MODERN TECHNIQUES TO DEOBFUSCATE AND UEFI/BIOS MALWARE

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Agenda:

- ❖ Few words about anti-reversing
- ❖ METASM
- ❖ Keystone + uEmu
- ❖ MIASM
- ❖ BIOS/UEFI rootkits:
  - ❖ Windows Boot Process
  - ❖ MBR / VBR / IPL / KCS
  - ❖ ELAM / Control Integrity
  - ❖ Secure Boot
  - ❖ BIOS Guard / Boot Guard
  - ❖ UEFI Protections + chipsec

ANTI-REVERSING

(few words)

- ✓ Obfuscation aims to protect software of being reversed, to protect intellectual property and, in our case, malicious code too. ☺

- ✓ Honestly, obfuscation does not really protect the program, but it can make the reverser's life harder than usual.

- ✓ Thus, at end, obfuscation buys time by enforcing reversers to spend resources and time to break a code.

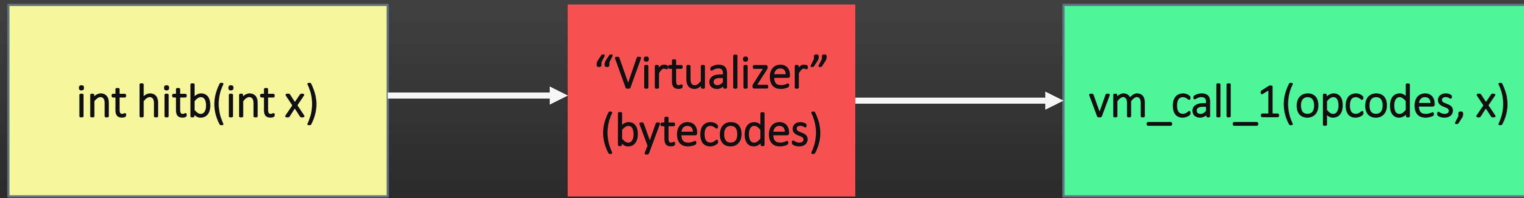
- ✓ We see obfuscated code every single day when analyzing droppers in VBA and Powershell, so it mightn't seem not to be a big deal.

- ✓ However, they use very basic obfuscated techniques when compared to sophisticated threats.

- ✓ We can use IDA Pro SDK to write plugins for:
  - ✓ extending the IDA Pro functionalities:
  - ✓ analyzing some code and data flow
  - ✓ automatizing the unpacking process of strange malicious files.
  - ✓ writing a loader to modified MBR structure. ☺
- ✓ Unfortunately, there are packers and protectors such as VMprotect, Themida, Arxan and Agile .NET that use modern obfuscation techniques, so making code reversing very complicated.

- ✓ Most protectors have been used with 64-bit code (and malware).
- ✓ Original IAT is removed from the original code (as usually applied by any packer). However, IAT from packers like Themida keeps only one function (TlsSetValue( )).
- ✓ Almost all of them provides string encryption.
- ✓ They check the memory integrity.
- ✓ Thus, it is not possible to dump a clean executable from the memory (using Volatility, for example) because original instructions are not decoded in the memory.
- ✓ Instructions (x86/x64 code) are virtualized and transformed into virtual machine instructions (RISC instructions).
- ✓ .NET protectors rename classes, methods, fields and external references.

- ✓ Some packers can use instruction encryption on memory as additional memory layer.
- ✓ Obfuscation used by these protectors is stack based, so it makes hard to handle virtualized code statically.
- ✓ Virtualized code is polymorphic, so there are many virtual machine representations referring the same CPU instruction.
- ✓ There are also lots of fake push instructions.
- ✓ There are many dead and useless codes.
- ✓ There is some code reordering using many unconditional jumps.
- ✓ All obfuscators use code flattening.



Fetching bytes, decoding them to instructions and dispatching to handlers

❖ Protectors using virtual machines introduces into the obfuscated code:

- ✓ A context switch component, which “transfers” registry and flag information into VM context (virtual machine). The oposite movement is done later from VM machine and native (x86/x64) context (suitable to keep within C structures during unpacking process ☺)

- ✓ This “transformation” from native register to virtualized registers can be one to one, but not always.

✓ Inside of the virtual machine, the cycle is:

- ✓ fetch instruction
- ✓ decode it
- ✓ find the pointer to instruction and lookup the associate opcode in a handler table
- ✓ call the target handler

- ✓ Constant unfolding: technique used by obfuscators to replace a constant by a bunch of code that produces the same resulting constant's value.

- ✓ Pattern-based obfuscation: exchanging of one instruction by a set of equivalent instructions.

- ✓ Abusing inline functions.

- ✓ Anti-VM techniques: prevents the malware sample to run inside a VM.

- ✓ Dead (garbage) code: this technique is implemented by inserting codes whose results will be overwritten in next lines of code or, worse, they won't be used anymore.

- ✓ Code duplication: different paths coming into the same destination (used by virtualization obfuscators).

- ✓ Control indirection 1: call instruction → update the stack pointer → return skipping some junk code after the call instruction (RET x).

- ✓ Control indirection 2: malware trigger an exception → registered exception is called → new branch of instructions.

- ✓ Opaque predicate: Apparently there is an evaluation (jz / jnz) to take a branch or another one, but the result is always evaluated to true (or false), which means an unconditional jump. Thus, there is a dead branch. Usually, a series of arithmetic / logic tricks are used.

- ✓ Anti-debugging: used as irritating techniques to slow the process analysis.

- ✓ Polymorphism: it is produced by using self-modification code (like shellcodes) and by using encrypting resources (similar most malware samples).

- ✓ Call stack manipulation: Changes the stack flow by using instruction tricks composed with the ret instruction, making the real return point hidden.

- ✓ Is it possible to deobfuscate virtualized instructions? Yes, it is possible by:

  - ✓ using reverse recursive substitution (similar -- not equal -- to backtracking feature from Metasm).

  - ✓ using symbolic equation system is another good approach (again...., Metasm and MIASM!).

- ✓ There are many good IDA Pro plugins such as Code Unvirtualizer, VMAttack, VMSweeper, and so on, which could be used to handle simple virtualization problems.

METASM + MIASM

1

```
add eax, ecx
```

2

```
sub eax, C3
add eax,ecx
add eax, C3
```

3

```
sub eax, C3
sub eax, A3
add eax,ecx
add eax, A3
push edx
mov edx, 62
inc edx
dec edx
add edx, 61
add eax, edx
pop edx
```

4

```
push ebx
mov ebx, C3
sub eax, ebx
pop ebx
sub eax, A3
sub eax, 38
add eax, ecx
add eax, 38
add eax, A3
push edx
push ecx
mov ecx, 62
mov edx, ecx
pop ecx
inc edx
add edx, 61
dec edx
add eax, edx
pop edx
```

How to reverse the obfuscation and, from stage 4, to return to the stage 1? ☺

- METASM works as disassembler, assembler, debugger, compiler and linker.
- Key features:
  - Written in Ruby
  - C compiler and decompiler
  - Automatic backtracking
  - Live process manipulation
  - Supports the following architecture:
    - Intel IA32 (16/32/64 bits)
    - PPC
    - MIPS
  - Supports the following file format:
    - MZ and PE/COFF
    - ELF
    - Mach-O
    - Raw (shellcode)

- root@kali:~/programs# git clone https://github.com/jjyg/metasm.git
- root@kali:~/programs# cd metasm/
- root@kali:~/programs/metasm# make
- root@kali:~/programs/metasm# make all

- Include the following line into .bashrc file to indicate the Metasm directory installation:
  - export RUBYLIB=$RUBYLIB:~/programs/metasm

```ruby
#!/usr/bin/env ruby
#

require "metasm"
include Metasm

coderef = Metasm::Shellcode.assemble(Metasm::Ia32.new, <<EOB)
item:
        push ebx
        mov ebx, 0xc3
        sub eax, ebx
        pop ebx
        sub eax, 0xa3
        sub eax, 0x38
        add eax, ecx
        add eax, 0x38
        add eax, 0xa3
        push edx
        push ecx
        mov ecx, 0x62
        mov edx, ecx
        pop ecx
        inc edx
        add edx, 0x61
        dec edx
        add eax, edx
        pop edx
        jmp eax
EOB

addrstart = 0
textcode = coderef.init_disassembler
textcode.disassemble(addrstart)
hitb_di = textcode.di_at(addrstart)
hitb = hitb_di.block
puts "\n[$] Our HITB 2019 Amsterdam test code:\n "
puts hitb.list
```

- based on metasm.rb file and Bruce Dang code.

This is our code from previous slide to be deobfuscated and backtracked. ☺

Starts the disassembler engine and dissassemble from the first address (zero).

```
hitb.list.each{|aborges|
        puts "\n[##] #{aborges.instruction}"
        back = aborges.backtrace_binding()
        a = back.keys
        b = back.values
        c = a.zip(b)
        puts "HITB 2019 Amsterdam data flow follows below:\n"
        c.each do |mykey, myvalue|

          puts " Result:  #{mykey} => #{myvalue}"

          if aborges.opcode.props[:setip]
                puts "\nHITB 2019 Amsterdam control flow follows below:\n"
                puts " * #{textcode.get_xrefs_x(aborges)}"
          end
        end
}

addrstart2 = 0
textcode2 = coderef.init_disassembler
textcode2.disassemble(addrstart2)

dd = textcode2.block_at(addrstart2)
final = textcode2.get_xrefs_x(dd.list.last).first
puts "\n[+] final output: #{final}"
```

Starts the backstrace engine and walk back in the code.

Determines which is the final instruction to walk back from there. ☺

```ruby
values = textcode2.backtrace(final, dd.list.last.address, {:log => backlog = [] , :include_start => true})
backlog.each{|item|
        case type = item.first
        when :start
                item, expression, address = item
                puts "[start] Here is the sequence of expression evaluations  #{expression} from 0x#{address.to_s(16)}\n"

        when :di
                item, new, old, instruction = item
                puts "[new update] instruction #{instruction},\n --> updating expression once again old #{old} new #{new}\n"
        end
}

effective = backlog.select{|y| y.first==:di}.map{|y| y[3]}.reverse
puts "\nThe effective instructions are:\n\n"
puts effective


```

Logs all the “backtracked” instructions.

Shows the effective instructions, which might alter the final result.

```
root@kali:~/programs/metasm# ./hitb2019.rb

[$] Our HITB 2019 Amsterdam test code:

0 push ebx
1 mov ebx, 0c3h
6 sub eax, ebx
8 pop ebx
9 sub eax, 0a3h
0eh sub eax, 38h
11h add eax, ecx
13h add eax, 38h
16h add eax, 0a3h
1bh push edx
1ch push ecx
1dh mov ecx, 62h
22h mov edx, ecx
24h pop ecx
25h inc edx
26h add edx, 61h
29h dec edx
2ah add eax, edx
2ch pop edx
2dh jmp eax

[##] push ebx
HITB 2019 Amsterdam data flow follows below:
 Result:  esp => esp-4
 Result:  dword ptr [esp] => ebx

[##] mov ebx, 0c3h
HITB 2019 Amsterdam data flow follows below:
 Result:  ebx => 0c3h
```

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```
[##] push ebx
HITB 2019 Amsterdam data flow follows below:
 Result:  esp => esp-4
 Result:  dword ptr [esp] => ebx

[##] mov ebx, 0c3h
HITB 2019 Amsterdam data flow follows below:
 Result:  ebx => 0c3h

[##] sub eax, ebx
HITB 2019 Amsterdam data flow follows below:
 Result:  eax => eax-ebx
 Result:  eflag_z => (((eax&0ffffffffh)-(ebx&0ffffffffh))&0ffffffffh)==0
 Result:  eflag_s => ((((eax&0ffffffffh)-(ebx&0ffffffffh))&0ffffffffh)>>1f
h)!=0
 Result:  eflag_c => (eax&0ffffffffh)<(ebx&0ffffffffh)
 Result:  eflag_o => ((((eax&0ffffffffh)>>1fh)!=0)==(!(((ebx&0ffffffffh)>>
1fh)!=0)))&&((((eax&0ffffffffh)>>1fh)!=0)!=(((((eax&0ffffffffh)-(ebx&0ffff
ffffh))&0ffffffffh)>>1fh)!=0))

[##] pop ebx
HITB 2019 Amsterdam data flow follows below:
 Result:  esp => esp+4
 Result:  ebx => dword ptr [esp]

[##] sub eax, 0a3h
HITB 2019 Amsterdam data flow follows below:
 Result:  eax => eax-0a3h
 Result:  eflag_z => (((eax&0ffffffffh)-((0a3h)&0ffffffffh))&0ffffffffh)==
0
 Result:  eflag_s => ((((eax&0ffffffffh)-((0a3h)&0ffffffffh))&0ffffffffh)>
>1fh)!=0
 Result:  eflag_c => (eax&0ffffffffh)<((0a3h)&0ffffffffh)
 Result:  eflag_o => ((((eax&0ffffffffh)>>1fh)!=0)==(!((((0a3h)&0ffffffffh
)>>1fh)!=0)))&&((((eax&0ffffffffh)>>1fh)!=0)!=(((((eax&0ffffffffh)-((0a3h)
&0ffffffffh))&0ffffffffh)>>1fh)!=0))
```

```
[+] final output: eax
[start] Here is the sequence of expression evaluations  eax from 0x2d
[new update] instruction 2ah add eax, edx,
 --> updating expression once again old eax new eax+edx
[new update] instruction 29h dec edx,
 --> updating expression once again old eax+edx new eax+edx-1
[new update] instruction 26h add edx, 61h,
 --> updating expression once again old eax+edx-1 new eax+edx+60h
[new update] instruction 25h inc edx,
 --> updating expression once again old eax+edx+60h new eax+edx+61h
[new update] instruction 22h mov edx, ecx,
 --> updating expression once again old eax+edx+61h new eax+ecx+61h
[new update] instruction 1dh mov ecx, 62h,
 --> updating expression once again old eax+ecx+61h new eax+0c3h
[new update] instruction 16h add eax, 0a3h,
 --> updating expression once again old eax+0c3h new eax+166h
[new update] instruction 13h add eax, 38h,
 --> updating expression once again old eax+166h new eax+19eh
[new update] instruction 11h add eax, ecx,
 --> updating expression once again old eax+19eh new eax+ecx+19eh
[new update] instruction 0eh sub eax, 38h,
 --> updating expression once again old eax+ecx+19eh new eax+ecx+166h
[new update] instruction 9 sub eax, 0a3h,
 --> updating expression once again old eax+ecx+166h new eax+ecx+0c3h
[new update] instruction 6 sub eax, ebx,
 --> updating expression once again old eax+ecx+0c3h new eax-ebx+ecx+0c3h
[new update] instruction 1 mov ebx, 0c3h,
 --> updating expression once again old eax-ebx+ecx+0c3h new eax+ecx
```

Great! ☺

The effective instructions are:

```
1 mov ebx, 0c3h
6 sub eax, ebx
9 sub eax, 0a3h
0eh sub eax, 38h
11h add eax, ecx
13h add eax, 38h
16h add eax, 0a3h
1dh mov ecx, 62h
22h mov edx, ecx
25h inc edx
26h add edx, 61h
29h dec edx
2ah add eax, edx
root@kali:~/programs/metasm#
```

These are the effective instructions. ☺

- ✓ Emulation is always an excellent method to solve practical reverse engineering problems and , fortunately, we have the uEmu and also could use the Keystone Engine assembler and Capstone Engine disassembler. ☺

- ✓ Keystone Engine acts an assembler engine and:

  - ✓ Supports x86, Mips, Arm and many other architectures.
  - ✓ It is implemented in C/C++ and has bindings to Python, Ruby, Powershell and C# (among other languages).

- ✓ Installing Keystone:

  - ✓ root@kali:~/Desktop# wget https://github.com/keystone-engine/keystone/archive/0.9.1.tar.gz
  - ✓ root@kali:~/programs# cp /root/Desktop/keystone-0.9.1.tar.gz .
  - ✓ root@kali:~/programs# tar -zxvf keystone-0.9.1.tar.gz
  - ✓ root@kali:~/programs/keystone-0.9.1# apt-get install cmake
  - ✓ root@kali:~/programs/keystone-0.9.1# mkdir build ; cd build
  - ✓ root@kali:~/programs/keystone-0.9.1/build# apt-get install time
  - ✓ root@kali:~/programs/keystone-0.9.1/build# ../make-share.sh
  - ✓ root@kali:~/programs/keystone-0.9.1/build# make install
  - ✓ root@kali:~/programs/keystone-0.9.1/build# ldconfig
  - ✓ root@kali:~/programs/keystone-0.9.1/build# tail -3 /root/.bashrc
  - ✓ export PATH=$PATH:/root/programs/phantomjs-2.1.1-linux-x86_64/bin:/usr/local/bin/kstool
  - ✓ export RUBYLIB=$RUBYLIB:~/programs/metasm
  - ✓ export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/usr/local/lib

```c
#include <stdio.h>
#include <keystone/keystone.h>

#define HITB2019AMS "push ebx; mov ebx, 0xc3; sub eax, ebx; pop ebx; sub eax, 0xa3; sub eax, 0x38; add eax, ecx; add eax, 0x38; add eax, 0xa3; push edx; push ecx; mov ecx, 0x62; mov edx, ecx; pop ecx; inc edx; add edx, 0x61; dec edx; add eax, edx; pop edx"

int main(int argc, char **argv)
{
    ks_engine *keyeng;
    ks_err keyerr = KS_ERR_ARCH;
    size_t count;
    unsigned char *encode;
    size_t size;

    keyerr = ks_open(KS_ARCH_X86, KS_MODE_32, &keyeng);
    if (keyerr != KS_ERR_OK) {
        printf("ERROR: A fail occurred while calling ks_open(), quit\n");
        return -1;
    }

    if (ks_asm(keyeng, HITB2019AMS, 0, &encode, &size, &count)) {
        printf("ERROR: A fail has occured while calling ks_asm() with count = %lu, error code = %u\n", count, ks_errno(keyeng));
    } else {
        size_t i;

        for (i = 0; i < size; i++) {
            printf("%02x ", encode[i]);
        }
    }

    ks_free(encode);
    ks_close(keyeng);

    return 0;
}
```

instructions from the original obsfuscated code

Creating a keystone engine

Assembling our instructions using keystone engine.

Freeing memory and closing engine.

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```
root@kali:~/programs/hitb2019ams# more Makefile
.PHONY: all clean

KEYSTONE_LDFLAGS = -lkeystone -lstdc++ -lm

all:
        ${CC} -o hitb2019ams hitb2019ams.c ${KEYSTONE_LDFLAGS}

clean:
        rm -rf *.o hitb2019ams
root@kali:~/programs/hitb2019ams#
root@kali:~/programs/hitb2019ams# make
cc -o hitb2019ams hitb2019ams.c -lkeystone -lstdc++ -lm
root@kali:~/programs/hitb2019ams#
root@kali:~/programs/hitb2019ams# ./hitb2019ams
53 bb c3 00 00 00 29 d8 5b 2d a3 00 00 00 83 e8 38 01 c8 83 c0 38 05 a3 00 00 00 52 51
b9 62 00 00 00 89 ca 59 42 83 c2 61 4a 01 d0 5a root@kali:~/programs/hitb2019ams#
root@kali:~/programs/hitb2019ams#
root@kali:~/programs/hitb2019ams# ./hitb2019ams | xxd -r -p - > hitb2019ams.bin
root@kali:~/programs/hitb2019ams#
root@kali:~/programs/hitb2019ams# hexdump -C hitb2019ams.bin
00000000  53 bb c3 00 00 00 29 d8  5b 2d a3 00 00 00 83 e8  |S.....).[-......|
00000010  38 01 c8 83 c0 38 05 a3  00 00 00 52 51 b9 62 00  |8....8.....RQ.b.|
00000020  00 00 89 ca 59 42 83 c2  61 4a 01 d0 5a           |....YB..aJ..Z|
0000002d
root@kali:~/programs/hitb2019ams#
```

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```
seg000:00000000 ; File Name   : C:\VMs\hitb2019ams.bin
seg000:00000000 ; Format      : Binary file
seg000:00000000 ; Base Address: 0000h Range: 0000h - 002Dh Loaded length: 002Dh
seg000:00000000
seg000:00000000                 .686p
seg000:00000000                 .mmx
seg000:00000000                 .model flat
seg000:00000000
seg000:00000000 ; ===========================================================================
seg000:00000000
seg000:00000000 ; Segment type: Pure code
seg000:00000000 seg000          segment byte public 'CODE' use32
seg000:00000000                 assume cs:seg000
seg000:00000000                 assume es:nothing, ss:nothing, ds:nothing, fs:nothing,
seg000:00000000                 push    ebx
seg000:00000001                 mov     ebx, 0C3h
seg000:00000006                 sub     eax, ebx
seg000:00000008                 pop     ebx
seg000:00000009                 sub     eax, 0A3h
seg000:0000000E                 sub     eax, 38h
seg000:00000011                 add     eax, ecx
seg000:00000013                 add     eax, 38h
seg000:00000016                 add     eax, 0A3h
seg000:0000001B                 push    edx
seg000:0000001C                 push    ecx
seg000:0000001D                 mov     ecx, 62h
seg000:00000022                 mov     edx, ecx
seg000:00000024                 pop     ecx
seg000:00000025                 inc     edx
seg000:00000026                 add     edx, 61h
seg000:00000029                 dec     edx
seg000:0000002A                 add     eax, edx
seg000:0000002C                 pop     edx
seg000:0000002C seg000          ends
```

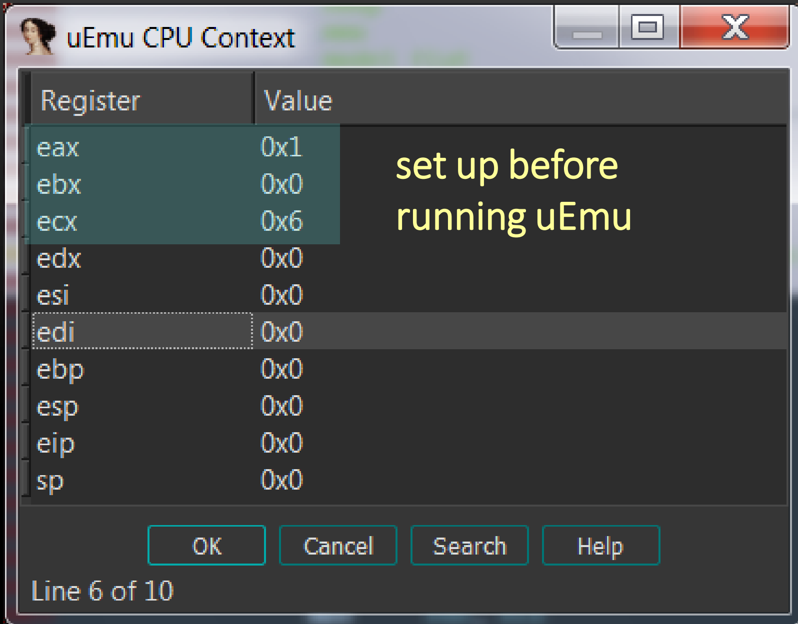
IDA Pro confirms our disassembly task. ☺

```c
#include <stdio.h>
#include <inttypes.h>
#include <capstone/capstone.h>


#define CODE "\x53\xbb\xb9\x00\x00\x00\x29\xd8\x5b\x83\xe8\x55\x83\xe8\x32\x01\xc8\x83\xc0\x50\x83\xc0\x37\x52\x51\xb9\x49\x00\x00\x00\x89\xca\x59\x42\x83\xc2\x70\x4a\x01\xd0\x5a"

int main(void)
{
        csh cs_handle;
        cs_insn *instruction;
        size_t count;

        if (cs_open(CS_ARCH_X86, CS_MODE_32, &cs_handle) != CS_ERR_OK)
                return -1;
        count = cs_disasm(cs_handle, CODE, sizeof(CODE)-1, 0x0001, 0, &instruction);
        if (count > 0) {
                size_t j;
                for (j = 0; j < count; j++) {
                        printf("0x%"PRIx32":\t%s\t\t%s\n", instruction[j].address, instruction[j].mnemonic, instruction[j].op_str);
                }

                cs_free(instruction, count);
        } else
                printf("Error: It's happened an error during the disassembling!\n");

        cs_close(&cs_handle);

    return 0;
}
```

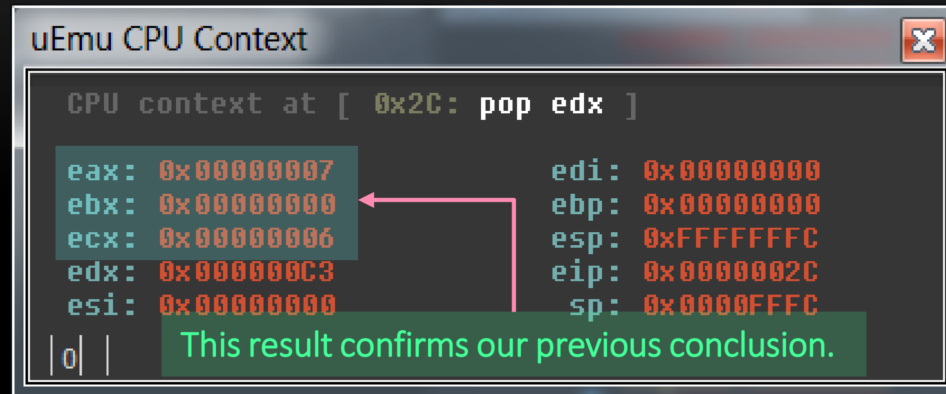
To install Capstone: apt-get install libcapstone3 libcapstone-dev ☺

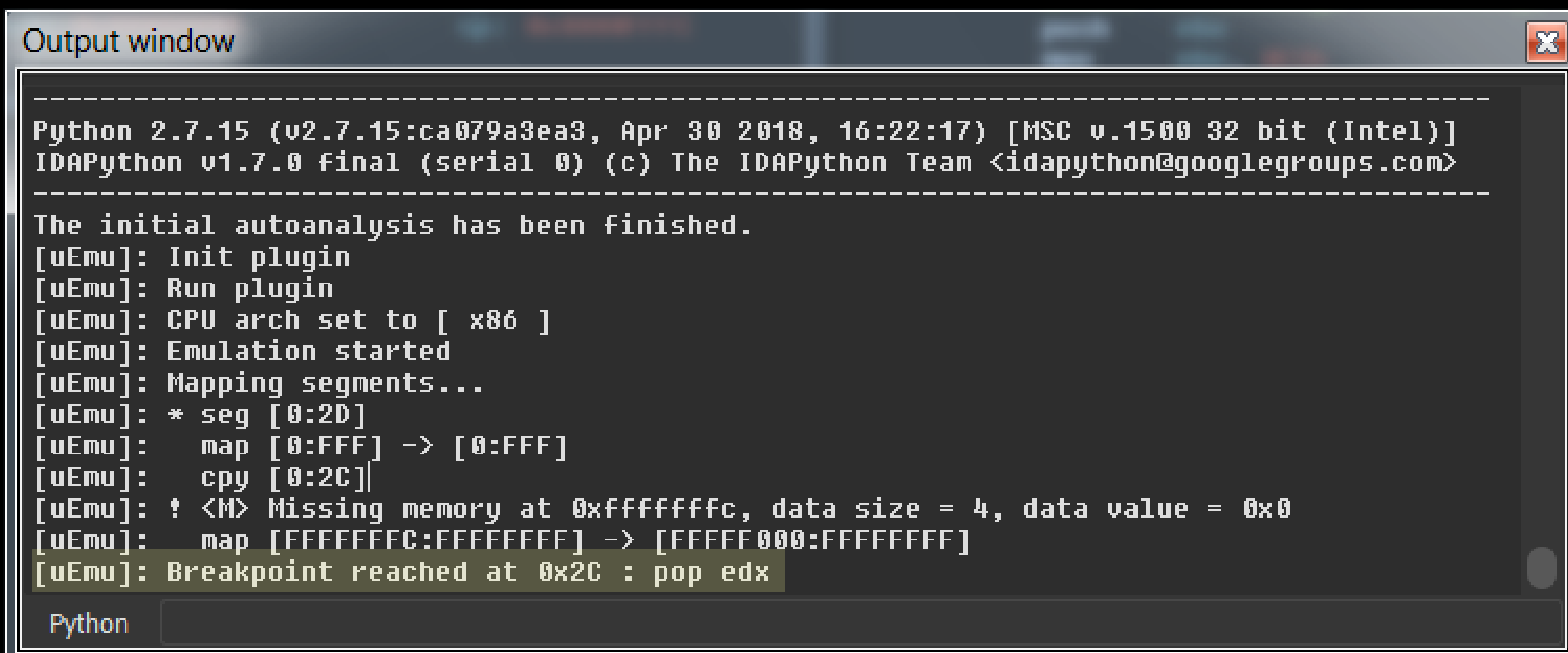
```
root@kali:~/programs/hitb2019ams/capstone# more Makefile
.PHONY: all clean

CAPSTONE_LDFLAGS = -lcapstone -lstdc++ -lm

all:
	${CC} -o hitb2019ams_rev hitb2019ams_rev.c ${CAPSTONE_LDFLAGS}

clean:
	rm -rf *.o hitb2019ams_rev
root@kali:~/programs/hitb2019ams/capstone#
root@kali:~/programs/hitb2019ams/capstone# make
cc -o hitb2019ams_rev hitb2019ams_rev.c -lcapstone -lstdc++ -lm
root@kali:~/programs/hitb2019ams/capstone#
root@kali:~/programs/hitb2019ams/capstone# ./hitb2019ams_rev
0x1:	push		ebx
0x2:	mov		ebx, 0xb9
0x7:	sub		eax, ebx
0x9:	pop		ebx
0xa:	sub		eax, 0x55
0xd:	sub		eax, 0x32
0x10:	add		eax, ecx
0x12:	add		eax, 0x50
0x15:	add		eax, 0x37
0x18:	push		edx
0x19:	push		ecx
0x1a:	mov		ecx, 0x49
0x1f:	mov		edx, ecx
0x21:	pop		ecx
0x22:	inc		edx
0x23:	add		edx, 0x70
0x26:	dec		edx
0x27:	add		eax, edx
0x29:	pop		edx
root@kali:~/programs/hitb2019ams/capstone#
```

Original code disassembled by Capstone. ☺



- ✓ Download uEmu from https://github.com/alexhude/uEmu
- ✓ Install Unicorn: pip install unicorn.
- ✓ Load uEmu in IDA using ALT+F7 hot key.
- ✓ Right click the code and choose the uEmu sub-menu.





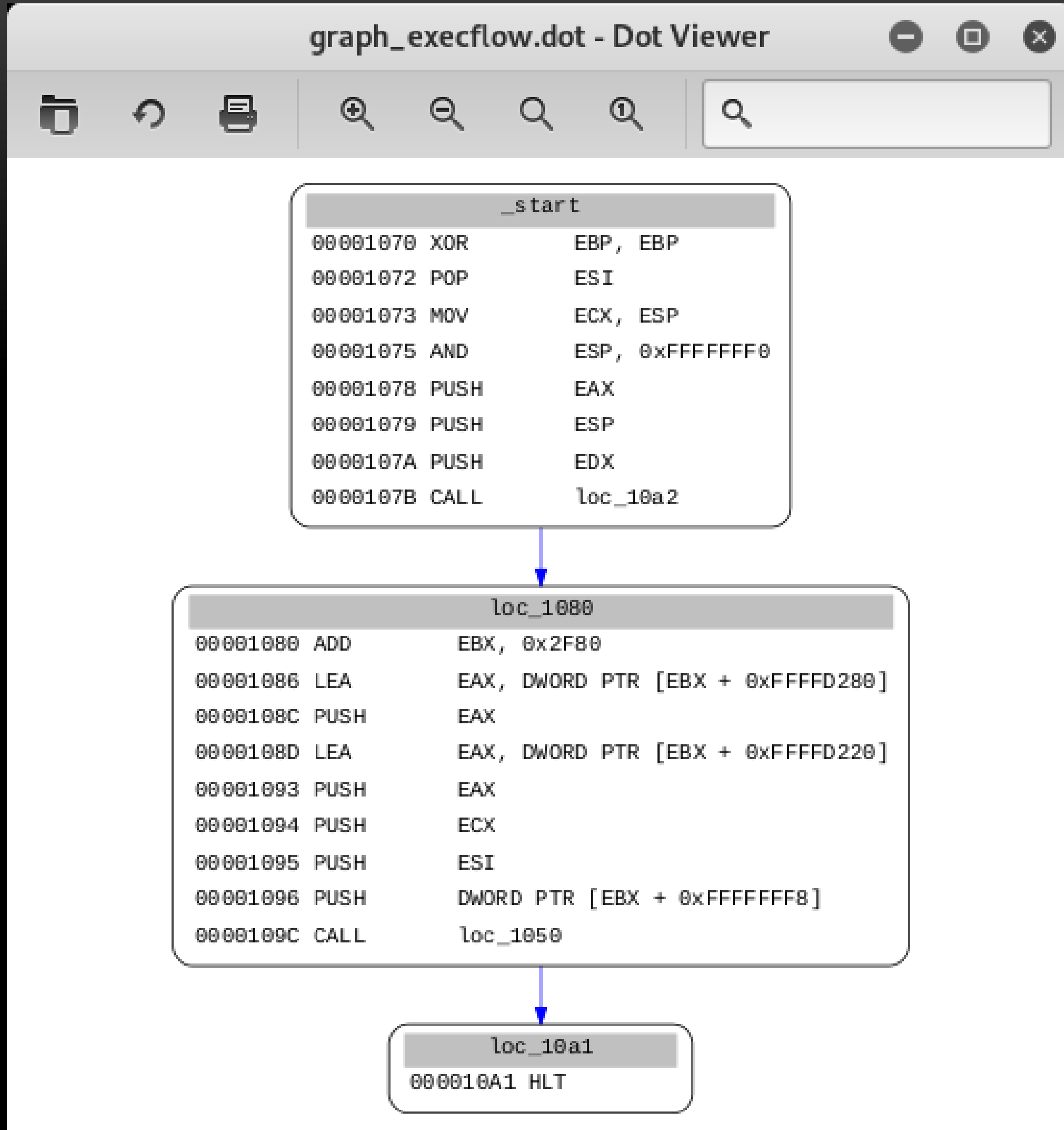
- ✓ MIASM is one of most impressive framework for reverse engineering, which is able to analyze, generate and modify several different types of programs.
- ✓ MIASM supports assembling and disassembling programs from different platforms such as ARM, x86, MIPS and so on, and it is also able to emulate code by using JIT.
- ✓ Therefore, MIASM is excellent to de-obfuscation.
- ✓ Installing MIASM:
  - ✓ git clone https://github.com/serpilliere/elfesteem.git elfesteem
  - ✓ cd elfesteem/
  - ✓ python setup.py build
  - ✓ python setup.py install
  - ✓ apt-get install clang
  - ✓ apt-get remove libtcc-dev
  - ✓ apt-get install llvm
  - ✓ cd ..
  - ✓ git clone http://repo.or.cz/tinycc.git
  - ✓ cd tinycc/
  - ✓ git checkout release_0_9_26
  - ✓ ./configure --disable-static
  - ✓ make
  - ✓ make install

- ✓ pip install llvmlite
- ✓ apt-get install z3
- ✓ apt-get install python-pycparser
- ✓ git clone https://github.com/cea-sec/miasm.git
- ✓ root@kali:~/programs/miasm# python setup.py build
- ✓ root@kali:~/programs/miasm# python setup.py install
- ✓ root@kali:~/programs/miasm/test# python test_all.py
- ✓ apt-get install graphviz
- ✓ apt-get install xdot
- ✓ (testing MIASM) root@kali:~/programs# python /root/programs/miasm/example/disasm/full.py -m x86_32 /root/programs/shellcode

```
INFO : Load binary
INFO : ok
INFO : import machine...
INFO : ok
INFO : func ok 0000000000001070 (0)
INFO : generate graph file
INFO : generate intervals
[0x1070 0x10A2]
INFO : total lines 0
```

- ✓ (testing MIASM) xdot graph_execflow.dot

ALEXANDRE BORGES – MALWARE AND SECURITY RESEARCHER



ALEXANDRE BORGES – MALWARE AND SECURITY RESEARCHER

```python
from miasm2.analysis.binary import Container
from miasm2.analysis.machine import Machine
from miasm2.jitter.csts import PAGE_READ, PAGE_WRITE

with open("hitb2019ams.bin") as fdesc:
    cont=Container.from_stream(fdesc)

machine=Machine('x86_32')
mdis=machine.dis_engine(cont.bin_stream)
ourblocks = mdis.dis_multiblock(0)
for block in ourblocks:
    print block
jitter = machine.jitter("llvm")
jitter.init_stack()
s = open("hitb2019ams.bin").read()
run_addr = 0x40000000
jitter.cpu.EAX=1
jitter.cpu.ECX=6
jitter.vm.add_memory_page(run_addr, PAGE_READ | PAGE_WRITE, s)
def code_sentinelle(jitter):
    jitter.run = False
    jitter.pc = 0
    return True
jitter.add_breakpoint(0x4000002c, code_sentinelle)
jitter.push_uint32_t(0x4000002c)
jitter.jit.log_regs = True
jitter.jit.log_mn = True
jitter.init_run(run_addr)
jitter.continue_run()

open('hitb2019ams_cfg.dot', 'w').write(ourblocks.dot())
```

Opens our file. The Container provides the byte source to the disasm engine.

Instantiates the assemble engine using the x86 32-bits architecture.

Runs the recursive transversal disassembling since beginning.

Set “llvm” as Jit engine to emulation and initialize the stack.

Set the virtual start address, register values and memory protection.

Adds a breakpoint at the last line of code.

Run the emulation.

Generates a dot graph.

```
root@kali:~/programs/hitb2019ams# python miasm.py
WARNING: not enough bytes in str
WARNING: cannot disasm at 2D
WARNING: not enough bytes in str
WARNING: cannot disasm at 2D
loc_0000000000000000:0x00000000
PUSH       EBX
MOV        EBX, 0xC3
SUB        EAX, EBX
POP        EBX
SUB        EAX, 0xA3
SUB        EAX, 0x38
ADD        EAX, ECX
ADD        EAX, 0x38
ADD        EAX, 0xA3
PUSH       EDX
PUSH       ECX
MOV        ECX, 0x62
MOV        EDX, ECX
POP        ECX
INC        EDX
ADD        EDX, 0x61
DEC        EDX
ADD        EAX, EDX
POP        EDX
->      c_next:loc_000000000000002D:0x0000002d
loc_000000000000002D:0x0000002d
```

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```
EAX 00000001 EBX 00000000 ECX 00000006 EDX 00000000 ESI 00000000 EDI 00000000
ESP 0123FFF8 EBP 00000000 EIP 40000000 zf 0 nf 0 of 0 cf 0
40000001 MOV         EBX, 0xC3
EAX 00000001 EBX 000000C3 ECX 00000006 EDX 00000000 ESI 00000000 EDI 00000000
ESP 0123FFF8 EBP 00000000 EIP 40000000 zf 0 nf 0 of 0 cf 0
40000006 SUB         EAX, EBX
EAX FFFFFF3E EBX 000000C3 ECX 00000006 EDX 00000000 ESI 00000000 EDI 00000000
ESP 0123FFF8 EBP 00000000 EIP 40000000 zf 0 nf 1 of 0 cf 1
40000008 POP         EBX
EAX FFFFFF3E EBX 00000000 ECX 00000006 EDX 00000000 ESI 00000000 EDI 00000000
ESP 0123FFFC EBP 00000000 EIP 40000000 zf 0 nf 1 of 0 cf 1
40000009 SUB         EAX, 0xA3
EAX FFFFFE9B EBX 00000000 ECX 00000006 EDX 00000000 ESI 00000000 EDI 00000000
ESP 0123FFFC EBP 00000000 EIP 40000000 zf 0 nf 1 of 0 cf 0
4000000E SUB         EAX, 0x38
```

```
ESP 0123FFF8 EBP 00000000 EIP 40000000 zf 0 nf 1 of 0 cf 0
40000025 INC         EDX
EAX FFFFFF44 EBX 00000000 ECX 00000006 EDX 00000063 ESI 00000000 EDI 00000000
ESP 0123FFF8 EBP 00000000 EIP 40000000 zf 0 nf 0 of 0 cf 0
40000026 ADD         EDX, 0x61
EAX FFFFFF44 EBX 00000000 ECX 00000006 EDX 000000C4 ESI 00000000 EDI 00000000
ESP 0123FFF8 EBP 00000000 EIP 40000000 zf 0 nf 0 of 0 cf 0
40000029 DEC         EDX
EAX FFFFFF44 EBX 00000000 ECX 00000006 EDX 000000C3 ESI 00000000 EDI 00000000
ESP 0123FFF8 EBP 00000000 EIP 40000000 zf 0 nf 0 of 0 cf 0
4000002A ADD         EAX, EDX
EAX 00000007 EBX 00000000 ECX 00000006 EDX 000000C3 ESI 00000000 EDI 00000000
ESP 0123FFF8 EBP 00000000 EIP 40000000 zf 0 nf 0 of 0 cf 1
```

```
loc_0000000000000000
PUSH        EBX
MOV         EBX, 0xC3
SUB         EAX, EBX
POP         EBX
SUB         EAX, 0xA3
SUB         EAX, 0x38
ADD         EAX, ECX
ADD         EAX, 0x38
ADD         EAX, 0xA3
PUSH        EDX
PUSH        ECX
MOV         ECX, 0x62
MOV         EDX, ECX
POP         ECX
INC         EDX
ADD         EDX, 0x61
DEC         EDX
ADD         EAX, EDX
POP         EDX
```

```
loc_000000000000002D
IOError
```

Our proposed code. ☺

```
root@kali:~/programs/hitb2019ams# python
Python 2.7.16 (default, Apr  6 2019, 01:42:57)
[GCC 8.3.0] on linux2
Type "help", "copyright", "credits" or "license" for more information.
>>>
>>> from miasm2.analysis.binary import Container
>>> from miasm2.analysis.machine import Machine
>>> from miasm2.jitter.csts import PAGE_READ, PAGE_WRITE
>>> with open("hitb2019ams.bin") as fdesc:
...     cont=Container.from_stream(fdesc)
...
>>> hitbmach=Machine('x86_32')
>>> hitbdis=hitbmach.dis_engine(cont.bin_stream)
>>> myblocks = hitbdis.dis_multiblock(0)
WARNING: not enough bytes in str
WARNING: cannot disasm at 2D
WARNING: not enough bytes in str
WARNING: cannot disasm at 2D
>>> sym = hitbmach.ira( )
>>> for block in myblocks:
...     sym.add_block(block)
...
[<miasm2.ir.ir.IRBlock object at 0x7f25bb863820>]
[]
>>> from miasm2.ir.symbexec import SymbolicExecutionEngine
>>> symb = SymbolicExecutionEngine(sym,hitbmach.mn.regs.regs_init)
>>> symbolic_pc = symb.run_at(0, step=True)
```

Get the IRA converter.

Initialize and run the Symbolic Execution Engine.

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```
Instr PUSH        EBX
Assignblk:
ESP = ESP + -0x4
@32[ESP + -0x4] = EBX

________________________________________________________________________________
_____
ESP                    = ESP_init + 0xFFFFFFFC
@32[ESP_init + 0xFFFFFFFC] = EBX_init

________________________________________________________________________________
_____
Instr MOV         EBX, 0xC3
Assignblk:
EBX = 0xC3

________________________________________________________________________________
_____
ESP                    = ESP_init + 0xFFFFFFFC
EBX                    = 0xC3
@32[ESP_init + 0xFFFFFFFC] = EBX_init

________________________________________________________________________________
_____
Instr SUB         EAX, EBX
Assignblk:
zf = (EAX + -EBX)?(0x0,0x1)
nf = (EAX + -EBX)[31:32]
pf = parity((EAX + -EBX) & 0xFF)
of = ((EAX ^ (EAX + -EBX)) & (EAX ^ EBX))[31:32]
cf = (((EAX ^ EBX) ^ (EAX + -EBX)) ^ ((EAX ^ (EAX + -EBX)) & (EAX ^ EBX)))[3
1:32]
af = ((EAX ^ EBX) ^ (EAX + -EBX))[4:5]
EAX = EAX + -EBX
```

ALEXANDRE BORGES – MALWARE AND SECURITY RESEARCHER

```
____
EAX                  = EAX_init + ECX_init
cf                   = ((((EAX_init + ECX_init) ^ (EAX_init + ECX_init + 0xFFF
FFF3D)) & ((EAX_init + ECX_init + 0xFFFFFF3D) ^ 0xFFFFFF3C)) ^ (EAX_init + E
CX_init) ^ (EAX_init + ECX_init + 0xFFFFFF3D) ^ 0xC3)[31:32]
pf                   = parity((EAX_init + ECX_init) & 0xFF)
zf                   = (EAX_init + ECX_init)?(0x0,0x1)
af                   = ((EAX_init + ECX_init) ^ (EAX_init + ECX_init + 0xFFFF
F3D) ^ 0xC3)[4:5]
of                   = (((EAX_init + ECX_init) ^ (EAX_init + ECX_init + 0xFFFF
FF3D)) & ((EAX_init + ECX_init + 0xFFFFFF3D) ^ 0xFFFFFF3C))[31:32]
nf                   = (EAX_init + ECX_init)[31:32]
@32[ESP_init + 0xFFFFFFF8] = ECX_init
@32[ESP_init + 0xFFFFFFFC] = EDX_init

____________________________________________________________________________
____
Instr POP        EDX
Assignblk:
IRDst = loc_000000000000002D:0x0000002d

____________________________________________________________________________
____
EAX                  = EAX_init + ECX_init
cf                   = ((((EAX_init + ECX_init) ^ (EAX_init + ECX_init + 0xFFF
FFF3D)) & ((EAX_init + ECX_init + 0xFFFFFF3D) ^ 0xFFFFFF3C)) ^ (EAX_init + E
CX_init) ^ (EAX_init + ECX_init + 0xFFFFFF3D) ^ 0xC3)[31:32]
pf                   = parity((EAX_init + ECX_init) & 0xFF)
zf                   = (EAX_init + ECX_init)?(0x0,0x1)
af                   = ((EAX_init + ECX_init) ^ (EAX_init + ECX_init + 0xFFFF
F3D) ^ 0xC3)[4:5]
IRDst                = 0x2D
of                   = (((EAX_init + ECX_init) ^ (EAX_init + ECX_init + 0xFFFF
FF3D)) & ((EAX_init + ECX_init + 0xFFFFFF3D) ^ 0xFFFFFF3C))[31:32]
nf                   = (EAX_init + ECX_init)[31:32]
@32[ESP_init + 0xFFFFFFF8] = ECX_init
@32[ESP_init + 0xFFFFFFFC] = EDX_init
```

BIOS/UEFI THREATS

- ✓ Since Windows Vista, the main protection against rootkits have been the KCS (Kernel-mode Code Signing Policy) that prevents any unsigned kernel module to be loaded.
- ✓ KCS forces all integrity checks on drivers started on boot (PnP/non-PnP) in x64 systems.
- ✓ In a general way, rootkits could try to bypass the KCS:
  - ✓ disabling it by changing BCD variables to put the system in testsigning mode.
  - ✓ exploiting some vulnerability to modify the boot process.
  - ✓ using a driver with valid certificate from third party companies to attack the system.
  - ✓ disabling the Secure Boot, which forces BIOS to verify UEFI and system boot files.

- ✓ Code Integrity can be only disabled by changing BCD variables whether the Secure Boot is disabled.
- ✓ Unfortunately, BIOS/UEFI threats attacks earlier boot stages, before KCS starts running, so KCS is not effective against bootkits.
- ✓ Therefore, the malware´s goal is to attack any point before common defenses start to compromise the boot process.
- ✓ Fortunately, the Code Integrity in Windows 8 and later are not controlled by only one variable (nt!g_CiEnabled) and there are several other "control variables".
- ✓ As the KCS is not able to fight against bootkits, which load before any system/kernel protection starts, so Secure Boot could help us because:
  - ✓ it checks the integrity of Windows boot files and UEFI components.
  - ✓ it checks the bootloader's integrity.

- On Windows 10, the protection against the kernel and Windows boot componenents were improved through the Virtual Secure Mode.

- VSM (Virtual Secure Mode) provides an isolation for the Windows kernel and critical system modules from other components by using virtualization extensions of the CPU.

- Therefore, non-critical drivers are not able to disable code integrity because they run in separated containers. ☺

- As we already know, VSM is composed by:
  - Local Security Authority (to keep processes based on LSASS working)
  - Kernel Mode Code Integrity (KMCI)
  - Hypervisor Code Integrity

- Finally, we can talk about the Device Guard that is composed by:
  - Configurable Code Integrity (CCI): assure that only trusted code runs from the boot loader.
  - VSM Protected Code Integrity: represents the KMCI (Kernel Mode Code Integrity) and Hypervisor Code Integrity (HVCI) in the VSM.
  - Platform and UEFI Secure Boot: protects the UEFI and boot components by using digital signature.
- To use the advantages and run on systems that Device Guard is active:
  - driver can't load data as executable code.
  - driver can't alter anything on the system memory.
  - allocated pages can't be executable and writable at same time.
- Likely, many malware samples don't follow these recommendation, so they don't work on systems that Device Guard is on.

- ✓ Windows offers other protection options to protect against malware such as ELAM (Early Launch Anti-Malware) to prevent malicious and unauthorized code to execute in the kernel land.

- ✓ There are many interesting aspects about ELAM:

  - ✓ It is based on callback methods, which monitors drivers and registries.

  - ✓ ELAM classifies drivers in good, bad and unknown.

  - ✓ Its decisions are based on image's name, hash, registry location and certificate issuer/publisher.

  - ✓ There are some possible values used in the ELAM policy, but the default one (PNP_INITIALIZE_BAD_CRITICAL_DRIVERS) is suitable for most sceneries because it allows to load bad critical drivers, but not bad non-critical drivers. ☺

- ✓ At winload.exe execution, ELAM can not access any binary on disk because the drivers to access the disk is not ready yet.

- ✓ ELAM is excellent against rootkit, but it is not appropriate against bootkits, which usually load before winload.exe executing (Windows executable that loads ELAM).

- ✓ In legacy systems, bootkits could attack:
  - ✓ MBR: they compromising either MBR boot code or partition table (located at 0x1be).
  - ✓ VBR: as VBR (Volume Boot Record) holds the information about the filesystem's type, so the idea is to compromise BIOS parameter block (BPB) to change the IPL loading process (next stage) or even executing a malicious code.
    - ✓ The target field to attack is the "Hidden sectors" field, which provides the IPL location, in the BPB.
    - ✓ The malicious code could be loaded from a hidden and encrypted file system. ☺
    - ✓ After the malicious code being execute, so the "real IPL" is loaded.

- ✓ IPL: the IPL (Initial Program Loader) holds necessary bootstrap code to locate the OS loader.

- ✓ Thus:

  - ✓ Compromising the IPL might cause the execution of a malicious code instead of loading the bootmgr module.

  - ✓ A malicious IPL could load a malicious kernel driver during the booting process.

  - ✓ Some malicious IPL codes are polymorphic. Take care. ☺

Boot Sector NTFS, Base Offset: 0

Offset	Title	Value
0	JMP instruction	EB 52 90
3	File system ID	NTFS
B	Bytes per sector	512
D	Sectors per cluster	8
E	Reserved sectors	0
10	(always zero)	00 00 00
13	(unused)	00 00
15	Media descriptor	F8
16	(unused)	00 00
18	Sectors per track	63
1A	Heads	255
1C	Hidden sectors	206,848

BIOS_PARAMETER__BLOCK_NTFS

- ✓ Changing the "Hidden sectors" field could cause loading a malicious code instead of executing the IPL.

- ✓ Once the bootmgr module is loaded, so the malware's goal is to circumvent the code integrity verification. ☺

- ✓ Furthermore, the bootmgr and windload.exe have a central responsability in perform the transition between real mode to protect mode.

- ✓ Both executables are critical for bootkits because they need to keep the control of the boot process during this transition.

- ✓ Once the the code integrity checking has been disabled, it is possible to replace important boot components such as kdcom.dll by a malicious one.

- ✓ BIOS disk services provides several operations:
  - ✓ extended read (0x42)
  - ✓ extended write (0x43)
  - ✓ extended get driver parameters (0x48)
- ✓ Subverting (hooking) INT 13h handle (including reading and writing operation from disk) it is one of the best way to compromise:
  - ✓ the bootmgr
  - ✓ winload.exe
  - ✓ the kernel.

- Of course, it is pretty easy to disassemble a MBR in IDA Pro:
  - dd.exe -v if=\\.\PHYSICALDRIVE0 of=mbr.bin bs=512 count=1
  - Set the offset to 0x7c00 and disassemble it as 16-bit code.

```
seg000:7C00 loc_7C00:                               ; CODE XREF: seg000:7D2A↓J
seg000:7C00                 xor     ax, ax
seg000:7C02                 mov     ss, ax
seg000:7C04                 mov     sp, 7C00h
seg000:7C07                 mov     es, ax
seg000:7C09                 mov     ds, ax
seg000:7C0B                 mov     si, 7C00h
seg000:7C0E                 mov     di, 600h
seg000:7C11                 mov     cx, 200h
seg000:7C14                 cld
seg000:7C15                 rep movsb
seg000:7C17                 push    ax
seg000:7C18                 push    61Ch
seg000:7C1B                 retf
seg000:7C1C ; ---------------------------------------------------------------------------
seg000:7C1C                 sti
seg000:7C1D                 mov     cx, 4
seg000:7C20                 mov     bp, 7BEh
seg000:7C23
seg000:7C23 loc_7C23:                               ; CODE XREF: seg000:7C30↓j
seg000:7C23                 cmp     byte ptr [bp+0], 0
seg000:7C27                 jl      short loc_7C34
seg000:7C29                 jnz     loc_7D3B
seg000:7C2D                 add     bp, 10h
seg000:7C30                 loop    loc_7C23
seg000:7C32                 int     18h             ; TRANSFER TO ROM BASIC
seg000:7C32                                         ; causes transfer to ROM-based BASIC (IBM-PC)
seg000:7C32                                         ; often reboots a compatible; often has no effect at all
seg000:7C34
seg000:7C34 loc_7C34:                               ; CODE XREF: seg000:7C27↑j
seg000:7C34                                         ; seg000:7CAE↓j
seg000:7C34                 mov     [bp+0], dl
seg000:7C37                 push    bp
seg000:7C38                 mov     byte ptr [bp+11h], 5
seg000:7C3C                 mov     byte ptr [bp+10h], 0
seg000:7C40                 mov     ah, 41h
```

Clean MBR. ☺

```
seg000:7C00 ; File Name   : C:\VMs\mbr_infected.bin
seg000:7C00 ; Format      : Binary file
seg000:7C00 ; Base Address: 0000h Range: 7C00h - 7E00h Loaded length: 0200h
seg000:7C00
seg000:7C00                 .686p
seg000:7C00                 .mmx
seg000:7C00                 .model flat
seg000:7C00
seg000:7C00 ; ===========================================================================
seg000:7C00
seg000:7C00 ; Segment type: Pure code
seg000:7C00 seg000          segment byte public 'CODE' use16
seg000:7C00                 assume cs:seg000
seg000:7C00                 ;org 7C00h
seg000:7C00                 assume es:nothing, ss:nothing, ds:nothing, fs:nothing, gs:nothing
seg000:7C00                 cli
seg000:7C01                 xor     eax, eax
seg000:7C04                 mov     ss, ax
seg000:7C06                 mov     es, ax
seg000:7C08                 mov     ds, ax
seg000:7C0A                 mov     sp, 7C00h
seg000:7C0D                 sti
seg000:7C0E                 mov     ds:byte_7C93, dl
seg000:7C12                 mov     eax, 20h
seg000:7C18                 mov     ebx, 22h
seg000:7C1E                 mov     cx, 8000h
seg000:7C21
seg000:7C21 loc_7C21:                               ; CODE XREF: seg000:7C2A↓j
seg000:7C21                 call    sub_7C38
seg000:7C24                 dec     eax
seg000:7C26                 cmp     eax, 0
seg000:7C2A                 jnz     short loc_7C21
seg000:7C2C                 mov     eax, ds:8000h
seg000:7C30                 jmp     far ptr 0:8000h
seg000:7C35 ; ---------------------------------------------------------------------------
seg000:7C35
seg000:7C35 loc_7C35:                               ; CODE XREF: seg000:7C36↓j
seg000:7C35                 hlt
seg000:7C36 ; ---------------------------------------------------------------------------
seg000:7C36                 jmp     short loc_7C35
```

Infected MBR. ☺

ALEXANDRE BORGES – MALWARE AND SECURITY RESEARCHER

- ✓ C:\> "C:\Program Files (x86)\VMware\VMware Workstation\vmware-vdiskmanager.exe" -r Windows_7_x86-cl2-000002.vmdk -t 0 infected.vmdk
- ✓ root@kali:~# qemu-img convert -f vmdk -O raw infected.vmdk infected.raw
- ✓ root@kali:~# dd if=infected.raw of=mbr_infected.bin bs=512 count=1
- ✓ root@kali:~# file mbr_infected.bin

  br_infected.bin: DOS/MBR boot sector

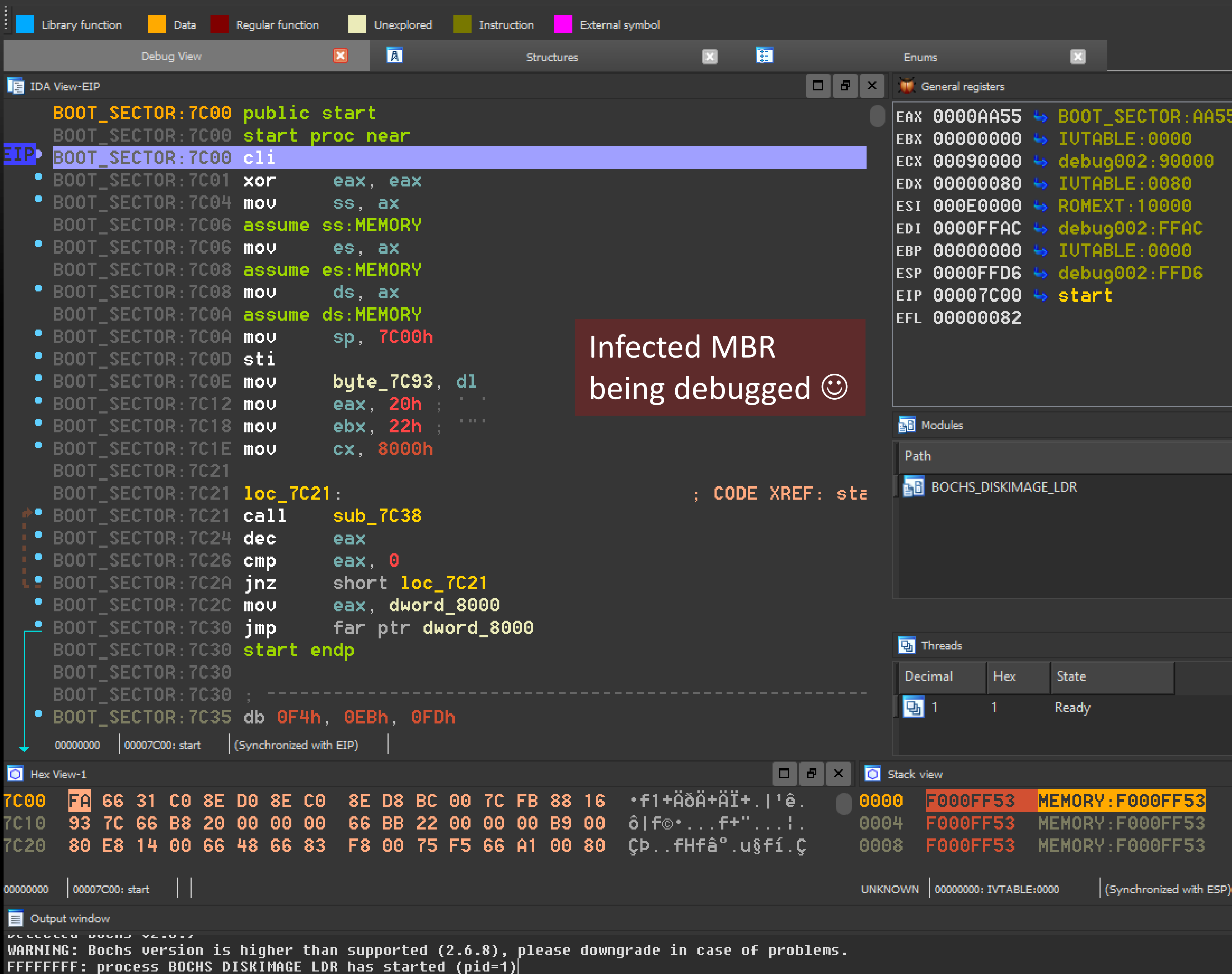
- ✓ Install Bochs and create a bochsrc file pointing to the converted image above:

```
romimage: file= "C:\Program Files (x86)\Bochs-2.6.9\BIOS-bochs-latest"
vgaromimage: file= "C:\Program Files (x86)\Bochs-2.6.9\VGABIOS-lgpl-latest"
megs: 32
ata0: enabled=1, ioaddr1=0x1f0, ioaddr2=0x3f0, irq=14
ata0-master: type=disk, path="C:\VMs\infected.raw", mode=flat, cylinders=1024, heads=16, spt=63
boot: disk
vga: extension=vbe
mouse: enabled=0
log: nul
logprefix: %t%e%d
panic: action=fatal
error: action=report
info: action=report
debug: action=ignore
# display_library: win32, options="gui_debug"
```

ALEXANDRE BORGES – MALWARE AND SECURITY RESEARCHER

```
C:\Program Files (x86)\Bochs-2.6.9>bochsdbg.exe -q -f bochsrc
========================================================================
                       Bochs x86 Emulator 2.6.9
               Built from SVN snapshot on April 9, 2017
                  Compiled on Apr  9 2017 at 09:49:25
========================================================================
00000000000i[      ] reading configuration from bochsrc
00000000000i[      ] installing win32 module as the Bochs GUI
00000000000i[      ] using log file nul
Next at t=0
(0) [0x0000fffffff0] f000:fff0 (unk. ctxt): jmpf 0xf000:e05b          ; ea5be000f0
<bochs:1> lb 0x7c00
<bochs:2> info break
Num Type           Disp Enb Address
  1 lbreakpoint    keep y   0x0000000000007c00
<bochs:3> c
(0) Breakpoint 1, 0x0000000000007c00 in ?? ()
Next at t=17404827
(0) [0x000000007c00] 0000:7c00 (unk. ctxt): cli                       ; fa
<bochs:4> u /8
00007c00: (                    ): cli                       ; fa
00007c01: (                    ): xor eax, eax              ; 6631c0
00007c04: (                    ): mov ss, ax                ; 8ed0
00007c06: (                    ): mov es, ax                ; 8ec0
00007c08: (                    ): mov ds, ax                ; 8ed8
00007c0a: (                    ): mov sp, 0x7c00            ; bc007c
00007c0d: (                    ): sti                       ; fb
00007c0e: (                    ): mov byte ptr ds:0x7c93, dl ; 8816937c
<bochs:5> s
Next at t=17404828
(0) [0x000000007c01] 0000:7c01 (unk. ctxt): xor eax, eax              ; 6631c0
<bochs:6> s
Next at t=17404829
```

ALEXANDRE BORGES – MALWARE AND SECURITY RESEARCHER



Infected MBR being debugged ☺

ALEXANDRE BORGES – MALWARE AND SECURITY RESEARCHER

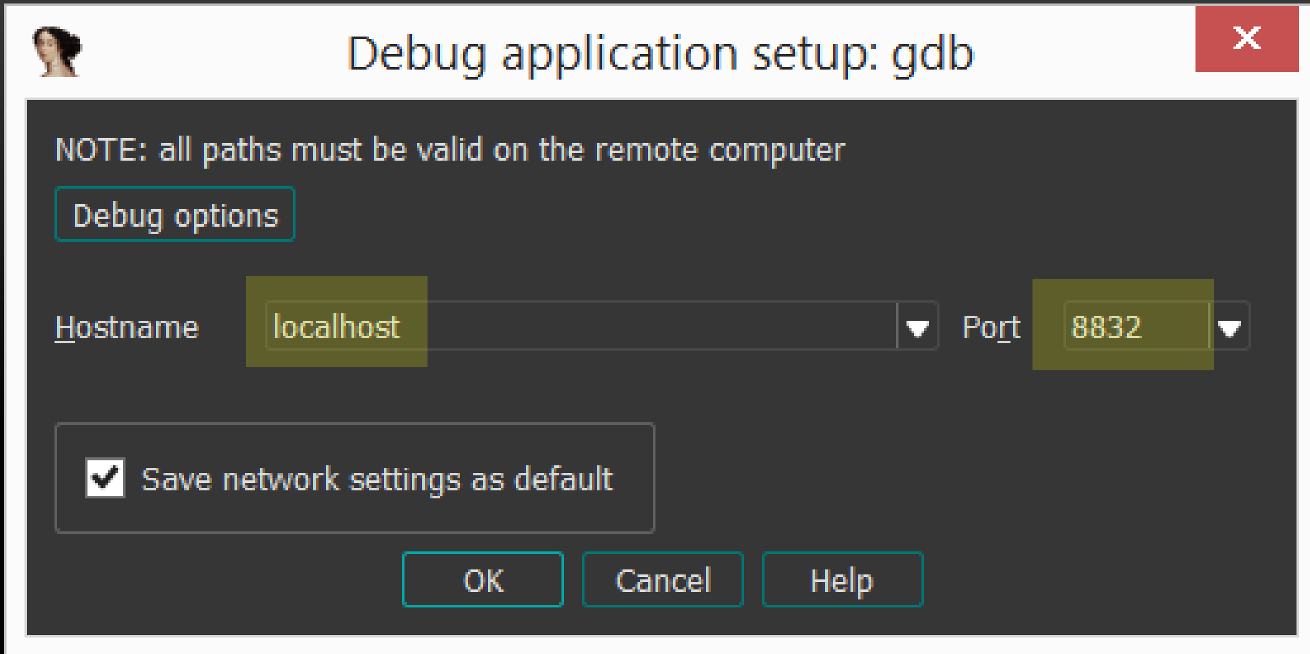
✓ Another way to debug and analyze a MBR using IDA Pro is also simple:

✓ Dowload the ida.py from http://hexblog.com/ida_pro/files/mbr_bochs.zip

✓ Copy the ida.py to your preferred folder (I've copied it to Bochs installation folder), edit the first lines to adapt it to your case:

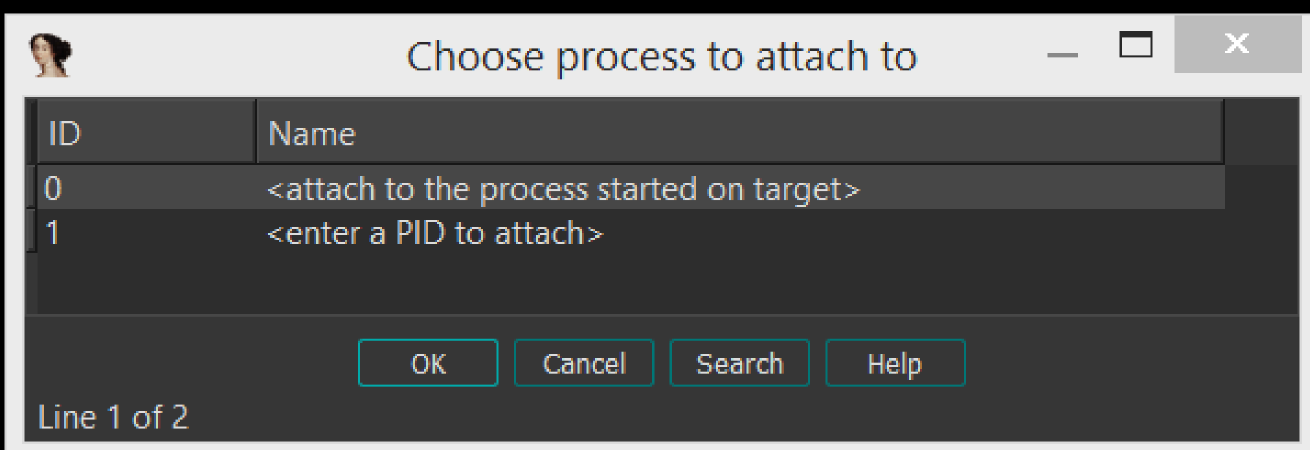
```
# Some constants
SECTOR_SIZE = 512
BOOT_START  = 0x7C00
BOOT_SIZE   = 0x7C00 + SECTOR_SIZE * 2
BOOT_END    = BOOT_START + BOOT_SIZE
SECTOR2     = BOOT_START + SECTOR_SIZE
MBRNAME     = "C:\VMs\mbr_infected.bin"
IMGNAME     = "C:\VMs\infected.raw"
```

- ✓ A better approach is to use a debugger instead of using an emulator.
- ✓ If you are using VMware Workstation, change the .vmx configuration file from the target machine to include the following lines:
  - ✓ monitor.debugOnStartGuest32 = "TRUE“ / monitor.debugOnStartGuest64 = "TRUE“
    - ✓ Breaks on the first instruction since the power on.
  - ✓ debugStub.listen.guest32 = "TRUE“ / debugStub.listen.guest64 = “TRUE”
    - ✓ Enables guest debugging.
  - ✓ debugStub.hideBreakpoints = "TRUE“
    - ✓ Use hardware breakpoint instead of using software breakpoints.
- ✓ Power on the virtual machine.
- ✓ Launch the IDA Pro, go to Debugger → Attach → Remote GDB debugger



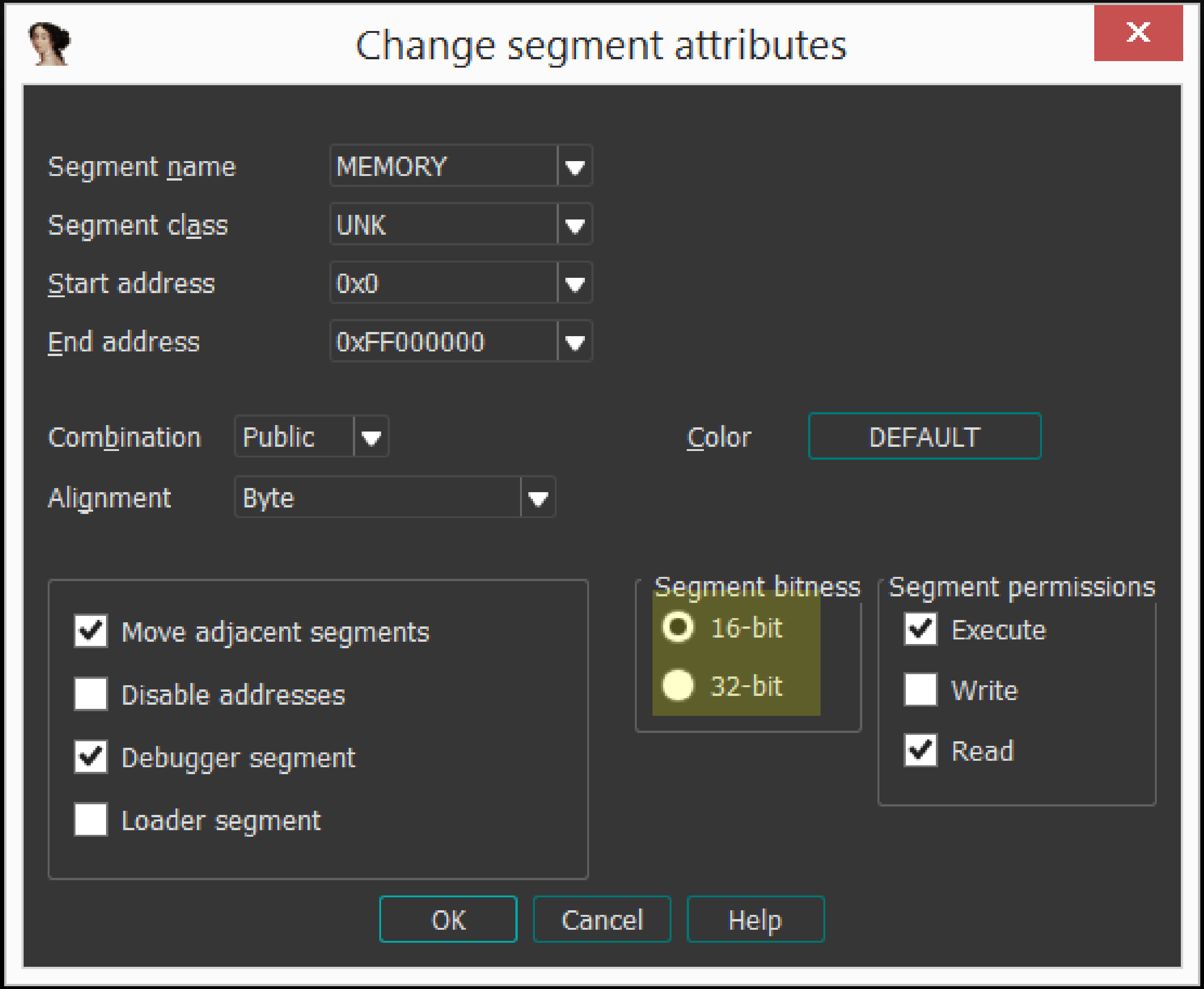
- ✓ We've set Hostname as "localhost" because we starts the debugger in the same host of the VM.
- ✓ The debugging port must be 8832.

- ✓ After configuring the Debug application setup, click on OK button and choose "attach to the process started on target" as shown below.

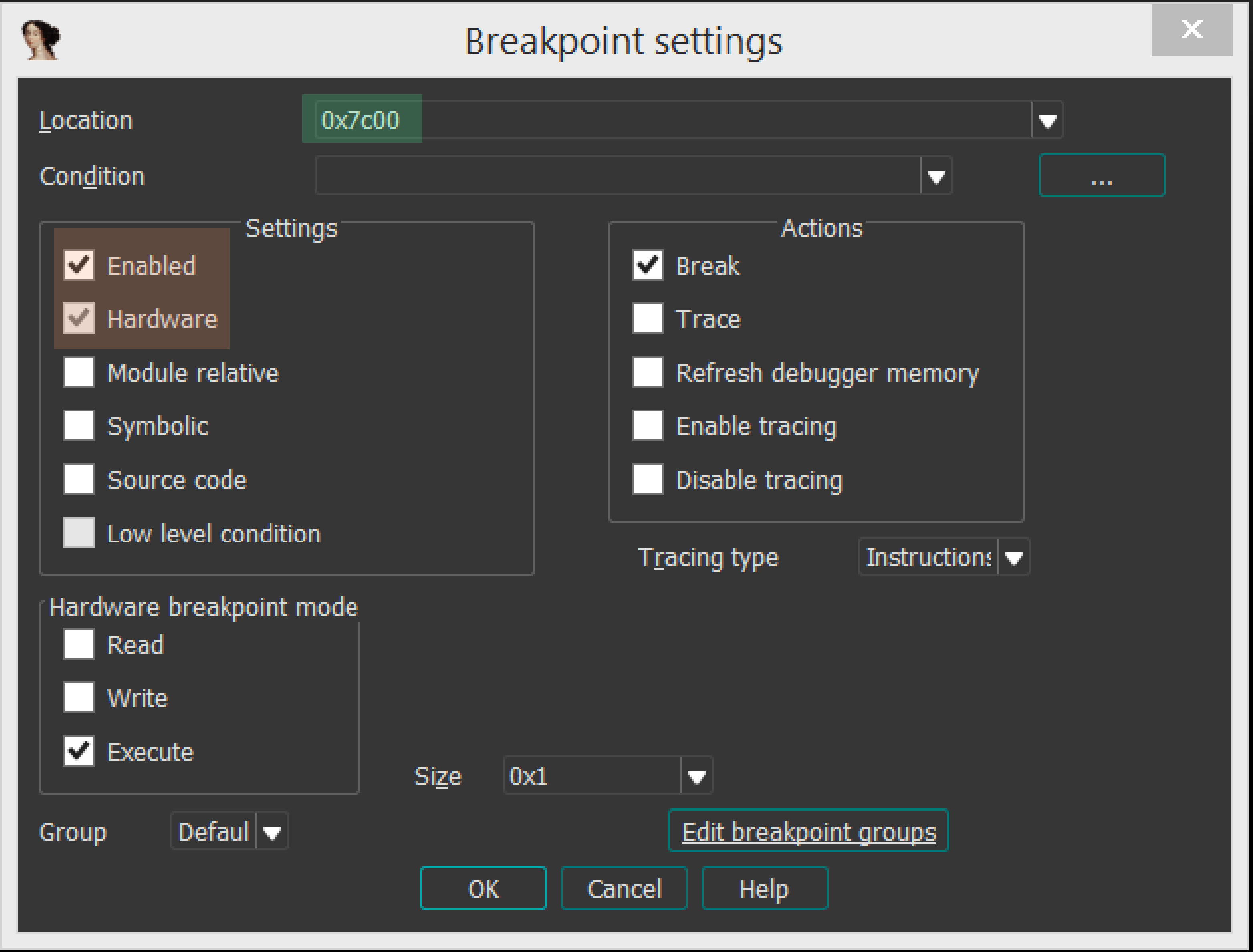


- ✓ After debugger starting, go to Views → Open subviews → Segments (or hit SHIFT+F7), right click and go to "Edit Segments".

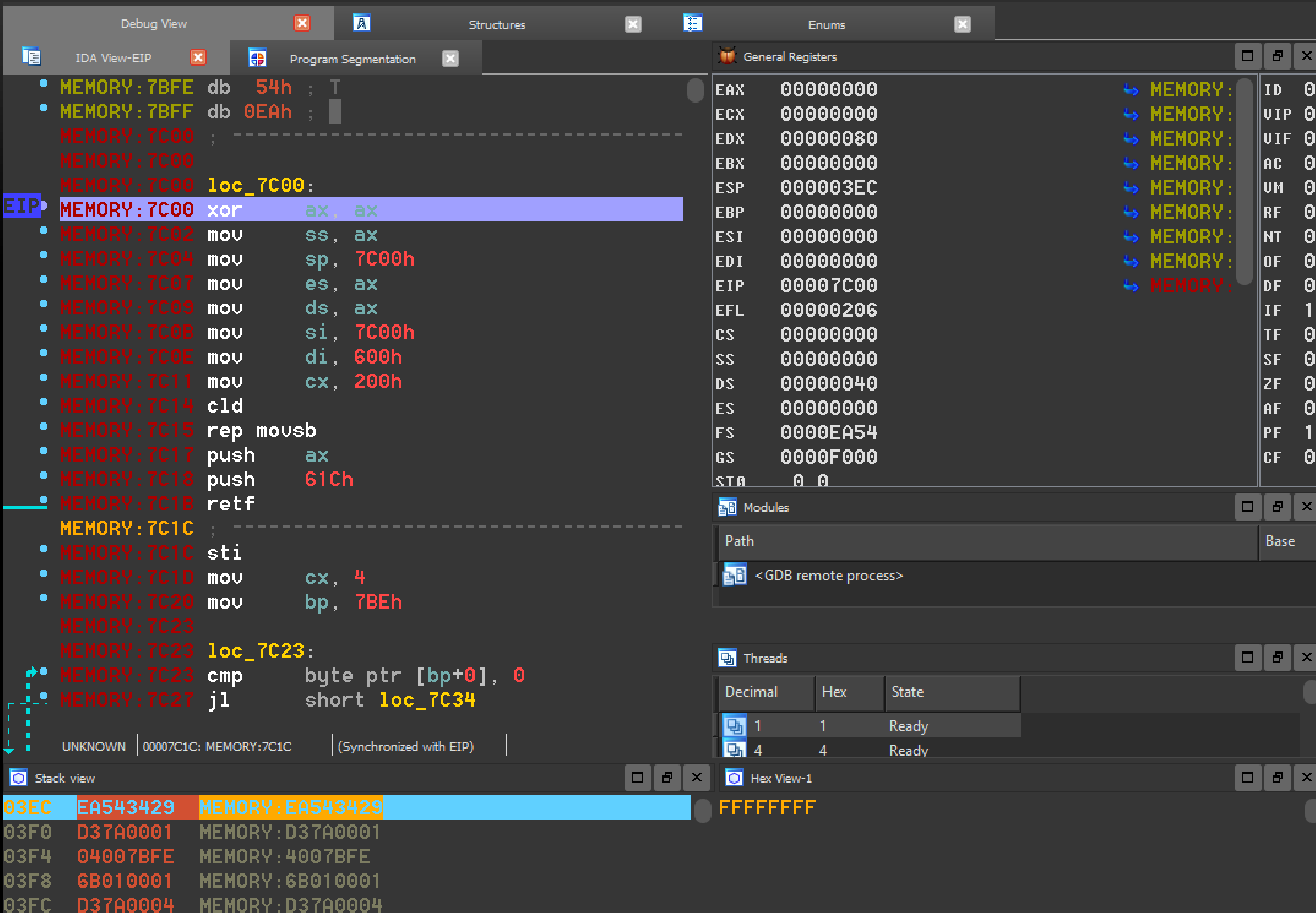
- ✓ Change the "Segment bitness" option to 16-bit (remember: MBR run in real mode, which is 16-bit):



- ✓ Go to Debugger → Breakpoints → Add breakpoint
- ✓ Set the breakpoint at 0x7c00 (start of the MBR code).



✓ Continue the process (F9) and discard eventual exceptions. ☺



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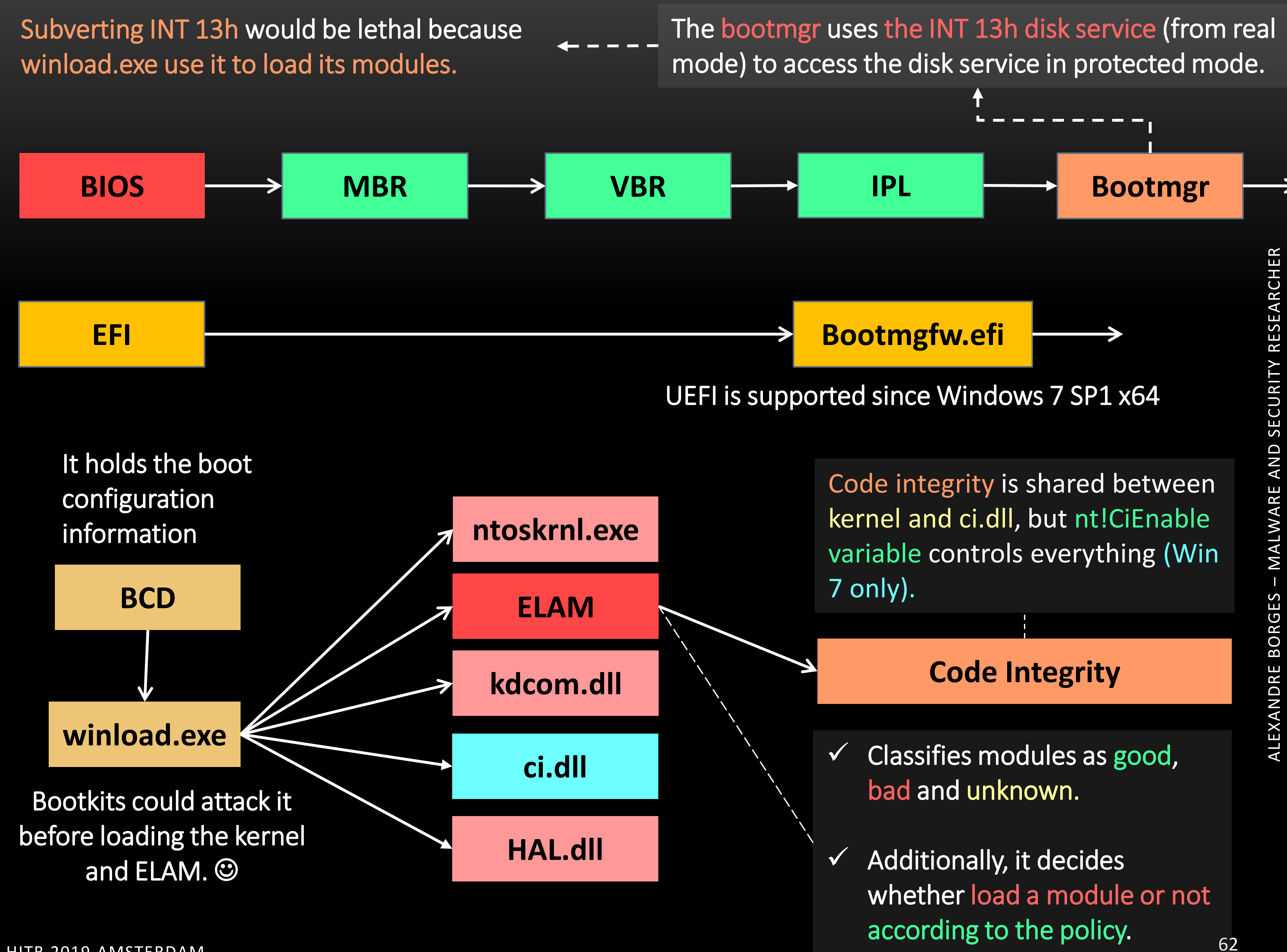
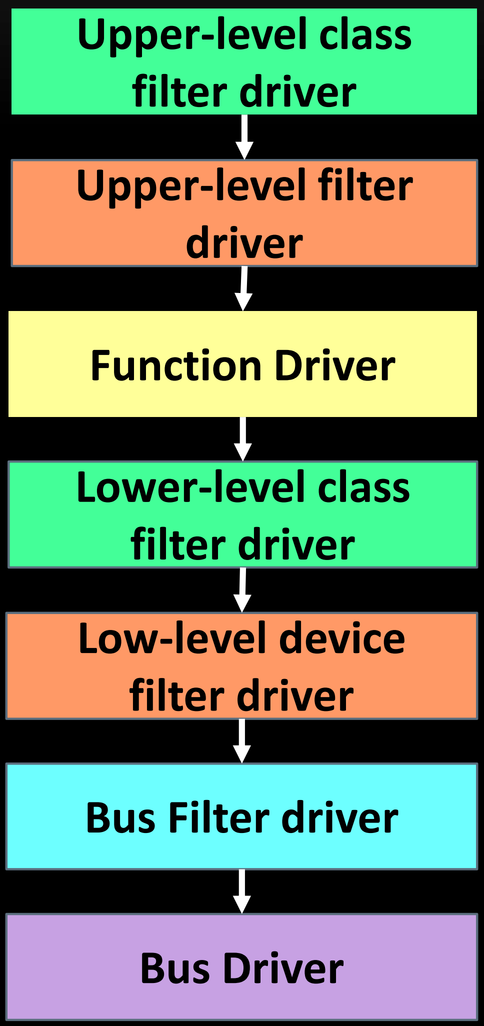

Subverting INT 13h would be lethal because winload.exe use it to load its modules.
The bootmgr uses the INT 13h disk service (from real mode) to access the disk service in protected mode.
BIOS
MBR
VBR
IPL
Bootmgr
EFI
Bootmgfw.efi
UEFI is supported since Windows 7 SP1 x64
It holds the boot configuration information
BCD
winload.exe
Bootkits could attack it before loading the kernel and ELAM. ☺
ntoskrnl.exe
ELAM
kdcom.dll
ci.dll
HAL.dll
Code integrity is shared between kernel and ci.dll, but nt!CiEnable variable controls everything (Win 7 only).
Code Integrity
✓ Classifies modules as good, bad and unknown.
✓ Additionally, it decides whether load a module or not according to the policy.

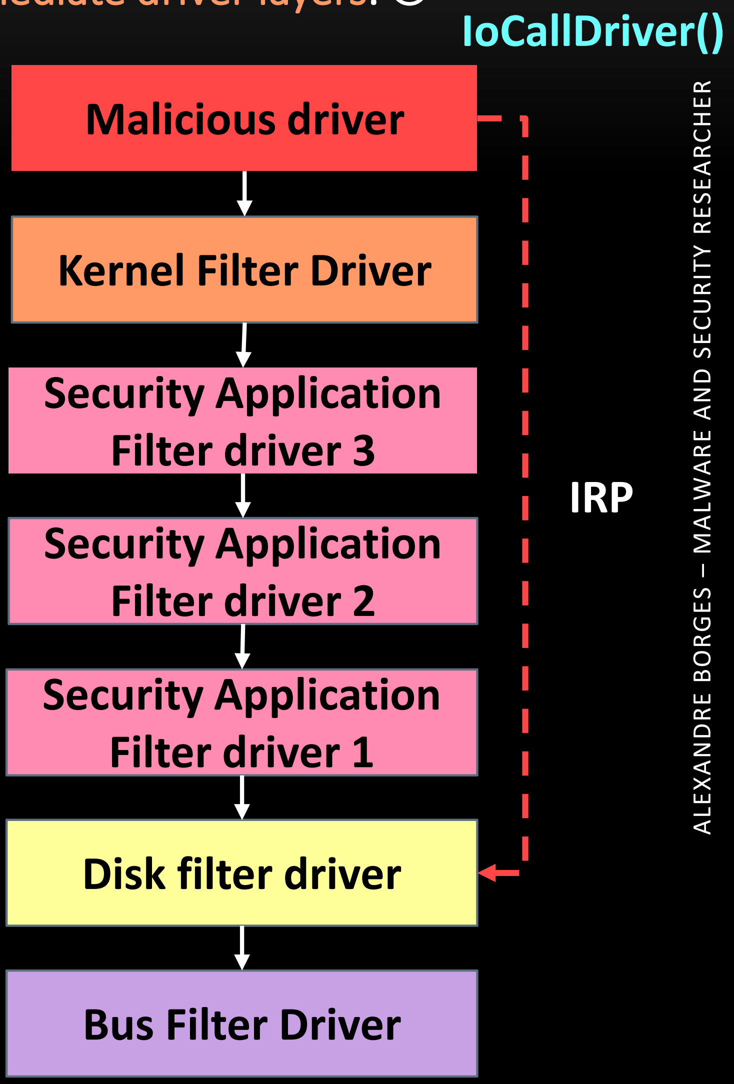
- ✓ Compromising the MBR code makes possible to load any malicious code from anywere (even encrypted and from a hidden storage) and compromise the kernel by disabling the code integrity module, so making possible to load malicious kernel drivers (rootkits).

- ✓ Remember that any malicious driver can "bypass" intermediate driver layers. ☺



Driver development is usually done in pair, where the class driver handle general tasks, while the miniport-driver implement specific routines to the individual device.

Using the right I/O control code (IOCTL_SCSI_PASS_TRHOUGH_DIRECT), the malicious driver is able to "bypass" protections provide by programs.



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- ✓ Additional bootkit/rootkit techniques:
  - ✓ Hooking the IRP_MJ_INTERNAL_CONTROL handler from the mini-port disk driver object (DRIVER_OBJECT) to monitor/modify the data flow to disk.
  - ✓ Bootkits/rootkits use callback methods to be notified about important events:
    - ✓ PsSetLoadImageNotifyRoutine: provides notification when a process, library or kernel memory is mapped into memory.
    - ✓ PsSetCreateThreadNotifyRoutine: points to a routine that is called when a thread starts or ends.
    - ✓ IoRegisterFsRegistrationChange: provides notification when a filesystem becomes available.

- ✓ IoRegisterShutdownNotification: the driver handler (IRP_MJ_SHUTDOWN) acts when the system is about going to down.

- ✓ KeRegisterBugCheckCallback: helps drivers to receive a notification to clean up before the shutdown.

- ✓ PsSetCreateProcessNotifyRoutine: this callback is invoked when a process starts or finishes. Usually, it is used by AVs and security programs.

- ✓ CmRegisterCallback( ) or CmRegisterCallbackEx( ) functions are called by drivers to register a RegistryCallback routine. This kind of callback is invoked when threads performs operations on the registry.

✓ Malware has been using RegistryCallback routines to check whether their persistence entries are kept and, just in case they have been removed, so the malware is able to add them back.

✓ Compromising INT 1 interruption, which is responsible for handling debugging events.

✓ Hiding partitions/filesystems at end of the disk. Additionally, encrypting them.

✓ Hooking key kernel modules routines such as DriverUnload( ) to prevent anyone to unload the malicious module.

✓ Some rootkits call NtRaiseHardError( ) to force a crash and, afterwards, loading a malicious driver.

✓ To force the BIOS reload the MBR to the memory (once it is infected or MFT is encrypted), the INT 19h is used.

- ✓ UEFI has changed the bootkit's attack profile: previously, BIOS' industry didn't have any standard, but UEFI established an unique one. Thus, a malware could be use to attack any platform (Write once, reuse always) ☺

- ✓ MBR + VBR + IPL are completely removed by UEFI. Additionally, UEFI support GPT format, whose signature is 0x200.

- ✓ UEFI is stored in the SPI flash and most part of the UEFI code is run in protected mode.

- ✓ The new bootmgfw.efi locates the winload.efi kernel loader (small changes.... ☺)

- ✓ Windows 8 has introducted the necessary support to UEFI Secure Boot.
- ✓ UEFI Secure Boot offers protection to boot components (OS bootloaders, UEFI DXE drivers and so on) against modification, but it doesn't offer protection against malware infecting the firmware.
- ✓ UEFI Secure Boot uses PKI to validate UEFI modules loaded from SPI.
- ✓ Unfortunately, this approach doesn't work with Terse Executable (TE) format, which doesn't have embedded digital signature. ☹

- UEFI Secure Boot is composed by:
  - Platform key (PK), which establishes a trust relationship between the platform owner and the platform firmware. This platform key verifies the KEK (Key Exchange Key).
  - KEK establishes a trust relationship between the platform firmware and OS.
  - Additionally, the KEK verifies db and dbx (both in NVRAM):
    - Authorized Database (db): contains autorized signing certificates and digital signatures.
    - Forbidden Database (dbx): contains forbidden certificates and digitial signatures.
- Of course, if the Platform Key is corrupted, so everything is not valid anymore because the Secure Boot turns out disabled. ☹

- Another two databases that are also used by Secure Boot:
  - dbr: contains public key (certificates) used to validate OS recovery loader's signatures.
  - dbt: contains timestamping certificates used to check an digital signature's timestamp of UEFI executable, which prevents the usage of an expired signature in an executable.
- Pay attention: the security of all components are based on the integrity of the SPI Flash.
- Of course, once we could modify the SPI Flash content, so the UEFI Secure Boot could be disabled.
- To help us to detect any compromise of platform firmware:
  - Verified Boot: checks whether the platform firmware was modified.
  - Measured Boot: get hashes from boot components and stores them into the TPM (Trusted Platform Module) configuration registers.

✓ UEFI components: SEC → PEI → DXE → BDS → TSL → RT → AL

- ✓ SEC → Security (Caches, TPM and MTRR initialization)
- ✓ PEI → Pre EFI Initialization (chipset initialization + memory controller)
- ✓ DXE → Driver Execution Environment (SMM initialization + devices initialization , Dispatch Drivers, FV enumumeration)
- ✓ BDS → Boot Device Select (Hardware discovery + physical device enumeration)
- ✓ TSL → Transient System Load
- ✓ RT → Run Time

✓ BDS + DXE are responsible for finding the OS loader (path indicated by UEFI variable)

- ✓ Before proceeding, remember SMM basics (ring -1):
  - ✓ Interesting place to hide malware because is protected from OS and hypervisors.
  - ✓ The SMM executable code is copied into SMRAM and locked there during the initialization.
  - ✓ To switch to SMM, it is necessary to triger a SMI (System Management Interrupt) and save the current content into SMRAM, so the SMI handler is being executed.
  - ✓ SMI handlers works as interfaces between the OS and hardware.
  - ✓ Compromising a SMM driver, for example, makes possible to gain SMM privilege and, from this point, to disable the SPI Flash protection to modify a DXE driver. Game over. ☺

✓ user mode malware → rootkit → SMM → SPI flash / BIOS

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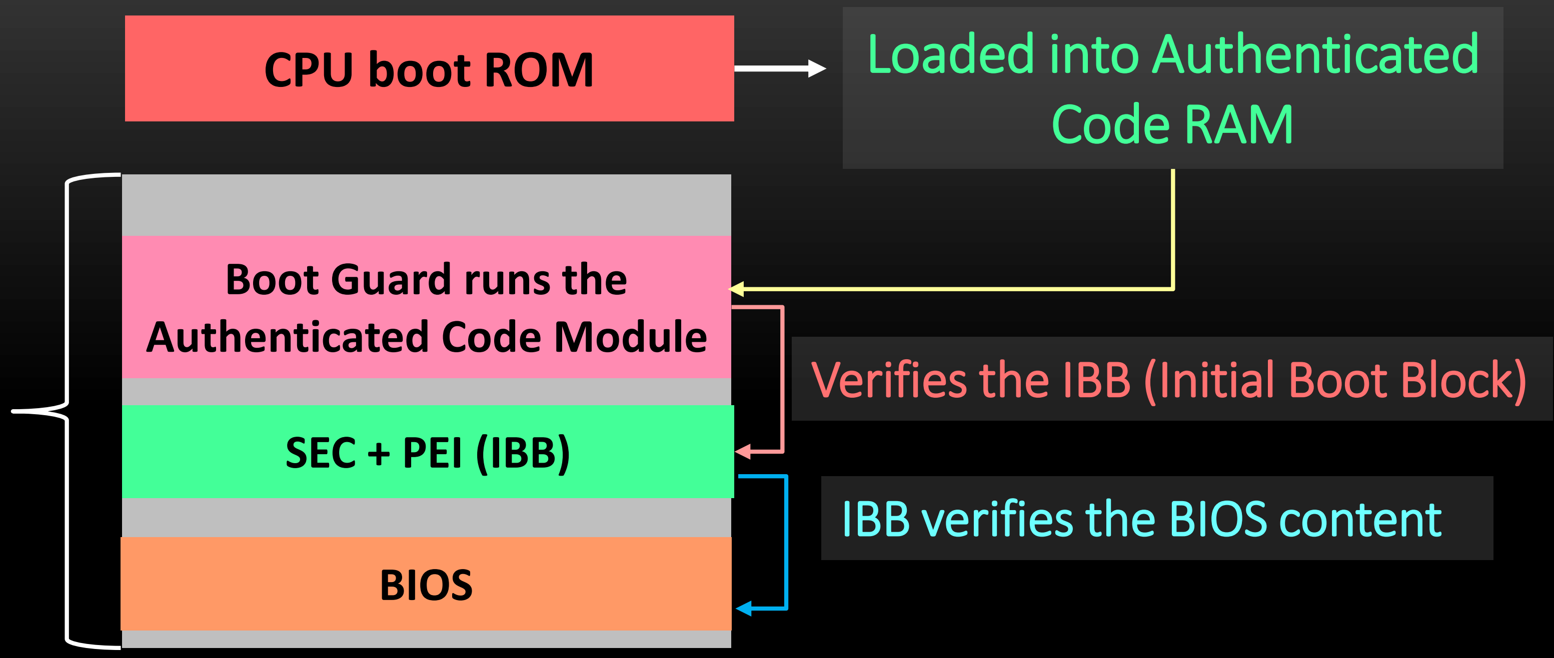
- ✓ If the OS Secure Boot is disabled, the boot process can be compromised because the Patch Guard is only "running" after the boot process.
- ✓ Check the KPP (Kernel Patch Protection) protected areas that are covered:
  - ✓ !analyze –show 109 (on WinDbg)
- ✓ The UEFI Secure Boot protects and prevents attacks to modify any component component before the OS boot stage.
- ✓ Who does protect the system before UEFI Secure Boot being active?
  - ✓ Boot Guard, which is based on cryptographic keys. ☺
- ✓ Who does protect the platform against attacks trying to compromise the flash and the entire platorm?
  - ✓ BIOS Guard, which protect and guarantee the integrity of the BIOS. ☺

- ✓ Boot Guard is used to validate the boot process by flashing a public key associated to the BIOS signature into the FPFs (Field Programmable Fuses) within the Intel ME.
- ✓ Is it a perfect solution? Unfortunately, few vendors have left these fuse unset. It could be lethal. ☺
- ✓ Additionally, a malware could alter the flash write protection and change the SPI flash.
- ✓ Even using the Boot Guard to protect the boot process, we have to protect the SPI flash using the BIOS Guard to protect against a SMM driver rootkit, for example.
- ✓ BIOS Guard is essential because, in the past, some malware threats already attacked the system by modifying the SMI routine of BIOS to compromise the update process.

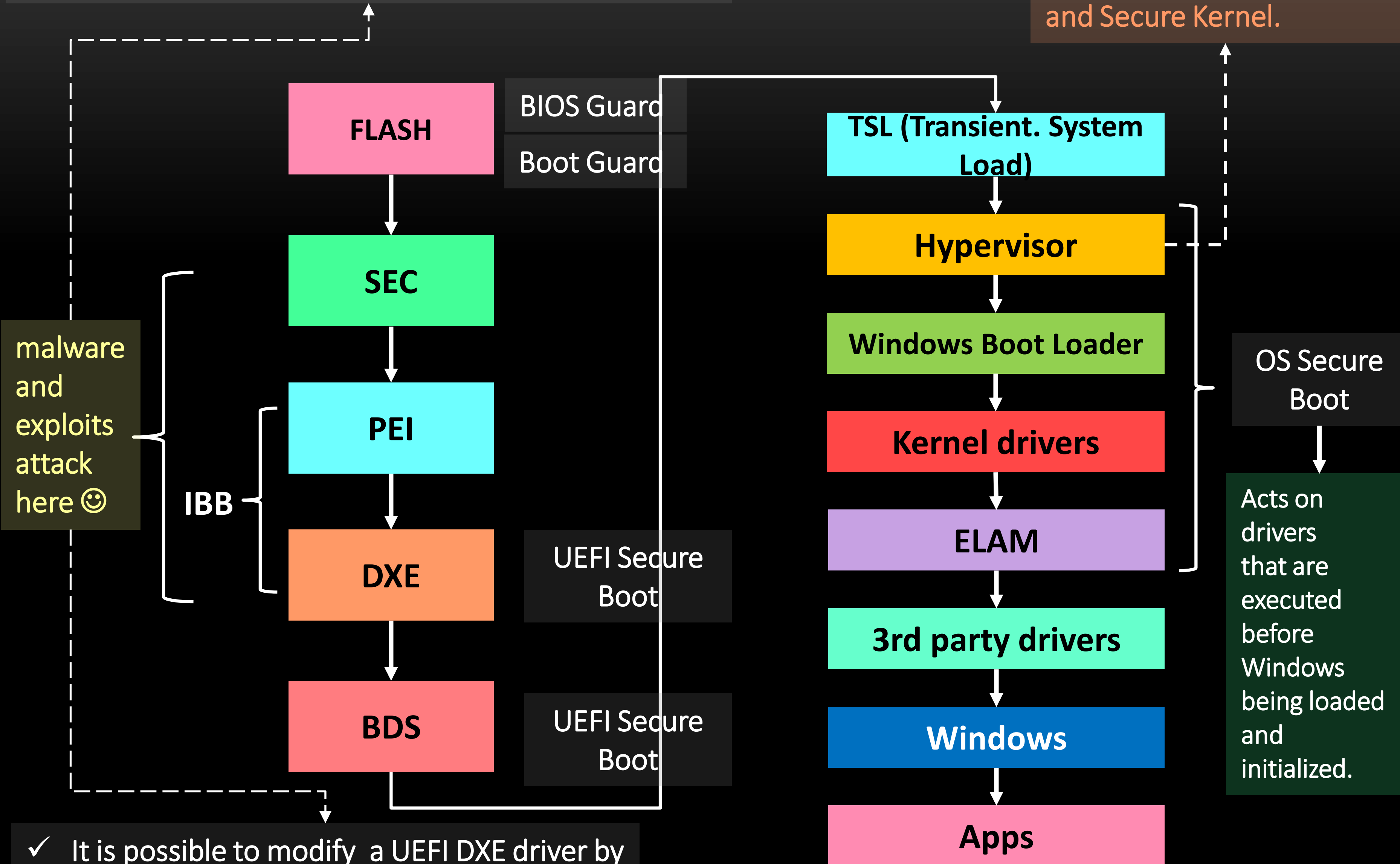


- ✓ The ACM implements Verified and Measured Boot. ☺
- ✓ Public key's hash, which is used to verify the signature of the code with the ACM, is hard-coded within the CPU.
- ✓ Boot Guard protection makes modifying BIOS very hard if the attacker doesn't know the private key.
- ✓ At end, it works as a certificate chain checking. ☺

- In this case, we have the BIOS Guard, which protects the entire platform against attacks:
  - SPI Flash Access, preventing an attacker to escalate privileges to SMM by altering the SPI.
  - BIOS update, which an attacker could update/replace the BIOS code with a bad-BIOS version through a DXE driver.
- BIOS Guard forces that only trusted modules, authorized by ACM, are able to modify the flash memory.
- Thus, protecting against implants.

✓ Modifying an existing DXE driver (or add a new one) could allow malicious execution at DXE stage.

✓ The Windows uses the UEFI to load the Hypervisor and Secure Kernel.



✓ It is possible to modify a UEFI DXE driver by compromising the SPI flash protection, so bypassing/disabling the UEFI Secure Boot.

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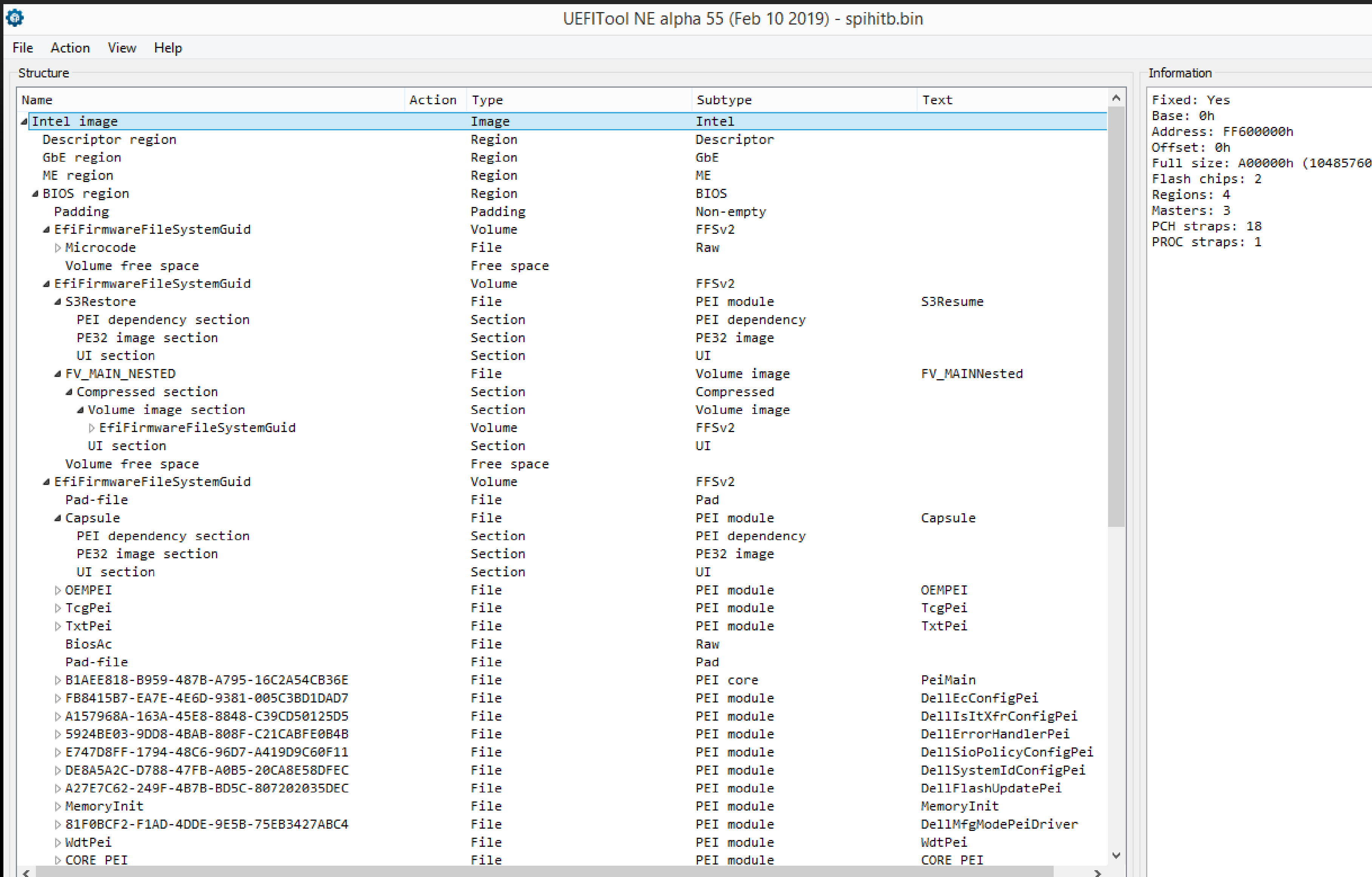
✓ https://github.com/LongSoft/UEFITool


UEFITool NE alpha 55 (Feb 10 2019) - spihitb.bin

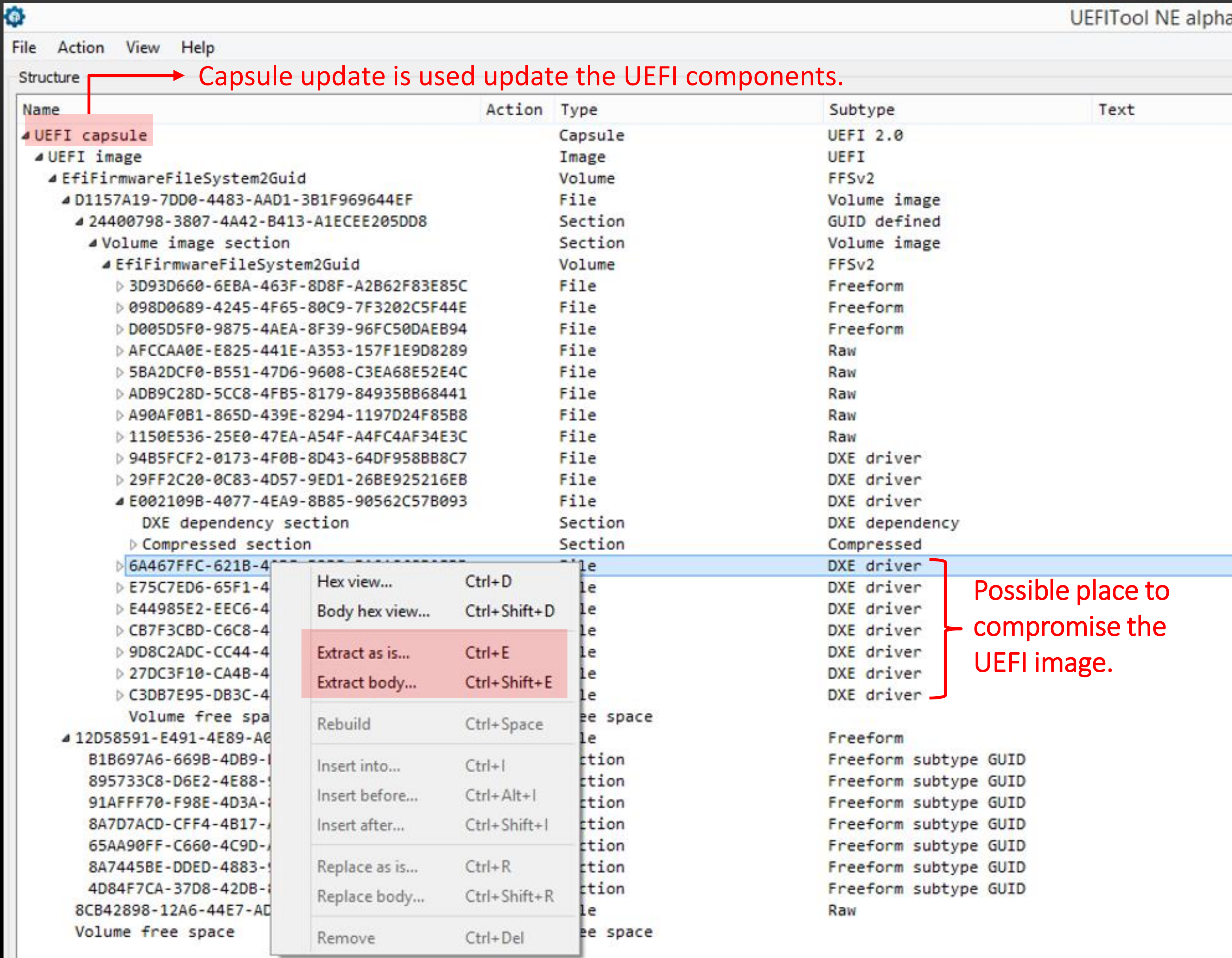
File Action View Help

Structure

Name	Action	Type	Subtype	Text
Intel image		Image	Intel	
Descriptor region		Region	Descriptor	
GbE region		Region	GbE	
ME region		Region	ME	
BIOS region		Region	BIOS	
Padding		Padding	Non-empty	
EfiFirmwareFileSystemGuid		Volume	FFSv2	
Microcode		File	Raw	
Volume free space		Free space		
EfiFirmwareFileSystemGuid		Volume	FFSv2	
S3Restore		File	PEI module	S3Resume
PEI dependency section		Section	PEI dependency	
PE32 image section		Section	PE32 image	
UI section		Section	UI	
FV_MAIN_NESTED		File	Volume image	FV_MAINNested
Compressed section		Section	Compressed	
Volume image section		Section	Volume image	
EfiFirmwareFileSystemGuid		Volume	FFSv2	
UI section		Section	UI	
Volume free space		Free space		
EfiFirmwareFileSystemGuid		Volume	FFSv2	
Pad-file		File	Pad	
Capsule		File	PEI module	Capsule
PEI dependency section		Section	PEI dependency	
PE32 image section		Section	PE32 image	
UI section		Section	UI	
OEMPEI		File	PEI module	OEMPEI
TcgPei		File	PEI module	TcgPei
TxtPei		File	PEI module	TxtPei
BiosAc		File	Raw	
Pad-file		File	Pad	
B1AEE818-B959-487B-A795-16C2A54CB36E		File	PEI core	PeiMain
FB8415B7-EA7E-4E6D-9381-005C3BD1DAD7		File	PEI module	DellEcConfigPei
A157968A-163A-45E8-8848-C39CD50125D5		File	PEI module	DellIsItXfrConfigPei
5924BE03-9DD8-4BAB-808F-C21CABFE0B4B		File	PEI module	DellErrorHandlerPei
E747D8FF-1794-48C6-96D7-A419D9C60F11		File	PEI module	DellSioPolicyConfigPei
DE8A5A2C-D788-47FB-A0B5-20CA8E58DFEC		File	PEI module	DellSystemIdConfigPei
A27E7C62-249F-4B7B-BD5C-807202035DEC		File	PEI module	DellFlashUpdatePei
MemoryInit		File	PEI module	MemoryInit
81F0BCF2-F1AD-4DDE-9E5B-75EB3427ABC4		File	PEI module	DellMfgModePeiDriver
WdtPei		File	PEI module	WdtPei
CORE_PEI		File	PEI module	CORE_PEI

Information

Fixed: Yes
Base: 0h
Address: FF600000h
Offset: 0h
Full size: A00000h (10485760)
Flash chips: 2
Regions: 4
Masters: 3
PCH straps: 18
PROC straps: 1



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- ✓ Exists other SPI flash protections that are set up at DXE stage:
  - ✓ SMM_BWP (SMM BIOS Write Protection): protects SPI flash against writing from malware running outside of the SMM.
  - ✓ BLE (BIOS Lock Enable bit): protects the SPI flash against unauthorized writes. Unfortunately, it can be modified by malware with SMM privileges.
  - ✓ BIOSWE (BIOS Write Enable Bit): it is a kind of "control bit", which is used to allow a BIOS update.
  - ✓ Protected Ranges: it is designed to protect specific regions as SPI flash, for example.
    - ✓ Additionally, there are six Protected Ranges registers: PR0 to PR5.
    - ✓ No doubts, it is a good protection against changes from SMM because its policies can't be changed from SMM. ☺

✓ chipsec_util.py spi dump spihitb.bin

```
PS C:\chipsec-master> python chipsec_util.py spi dump spihitb.bin

################################################################
##                                                            ##
##  CHIPSEC: Platform Hardware Security Assessment Framework  ##
##                                                            ##
################################################################
[CHIPSEC] Version 1.3.5.dev1

WARNING: *******************************************************************
WARNING: Chipsec should only be used on test systems!
WARNING: It should not be installed/deployed on production end-user systems.
WARNING: See WARNING.txt
WARNING: *******************************************************************

[CHIPSEC] API mode: using CHIPSEC kernel module API
[CHIPSEC] Executing command 'spi' with args ['dump', 'spihitb.bin']

[CHIPSEC] dumping entire SPI flash memory to 'spihitb.bin'
[CHIPSEC] it may take a few minutes (use DEBUG or VERBOSE logger options to se
[CHIPSEC] BIOS region: base = 0x00600000, limit = 0x009FFFFF
[CHIPSEC] dumping 0x00A00000 bytes (to the end of BIOS region)
[spi] reading 0xa00000 bytes from SPI at FLA = 0x0 (in 163840 0x40-byte chunks
[CHIPSEC] completed SPI flash dump to 'spihitb.bin'
[CHIPSEC] (spi dump) time elapsed 134.150
```

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✓ chipsec_util.py decode spi.bin

```
Master Read/Write Access to Flash Regions
--------------------------------------------
 Region                 | CPU    | ME
--------------------------------------------
0 Flash Descriptor      | R      | R
1 BIOS                  | RW     |
2 Intel ME              |        | RW
3 GBe                   | RW     | RW
```

- ✓ Remember that a BIOS update could be composed by different parts such as CPU microcode (internal firmware), Gbe (hardware network stack), BMC (Baseboard Management Controller, which provides monitoring and management), AMT (Active Management Platform, which provides remote access to devices), ME (Management engine), EC (Embedded Controller) and so on.

- ✓ ME: an x86 controller that provides root-of-trust.

- ✓ EC: defines which component has read/write access to other regions. It also works as security root of trust.

✓ chipsec_main --module common.bios_wp

```
[*] running module: chipsec.modules.common.bios_wp
[x][ =======================================================================
[x][ Module: BIOS Region Write Protection
[x][ =======================================================================
[*] BC = 0x02 << BIOS Control (b:d.f 00:31.0 + 0xDC)
    [00] BIOSWE           = 0 << BIOS Write Enable
    [01] BLE              = 1 << BIOS Lock Enable
    [02] SRC              = 0 << SPI Read Configuration
    [04] TSS              = 0 << Top Swap Status
    [05] SMM_BWP          = 0 << SMM BIOS Write Protection
[!] Enhanced SMM BIOS region write protection has not been enabled

[*] BIOS Region: Base = 0x00600000, Limit = 0x009FFFFF
SPI Protected Ranges
------------------------------------------------------------
PRx (offset) | Value    | Base     | Limit    | WP? | RP?
------------------------------------------------------------
PR0 (74)     | 00000000 | 00000000 | 00000000 | 0   | 0
PR1 (78)     | 00000000 | 00000000 | 00000000 | 0   | 0
PR2 (7C)     | 00000000 | 00000000 | 00000000 | 0   | 0
PR3 (80)     | 00000000 | 00000000 | 00000000 | 0   | 0
PR4 (84)     | 00000000 | 00000000 | 00000000 | 0   | 0

[!] None of the SPI protected ranges write-protect BIOS region
```

✓ Unfortunately, the SMM BIOS write protection (SMM_BWP), which protects the entire BIOS area, is not enabled. ☹

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✓ chipsec_main.py -m common.spi_lock

```
[*] running module: chipsec.modules.common.spi_lock
[x][ =======================================================================
[x][ Module: SPI Flash Controller Configuration Lock
[x][ =======================================================================
[*] HSFS = 0xE008 << Hardware Sequencing Flash Status Register (SPIBAR + 0x4)
    [00] FDONE            = 0 << Flash Cycle Done
    [01] FCERR            = 0 << Flash Cycle Error
    [02] AEL              = 0 << Access Error Log
    [03] BERASE           = 1 << Block/Sector Erase Size
    [05] SCIP             = 0 << SPI cycle in progress
    [13] FDOPSS           = 1 << Flash Descriptor Override Pin-Strap Status
    [14] FDV              = 1 << Flash Descriptor Valid
    [15] FLOCKDN          = 1 << Flash Configuration Lock-Down
[+] PASSED: SPI Flash Controller configuration is locked

[CHIPSEC] ***************************  SUMMARY  ***************************
[CHIPSEC] Time elapsed            0.038
[CHIPSEC] Modules total           1
[CHIPSEC] Modules failed to run 0:
[CHIPSEC] Modules passed          1:
[+] PASSED: chipsec.modules.common.spi_lock
[CHIPSEC] Modules failed          0:
[CHIPSEC] Modules with warnings 0:
[CHIPSEC] Modules skipped 0:
[CHIPSEC] *****************************************************************
```

- ✓ The HSFSS.FLOCKDN bit, which comes from HSFSTS SPI MMIO Register, prevents changes to Write Protection Enable bit.

- ✓ At end, a malware couldn't disable the SPI protected ranges to enable access to SPI flash memory. ☺

✓ python chipsec_main.py --module common.bios_ts

```
[+] loaded chipsec.modules.common.bios_ts
[*] running loaded modules ..

[*] running module: chipsec.modules.common.bios_ts
[x][ =======================================================================
[x][ Module: BIOS Interface Lock (including Top Swap Mode)
[x][ =======================================================================
[*] BiosInterfaceLockDown (BILD) control = 1
[*] BIOS Top Swap mode is disabled (TSS = 0)
[*] RTC TopSwap control (TS) = 0
[+] PASSED: BIOS Interface is locked (including Top Swap Mode)

[CHIPSEC] ***************************  SUMMARY  ***************************
[CHIPSEC] Time elapsed          0.043
[CHIPSEC] Modules total         1
[CHIPSEC] Modules failed to run 0:
[CHIPSEC] Modules passed        1:
[+] PASSED: chipsec.modules.common.bios_ts
[CHIPSEC] Modules failed        0:
[CHIPSEC] Modules with warnings 0:
[CHIPSEC] Modules skipped 0:
[CHIPSEC] *****************************************************************
```

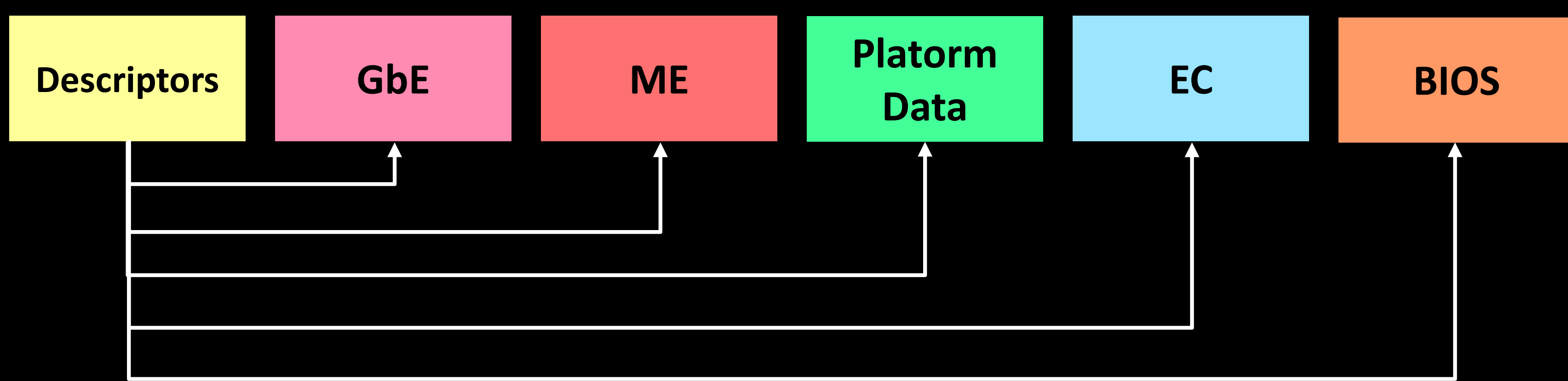
- ✓ BIOS Top Swap Mode allows a fault-tolerant update of BIOS boot block.
- ✓ If BIOS Top Swap Mode is not locked, so malware could redirect the reset vector execution to the backup bootblock, so loading a malicious bookblock code. ☺

✓ python chipsec_main.py --module common.smrr

```
[*] Checking SMRR range base programming..
[*] IA32_SMRR_PHYSBASE = 0xCB000004 << SMRR Base Address MSR (MSR 0x1F2)
    [00] Type                = 4 << SMRR memory type
    [12] PhysBase            = CB000 << SMRR physical base address
[*] SMRR range base: 0x00000000CB000000
[*] SMRR range memory type is Write-through (WT)
[+] OK so far. SMRR range base is programmed

[*] Checking SMRR range mask programming..
[*] IA32_SMRR_PHYSMASK = 0xFF800800 << SMRR Range Mask MSR (MSR 0x1F3)
    [11] Valid               = 1 << SMRR valid
    [12] PhysMask            = FF800 << SMRR address range mask
[*] SMRR range mask: 0x00000000FF800000
[+] OK so far. SMRR range is enabled

[*] Verifying that SMRR range base & mask are the same on all logical CPUs..
[CPU0] SMRR_PHYSBASE = 00000000CB000004, SMRR_PHYSMASK = 00000000FF800800
[CPU1] SMRR_PHYSBASE = 00000000CB000004, SMRR_PHYSMASK = 00000000FF800800
[CPU2] SMRR_PHYSBASE = 00000000CB000004, SMRR_PHYSMASK = 00000000FF800800
[CPU3] SMRR_PHYSBASE = 00000000CB000004, SMRR_PHYSMASK = 00000000FF800800
[CPU4] SMRR_PHYSBASE = 00000000CB000004, SMRR_PHYSMASK = 00000000FF800800
[CPU5] SMRR_PHYSBASE = 00000000CB000004, SMRR_PHYSMASK = 00000000FF800800
[CPU6] SMRR_PHYSBASE = 00000000CB000004, SMRR_PHYSMASK = 00000000FF800800
[CPU7] SMRR_PHYSBASE = 00000000CB000004, SMRR_PHYSMASK = 00000000FF800800
[+] OK so far. SMRR range base/mask match on all logical CPUs
[*] Trying to read memory at SMRR base 0xCB000000..
[+] PASSED: SMRR reads are blocked in non-SMM mode

[+] PASSED: SMRR protection against cache attack is properly configured
```

✓ SMRR (System Management Range Registers) block the access to SMRAM (reserved by BIOS SMI handlers) while CPU is not in SMM mode, preventing it to execute SMI exploits on cache.

- ✓ Few important side notes are:
  - ✓ Just in case the SMM code try to "read" some information from outside of SMM, so it would be interesting to check if the pointer is valid by using SmmIsBufferOutsideSmmValid( ) function.
  - ✓ ME (Management Engine) Applications can use the HECI (Host Embedded Communication Interface) to communicate with the kernel from Windows, for example. So ME and HECI handlers are a very critical components.
  - ✓ The same concern should be dedicated to AMT, which is an ME application.
  - ✓ The SPI flash is composed by descriptors, GbE, ME, Data, EC and BIOS, where ME has full access to the DRAM and it is always working. ☺



✓ My sincere thank you to:

✓ My wife.

✓ You, who have reserved some time attend my talk.

✓ Please, you should never forget:

" The best of this life are people." ☺

- ✓ Malware and Security Researcher.
- ✓ Speaker at DEFCON USA 2018
- ✓ Speaker at DEFCON CHINA 2019
- ✓ Speaker at CONFidence Conf. 2019
- ✓ Speaker at BSIDES 2018/2017/2016
- ✓ Speaker at H2HC 2016/2015
- ✓ Speaker at BHACK 2018
- ✓ Consultant, Instructor and Speaker on Malware Analysis, Memory Analysis, Digital Forensics and Rookits.
- ✓ Reviewer member of the The Journal of Digital Forensics, Security and Law.
- ✓ Referee on Digital Investigation: The International Journal of Digital Forensics & Incident Response

THANK YOU FOR ATTENDING MY TALK. ☺

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