Emulating NotPetya bootloader with Miasm

aguinet.github.io//blog/2020/08/29/miasm-bootloader.html

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NotPetya is a famous malware of the Petya family. It appeared in June 2017. The part running from the Master Boot Record (MBR) has been statically and dynamically studied, using for instance the Bochs debugger from IDA. Is another approach possible? This article's goal is to show that we can emulate this bootloader using Miasm.

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Introduction

This Petya variant first appeared in June 2017 in Ukraine. According to Mikko Hyppönen, Chief Research Officer at F-Secure, the infection vector would be the update mechanism of the accountability software M.E.Doc, widely deployed within Eastern countries.

This malware family has the particularity of overwriting the bootloader of the compromised machine in order to encrypt parts of the hard drive when it reboots. This article uses this bootloader as a pretext for a tutorial concerning the emulation and reverse engineering of these little beasts thanks to the Miasm framework. The associated code is available here: https://github.com/aguinet/miasm-bootloader/. It contains a Python implementation of a subset of the interfaces of a classic x86 PC BIOS. The code was written in a way that is easily reusable for other cases, or even to help the development / debugging of bootloaders in general.

Related works

Many articles have already studied the behaviour of the NotPetya MBR, as well as its various cryptographic implementations and mechanisms (and their faults). Here are some significant ones:

- MISC n°86 : "Pleased to meet you, my name is Petya !", written by Damien Schaeffer in July 2016
- MISC n°93 : "Petya or Not Petya, that is the question", written by "Teddy and Benjamin" in September 2017, with a very thorough static reverse engineering of the bootloader.
- Crowdstrike : Full Decryption of Systems Encrypted by Petya/NotPetya. Study of an implementation error within the Salsa20 algorithm embedded in the bootloader (more on that subject later in the article).

NotPetya

This section deals only in a very general way with the malware's cycle of life. It allows us to highlight the part studied in this article.

Once NotPetya has run on the victim's machine, it generates an AES encryption key that will be used to achieve the first encryption phase. This key is itself encrypted with an RSA public key.

The malware then checks that the system uses a classical partition scheme and, if it has admin rights, enters its own data on the first sectors of the disc (from 1 to 18, then 32 to 34), with its own MBR in the first sector. If the system uses UEFI (with a GPT partition scheme), the malware skips this step. The machine then is restarted and the NotPetya bootloader executed: a Salsa20 key and a nonce are generated. These secrets are used to encrypt the Master File Table (MFT) [1] of NTFS file system. This data structure contains the metadata needed to find the data associated with each file. This operation looks like a classical "chkdsk". Once this operation is done, the machine restarts one last time and then displays the ransom message.

Miasm

Miasm is a reverse engineering framework developed in Python. It has many features, among which:

- open, modify and generate binaries in PE, ELF 32, 64 LE, BE.
- assemble/disassemble x86, ARM, MIPS, SH4, PPC and MSP430 code.
- lift instruction semantics into a custom intermediate representation.
- emulate this intermediate representation, with various JIT (Just-in-time) compilers to speed things up.
- simplify/modify this intermediate representation, to de-obfuscate code for instance.

Why emulate NotPetya with Miasm?

There are various ways to emulate a bootloader. A classical approach is to use QEMU (or any other virtualization/emulation solution) by writing the bootloader on a virtual hard disk, but it makes it difficult to instrument the bootloader code. Such a thing is however possible via IDA’s Bochs debugger. This approach was adopted by Teddy and Benjamin in MISC No. 93, but also by Saurabh Sharma [2]. This method usually works well and makes debugging a bootloader an easy task.

In the article associated with the presentation of his Miasm tool at SSTIC in 2012 [3], Fabrice Desclaux showed Miasm possibilities. One of the proposed applications was the emulation of a bootloader.

The ability to fully emulate a bootloader (until the BIOS interruption) with a framework like Miasm gives a sharper control over what’s happening, possibly allow de-obfuscation, and use all the tools developed in Miasm for this task. It becomes for example very simple to instrument the code in order to see the data read/written on the disk, the secrets generated, etc.

Eventually, NotPetya’s bootloader code is succinct, non-obfuscated and extremely simple (it runs in real mode, in 16 bits and calls only a few BIOS interruptions), so it is a nice case study to play with Miasm!

PC/x86 bootloader

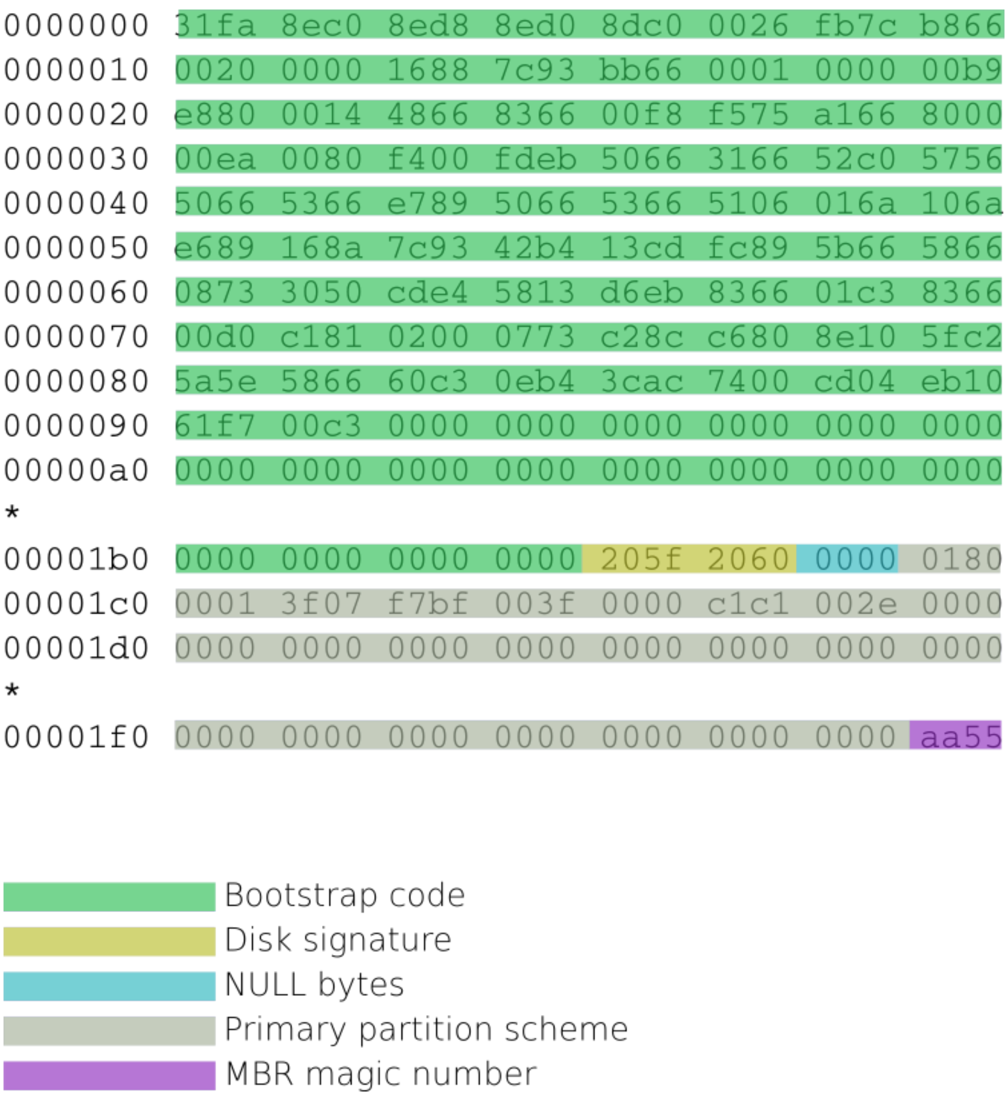
Introduction

We will only discuss here the inner workings of “old-school” BIOS bootloaders. We will not talk about UEFI.

On x86 PCs, when the machine starts, the BIOS loads the first disk sector (named Master Boot Record, or MBR) at `0x7C00` , and then jumps to this address. The MBR hence contains the bootloader code. At this moment, the processor only supports 16-bit instructions and can only address memory in real mode [4].

As a reminder, one disk sector contains 512 bytes. Therefore, it is not possible to store a lot of code on this sector only. That’s why bootloaders are usually designed in several stages. Indeed, the code in the first sector (the first stage) will load the stage 2 code from the hard drive , and then jump into it.

Below is the MBR’s structure written by NotPetya:



```
0000000 31fa 8ec0 8ed8 8ed0 8dc0 0026 fb7c b866
0000010 0020 0000 1688 7c93 bb66 0001 0000 00b9
0000020 e880 0014 4866 8366 00f8 f575 a166 8000
0000030 00ea 0080 f400 fdeb 5066 3166 52c0 5756
0000040 5066 5366 e789 5066 5366 5106 016a 106a
0000050 e689 168a 7c93 42b4 13cd fc89 5b66 5866
0000060 0873 3050 cde4 5813 d6eb 8366 01c3 8366
0000070 00d0 c181 0200 0773 c28c c680 8e10 5fc2
0000080 5a5e 5866 60c3 0eb4 3cac 7400 cd04 eb10
0000090 61f7 00c3 0000 0000 0000 0000 0000 0000
00000a0 0000 0000 0000 0000 0000 0000 0000 0000
*
00001b0 0000 0000 0000 0000 205f 2060 0000 0180
00001c0 0001 3f07 f7bf 003f 0000 c1c1 002e 0000
00001d0 0000 0000 0000 0000 0000 0000 0000 0000
*
00001f0 0000 0000 0000 0000 0000 0000 0000 aa55
```

NotPetya case

NotPetya works exactly this way. The bootstrap code (in green in the figure above) is the assembly code below. The code at address `0x7C38` (that we named `disk_read_stage2`), writes data in sectors 2 to 34 (inclusive) in memory at `0x8000` , and then jumps to this address:

```
seg000:7C00 cli
seg000:7C01 xor ax, ax
seg000:7C03 mov ds, ax
seg000:7C05 mov ss, ax
seg000:7C07 mov es, ax
seg000:7C09 lea sp, start
seg000:7C0D sti
seg000:7C0E mov eax, 32
seg000:7C14 mov byte ptr ds:word_7C93, dl
seg000:7C18 mov ebx, 1
seg000:7C1E mov cx, 8000h
seg000:7C21 call disk_read_stage2
seg000:7C24 dec eax
seg000:7C26 cmp eax, 0
seg000:7C2A jnz short loc_7C21
seg000:7C2C mov eax, dword ptr ds:8000h
seg000:7C30 jmp far ptr 0:8000h
```

Emulation with Miasm

Installation

The system used for these tests is Linux-based. Windows 10 users should be able to make it work by using Windows Subsystem for Linux (WSL), by installing for example Ubuntu using the Windows Store [5].

We recommend using the version of Miasm specified in the `README` file from the GitHub repository. At the time of writing lines, the version used is v0.1.1. To recover this specific version, do:

```
$ git clone --depth=1 --branch=v0.1.1 https://github.com/cea-sec/miasm/
```

We use the LLVM-based Miasm JIT engine, which needs the `llvmlite` python package. Other needed dependencies are installable directly through the provided `requirements.txt` file:

```
$ cd /path/to/src && pip install -r requirements.txt
```

Then just install Miasm:

```
$ cd /path/to/miasm && pip install -r requirements.txt && python ./setup.py install
```

Implementation

All the techniques described in this article can be tried thanks to the `src/emulate_mbr.py` script in the aforementioned GitHub repository.

Multiple options are provided, some of them could be used to win some time during your experiments:

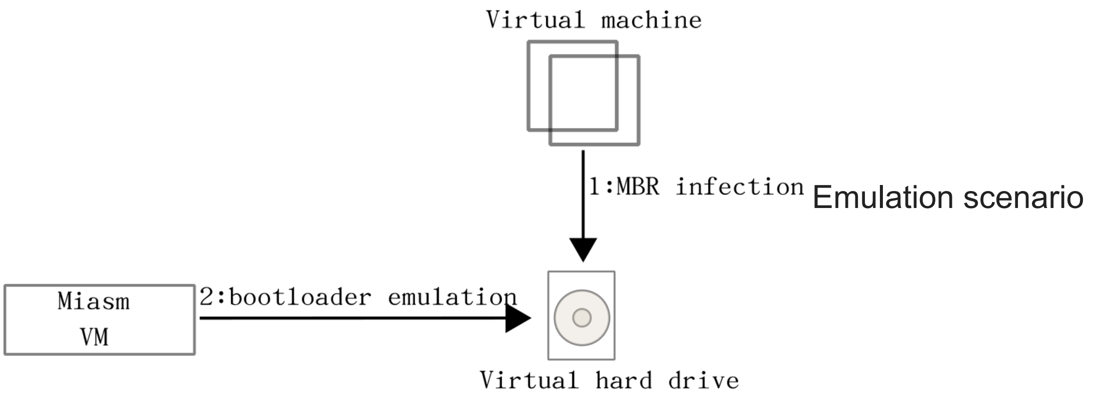
- `--dry` : simulates the success of disk writings, but actually writes nothing.
- `--skip-encryption` : the encryption function (which is the hottest one) will be ignored (actually transforming it into a function that does nothing).
- `--verbose-bios-data` : dumps log messages from our BIOS implementation, with a dump of read and written disk data.
- `--verbose-bios` : same as `--verbose-bios-data` , without the read and written disk data.

The `--help` flag can be used to have a more detailed list of available options.

The activation of Miasm's logs can considerably slow down the performances of the overall script. The `--log-miasm-newblocks` option only dumps blocks that have never been "jitted" by Miasm.

Creation of a test disk

We performed our tests with virtual machines running Windows XP and Windows 10. The underlying hypervisor does not matter (VMWare, VirtualBox), as long as the disk created has a fixed size and is using VMDK. The emulation of the bootloader is done directly on the virtual machine's disk. An advantage to this method is that there is no need to extract the bootloader from the original malware DLL or from the generated VMDK.



The test scenario is the following:

1. voluntary infection of the virtual machine with NotPetya
2. wait for at least 10s (the machine shouldn't reboot by itself, or the bootloader will actually launch its encryption code)
3. shutdown the virtual machine: the MBR has been replaced
4. run the emulation: the MFT is encrypted by the bootloader which then displays the ransom

If your virtual machine is not using a flat VMDK representation, you can convert it using QEMU:

```
$ qemu-img convert -f vmdk mydisk.vmdk -O raw mydisk.raw
```

We also give a test image in the aforementioned Git repository (file `disk.raw.bz2`). Once unzipped, it is a 1GB file, and contains a simple NTFS partition with some test files.

We can now emulate the NotPetya bootloader. In order to do this, we need to emulate a BIOS capable of:

- reading/writing disk sectors
- showing characters on the screen
- capturing key strokes
- booting on an MBR (“light” boot/reboot)

We are going to see how to implement this using Miasm.

System abstraction

We implement an abstraction of a simple system as seen by the BIOS. It contains:

- a virtual disk (the `HardDrive` class)
- a video screen, which goes through a classical Unix terminal, using the `stdout` pipe
- a keyboard, which uses the `stdin` pipe to gather key strokes (functions in `async_kb.py`)

Abstraction is implemented in the `System` class, of which one instance is used during the emulation. This instance is initialized alongside the Miasm VM.

Miasm virtual machine initialization

As explained in the introduction, the MBR code is loaded and executed by the BIOS at the address `0x7C00`. Then, this code will load and write its second stage at the address `0x8000`. The left space is dedicated to the stack. It begins at the address `0x500` and ends at the address `0x07C00`. Therefore, the corresponding space is `[0x00000500:0x00007BFF]`.

First, we need to declare these memory spaces to the Miasm virtual machine:

```
HD0 = HardDrive(hd_path)
sys_ = System([HD0])
mbr = HD0.read_sector(0)
stage1_addr = 0x07C00
stage2_addr = 0x08000
jitter.vm.add_memory_page(stage1_addr, PAGE_READ | PAGE_WRITE | PAGE_EXEC, mbr,
"NotPetyaS1")
jitter.vm.add_memory_page(stage2_addr, PAGE_READ | PAGE_WRITE | PAGE_EXEC,
"\x00"*SECTOR_LEN*32, "NotPetyaS2")
jitter.vm.add_memory_page(0x500, PAGE_READ | PAGE_WRITE, "\x00"*(0x7C00-0x500+1),
"Stack")
# Pretty print of the memory layout
print(jitter.vm)
```

Now, the memory layout of the Miasm virtual machine is the following:

```
Addr                Size                Access Comment
0x500               0x7700              RW_    Stack
0x7C00              0x200               RWX    NotPetyaS1
0x8000              0x4000              RWX    NotPetyaS2
```

NotPetya loads 32 sectors from the disk to the memory when executing the first stage. This is why the allocated memory for the second stage is 32 sectors long (32*512 bytes).

BIOS interruption handling in Miasm

Miasm allows us to specify an interruption handler which will be called whenever an `INT` instruction is executed. To do so, we have to tell Miasm to call our BIOS interruption handler `exception_int` with the help of `add_exception_handler` of the current used jitter:

```
jitter.add_exception_handler(EXCEPT_INT_XX, lambda jitter: exception_int(jitter,
sys_))
```

Interruption support

Now, we have to implement the different BIOS interruption handlers. We can split them into four main families :

- `INT 10h` : access to the screen (write characters, change colors…),
- `INT 13h` : access to the disk (read/write sectors, get disk geometry…),
- `INT 16h` : access to the keyboard (read keystroke…),
- `INT 19h` : boot on the disk's MBR.

INT 13h

Here is an example of the `INT 13h` interruption, with the `0x43` code function (`Extended Read Sectors From Drive`). This code implements the instruction to load multiple sectors from the disk to the memory:

```
@func(disk_interrupts, 0x42)
def extended_read_sectors(jitter, sys_):
    drive_idx = get_xl(jitter.cpu.DX)
    print "Extended read sectors, drive idx 0x%x" % drive_idx

    dap = jitter.vm.get_mem((jitter.cpu.DS << 4)+jitter.cpu.SI, 16)
    dap_size, _, num_sect, buff_addr, abs_sect = struct.unpack("<BBHIQ", dap)

    hd = sys_.hd(drive_idx)

    print("  Read %d sectors from sector %d" % (num_sect, abs_sect))
    size = num_sect * SECTOR_LEN
    data = hd.read(abs_sect * SECTOR_LEN, size)

    jitter.cpu.cf = 0 # No error
    # AL is the number of sectors read
    # AH is the return code, 0 = successful completion
    jitter.cpu.AX = set_16bit_reg(low=int(len(data) / SECTOR_LEN), high=0)
    jitter.vm.set_mem(buff_addr, data)
```

Note: this Python code doesn't include error management for readability reasons. The `sys_` object is the system abstraction explained in System abstraction.

Sectors can be loaded from disk in two different ways by using a different kind of addressing mechanism for the same `INT 13h` interruption:

1. CHS (Cylinder, Head, Sector) addressing mechanism, used by the `02h` / `03h` codes. It can read/write one or many sectors by specifying the index of the cylinder and the head,

2. LBA (Logical Bloc Addressing) addressing mechanism, used by the `42h` / `43h` codes. It can read/write one or several sectors by specifying the corresponding sector in a absolute way, i.e. by specifying the offset from the first sector number on the disk regardless of heads/cylinders.

NotPetya uses the LBA addressing mechanism. This method needs to fill a DAP (Disk Address Packet) structure. This structure describes which sectors to read/write and where to read/write them into live memory.

One can see that an extended LBA structure exists to read or write multiple sectors at the same time:

0	1	Packet size
1	1	Zeroed field
2	2	Number of sectors to load
4	4	Buffer address to load sectors to (seg:off)

8	8	Absolute offset of the first sector to read

To sum up:

1. the DAP is parsed,
2. data is read from the virtual disk,
3. the read data is stored in the corresponding memory page of the instantiated Miasm virtual machine.

The writing mechanism is the exact opposite: the specified buffer address in the DAP contains the data to write.

INT 19h

The second chosen example is the `INT 19h` interruption (diskboot). It reboots the machine [67] and is used in two locations :

1. at address `0x892E`, which is called if a fatal error occurs,
2. at address `0x820D`, when the machine reboots after the MFT encryption.

The `INT 19h` interruption is called right after the POST (Power On Self Test) procedure by the BIOS. After that, the MBR code is loaded into live memory at `0x7C00`. Then, the BIOS jumps at this address.

So we can say here that it is used as a sort of *soft reboot* because the reboot is not a complete one. This instruction is part of the boot process after BIOS execution. Some BIOS can handle boot medium priority while others just loop over available mediums and boot on the first one it can.

Here, we will emulate this instruction simply by loading again the MBR code into the memory page dedicated to it (stage 1), and then jump onto it (at address `0x7C00`):

```
diskboot_interrupts = FuncTable("INT 19h (diskboot)")
@func(diskboot_interrupts, 0x02)
def reboot(jitter, sys_):
    # Here, we assume only one bootable disk (index 0)
    hd = sys_.hd(0)
    mbr = hd.read_sector(0)
    jitter.vm.set_mem(0x7C00, mbr)
    jitter.pc = 0x7C00
```

For a few more hacks…

The `STI` (*Set Interrupt Flag*) instruction is used at address `0x7C0D`. It can activate masked interruptions (*flag* `IF` and offset 9 of the `FLAGS` register). This *flag* doesn't have any effect on non-maskable interruptions. Because hardware interruptions are fully emulated, Miasm doesn’t contain (legitimately) semantics for this instruction.

So we simply decided to ignore it by setting a breakpoint at its corresponding address:

```
jitter.add_breakpoint(0x7C0D, handle_sti)
```

Then, we redirect the execution flow to the next instruction. Because this instruction is only 1 byte long, a simple incrementation of the program counter does the trick:

```
def handle_sti(jitter):
    jitter.pc += 1
    return True
```

Yippie kay yay motherfucker !

Now that the useful handlers are implemented and the MBR code is loaded and mapped in Miasm virtual machine, emulation of NotPetya can begin:

```
jitter.init_run(stage1_addr)
jitter.continue_run()
```

If the `--verbose-bios-data` flag is set (see Implementation), output of the script prints the content of the various read and write operations on the disk. For example, here is the content of the second sector (of the 32 loaded sectors by the bootloader at `0x8000`):

```
Extended read sectors, drive idx 0x0
  Read 1 sectors from sector 2
00000000: 50 FF 76 04 E8 91 0A 83  C4 0A E8 3B 07 CD 19 5E  P.v........;...^
00000010: C9 C3 6A 0E E8 39 07 5B  68 70 9C E8 C0 03 5B C3  ..j..9.[hp....[.
00000020: C8 04 04 00 56 6A 00 6A  01 6A 00 6A 20 8D 86 FC  ....Vj.j.j.j ...
00000030: FD 50 8A 46 06 50 E8 21  0A 83 C4 0C 6A 00 68 8E  .P.F.P.!....j.h.
[...]
```

The loaded code matchs stage 2. Also, one can easily see the content loaded from sector 32:

```
Extended read sectors, drive idx 0x80
  Read 1 sectors from sector 32
00000000: 00 AA 92 E7 82 11 15 D3  20 96 A7 75 51 C0 36 08  ........ ..uQ.6.
00000010: E8 65 42 8C 73 9F 06 53  77 CB C5 95 60 C8 38 69  .eB.s..Sw...`.8i
00000020: 9B 0D A4 99 E0 13 12 30  79 31 4D 7A 37 31 35 33  .......0y1Mz7153
00000030: 48 4D 75 78 58 54 75 52  32 52 31 74 37 38 6D 47  HMuxXTuR2R1t78mG
00000040: 53 64 7A 61 41 74 4E 62  42 57 58 00 00 00 00 00  SdzaAtNbBWX.....
00000050: 00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
00000060: 00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
00000070: 00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
00000080: 00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
00000090: 00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
000000A0: 00 00 00 00 00 00 00 00  00 48 34 79 5A 73 77 56  .........H4yZswV
000000B0: 54 64 43 6B 43 77 55 68  72 31 4D 52 6D 4A 65 69  TdCkCwUhr1MRmJei
000000C0: 76 31 34 46 4B 39 6A 5A  6A 4D 36 36 4C 44 79 65  v14FK9jZjM66LDye
000000D0: 71 52 4C 64 6B 38 53 58  53 53 73 53 53 45 78 34  qRLdk8SXSSsSSEx4
000000E0: 44 51 57 4E 47 00 00 00  00 00 00 00 00 00 00 00  DQWNG...........
000000F0: 00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
[...]
000001F0: 00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ...............
```

This sector is where NotPetya stores data. According to the description done in MISC 805 n°93, we can deduct its content :

- `0x00` is the encrypted disk flag,
- `AA 92 E7 82 11 15 D3 20 96 A7 75 51 C0 36 08 E8 65 42 8C 73 9F 06 53 77 CB C5 95 60 C8 38 69` is the 32 bytes long Salsa20 key,
- `0D A4 99 E0 13 12 30 79` is a 8 bytes long nonce,
- next data is the random string printed when the malware was executed on Windows at the beginning.

After the encryption is done by the bootloader, key and nonce are erased from disk with 32 successive writings of zeros.

Moreover, we can see that sector 35 is used to store the number of total encrypted MFT entries. For example, here is the content of sector 35 right after the MFT header encryption:

```
Extended write sectors, drive idx 0x80
  Write 1 sectors at offset 35 (from memory at 0x5C74)
00000000: 01 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
[...]
```

Retrieving secrets in memory

One of the advantages of emulation is the ability to easily analyze memory pages. In our case, it is possible to retrieve the Salsa20 key used, even after the MFT table has been encrypted (during the “false chkdsk”, see NotPetya).

In fact, as explained in section INT 19h; after the encryption is over, the bootloader executes a “soft reboot” with the help of the interruption `INT 19h`. It doesn’t reboot completely the computer therefore the BIOS is not executed again. The data present in memory before the “soft reboot” is not tampered with. If the computer goes through hard reboot or reset, there would be great chances for the BIOS to overwrite data present on the stack with its own, including the precious Salsa20 key.

So, if the computer has not been rebooted or reset, it is pretty interesting to see if the Salsa20 key is still in memory. To do so, we simply read the key written in sector 32 (see this section) and store its value. Then, we place a breakpoint on the instructions in charge to show the ransom message, at address `0x85AF`:

```
key = HD0.read(32*SECTOR_LEN + 1, 32)
jitter.add_breakpoint(0x85AF, functools.partial(find_key_in_mem, key=key))
```

The `find_key_in_mem` function browses the virtual machine memory to find the key stored in the previous step:

```
def find_key_in_mem(jitter, key):
    # Find if the salsa20 key is still in memory!
    mem = jitter.vm.get_all_memory()
      print >>sys.stderr, "\n[+] Looking for key %s in memory..." % key.encode("hex")
    for addr,v in mem.iteritems():
        idx = v['data'].find(key)
        if idx == -1:
            continue
        print >>sys.stderr, "[+] Key found at address %s!" % hex(addr + idx)
        break
    else:
        print >>sys.stderr, "[-] Key not found in memory!"
    return True
```

This operation can be activated in the script using `--hook=find_key` option, like this:

```
$ python ./emulate-mbr.py --hook=find_key disk.raw

Repairing file system on C:
[... encryption happends here ...]

[+] Looking for key [your salsa20 key] in memory...
[+] Key found at address 0x674a!
```

To speed up the process, the `--skip-encryption` option can be used (see Implementation). Be careful, even if this option is used, the encryption flag in sector 32 is still set. The flag `--dry` prevents this behaviour.

Because we know the address where the key is stored (`0x674A`), we can put a breakpoint on a write access at this location, allowing us to know which part of the bootloader writes this key:

```
def print_ip(jitter):
    print(hex(jitter.pc))
    return False

jitter.exceptions_handler.callbacks[EXCEPT_BREAKPOINT_MEMORY] = []
jitter.add_exception_handler(EXCEPT_BREAKPOINT_MEMORY, print_ip)
jitter.vm.add_memory_breakpoint(0x674a, 1, PAGE_WRITE)
```

Because there is no ASLR or equivalent mechanism, this address will always be the same!

Bootloader modification to decrypt the MFT

If we have a mechanism to write directly into the memory of the machine (for example by using a PCI Express card [8], or other interfaces like FireWire or Thunderbolt [9]), it is possible to decrypt the MFT data. The attack consists in patching the bootloader memory so that its uses the remaining key on the stack. This section simulates this attack using Miasm.

To do so, we will inject some code at address `0x82A8`. This function checks that the key entered is the expected one. Given that it has been erased from the hard drive, and that the ransom text is completely random [10], the bootloader has in theory no way to know if the entered key is the right one. This function will always return 0 (incorrect key). The injected code will copy the key Salsa20 from the `0x674A` address to a specific location on the stack, so that the decryption function at `0x835A` will use this key. We will then jump on this function.

Associated assembly code is the following:

```
    ; Save registers on the stack
    PUSHA
    LEA DI, WORD PTR [BP-0x44]
    LEA BX, WORD PTR [key_addr]
    XOR CX,CX

    ; Copy the key that remains on the stack to [bp-0x44]
loop:
    MOV EAX, DWORD PTR [BX]
    MOV DWORD PTR [DI], EAX
    ADD DI, 4
    ADD BX, 4
    INC CX
    CMP CX,8
    JNZ loop

    ; Restore previously saved registers
    POPA
    ; Jump on the decryption function (CS:OFFSET => using an absolute address)
    JMP 0000:0x835A
```

We use Miasm to assemble it using the following function:

```
def asm_shellcode(asm, labels = None):
    machine = Machine("x86_16")
    symbol_pool = asmblock.AsmSymbolPool()

    # Assemble
    blocks, symbol_pool = parse_asm.parse_txt(machine.mn, 16, asm, symbol_pool)

    # Set custom labels
    if not labels is None:
        for name,value in labels.iteritems():
            sym = symbol_pool.getby_name(name)
            symbol_pool.set_offset(sym, value)

    # Resolve all the labels
    patches = asmblock.asm_resolve_final(machine.mn,
                                         blocks,
                                         symbol_pool)

    # Patch the final code with the label values
    shellcode = StrPatchwork()
    for offset, raw in patches.items():
        shellcode[offset] = raw
    return str(shellcode)
```

Let’s take a look at this function. The code is first assembled using an x86 16-bit assembler. Given labels are then associated to concrete values using the `symbol_pool.set_offset` function. Remaining labels (in our case `loop`) are resolved with the `asmblock.asm_resolve_final` function, which returns assembly code for each block. We finally use the `StrPatchwork` function to assemble the final “shellcode”.

The `read_key_and_patch` function loads the key in memory, dumps it and writes the freshly assembled code in memory:

```
def read_key_and_patch(jitter):
    # Key is still in the stack, at 0x674A. You can find this value by activating the
    # find_key_in_mem breakpoint!
    key_addr = 0x674A
    key = jitter.vm.get_mem(key_addr, 32)
    print >>sys.stderr, "\n[+] Key from memory: %s" % key.encode("hex")

    # Assemble our "shellcode" thanks to Miasm!
    shellcode = """
...
    """
    shellcode = asm_shellcode(shellcode, {"key_addr": key_addr})

    # Patch the bootloader in memory to decrypt using the key
    jitter.vm.set_mem(0x82A8, shellcode)
    return True
```

The remaining thing to do is to put a breakpoint at the same address as in section Retrieving secrets in memory (`0x85AF`) to call this function:

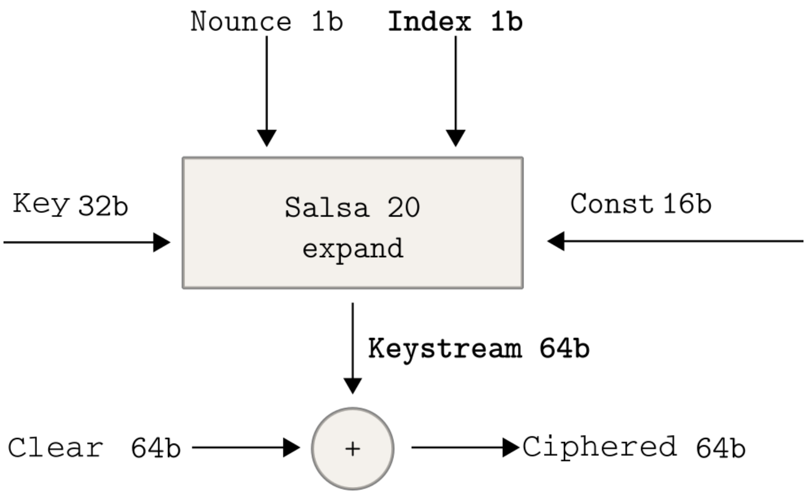
```
jitter.add_breakpoint(0x85AF, read_key_and_patch)
```

Everything is now set up. When the bootloader asks for the decryption key, user will just have to press `enter` . `--hook=patch_bootloader` flag of the `emulate_mbr` script performs this attack.

It is worth mentioning that we actually tried this at Synacktiv's headquarters using vulnerabilities in HP's iLO4 to gather the Salsa20 key from memory, patch the bootloader and decrypt MFT data.

Encryption keystream study

The encryption algorithm used is Salsa20 stream cipher. The general principle is: a random data flow based on a key - commonly called the keystream - is generated, and this stream is XORed with the data which will be encrypted. An advantage of stream ciphers is that the data to be encrypted do not need to be padded. On the other hand, one needs to be careful not to use the same parts of this stream twice.



Data encryption with Salsa20

We can verify this using Miasm, by looking at the data before and after encryption, and by showing their XOR difference.

In order to do this, we already know how to put breakpoints. The beginning of the encryption function is at address `0x9798` , and the end at address `0x9877` . We are going to out the first breakpoint just after ‘enter `instruction, and the second just before` leave` statement, in order to have the stack properly aligned to recover data before and after encryption. The associated code is the following:

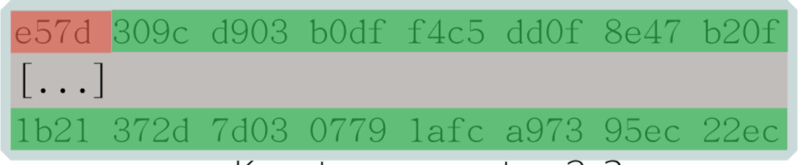
```
_last_buf = None
def encrypt_start(jitter, options):
    global _last_buf
    buf_ptr  = upck16(jitter.vm.get_mem((jitter.cpu.SS << 4) + jitter.cpu.BP + 0xC,
2))
    buf_size = upck16(jitter.vm.get_mem((jitter.cpu.SS << 4) + jitter.cpu.BP + 0xE,
2))
    _last_buf = jitter.vm.get_mem((jitter.cpu.DS << 4) + buf_ptr, buf_size)
    return True

def encrypt_end(jitter, options):
    global _last_buf
    buf_ptr  = upck16(jitter.vm.get_mem((jitter.cpu.SS << 4) + jitter.cpu.BP + 0xC,
2))
    buf_size = upck16(jitter.vm.get_mem((jitter.cpu.SS << 4) + jitter.cpu.BP + 0xE,
2))
    encr_buf = jitter.vm.get_mem((jitter.cpu.DS << 4) + buf_ptr, buf_size)
    keystream = ''.join(chr(ord(a)^ord(b)) for a,b in
zip(_last_buf,encr_buf)).encode("hex")
    keystream = ' '.join(keystream[i:i+4] for i in xrange(0,len(keystream),4))
    print >>sys.stderr, "Keystream for next 2 sectors: %s" % keystream
    return True

jitter.add_breakpoint(0x979C, functools.partial(encrypt_start, options=options))
jitter.add_breakpoint(0x9876, functools.partial(encrypt_end, options=options))
```

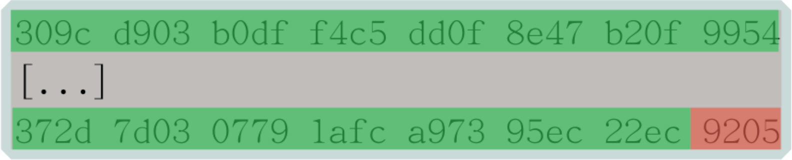
The `--dump-keystream` flag of the `emulate_mbr` script enables this.

By looking at the output, we can see that between two sectors (`2*512` bytes), the keystream is only shifted by two bytes, instead of the normally required `2*512` bytes. This shift is schematized in the image below:



```
e57d 309c d903 b0df f4c5 dd0f 8e47 b20f
[...]
1b21 372d 7d03 0779 1afc a973 95ec 22ec
```

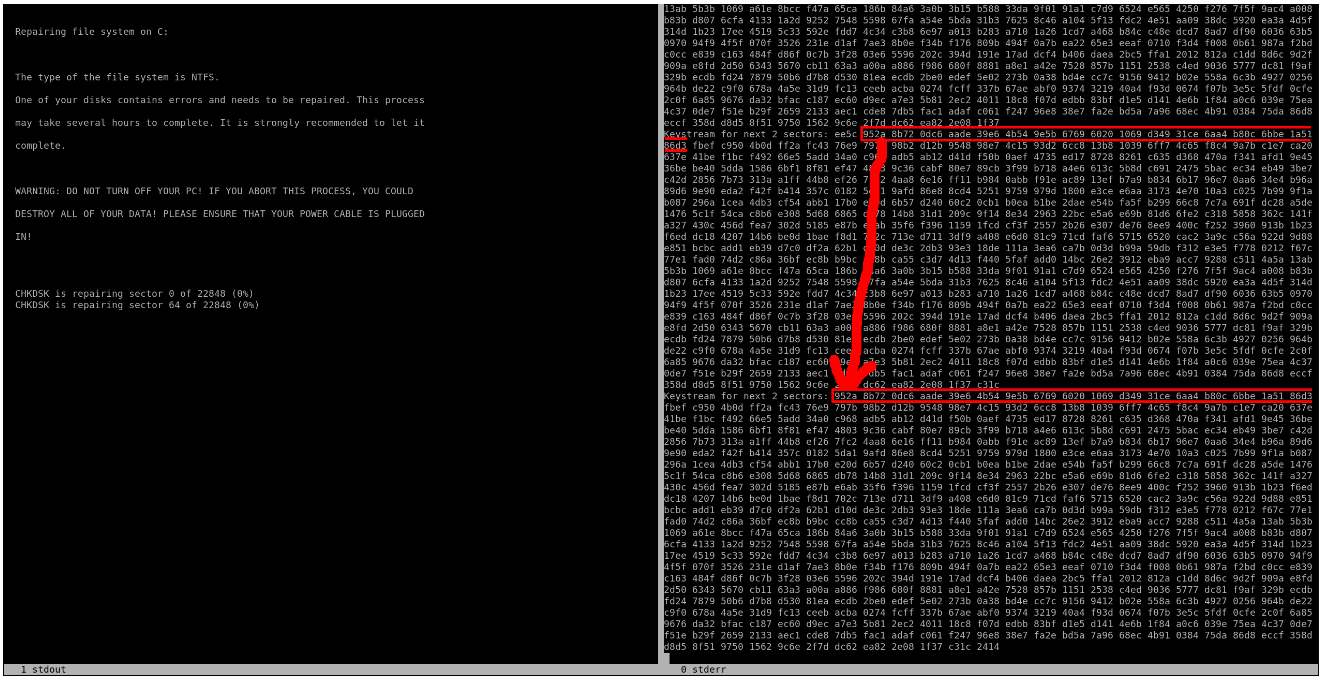
Keystream sector 2-3



```
309c d903 b0df f4c5 dd0f 8e47 b20f 9954
[...]
372d 7d03 0779 1afc a973 95ec 22ec 9205
```

Keystream sector 4-5

We can also see that on a screenshot of the output of the `emulate_mbr` script below:



```
Repairing file system on C:


The type of the file system is NTFS.

One of your disks contains errors and needs to be repaired. This process

may take several hours to complete. It is strongly recommended to let it

complete.


WARNING: DO NOT TURN OFF YOUR PC! IF YOU ABORT THIS PROCESS, YOU COULD

DESTROY ALL OF YOUR DATA! PLEASE ENSURE THAT YOUR POWER CABLE IS PLUGGED

IN!



CHKDSK is repairing sector 0 of 22848 (0%)
CHKDSK is repairing sector 64 of 22848 (0%)
```

```
13ab 5b3b 1069 a61e 8bcc f47a 65ca 186b 84a6 3a0b 3b15 b588 33da 9f01 91a1 c7d9 6524 e565 4250 f276 7f5f 9ac4 a008
b83b d807 6cfa 4133 1a2d 9252 7548 5598 67fa a54e 5bda 31b3 7625 8c46 a104 5f13 fdc2 4e51 aa09 38dc 5920 ea3a 4d5f
314d 1b23 17ee 4519 5c33 592e fdd7 4c34 c3b8 6e97 a013 b283 a710 1a26 1cd7 a468 b84c c48e dcd7 8ad7 df90 6036 63b5
0970 94f9 4f5f 070f 3526 231e d1af 7ae3 8b0e f34b f176 809b 494f 0a7b ea22 65e3 eeaf 0710 f3d4 f008 0b61 987a f2bd
c0cc e839 c163 484f d86f 0c7b 3f28 03e6 5596 202c 394d 191e 17ad dcf4 b406 daea 2bc5 ffa1 2012 812a c1dd 8d6c 9d2f
909a e8fd 2d50 6343 5670 cb11 63a3 a00a a886 f986 680f 8881 a8e1 a42e 7528 857b 1151 2538 c4ed 9036 5777 dc81 f9af
329b ecdb fd24 7879 50b6 d7b8 d530 81ea ecdb 2be0 edef 5e02 273b 0a38 bd4e cc7c 9156 9412 b02e 558a 6c3b 4927 0256
964b de22 c9f0 678a 4a5e 31d9 fc13 ceeb acba 0274 fcff 337b 67ae abf0 9374 3219 40a4 f93d 0674 f07b 3e5c 5fdf 0cfe
2c0f 6a85 9676 da32 bfac c187 ec60 d9ec a7e3 5b81 2ec2 4011 18c8 f07d edbb 83bf d1e5 d141 4e6b 1f84 a0c6 039e 75ea
4c37 0de7 f51e b29f 2659 2133 aec1 cde8 7db5 fac1 adaf c061 f247 96e8 38e7 fa2e bd5a 7a96 68ec 4b91 0384 75da 86d8
eccf 358d d8d5 8f51 9750 1562 9c6e 2f7d dc62 ea82 2e08 1f37
Keystream for next 2 sectors: ee5c 952a 8b72 0dc6 aade 39e6 4b54 9e5b 6769 6020 1069 d349 31ce 6aa4 b80c 6bbe 1a51
86d3 fbef c950 4b0d ff2a fc43 76e9 797b 98b2 d12b 9548 98e7 4c15 93d2 6cc8 13b8 1039 6ff7 4c65 f8c4 9a7b c1e7 ca20
637e 41be f1bc f492 66e5 5add 34a0 c968 adb5 ab12 d41d f50b 0aef 4735 ed17 8728 8261 c635 d368 470a f341 afd1 9e45
36be be40 5dda 1586 6bf1 8f81 ef47 4803 9c36 cabf 80e7 89cb 3f99 b718 a4e6 613c 5b8d c691 2475 5bac ec34 eb49 3be7
c42d 2856 7b73 313a a1ff 44b8 ef26 7fc2 4aa8 6e16 ff11 b984 0abb f91e ac89 13ef b7a9 b834 6b17 96e7 0aa6 34e4 b96a
89d6 9e90 eda2 f42f b414 357c 0182 5da1 9afd 86e8 8cd4 5251 9759 979d 1800 e3ce e6aa 3173 4e70 10a3 c025 7b99 9f1a
b087 296a 1cea 4db3 cf54 abb1 17b0 e20d 6b57 d240 60c2 0cb1 b0ea b1be 2dae e54b fa5f b299 66c8 7c7a 691f dc28 a5de
1476 5c1f 54ca c8b6 e308 5d68 6865 db78 14b8 31d1 209c 9f14 8e34 2963 22bc e5a6 e69b 81d6 6fe2 c318 5858 362c 141f
a327 430c 456d fea7 302d 5185 e87b e6ab 35f6 f396 1159 1fcd cf3f 2557 2b26 e307 de76 8ee9 400c f252 3960 913b 1b23
f6ed dc18 4207 14b6 be0d 1bae f8d1 702c 713e d711 3df9 a408 e6d0 81c9 71cd faf6 5715 6520 cac2 3a9c c56a 922d 9d88
e851 bcbc add1 eb39 d7c0 df2a 62b1 d10d de3c 2db3 93e3 18de 111a 3ea6 ca7b 0d3d b99a 59db f312 e3e5 f778 0212 f67c
77e1 fad0 74d2 c86a 36bf ec8b b9bc cc8b ca55 c3d7 4d13 f440 5faf add0 14bc 26e2 3912 eba9 acc7 9288 c511 4a5a 13ab
5b3b 1069 a61e 8bcc f47a 65ca 186b 84a6 3a0b 3b15 b588 33da 9f01 91a1 c7d9 6524 e565 4250 f276 7f5f 9ac4 a008 b83b
d807 6cfa 4133 1a2d 9252 7548 5598 67fa a54e 5bda 31b3 7625 8c46 a104 5f13 fdc2 4e51 aa09 38dc 5920 ea3a 4d5f 314d
1b23 17ee 4519 5c33 592e fdd7 4c34 c3b8 6e97 a013 b283 a710 1a26 1cd7 a468 b84c c48e dcd7 8ad7 df90 6036 63b5 0970
94f9 4f5f 070f 3526 231e d1af 7ae3 8b0e f34b f176 809b 494f 0a7b ea22 65e3 eeaf 0710 f3d4 f008 0b61 987a f2bd c0cc
e839 c163 484f d86f 0c7b 3f28 03e6 5596 202c 394d 191e 17ad dcf4 b406 daea 2bc5 ffa1 2012 812a c1dd 8d6c 9d2f 909a
e8fd 2d50 6343 5670 cb11 63a3 a00a a886 f986 680f 8881 a8e1 a42e 7528 857b 1151 2538 c4ed 9036 5777 dc81 f9af 329b
ecdb fd24 7879 50b6 d7b8 d530 81ea ecdb 2be0 edef 5e02 273b 0a38 bd4e cc7c 9156 9412 b02e 558a 6c3b 4927 0256 964b
de22 c9f0 678a 4a5e 31d9 fc13 ceeb acba 0274 fcff 337b 67ae abf0 9374 3219 40a4 f93d 0674 f07b 3e5c 5fdf 0cfe 2c0f
6a85 9676 da32 bfac c187 ec60 d9ec a7e3 5b81 2ec2 4011 18c8 f07d edbb 83bf d1e5 d141 4e6b 1f84 a0c6 039e 75ea 4c37
0de7 f51e b29f 2659 2133 aec1 cde8 7db5 fac1 adaf c061 f247 96e8 38e7 fa2e bd5a 7a96 68ec 4b91 0384 75da 86d8 eccf
358d d8d5 8f51 9750 1562 9c6e 2f7d dc62 ea82 2e08 1f37 c31c
Keystream for next 2 sectors: 952a 8b72 0dc6 aade 39e6 4b54 9e5b 6769 6020 1069 d349 31ce 6aa4 b80c 6bbe 1a51 86d3
fbef c950 4b0d ff2a fc43 76e9 797b 98b2 d12b 9548 98e7 4c15 93d2 6cc8 13b8 1039 6ff7 4c65 f8c4 9a7b c1e7 ca20 637e
41be f1bc f492 66e5 5add 34a0 c968 adb5 ab12 d41d f50b 0aef 4735 ed17 8728 8261 c635 d368 470a f341 afd1 9e45 36be
be40 5dda 1586 6bf1 8f81 ef47 4803 9c36 cabf 80e7 89cb 3f99 b718 a4e6 613c 5b8d c691 2475 5bac ec34 eb49 3be7 c42d
2856 7b73 313a a1ff 44b8 ef26 7fc2 4aa8 6e16 ff11 b984 0abb f91e ac89 13ef b7a9 b834 6b17 96e7 0aa6 34e4 b96a 89d6
9e90 eda2 f42f b414 357c 0182 5da1 9afd 86e8 8cd4 5251 9759 979d 1800 e3ce e6aa 3173 4e70 10a3 c025 7b99 9f1a b087
296a 1cea 4db3 cf54 abb1 17b0 e20d 6b57 d240 60c2 0cb1 b0ea b1be 2dae e54b fa5f b299 66c8 7c7a 691f dc28 a5de 1476
5c1f 54ca c8b6 e308 5d68 6865 db78 14b8 31d1 209c 9f14 8e34 2963 22bc e5a6 e69b 81d6 6fe2 c318 5858 362c 141f a327
430c 456d fea7 302d 5185 e87b e6ab 35f6 f396 1159 1fcd cf3f 2557 2b26 e307 de76 8ee9 400c f252 3960 913b 1b23 f6ed
dc18 4207 14b6 be0d 1bae f8d1 702c 713e d711 3df9 a408 e6d0 81c9 71cd faf6 5715 6520 cac2 3a9c c56a 922d 9d88 e851
bcbc add1 eb39 d7c0 df2a 62b1 d10d de3c 2db3 93e3 18de 111a 3ea6 ca7b 0d3d b99a 59db f312 e3e5 f778 0212 f67c 77e1
fad0 74d2 c86a 36bf ec8b b9bc cc8b ca55 c3d7 4d13 f440 5faf add0 14bc 26e2 3912 eba9 acc7 9288 c511 4a5a 13ab 5b3b
1069 a61e 8bcc f47a 65ca 186b 84a6 3a0b 3b15 b588 33da 9f01 91a1 c7d9 6524 e565 4250 f276 7f5f 9ac4 a008 b83b d807
6cfa 4133 1a2d 9252 7548 5598 67fa a54e 5bda 31b3 7625 8c46 a104 5f13 fdc2 4e51 aa09 38dc 5920 ea3a 4d5f 314d 1b23
17ee 4519 5c33 592e fdd7 4c34 c3b8 6e97 a013 b283 a710 1a26 1cd7 a468 b84c c48e dcd7 8ad7 df90 6036 63b5 0970 94f9
4f5f 070f 3526 231e d1af 7ae3 8b0e f34b f176 809b 494f 0a7b ea22 65e3 eeaf 0710 f3d4 f008 0b61 987a f2bd c0cc e839
c163 484f d86f 0c7b 3f28 03e6 5596 202c 394d 191e 17ad dcf4 b406 daea 2bc5 ffa1 2012 812a c1dd 8d6c 9d2f 909a e8fd
2d50 6343 5670 cb11 63a3 a00a a886 f986 680f 8881 a8e1 a42e 7528 857b 1151 2538 c4ed 9036 5777 dc81 f9af 329b ecdb
fd24 7879 50b6 d7b8 d530 81ea ecdb 2be0 edef 5e02 273b 0a38 bd4e cc7c 9156 9412 b02e 558a 6c3b 4927 0256 964b de22
c9f0 678a 4a5e 31d9 fc13 ceeb acba 0274 fcff 337b 67ae abf0 9374 3219 40a4 f93d 0674 f07b 3e5c 5fdf 0cfe 2c0f 6a85
9676 da32 bfac c187 ec60 d9ec a7e3 5b81 2ec2 4011 18c8 f07d edbb 83bf d1e5 d141 4e6b 1f84 a0c6 039e 75ea 4c37 0de7
f51e b29f 2659 2133 aec1 cde8 7db5 fac1 adaf c061 f247 96e8 38e7 fa2e bd5a 7a96 68ec 4b91 0384 75da 86d8 eccf 358d
d8d5 8f51 9750 1562 9c6e 2f7d dc62 ea82 2e08 1f37 c31c 2414
```

Screenshot of the keystream

Thus, parts of the keystream are reused between sectors, which may help to recover some of its original data.

Indeed, if we consider `p` to be the clear text, `k` the keystream and `c` the encrypted text, then the encryption function `E` is defined as `E (p) = p xor k = c`. A part of the MFT structures being invariant and known, it is therefore possible, in two sectors, to find part of the keystream used for these two sectors. This one is reused for the two following sectors by being simply shifted by two bytes, so some of the clear text from these other areas can be found.

This vulnerability in the Salsa20 implementation of the bootloader has been exploited by CrowdStrike to recover a large portion of MFT's original data (between 98.10% and 99.97% depending on the method).

Conclusion

Emulation of the NotPetya bootloader code allows the verification of various assumptions and the understanding, in a very tangible way, of the different steps related to the encryption of MFT entries. In addition, it allows to easily find the bias in the Salsa20 keystream implementation (without having to statically reverse the algorithm), or to simulate the recovery of the key, which remains in memory after the encryption.

This article only shows a small subset of Miasm's possibilities, and we hope that the approach adopted in this article will encourage uninitiated readers to try and play with it :).

Acknowledgments

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Appendix: application using vulnerabilities in HP iLO 4

With Alexandre Gazet & Fabien Perigaud, we spent some time in Synacktiv's offices to combine the attacks described in this article with vulnerabilities they found with Joffrey Czarny on HP iLO 4's management engine. These vulnerabilities allowed us to read and write the memory of an infected server stuck at NotPetya's bootloader stage, so that we were able to recover the encryption key and patch the bootloader in order to decrypt the MFT.

A full write up of the experiment can be read on Airbus seclab website.

1. https://fr.wikipedia.org/wiki/Master_File_Table ↩
2. https://shasaurabh.blogspot.fr/2017/07/debugging-mbr-ida-pro-and-bochs-emulator.html ↩
3. https://www.sstic.org/2012/presentation/miasm_framework_de_reverse_engineering/ ↩
4. https://fr.wikipedia.org/wiki/Mode_r%C3%A9el ↩
5. https://docs.microsoft.com/en-us/windows/wsl/install-win10 ↩
6. https://wiki.osdev.org/ATA_in_x86_RealMode_(BIOS)) ↩
7. http://webpages.charter.net/danrollins/techhelp/0243.HTM ↩
8. https://www.sstic.org/media/SSTIC2011/SSTIC-actes/attaques_dma_peer-to-peer_et_contremesures/SSTIC2011-Article-attaques_dma_peer-to-peer_et_contremesures-lone-sang_duflot_nicomette_deswarte.pdf ↩
9. https://github.com/carmaa/inception ↩
10. https://www.crowdstrike.com/blog/petrwrap-ransomware-technical-analysis-triple-threat-file-encryption-mft-encryption-credential-theft/ ↩