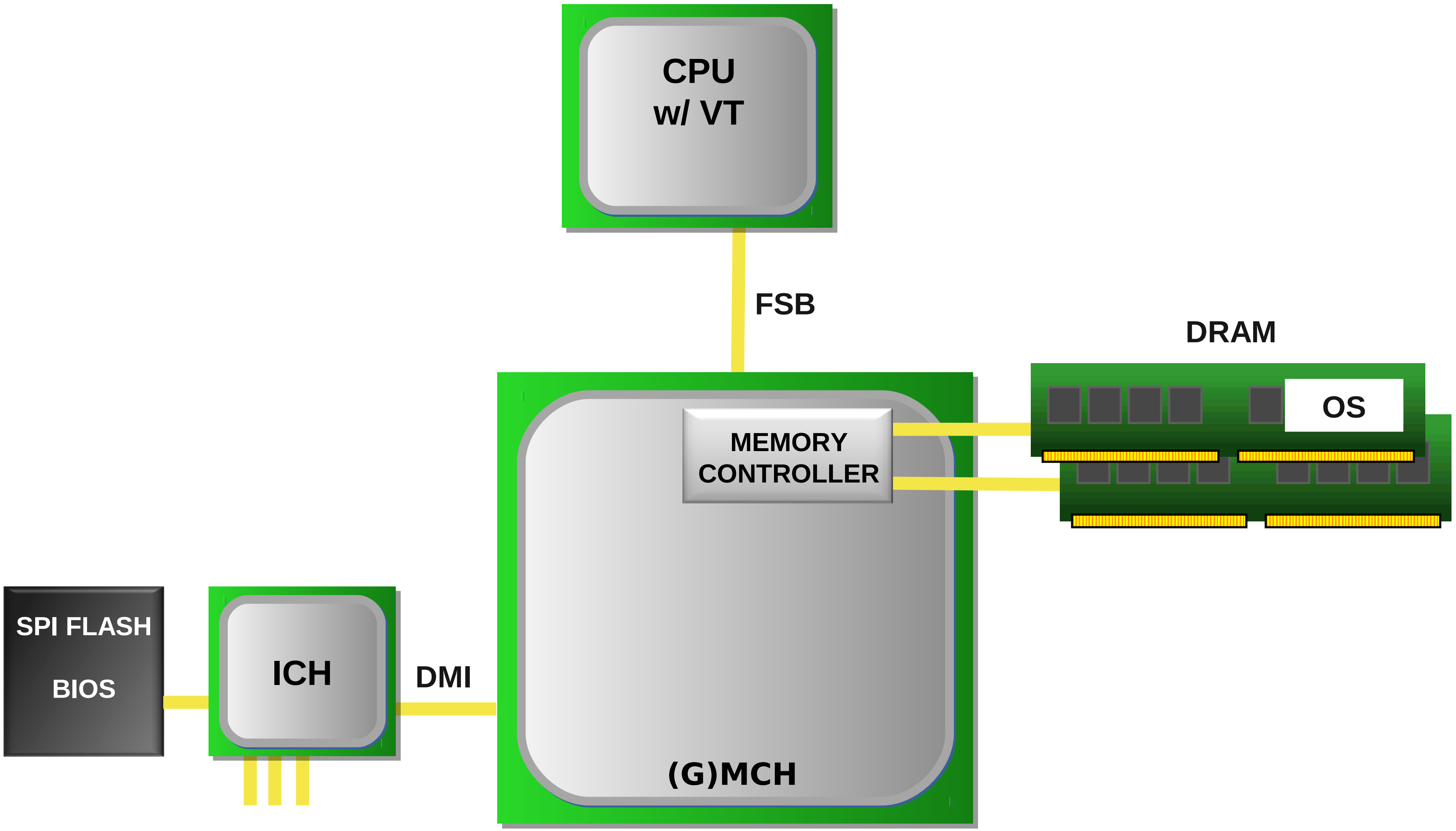
To my wife, Natalia

AGENDA

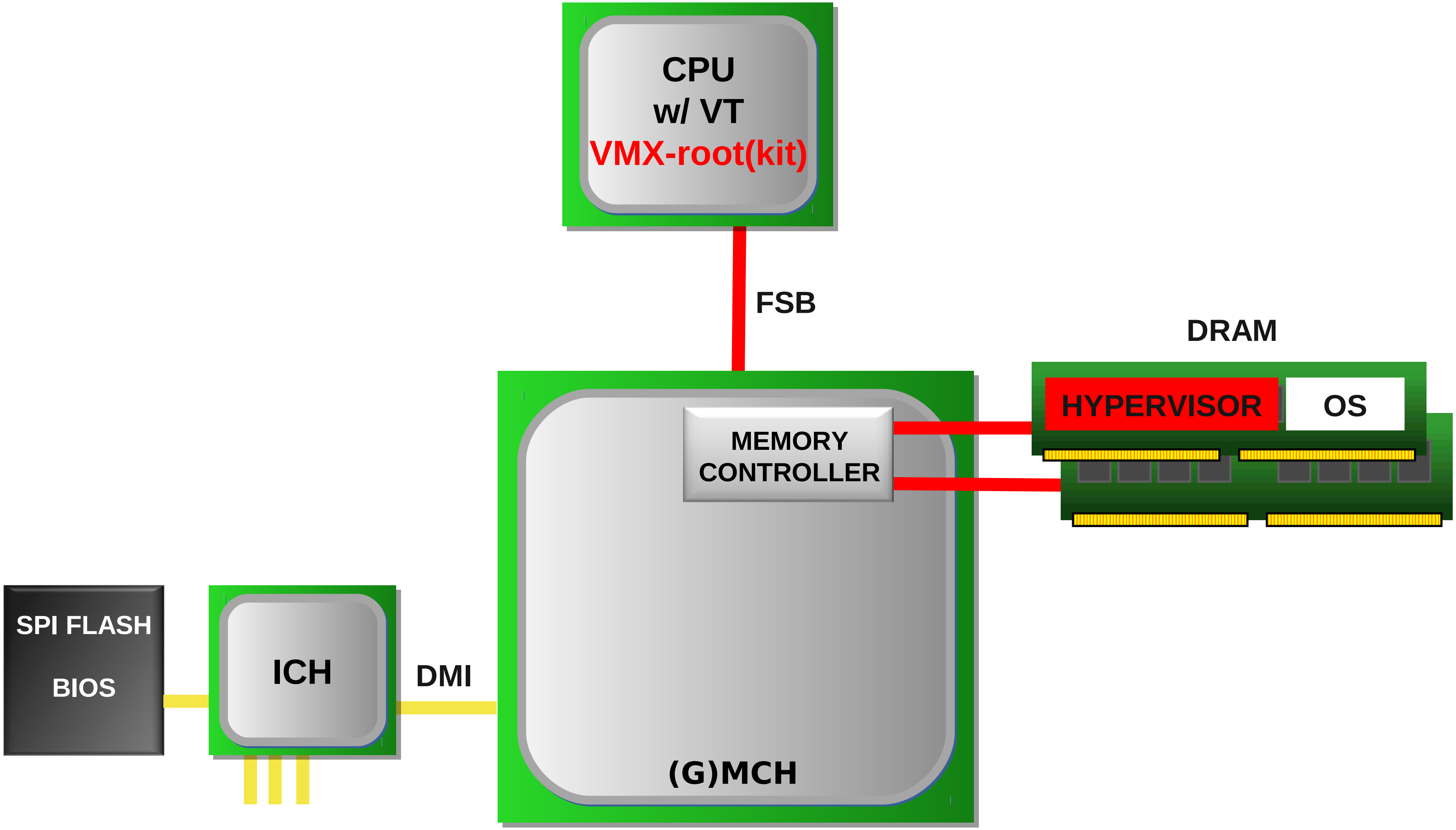
- Introduction
- Chipset based detection of virtualization malware
- DeepWatch: proof of concept detector
- Removing virtualization rootkits
- Limitations
- Demo
- Detecting SMM rootkits
- Bypassing detection
- Comparing with other detection approaches
- Summary

INTRODUCTION

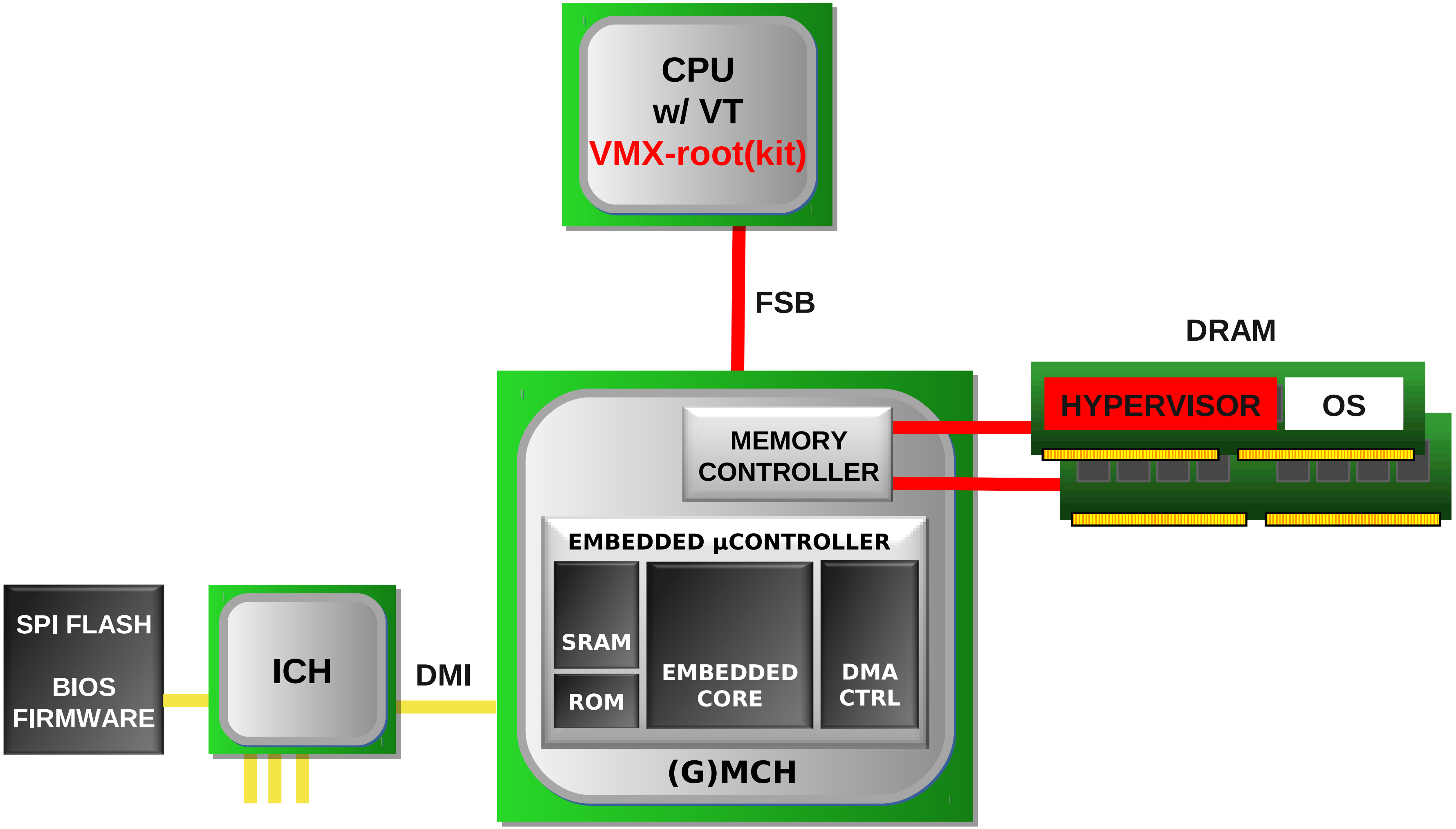
(G)MCH-BASED PLATFORM OVERVIEW



(G)HMM.. PROBLEM



EMBEDDED µCONTROLLER


CPU
w/ VT
VMX-root(kit)
FSB
DRAM
HYPERVISOR
OS
MEMORY CONTROLLER
EMBEDDED µCONTROLLER
SRAM
ROM
EMBEDDED CORE
DMA CTRL
(G)MCH
SPI FLASH
BIOS FIRMWARE
ICH
DMI

uC SUMMARY

- (G)MCH a.k.a. NorthBridge has embedded microcontroller(s)
- Embedded uController in NorthBridge appears as a separate integrated device on PCI bus with one or more PCI functions
- Assigned with its B/D/F for device enumeration by BIOS
- Embedded uController may integrate different hardware engines such as various bus controllers, PIC, crypto accelerators, DMA engine(s) etc.

uC FIRMWARE

- Embedded uController runs firmware
  - Real-time operating system (RTOS)
  - Firmware drivers operating hardware engines
  - Firmware applications
- Embedded firmware can operate hardware engines in chipset such as crypto hardware, internal DMA ..
- Internal SRAM memory or memory stolen from DRAM is used for firmware code, stack/heap ..
- External non-volatile memory is used for storing firmware binaries, e.g.:
  - Serial Peripheral Interface (SPI) Flash memory

uC EXAMPLE

- Intel® Active Management Technology (iAMT) [13]
- New Intel chipsets have embedded uController which executes Intel firmware digitally signed and stored in non-volatile SPI Flash

SO CAN WE USE uC TO DETECT VIRTUALIZATION MALWARE ??

BUT THIS IS INSANE

- Embedded firmware runs on embedded core in the chipset
- .. “underneath” any hypervisor executing on the host CPU
- uC’s internal DMA hardware can be programmed by this firmware to access OS/hypervisor memory in DRAM
- .. and scan for code/structures of **known** HW virtualization rootkits and **remove** them
- .. or verify integrity of running hypervisor

HERE GOES A ROOTKIT

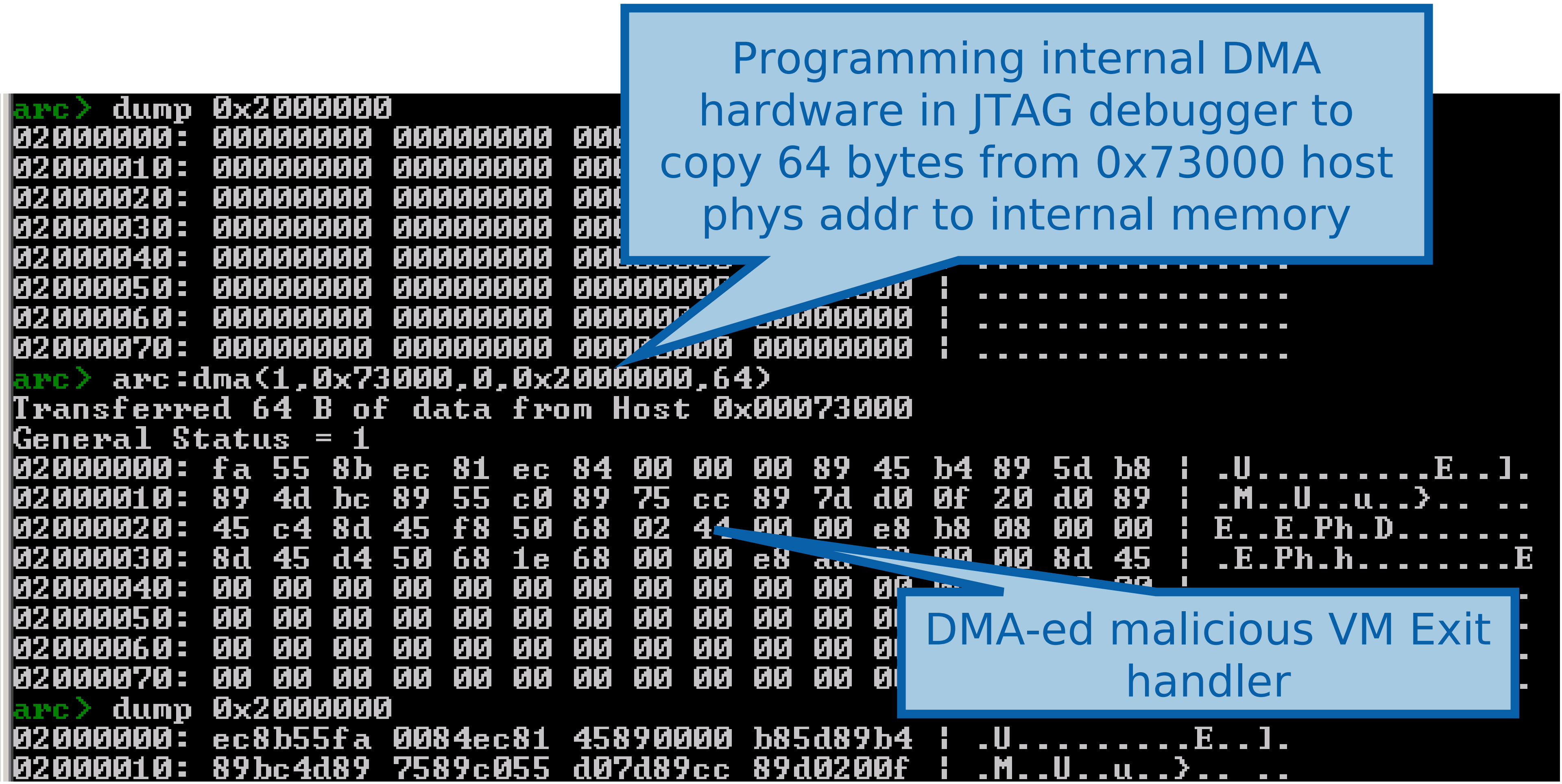
```
er.asm - Far
\deepwatch\src\vmexit_handler.asm                 Win     Line          1/242
00073000    8bff                      mov edi, edi
00073002    fa                        cli
00073003    55                        push ebp
00073004    8bec                      mov ebp, esp
00073006    83ec4c                    sub esp, 0x4c
00073009    60                        pushad
0007300a    8945c8                    mov dword ptr [ebp - 0x38], eax
0007300d    895dcc                    mov dword ptr [ebp - 0x34], ebx
00073010    894dd0                    mov dword ptr [ebp - 0x30], ecx
00073013    8955d4                    mov dword ptr [ebp - 0x2c], edx
00073016    8975e0                    mov dword ptr [ebp - 0x20], esi
00073019    897de4                    mov dword ptr [ebp - 0x1c], edi
0007301c    0f20d0                    mov eax, cr2
0007301f    8945d8                    mov dword ptr [ebp - 0x28], eax
00073022    b802440000                mov eax, 0x4402
00073027    0f78c1                    vmread ecx, eax
```

VM Exit handler

```
C:\work\deepwatch>bpknock.exe 0xc70
knock answer: 0x7280202

C:\work\deepwatch>net start vtrootkit

The vtrootkit service was started successfully.


C:\work\deepwatch>bpknock.exe 0xc70
knock answer: 0xbadd00d
```

“Magic” CPUID

PROGRAMMING uC DMA WITH BARE HANDS

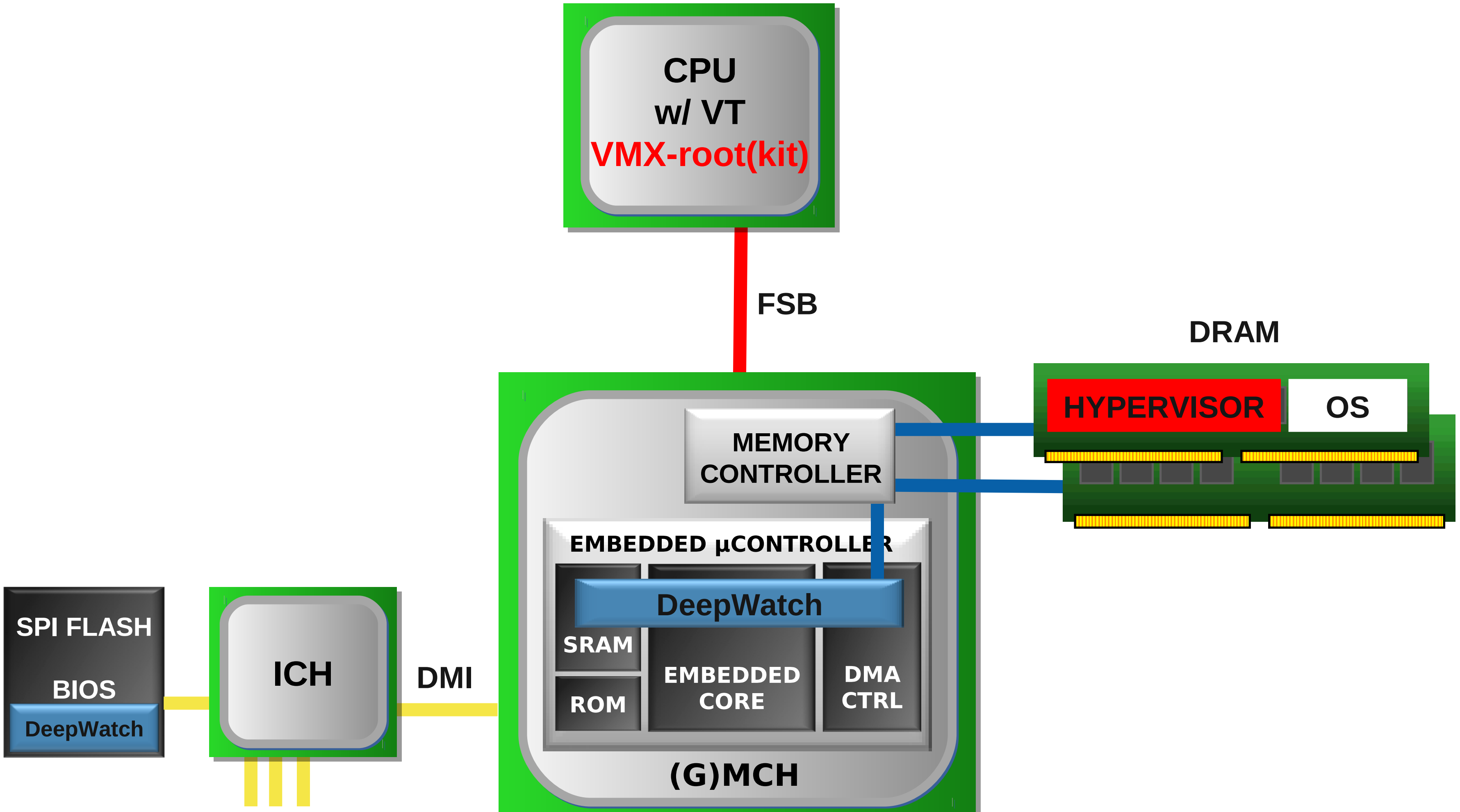


INTRODUCING DeepWatch: CHIPSET BASED DETECTOR PoC

“DeepWatch” named after Labyrinth of Reflections novel by Sergei Lukyanenko (http://en.wikipedia.org/wiki/Labyrinth_of_Reflections)

DeepWatch

- DeepWatch is implemented as a Proof of Concept in (G)MCH firmware on Intel® Q35 chipset codename “Bearlake”
- Detects Intel® VT-x based rootkits on Intel® Core 2 Duo CPU
- Implemented in debug Intel firmware on debug Silicon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CURRENT IMPLEMENTATION

- DeepWatch firmware is stored with the rest of Intel firmware in SPI Flash
- DeepWatch firmware thread starts with BIOS POST code after BIOS initialized memory controller
- DeepWatch periodically programs internal DMA hardware in uC to access physical memory
- DMA transfers 32/64 kB chunks of physical memory into internal memory
- DeepWatch then scans DMA-ed contents for code/data of known VT-x rootkits

VM EXIT HANDLER

- Hypervisor may have a lot of various code !! So what exactly to detect ??
- Hypervisor traps on certain instructions (e.g. CPUID) or events (e.g. exceptions)
  - Traps may be unconditional or conditional
- Trapping by the hypervisor is called “VM Exit”
- VM Exits are handled by VM Exit handler code
  - VM Exit handler reads VM Exit reason and lots of other information about VM Exit and guest state from VMCS
  - May be located anywhere in physical memory
- DeepWatch uses opcodes specific to malicious VM Exit handler as a “signature”

KICKING OFF DEEP WATCH SCAN

arc: halted 0x1058640 in _hl_blockedPeek() at hl_bios.c:108

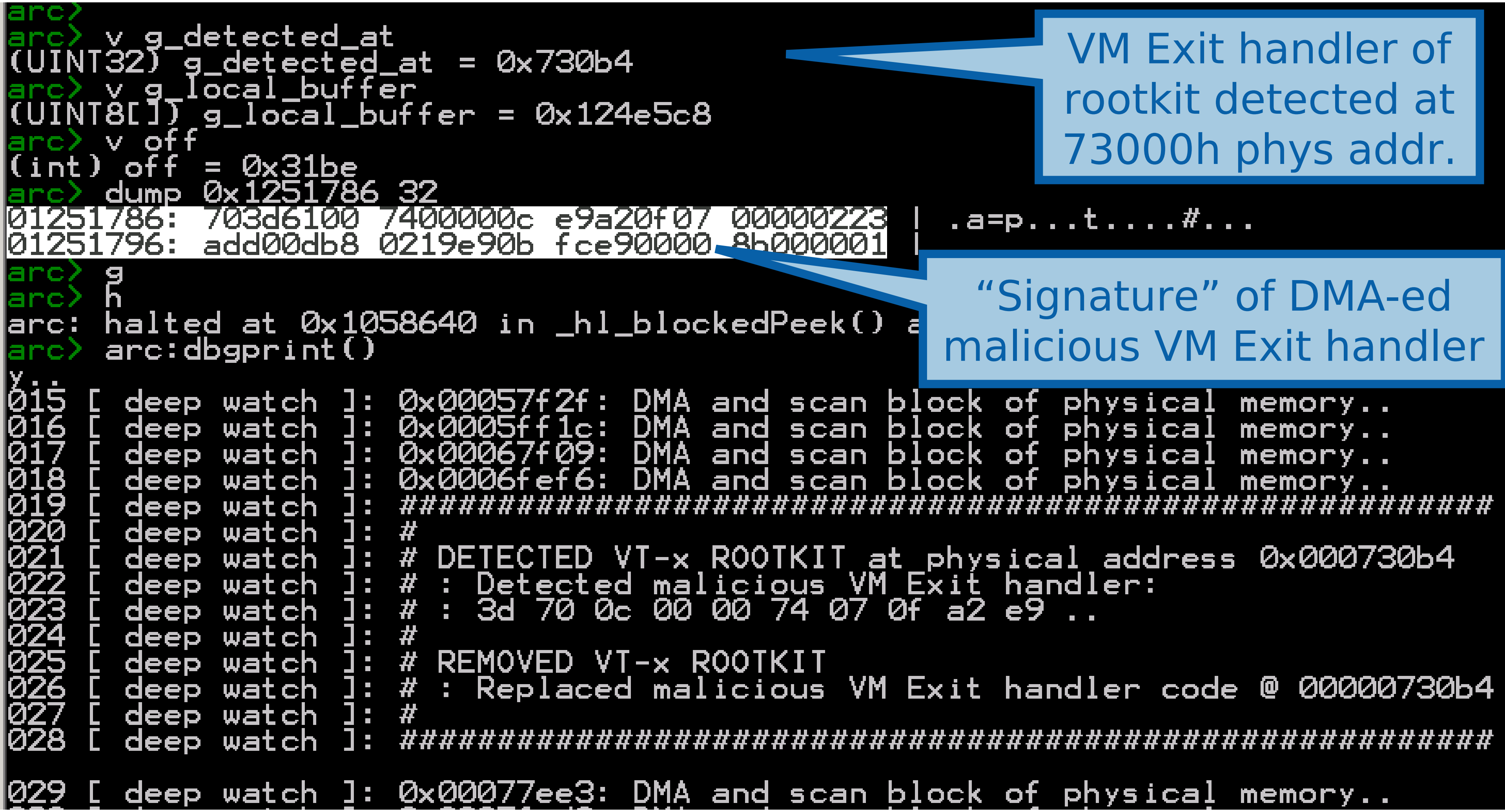
```
arc>
arc> v g_pill_sig
(UINT8[]) g_pill_sig = 0x1076660
arc> dump 0x1076660 32
01076660: 000c703d 0f077400 0223e9a2 0db80000 | =p...t....#.....
01076670: 000badd0 000c703d 0f077400 0223e9a2 | ....=p...t....#.
arc> v g_detected_at
(UINT32) g_detected_at = 0x0
arc> v g_local_buffer
(UINT8[]) g_local_buffer = 0x124e5c8
arc> dump 0x124e5c8 32
0124e5c8: 00000000 00000000 00000000 0000000
0124e5d8: 00000000 00000000 00000000 00000000 | ................
arc>
arc> g
arc> h
arc: halted at 0x1058640 in _hl_blockedPeek(
arc> arc:dbgprint()
000 [ deep watch ]: # START DMA AND SCAN OF HOST PHYSICAL MEMORY..
001 [ deep watch ]: # base physical address 0x00000000
002 [ deep watch ]: # size to scan          0x100000 bytes
003 [ deep watch ]: # signature length     0x13 bytes
004 [ deep watch ]: 0x00000000: DMA and scan block of physical memory..
005 [ deep watch ]: 0x00007fed: DMA and scan block of physical memory..
006 [ deep watch ]: 0x0000ffda: DMA and scan block of physical memory..
007 [ deep watch ]: 0x00017fc7: DMA and scan block of physical memory..
008 [ deep watch ]: 0x0001ffb4: DMA and scan block of physical memory..
```

g_pill_sig points to signature buffer

g_detected_at will be set to physical address of detected VM Exit handler

g_local_buffer points DMA destination buffer

DETECTING ROOTKIT SIGNATURE



WHY IS IT INTERESTING ??

- Detects virtualization rootkits rather than virtualization
- Detects rootkits in memory regions inaccessible to host OS and anti-viruses
- Detection can be unnoticeable by the user:
  - doesn’t consume main CPU time !!
  - fast DMA access to DRAM (hundreds MBytes per second)
  - could scan for rootkit in memory/SSD while host is in sleep
- Can provide capability to anti-virus engines to detect virtualization rootkits
- Can provide hardware based verification of Patch Guard or other OS kernel-mode rootkit detectors

DETECTION.. DETECTION.. HOW ABOUT REMOVING VIRTUALIZATION ROOTKITS ??

REMOVING VIRTUALIZATION ROOTKIT

- Once detected VM Exit handler code we can program internal DMA hardware in the opposite direction
- And replace VM Exit handler with any contents

Option 0:

- Corrupt or wipe off malicious VM exit handler/VMCS
- Quick and dirty .. but unaesthetic

OPTION 1 – “0WN THE ROOTKIT”

- Detect VM Exit handler code of the rootkit
- Replace VM Exit handler code with your own VM exit handler
- New VM Exit handler works as a legitimate hypervisor - traps on events/instructions and resumes the guest OS
- OS is still virtualized but by new hypervisor – harmless ;)

- Wait for the demo !!

OPTION 1 (cont'd)

- VM Exit handler of malicious hypervisor responds with **`0xbadd00d`** to magic CPUID request
- DeepWatch replaced it with the handler that responds with **`0xdeadd00d`**

```
C:\work\deepwatch>bpknock.exe 0xc70
knock answer: 0x7280202

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The vtrootkit service was started successfully.


C:\work\deepwatch>bpknock.exe 0xc70
knock answer: 0xbadd00d

C:\work\deepwatch>bpknock.exe 0xc70
knock answer: 0xdeadd00d

C:\work\deepwatch>Malicious VM Exit handler was replaced
1Left    2Right   3View..  4Edit..  5Print   6MkLink  7Find    8H
```

OPTION 2 – "ROOTKIT SUICIDE"

- Detect VM Exit handler code of the rootkit
- Replace VM Exit handler code with a new code
- .. that restores guest state and does VMXOFF
- Upon the next VM Exit, rootkit restores guest OS state with "trampoline" code and leaves VMX mode of operation
- .. effectively turning itself off ;)
- It's like Blue Chicken but forever

LIMITATIONS

LIMITATIONS

- Detection is OS-independent but chipset-specific
- Embedded uController and internal DMA hardware are chipset specific
- DeepWatch detects only VT-x based rootkits

SIGNATURE SCAN or INTEGRITY CHECKS ??

- Current DeepWatch uses simple and effective signature matching ;)
- But it’s not about signature scan; it can combine multiple techniques
- Heuristics:
  - E.g. search for VMCS structures by revision id to get an address of VM Exit handler
  - Then hash VM Exit handler and compare against white-list
- Integrity checks of host OS/hypervisor pages:
  - How does it know what to hash ??
  - A lot of information can be learned about OS and VMM from bare memory dump [20-24]
  - Find hypervisor CR3, page tables, VMCS structures etc.
- DeepWatch can cooperate with the host code (SMI handler like HyperGuard) that has this information about OS/VMM

For information on HyperGuard please see

“Xen 0wning Thrillogy”

by Joanna Rutkowska/Alex Tereshkin/Rafał Wojtczuk

(Invisible Things Lab)

DEMO

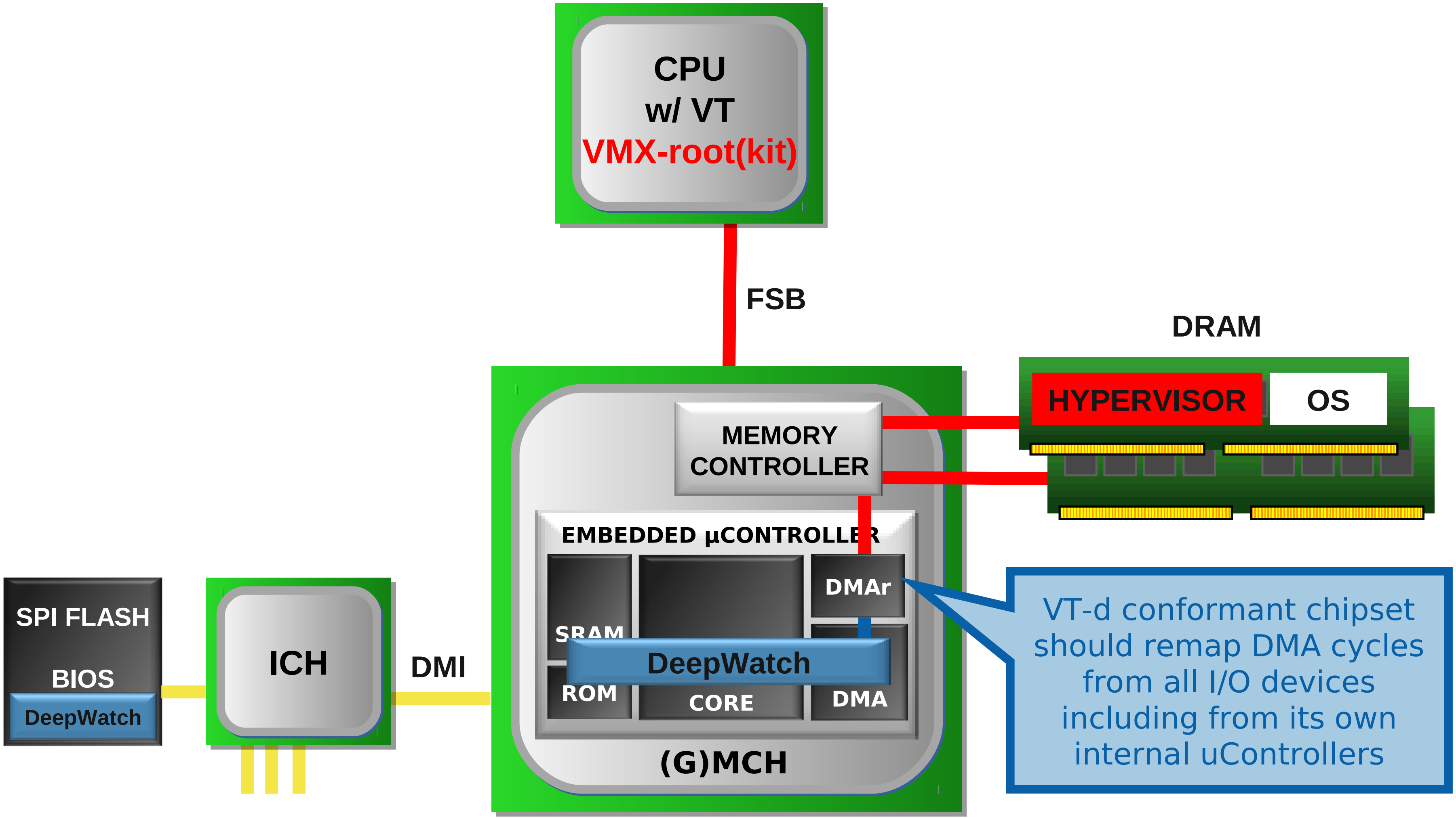
REMOVING VT-x BASED ROOTKIT

DETECTING SMM ROOTKITS

- SMM malware compromises SMM memory (SMRAM) protections to run in System Management Mode [17-19]
  - Also today's talk by Shawn Embleton & Sherri Sparks
- Chipset/CPU don't allow non-SMM CPU access to SMRAM after it's locked
- Chipset doesn't allow DMA access to SMRAM by I/O devices
- Anti-viruses or external DMA devices cannot verify SMRAM contents after it's locked by malware

- But chipset could allow its own embedded uController to access SMRAM so that
- DeepWatch could verify SMI handler code and static data in SMRAM

FORGOT A SMALL DETAIL: DMA REMAPPING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EMBEDDED µCONTROLLER
DMAr
SRAM
ROM
CORE
DMA
DeepWatch
(G)MCH
SPI FLASH
BIOS
DeepWatch
ICH
DMI
VT-d conformant chipset should remap DMA cycles from all I/O devices including from its own internal uControllers

DMA REMAPPING

- VT-d capable chipsets have one or more DMA-remapping engines virtualizing Directed I/O access [12]
- Internal devices are also a subject to DMA-remapping
- Chipset has dedicated register-set for each DMA-remap unit accessible by software as MMIO range which software can use to protect certain memory regions from certain I/O devices
- Rootkit can create DMA-remapping page tables to translate addresses of DMA requests issued by embedded uC (identified by its PCI B/D/F) to different host physical addresses
  - or read/write protect entries in DMAr pages tables
  - or mark context-entry as not Present to cause translation fault
  - or enable PLMR/PHMR DMA-protected regions to prevent any DMA
- And relocate code/data (VMExit handler, VMCS ..) to memory protected by DMAr page tables or to PMR regions

SO WHAT CAN WE DO ABOUT THIS ??

- DMA-remapping unit can distinguish DMA requests issued by DeepWatch internal device function inside embedded uC
- by its requester id from DMA requests issued by other internal functions
- and not translate them
- Or disable and lock DMA-remapping of DeepWatch device function if DeepWatch is used
- And allow only trusted software like SMX authenticated code modules (Intel® TXT) to enable and program DMA-remap engine for DeepWatch

COMPARING WITH OTHER DETECTION APPROACHES

ANOMALY BASED DETECTION

- Timing measurements of instructions causing VM Exit
  - Local timing: RDTSC, ACPI timer, Local APIC, RTC [8, by bugcheck]
  - Remote timing: NTP [8]
  - Using another thread on SMT CPU to measure VM Exit latency [7]
  - Using timers of integrated devices in the chipset
- TLB profiling of instructions causing VM Exit events
  - Measure timing of address translation due to TLB evictions by a hypervisor [5,6,8,9]
  - TLB coloring: observe if TLB VA-2-PA mappings changed due to VM Exit [9]
  - Measure # of TLB misses due to flushing TLB's upon VM Entry/Exit
- Using µArchitectural side-channel attacks
  - RSB based side-channel: corruption of RSB state by VM Exit handler [25]
- Other: CPU errata, causing faults or exhausting resources, Last Branch Record, different CPU behavior in VMX root vs. in non-root modes

COMMON PROBLEMS

- Do not distinguish good hypervisors from bad
  - *Detected SSDT hook, it may be XXX anti-virus or a kernel rootkit. Remove ??*
- Probabilistic: need to run lots of tests to reduce probability of a false positive
- How about removing rootkits from the system ??
- Conceptual contradiction: any VMX non-root detector is less privileged than any VMX root(kit)
  - Detector shouldn't have any legitimate way to affect more privileged VMX root(kit) by design of virtualization
- Agents win ;)

HARDWARE MEMORY ACQUISITION

- Uses DMA capable device to acquire physical memory dump and perform forensic analysis [15]

- DMA remapping (VT-d) hardware in chipsets protects VMM pages from external I/O devices. Hypervisor can always avoid detection by programming DMA remap
- Method requires discrete DMA capable card. Can IT security folks scan memory of every host physically with external device ??

SUMMARY

- DeepWatch approach = using embedded µController(s) in chipset to reliably detect and **remove** virtualization malware
- DeepWatch can use various techniques: integrity checking, signature scan or combine them
- This approach can bring benefits to OS anti-rootkit solutions or to traditional anti-malware engines
- Can enable detection of other rootkits inaccessible to OS/anti-viruses such as SMM rootkits
- Single solutions fail. DeepWatch should coexist with preventative and other detection solutions (like HyperGuard)

FINAL REMARKS

- This work is now a joint research with Intel Corporate Technology Group, Networking Technology Lab
- Acknowledgements:

  Dean Krekos, Sagar Dalvi, Jason Fung, Toby Kohlenberg, Howard Herbert

  All authors of research in virtualization rootkits and their detection techniques
- Updated materials: http://www.c7zero.info

Thank you !!

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