PROFILE AND TOC

TOC:

• Introduction
• Rootkits: Ring 0
• Advanced Malwares and Rootkits: Ring -2

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INTRODUCTION
RING 0/-2 ROOTKITS

RING 0:

- Kernel Callback methods
- WinDbg structures
- Kernel Drivers Structures
- Malicious Drivers
- Modern C2 communication
- Kernel Pools and APCs

ADVANCED MALWARES:

- MBR/VBR/UEFI rootkits
- Techniques used by rootkits
- Kernel Code Signing Bypasses
- MBR + IPL infection
- BIOS, UEFI and boot architecture
- Boot Guard
- Secure Boot attacks
- WSMT (Windows SMM Security Mitigation Table)
- BIOS Guard
- BIOS/UEFI Protections
ROOTKITS: RING 0
ROOTKITS: RING 0

• **Kernel Callback Functions**, which are oftenly used by antivirus programs for monitoring and alerting the kernel modules about a specific event occurrence. Therefore, they are used by malwares (kernel drivers) for **evading defenses**.

• **Most known callback methods** are:
  - **PsSetLoadImageNotifyRoutine**: it provides notification when a process, library or kernel memory is mapped into memory.
  - **IoRegisterFsRegistrationChange**: it provides notification when a filesystem becomes available.
  - **IoRegisterShutdownNotification**: the driver handler (IRP_MJ_SHUTDOWN) acts when the system is about going to down.
  - **KeRegisterBugCheckCallback**: it helps drivers to receive a notification (for cleaning tasks) before a system crash.
ROOTKITS: RING 0

- **PsSetCreateThreadNotifyRoutine**: indicates a routine that is called every time when a thread starts or ends.
- **PsSetCreateProcessNotifyRoutine**: when a process starts or finishes, this callback is invoked (rootkits and AVs).
- **DbgSetDebugPrintCallback**: it is used for capturing debug messages.
- **CmRegisterCallback** or **CmRegisterCallbackEx** are called by drivers to register a RegistryCallback routine, which is called every time a thread performs an operation on the registry.
- Malwares have been using this type of callbacks for checking whether their persistence entries are kept and, just in case they were removed, so the malware adds them back.
ROOTKITS: RING 0

0: kd> dd nt!CmpCallBackCount L1
ffffffff801`aa733fcc 00000002

0: kd> dps nt!CallbackListHead L2
ffffffff801`aa769190 ffffc000`c8d62db0
ffffffff801`aa769198 ffffc000`c932c8b0

0: kd> dt nt!_LIST_ENTRY ffffc000`c8d62db0
[ 0xfffffc000`c932c8b0 - 0xffffff801`aa769190 ]
+0x000 Flink : 0xfffffc000`c932c8b0 _LIST_ENTRY [ 0xffffff801`aa769190 - 0xfffffc000`c8d62db0 ]
+0x008 Blink : 0xffffff801`aa769190 _LIST_ENTRY [ 0xfffffc000`c8d62db0 - 0xfffffc000`c932c8b0 ]

ALEXANDRE BORGES - MALWARE AND SECURITY RESEARCHER
ROOTKITS: RING 0

0: kd> !list -t _LIST_ENTRY.Flink -x "dps" -a "L8" 0xfffffc000`c932c8b0

ffffc000`c932c8b0  fffff801`aa769190 nt!CallbackListHead

.....

ffffc000`c932c8c8  01d3c3ba`27edfc12
ffffc000`c932c8d0  fffff801`6992a798 vsdatant+0x67798
ffffc000`c932c8d8  fffff801`69951a68 vsdatant+0x8ea68
ffffc000`c932c8e0  00000000`000a000a

.....

ffff801`aa7691c0  00000000`bee0bee0
ffff801`aa7691c8  fffff801`aa99b600 nt!HvpGetCellFlat
• At same way, `PsSetCreateProcessNotifyRoutine( )` routine adds a driver-supplied callback routine to, or removes it from, a list of routines to be called whenever a process is created or deleted.

```plaintext
0: kd> dd nt!PspCreateProcessNotifyRoutineCount L1
fffff801`aab3f668 00000009

0: kd> .for (r $t0=0; $t0 < 9; r $t0=$t0+1) { r $t1=poi($t0 * 8 + nt!PspCreateProcessNotifyRoutine); .if ($t1 == 0) { .continue }; r $t1 = $t1 & 0xFFFFFFFFFFFFFFF0; dps $t1+8 L1;}
```

• Malwares composed by kernel drivers, which use the `PsSetLegoNotifyRoutine( )` kernel callback to register a malicious routine that is called during the thread termination. The KTHREAD.LegoData field provides the direct address.
ROOTKITS: RING 0

0: kd> .for (r $t0=0; $t0 < 9; r $t0=$t0+1) { r $t1=poi($t0 * 8 + 
nt!PspCreateProcessNotifyRoutine); .if ($t1 == 0) { .continue }; r $t1 = $t1 & 
0xFFFFF0000000000; dps $t1+8 L1;}

ffffe001`134c8b08  fffff801`aa5839c4  nt!ViCreateProcessCallback
ffffe001`139e1138  fffff801`678175f0  cng!CngCreateProcessNotifyRoutine
ffffe001`13b43138  fffff801`67e6c610  kl1+0x414610
ffffe001`13bdb268  fffff801`685d1138  PGPfsfd+0x1c138
ffffe001`13b96858  fffff801`68a53000  ksecdd!KsecCreateProcessNotifyRoutine
ffffe001`14eeacc8  fffff801`68d40ec0  tcpip!CreateProcessNotifyRoutineEx
ffffe001`164ffce8  fffff801`67583c70  CI!!_PEProcessNotify
ffffe001`13b6e4b8  fffff801`68224a38  klf!PstUnregisterProcess+0xfac
ffffe001`1653e4d8  fffff801`699512c0  vsdatant+0x8e2c0
By now, we have seen malwares using \texttt{KTHREAD.LegoData} field for registering a malicious routine, which would be called during the thread termination.
Windows offers different types of drivers such as legacy drivers, filter drivers and minifilter drivers (malwares can be written using any one these types), which could be developed using WDM or WDF frameworks (of course, UMDF and KMDF take part).

- To analyze a malicious driver, remember this sequence of events:
  - The driver image is mapped into the kernel memory address space.
  - An associated driver object is created and registered with Object Manager, which calls the entry point and fills the DRIVER_OBJECT structure’s fields.
ROOTKITS: RING 0

- Most ring 0 malwares install filter drivers for:
  - modifying aspects and behavior of existing drivers
  - filtering results of operations (reading file, for example)
  - adding new malicious features to a driver/devices (for example, keyloggers)

- Oftenly found in filter drivers (mainly the malicious one) for intercepting and altering data, a driver can easily “attach” (using $IoAttachDevice()$) one device object to another device object (similar to a “pipeline) to receive I/O requests (see next slide).

- The $AddDevice()$ routine is used to create an unnamed Device Object and to attach it to a named Device Object (ex: aborges) from a layered driver (lower-level driver).
ROOTKITS: RING 0

• Each IRP will be processed by a dispatch routine, which is picked up from its MajorFunction Table.

• The correct dispatch routine will be called to handle the request, picking the IRP parameters from the own IO_STACK_LOCATION by calling the IoGetCurrentIrpStackLocation() routine.

• Additionally, these IRP parameters could be passed to the next IO_STACK_LOCATION by using the IoCopyCurrentIrpStackLocation() routine or even to the next driver by calling IoSkipCurrentStackLocation() routine.
ROOTKITS: RING 0

- Alternatively, this IRP could be passed down to the layered driver by using function such as IoCallDriver().

- Usually, rootkits use the same IoCallDriver() to send directly request to the filesystem driver, evading any kind of monitoring or hooking at middle of the path. 😊
ROOTKITS: RING 0

Driver Stack
- Tcpi.sys
  - Upper Filter Driver
  - Function Driver
  - Lower Filter Driver
  - Miniport driver

Device Stack
- Physical Device Object
  - Lower Filter Device Object
    - Function Device Object
      - Upper Filter Device Object

IO_STACK_LOCATION 4
IO_STACK_LOCATION 3
IO_STACK_LOCATION 2
IO_STACK_LOCATION 1

No Completion Routine
Completion Routine 4
Completion Routine 3
Completion Routine 2

The IoCompleteRequest() manages calling these routines in the correct order (bottom-up). 😊
A IRP is usually generated by the I/O Manager in response to requests.

An IRP can be generated by drivers through the IoAllocateIrp() function.

Analyzing malware, we are usually verify functions such as IoGetCurrentIrpStackLocation(), IoGetNextIrpStackLocation() and IoSkipCurrentIrpStackLocation().

At end, each device holds the responsibility to prepare the IO_STACK_LOCATION to the next level, as well a driver could call the IoSetCompletionRoutine() to set a completion routine up at CompletionRoutine field.
Parameters field depends on the major and minor functions!
ROOTKITS: RING 0

Parameter field depends on major and minor function number. Thus, the IRPs being used are related to the action.

<table>
<thead>
<tr>
<th>MEMBER NAME</th>
<th>IRPs that use this member</th>
</tr>
</thead>
<tbody>
<tr>
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<td>IRP_MJ_CREATE</td>
</tr>
<tr>
<td>Read</td>
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</tr>
<tr>
<td>Write</td>
<td>IRP_MJ_WRITE</td>
</tr>
<tr>
<td>QueryFile</td>
<td>IRP_MJ_QUERY_INFORMATION</td>
</tr>
<tr>
<td>SetFile</td>
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</tr>
<tr>
<td>QueryVolume</td>
<td>IRP_MJ_QUERY_VOLUME_INFORMATION</td>
</tr>
<tr>
<td>DeviceIoControl</td>
<td>IRP_MJ_DEVICE_CONTROL and IRP_MJ_INTERNAL_DEVICE_CONTROL</td>
</tr>
<tr>
<td>MountVolume</td>
<td>IRP_MN_MOUNT_VOLUME</td>
</tr>
<tr>
<td>VerifyVolume</td>
<td>IRP_MN_VERIFY_VOLUME</td>
</tr>
<tr>
<td>Scsi</td>
<td>IRP_MJ_INTERNAL_DEVICE_CONTROL (SCSI)</td>
</tr>
<tr>
<td>QueryDeviceRelations</td>
<td>IRP_MN_QUERY_DEVICE_RELATIONS</td>
</tr>
<tr>
<td>QueryInterface</td>
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<td>WaitWake</td>
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<tr>
<td>PowerSequence</td>
<td>IRP_MN_POWER_SEQUENCE</td>
</tr>
<tr>
<td>Power</td>
<td>IRP_MN_SET_POWER and IRP_MN_QUERY_POWER</td>
</tr>
<tr>
<td>StartDevice</td>
<td>IRP_MN_START_DEVICE</td>
</tr>
<tr>
<td>WMI</td>
<td>WMI minor IRPs</td>
</tr>
</tbody>
</table>
ROOTKITS: RING 0

```
kd> lm Dvm aborges
    Browse full module list
    start   end   module name
    9a3c3000 9a3ca000 aborges (no symbols)
    Loaded symbol image file: aborges.sys
    Image path: \SystemRoot\system32\drivers\aborges.sys
    Image name: aborges.sys
    Browse all global symbols functions data
    Timestamp: Thu Feb 28 22:28:14 2013 (5130042E)
    CheckSum: 0000E646
    ImageSize: 00007000
    Translations: 0000.04b0 0000.04e4 0409.04b0 0409.04e4

kd> !object \driver\aborges
    Object: 86862c60  Type: (851ea6c0) Driver
    ObjectHeader: 86862c48 (new version)
    HandleCount: 0  PointerCount: 15
    Directory Object: 8a252f50  Name:

kd> !drvobj \driver\aborges
    Driver object (86862c60) is for:
    Driver Extension List: (id, addr)
    Device Object list:
    85212888 85212a80 85212bb8 85214958
    8640ac98 863c7860 86455bd0 8645b8e8
    865d3d98 863faef8 86451900 868339f8
    8683fd98
```

Malicious driver
**ROOTKITS: RING 0**

kd> `dt DRIVER_OBJECT 86862c60`

```
nt!_DRIVER_OBJECT
+0x000 Type         : 0x14
+0x002 Size         : 0x168
+0x004 DeviceObject : 0x85212888 _DEVICE_OBJECT
+0x008 Flags        : 0x12
+0x00c DriverStart  : 0x9a3c3000 Void
+0x010 DriverSize   : 0x7000
+0x014 DriverSection: 0x86839ea8 Void
+0x018 DriverExtension: 0x86862d08 _DRIVER_EXTENSION
+0x01c DriverName   : _UNICODE_STRING "\Driver\aborges"
+0x024 HardwareDatabase: 0x82d8a270 _UNICODE_STRING "\REGISTRY\MACHINE\HARDWARE\DESCRIPTION\SYSTEM"
+0x028 FastIoDispatch: (null)
+0x02c DriverInit    : 0x9a3c8f05 long +0
+0x030 DriverStartIo : (null)
+0x034 DriverUnload  : 0x9a3c3b36 void +0
+0x038 MajorFunction : [28] 0x9a3c4f90 long +0
```
ROOTKITS: RING 0

kd> \drvobj 86862c60 3
Driver object (86862c60) is for:
\Driver\aborges
Driver Extension List: (id , addr)

Device Object list:
85212888 85212a80 85212bb8 85214958
8640ac98 863c7860 86455bd0 8645b8e8
865d3d98 863faef8 86451900 868339f8
8683fd98

DriverEntry: 9a3c8f05 aborges
DriverStartIo: 00000000
DriverUnload: 9a3c3b36 aborges
AddDevice: 00000000

Dispatch routines:
[00] IRP_MJ_CREATE 9a3c4f90 nt!IoAllocateDeviceRequest
[01] IRP_MJ_CREATE_NAMED_PIPE 82aca0bf nt!IoAllocateDeviceRequest
[02] IRP_MJ_CLOSE 9a3c4e38 aborges+0x1e38
[03] IRP_MJ_READ 9a3c5540 aborges+0x2540
[04] IRP_MJ_WRITE 9a3c6290 aborges+0x3290
[05] IRP_MJ_QUERY_INFORMATION 82aca0bf nt!IoAllocateDeviceRequest
[06] IRP_MJ_SET_INFORMATION 82aca0bf nt!IoAllocateDeviceRequest
[07] IRP_MJ_QUERY_EA 82aca0bf nt!IoAllocateDeviceRequest
[08] IRP_MJ_SET_EA 82aca0bf nt!IoAllocateDeviceRequest
[09] IRP_MJ_FLUSH_BUFFERS 82aca0bf nt!IoAllocateDeviceRequest
[0a] IRP_MJ_QUERY_VOLUME_INFORMATION 82aca0bf nt!IoAllocateDeviceRequest
[0b] IRP_MJ_SET_VOLUME_INFORMATION 82aca0bf nt!IoAllocateDeviceRequest
[0c] IRP_MJ_DIRECTORY_CONTROL 82aca0bf nt!IoAllocateDeviceRequest
[0d] IRP_MJ_FILE_SYSTEM_CONTROL 82aca0bf nt!IoAllocateDeviceRequest
[0e] IRP_MJ_DEVICE_CONTROL 9a3c3c82 aborges+0xc82
ROOTKITS: RING 0

 Dispatch routines:

| IRP_MJ_CREATE | 9a3c4f90 | aborges=0x1f90
| IRP_MJ_CREATE_NAMED_PIPE | 82aca0bf | nt!IopInvalidDeviceRequest
| IRP_MJ_CLOSE | 9a3c4e38 | aborges=0x1e38
| IRP_MJ_READ | 9a3c5540 | aborges=0x2540
| IRP_MJ_WRITE | 9a3c6290 | aborges=0x3290
| IRP_MJ_QUERY_INFORMATION | 82aca0bf | nt!IopInvalidDeviceRequest
| IRP_MJ_SET_INFORMATION | 82aca0bf | nt!IopInvalidDeviceRequest
| IRP_MJ_QUERY_EA | 82aca0bf | nt!IopInvalidDeviceRequest
| IRP_MJ_SET_EA | 82aca0bf | nt!IopInvalidDeviceRequest
| IRP_MJ_FLUSH_BUFFERS | 82aca0bf | nt!IopInvalidDeviceRequest
| IRP_MJ_QUERY_VOLUME_INFORMATION | 82aca0bf | nt!IopInvalidDeviceRequest
| IRP_MJ_SET_VOLUME_INFORMATION | 82aca0bf | nt!IopInvalidDeviceRequest
| IRP_MJ_DIRECTORY_CONTROL | 82aca0bf | nt!IopInvalidDeviceRequest
| IRP_MJ_FILE_SYSTEM_CONTROL | 82aca0bf | nt!IopInvalidDeviceRequest
| IRP_MJ_DEVICE_CONTROL | 9a3c3c82 | aborges=0xc82
### Rootkits: Ring 0

```plaintext
kd> !fltkd.filters

Filter List:
- FLT FILTER 85a88754 "Frame 0"
- FLT FILTER 86df0008 "abftldrv" "135000"
- FLT INSTANCE: 86df4008 "abftldrv" "135000"
-FLT FILTER: 85b56560 "FileInfo" "45000"
- FLT INSTANCE: 85bb10b8 "FileInfo" "45000"
- FLT INSTANCE: 85c74430 "FileInfo" "45000"
- FLT INSTANCE: 85d71008 "FileInfo" "45000"
- FLT INSTANCE: 85d92950 "FileInfo" "45000"

kd> dt _FLT_FILTER 86df0008

fltmgr!_FLT_FILTER:
+0x000 Base : _FLT_OBJECT
+0x014 Frame : 0x85a886f8 _FLT_FRAME
+0x018 Name : UNICODE_STRING "abftldrv"
+0x020 DefaultAltitude : UNICODE_STRING "135000"
+0x028 Flags : 6 (No matching name)
+0x02c DriverObject : 0x86ded938 _DRIVER_OBJECT
+0x030 InstanceList : _FLT_RESOURCE_LIST_HEAD
+0x074 VerifierExtension : (null)
+0x078 VerifiedFiltersLink : _LIST_ENTRY [ 0x0 - 0x0 ]
+0x080 FilterUnload : (null)
+0x084 InstanceSetup : 0x8f5e663c long abftldrv!AbftldrvInstanceSetup+0
+0x088 InstanceQueryTeardown : (null)
+0x08c InstanceTeardownStart : (null)
+0x090 InstanceTeardownComplete : (null)
+0x094 SupportedContextsListHead : 0x86ded50 _ALLOCATE_CONTEXT_HEADER
+0x098 SupportedContexts : [6] (null)
+0x0b0 PreVolumeMount : 0x8f5da8cc _FLT_PREOP_CALLBACK_STATUS abftldrv!AbftldrvPreRedirect+0
+0x0b4 PostVolumeMount : (null)
+0x0b8 GenerateFileName : 0x8f5e28fa long abftldrv!AbftldrvGenerateFileName+0
+0x0bc NormalizeNameComponent : (null)
+0x0c0 NormalizeNameComponentEx : 0x8f5e29b2 long abftldrv!AbftldrvNormalizeNameComponentEx+0
+0x0c4 NormalizeContextCleanup : (null)
+0x0c8 RemoveNotification : (null)
+0x0cc Operations : 0x86df0164 _FLT_OPERATION_REGISTRATION
+0x0d0 OldDriverUnload : (null)
```
ROOTKITS: RING 0

```
kd> dx -id 0,0,85a88754 -r1 ((fltmgr! FLT_OPERATION_REGISTRATION *) 0x86df0164)
((fltmgr! FLT_OPERATION_REGISTRATION *) 0x86df0164)
: 0x86df0164 [Type: _FLT_OPERATION_REGISTRATION *]
  [+0x000] MajorFunction : 0xec [Type: unsigned char]
  [+0x004] Flags : 0x0 [Type: unsigned long]
  [+0x008] PreOperation : 0x8f5da0cc [Type: _FLT_PREOP_CALLBACK_STATUS]
(*)(_FLT_CALLBACK_DATA *, _FLTRELATEDOBJECTS *, void **)
  [+0x00c] PostOperation : 0x0 [Type: _FLT_POSTOP_CALLBACK_STATUS]
|(*)(_FLT_CALLBACK_DATA *, _FLTRELATEDOBJECTS *, void *, unsigned long)|
  [+0x010] Reserved1 : 0x0 [Type: void *]
```

```
k> u 0x8f5da0cc
abftldrv!AbftldrvPreRedirect:
8f5da0cc 8bff
abftldrv!AbftldrvPreRedirect:
8f5da0cc 8bff
  mov edi,edi
8f5da0ce 55
push ebp
8f5da0cf 8bec
mov ebp,esp
8f5da0d1 8b450c
mov eax,dword ptr [ebp+0Ch]
8f5da0d4 8b4010
mov eax,dword ptr [eax+10h]
8f5da0d7 85c0
test eax,eax
8f5da0d9 7411
je abftldrv!AbftldrvPreRedirect+0x20 (8f5da0ec)
8f5da0db 8b400c
mov eax,dword ptr [eax+0Ch]
```
ROOTKITS: RING 0

• Naturally, as closest at bottom of device stack occurs the infection (SCSI miniport drivers instead of targeting File System Drivers), so more efficient it is.

• Nowadays, most monitoring tools try to detect strange activities at upper layers.

• Malwares try to intercept requests (read / write operations) from hard disk by manipulating the MajorFunction array (IRP_MJ_DEVICE_CONTROL and IRP_INTERNAL_CONTROL) of the DRIVER_OBJECT structure. 😊
ROOTKITS: RING 0

- Rootkits try to protect itself from being removed by modifying routines such as IRP_MJ DEVICE_CONTROL and hooking requests going to the disk (IOCTL_ATA_* and IOCTL_SCSI_*).

- Another easy approach is to hook the DriverUnload() routine for preventing the rootkit of being unloaded.

- However, any used tricks must avoid touching critical areas protected by KPP (Kernel Patch Guard) and one of tricky methods for find which are those areas is trying the following:
ROOTKITS: RING 0

kd> !analyze –show 109

| 0  | A generic data region          |
| 1  | Modification of a function or .pdata |
| 2  | A processor IDT               |
| 3  | A processor GDT              |
| 4  | Type 1 process list corruption |
| 5  | Type 2 process list corruption |
| 6  | Debug routine modification   |
| 7  | Critical MSR modification    |
| 8  | Object type                  |
| 9  | A processor IVT              |
| a  | Modification of a system service function |
| b  | A generic session data region |
| c  | Modification of a session function or .pdata |
| d  | Modification of an import table |
| e  | Modification of a session import table |
| f  | Ps Win32 callout modification |
| 10 | Debug switch routine modification |
| 11 | IRP allocator modification   |
| 12 | Driver call dispatcher modification |
| 13 | IRP completion dispatcher modification |
| 14 | IRP deallocator modification |

Thanks, Alex Ionescu 😊
ROOTKITS: RING 0

• Most time, malwares have allocated a kind of hidden filesystem in free sectors to store configuration files and they are referred by random device object names generated during the boot.

• Few authors of ring 0 malwares are careless because they write malicious drivers that provide access to shared user-mode buffers using Neither method (METHOD_NEITHER), without any data validation, exposing it to memory corruption and, most time, leakage of information. Ridiculous. 😊
Additionally, malwares composed by executable + drivers have been using APLC (Advanced Local Procedure Call) in the communication between user mode code and kernel drivers instead of using only IOCTL commands.

Remember APLC interprocess-communication technique has been used since Windows Vista, as between lsass.exe and SRM (Security Reference Monitor). Most analysts are not used to seeing this approach.

Malwares do not choose an specific driver during the boot for injection, but try to randomly pick up a driver by parsing structures such as _KLDR_DATA_TABLE_ENTRY.
Certainly, hooking the filesystem driver access is always a possible alternative:

- `IoCreateFile()` → gets a handle to the filesystem.
- `ObReferenceObjectByHandle()` → gets a pointer to `FILE_OBJECT` represented by the handle.
- `IoCreateDevice()` → creates a device object (`DEVICE_OBJECT`) for use by a driver.
- `IoGetRelatedDeviceObject()` → gets a pointer to `DEVICE_OBJECT`.
- `IoAttachDeviceToDeviceStack()` → creates a new device object and attaches it to `DEVICE_OBJECT` pointer (previous function).
ROOTKITS: RING 0

• As it is done by AVs, malwares also hook functions such as ZwCreate() for intercepting all opened requests sent to devices.

• After infecting a system by dropping kernel drivers, malwares usually force the system reboot calling ZwRaiseHardError() function and specifying OptionShutdownSystem as 5th parameter.

• Of course, it could be worse and the malware could use IoRegisterShutdownNotification() routine registers the driver to receive an IRP_MJ_SHUTDOWN IRP notification when the system is shutdown for restoring the malicious driver in the next boot just in case it is necessary.
ROOTKITS: RING 0

- Malwares continue allocating (usually RWX, although on Windows 8+ it could specify NonPagePoolNX) and marking their pages by using ExAllocatePoolWithTag() function (and other at same family ExAllocatePool*). Fortunately, it can be easily found by using memory analysis:

```python
root@kali:~# more /root/volatility26/volatility/plugins/rootkitscanner.py
import volatility.poolscan as poolscan
import volatility.plugins.common as common
import volatility.utils as utils
import volatility.obj as obj

class RootkitPoolScanner(poolscan.SinglePoolScanner):

    """Configurable pool scanner""

    checks = [
        # Replace XXXX with the 4-byte tag you're trying to find
        ('PoolTagCheck', dict(tag = "Ddk")),
        # Replace > 0 with a size comparison test (i.e. >= 40, < 1000)
        ('CheckPoolSize', dict(condition = lambda x : x > 0)),
        # Assign a value of False or True depending on the desired allocations
        ('CheckPoolType', dict(paged = False, non_paged = True)),
    ]
```
ROOTKITS: RING 0

```
sub_8643B46D proc near
    arg_0= dword ptr 4
    arg_4= word ptr 8

    push   ebx
    mov    bx, [esp+4+arg_4]
    test   bx, bx
    push   esi
    push   edi
    movzx  edi, bx
    jbe    short loc_8643B4AE

    push   'kDD'
    push   edi
    push   0
    call   dword ptr ds:ExAllocatePoolWithTag
    test   eax, eax
    mov    esi, [esp+8Ch+arg_0]
    mov    [esi+4], eax
    jz    short loc_8643B4AE

    push   edi
    push   0
    push   eax
    call   memset
    add    esp, 0Ch
    and    word ptr [esi], 0
    mov    [esi+2], bx
    mov    al, 1
    jmp    short loc_8643B4B0

sub_8643B46D endp
```
ROOTKITS: RING 0

```
k> !poolfind Driv

Scanning large pool allocation table for tag 0x76697244 (Driv) (86711000 : 86911000)

85fce408 : tag Driv (Protected), size       0xf0, Nonpaged pool
85fd2158 : tag Driv, size                 0x1b0, Nonpaged pool
85fd2470 : tag Driv (Protected), size       0xf0, Nonpaged pool
85fd0e50 : tag Driv, size                 0x1b0, Nonpaged pool
85fa8698 : tag Driv (Protected), size       0xf0, Nonpaged pool
85fd5140 : tag Driv, size                 0x10, Nonpaged pool
85fd5e50 : tag Driv, size                 0x1b0, Nonpaged pool
8655e658 : tag Driv (Protected), size       0xf0, Nonpaged pool
85f9b98 : tag Driv (Protected), size       0xf0, Nonpaged pool
85f911c8 : tag Driv (Protected), size       0xf0, Nonpaged pool
85f931c8 : tag Driv (Protected), size       0xf0, Nonpaged pool
85fb9248 : tag Driv, size                 0x1b0, Nonpaged pool
85fbd00 : tag Driv (Protected), size       0xf0, Nonpaged pool
85fc9800 : tag Driv (Protected), size       0xf0, Nonpaged pool
853e0540 : tag Driv (Protected), size       0xf0, Nonpaged pool
```
0: kd> dt nt!_KTHREAD

- **APC (user and kernel mode)** are executed in the thread context, where normal APC executes at **PASSIVE_LEVEL** (thread is on alertable state) and special ones at **APC_LEVEL** (software interruption below DISPATCH LEVEL, where run Dispatch Procedure Calls).

- **APC Injection** ➔ It allows a program to execute a code in a specific thread by attaching to an **APC queue** (without using the `CreateRemoteThread()` function) and preempting this thread in alertable state to run the malicious code. (QueueUserAPC(), KeInitializeAPC() and KeInsertQueueAPC()).
ADVANCED MALWARES AND ROOTKITS RING -2
ADVANCED MALWARES

- **MBR rootkits**: Petya and TLD4 (both in bootstrap code), Omasco (partition table) and Mebromi (MBR + BIOS, triggering SW System Management Interrupt (SMI) 0x29/0x2F for erasing the SPI flash)
- **VBR rootkits**: Rovnix (IPL) and Gapz (BPB – Bios Parameter Block, which it is specific for the filesystem)
- **UEFI rootkits**: replaces EFI boot loaders and, in some cases, they also install custom firmware executable (EFI DXE)
- Modern malwares alter the BPB (BIOS parameter block), which describes the filesystem volume, in the VBR.
- We should remember that a rough overview of a disk design is: MBR → VBR → IPL → NTFS

Locate the active partition and reads the first sector

Initial Program Loader. It has 15 sectors containing the bootstrap code for parsing the NTFS and locating the OS boot loader.

It contains necessary boot code for loading the OS loader.
ADVANCED MALWARES

Overwritten with an offset of the bootkit on the disk.
Thus, in this case, the malicious code will be executed instead of the IPL.

BIOS_PARAMETER __BLOCK_NTFS

<table>
<thead>
<tr>
<th>Offset</th>
<th>Title</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>JMP instruction</td>
<td>EB 52 90</td>
</tr>
<tr>
<td>3</td>
<td>File system ID</td>
<td>NTFS</td>
</tr>
<tr>
<td>B</td>
<td>Bytes per sector</td>
<td>512</td>
</tr>
<tr>
<td>D</td>
<td>Sectors per cluster</td>
<td>8</td>
</tr>
<tr>
<td>E</td>
<td>Reserved sectors</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>(always zero)</td>
<td>00 00 00</td>
</tr>
<tr>
<td>13</td>
<td>(unused)</td>
<td>00 00</td>
</tr>
<tr>
<td>15</td>
<td>Media descriptor</td>
<td>F8</td>
</tr>
<tr>
<td>16</td>
<td>(unused)</td>
<td>00 00</td>
</tr>
<tr>
<td>18</td>
<td>Sectors per track</td>
<td>63</td>
</tr>
<tr>
<td>1A</td>
<td>Heads</td>
<td>255</td>
</tr>
<tr>
<td>1C</td>
<td>Hidden sectors</td>
<td>206,848</td>
</tr>
</tbody>
</table>
Eventually, analyzing and debugging the MBR/VBR (loaded as binary module) is unavoidable, but it’s not so difficult as it seems. Furthermore, we never know when an advanced malware or a ransomwares (TDL4 and Petya) will attack us. 😊
ADVANCED MALWARES

- MBR modifications (partition table or MBR code) and VBR+IPL modifications (BPB or IPL code) have been used as an effective way to bypass the KCS.

- As injecting code into the Windows kernel has turned out to be a bit more complicated, modern malwares are used to bypassing the KCS (Kernel-Mode Code Signing Policy) by:
  - Disabling it → Booting the system on Testing Mode. Unfortunately, it is not so trivial because the Secure Boot must be disabled previously and, afterwards, it must be rebooted. 😊
  - Changing the kernel memory → MBR and/or VBR could be changed. However, as BIOS reads the MBR and handle over the execution to the code there, so changing memory could be lethal. 😊
  - Even trying to find a flaw in the firmware → it is not trivial and the Secure Boot must be disabled.

ALEXANDRE BORGES - MALWARE AND SECURITY RESEARCHER
Setting TESTING mode is a very poor drive signature “bypassing”. Actually, there are more elegant methods. 😊
ADVANCED MALWARES

BIOS → MBR → VBR → Bootmgr

- BIOS: Mebromi
- MBR: Mebromi, Petya, Omasco, TLD4
- VBR: Rovnix and Gapz
- Bootmgr: Bootmgfw.efi

UEFI support since Windows 7 SP1 x64

BCD → Winload.exe

- BCD: Read its configuration from Boot Configuration Data (BCD)
- Winload.exe: Code Integrity
  - Classifies modules as good, bad and unknown.
  - Additionally, it decides whether load a module or not according to the policy.

BPB + VBR code + strings + 0xAA55

Bootkits could attack it before loading the kernel and ELAM. 😊

Classifies modules as good, bad and unknown. Additionally, it decides whether load a module or not according to the policy.
ADVANCED MALWARES

• Malwares infect the bootmgr, which switches the processor execution from real mode to protected mode, and use the int 13h interrupt to access the disk drive, patch modules and load malicious drivers.

• The winload.exe roles are the following:
  • enables the protect mode.
  • checks the modules’ integrity and loads the Windows kernel.
  • loads the several DLLs (among them, the ci.dll, which is responsible for Code Integrity) and ELAM (Early Launch Anti Malware, which was introduced on Windows 8 as callback methods and tries to prevent any strange code execution in the kernel).
  • loads drivers and few system registry data.
**ADVANCED MALWARES**

- Furthermore, if the integrity checking of the winload.exe is subverted, so a malicious code could be injected into the kernel because we wouldn’t have an integrity control anymore.

- Most advanced rootkits continue storing/reading (opcode 0x42, 0x43 and 0x48) their configuration and payloads from encrypted hidden filesystems (usually, FAT32) and implementing modified symmetric algorithms (AES, RC4, and so on) in these filesystems.
ADVANCED MALWARES

• SMM basics:
  • Interesting place to hide malwares because is protected from OS and hypervisors.
  • The SMM executable code is copied into SMRAM and locked during the initialization.
  • To switch to SMM, it is necessary to trigger a SMI (System Management Interrupt), save the current content into SMRAM and execute the SMI handler code.
  • A SMI could be generated from a driver (ring 0) by writing a value into APMC I/O / port B2h or using a I/O instruction restart CPU feature.
  • The return (and execution of the prior execution) is done by using RSM instruction.
ADVANCED MALWARES

SPI malwares
(Flash Write Protection)

SMM malwares

UEFI/BIOS malwares

SPI Flash

SMM

UEFI Services

MBR

VBR

LOADER

OS

Bootkit malwares

UEFI: Bootx64.efi and Bootmgfw.efi

Ring 0 malwares like rootkits

(Kernel Code Signing Policies)

ALEXANDRE BORGES - MALWARE AND SECURITY RESEARCHER
SEC \rightarrow PEI \rightarrow DXE \rightarrow BDS \rightarrow TSL \rightarrow RT \rightarrow AL

- **SEC** \rightarrow Security (Caches, TPM and MTRR initialization)
- **PEI** \rightarrow Pre EFI Initialization (SMM/Memory )
- **DXE** \rightarrow Driver Execution Environment (platform + devices initialization, Dispatch Drivers, FV enumeration)
- **BDS** \rightarrow Boot Dev Select (EFI Shell + OS Boot Loader)
- **TSL** \rightarrow Transient System Load
- **RT** \rightarrow Run Time

IBB – Initial Boot Block

After Life
ADVANCED MALWARES

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

OS Secure Boot
Acts on drivers that are executed before Windows being loaded and initialized.

IBB
malwares and exploits attack here 😊
ADVANCED MALWARES

- Remember: the SPI Flash is composed by many regions such as Flash Descriptors, BIOS, ME (Management Engine), GbE and ACPI EC. Access Control table defines who can have READ/WRITE access to other regions.

Descriptors | GbE | ME | ACPI | BIOS

ROM + FW (Manifest+ Modules)

ME: has full access to the DRAM, invisible at same time, is always working (even then the system is shutdown) and has access to network interface. Conclusion: a nightmare. 😊
ADVANCED MALWARES

- Intel Boot Guard (controlled by ME), introduced by Intel, is used to validate the boot process through flashing a public key associated to BIOS signature into FPFs (Field Programmable Fuses) from Intel ME.

- Obviously, few vendors have been leaving closemnt fuse unset, so it could be lethal 😊

- Of course, for a perfect Boot Guard working, the SPI region must be locked and the Boot Guard configuration must be set against a SMM driver rootkit 😊
ADVANCED MALWARES

- Public key’s hash, used for verifying the signature of the code with the ACM, is hard-coded within the CPU.
- It almost impossible to modify the BIOS without knowing the private key.
- At end, it works as a certificate chain. 😊
Another protection feature named BIOS Guard is also running in the SMM, which protects the platform against not-authorized:

- **SPI Flash Access** (through BIOS Guard Authenticated Code Module) prevents an attacker to escalate privileges to SMM by writing a new image to SPI.
- **BIOS update** attacker (through a DXE driver) could update the BIOS to a flawed BIOS version.
- **Boot infection/corruption.**

**BIOS Guard** allows that only trusted modules (by ACM) be able to modify the SPI flash memory and protect us against rookit implants.
ADVANCED MALWARES

• Secure Boot:

  • Protects the entire path shown previously against bootkit infection.

  • Protects key components during kernel loading, key drivers and important system files, requesting a valid digital signature.

  • Prevents loading of any code that are not associated a valid digital signature.

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ADVANCED MALWARES

- Two essential items on Secure Boot are:
  - Platform Key (PK – must be valid), which establishes a trust relationship between the platform owner and the platform firmware, verifies the Key Exchange Key (KEK).
  - KEK, which establishes a trust relationship between the OS and the platform firmware, verifies:
    - Authorized Database (db) → contains authorized signing certificates and digital signatures
    - Forbidden Database (dbx) → contains forbidden certificates and digital signatures.
• Obviously, if the Platform Key is corrupted, everything is not valid anymore because the SecureBoot turns out disabled when this fact happens.

• Unfortunately, few vendors continue storing important Secure Boot settings in UEFI variables. However, if these UEFI variables are exploited through ring 0/-2 malware or bootkit, so the SecureBoot can be disabled.
ADVANCED MALWARES

- Without ensuring the UEFI image integrity, a rookit could load another UEFI image without being noticed. 😊

- **UEFI BIOS** supports TE (Terse Executable) format (signature 0x5A56 - VZ).

- As **TE format doesn’t support signatures**, BIOS shouldn’t load this kind of image because Signature checking would be skipped.

- Therefore, a **rootkit** could try to replace the typical PE/COFF loader by a TE EFI executable, so skipping the signature checking and disabling the Secure Boot.
Fortunately, new releases of Windows 10 (version 1607 and later) has introduced an interesting SMM protection known as Windows SMM Security Mitigation Table (WSMT).

In Windows 10, the firmware executing SMM must be “authorized and trusted” by VBS (Virtualized Based Security).
These SMM Protections flags that can be used to enable or disable any WSMT feature.

- **FIXED_COMM_BUFFERS**: it guarantees that any input/output buffers be filled by value within the expected memory regions.

- **SYSTEM_Resource_PROTECTION**: it works as an indication that the system won’t allow out-of-band reconfiguration of system resources.

- **COMM_BUFFER_NESTED_PTR_PROTECTION**: it is a validation method that try to ensure that any pointer with the fixed communication buffer only refer to address ranges that are within a pre-defined memory region.
ADVANCED MALWARES

- chipsec_util.py spi dump spi.bin
- chipsec_uti.py decode spi.bin

<table>
<thead>
<tr>
<th>Region</th>
<th>CPU</th>
<th>ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Flash Descriptor</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>1 BIOS</td>
<td>RW</td>
<td></td>
</tr>
<tr>
<td>2 Intel ME</td>
<td>RW</td>
<td>RW</td>
</tr>
<tr>
<td>3 GBe</td>
<td>RW</td>
<td>RW</td>
</tr>
</tbody>
</table>

Is the customer Safe? 😊
ADVANCED MALWARES

BIOS Write Enable should be clear (BIOSWE=0) and BIOS Lock Enable should be set (BLE=1)! In this case, it is exactly the opposite!

SMM-based write-protection is disabled! Please, set SMM_BWP to 1 and lock the SMI configuration by setting GBL_SMI_LCK and TCO_LCK to 1!

None of Protect Range registers are protecting the flash against writes!

The HSFS.FLOCKDN bit should also be set!

chipsec_main --module common.bios_wp
ADVANCED MALWARES

```
[*] running module: chipsec.modules.common.bios_kbrd_buffer

[*] running module: chipsec.modules.common.bios_smi

[!] Module: SMI Events Configuration

[-] SMM BIOS region write protection has not been enabled (SMM_BWP is not used)

[*] Checking SMI enables..
  Global SMI enable: 1
  TCO SMI enable : 1

[+] All required SMI events are enabled

[*] Checking SMI configuration locks..

[-] TCO SMI event configuration is not locked. TCO SMI events can be disabled

[+] SMI events global configuration is locked (SMI Lock)

[-] FAILED: Not all required SMI sources are enabled and locked
```

chipsec_main.py -m common.bios_smi
ADVANCED MALWARES

- The BIOS_CNTL register contains:
  
  - **BIOS Write Enable (BWE)** ⇒ if it is set to 1, an attacker could write to SPI flash.
  - **BIOS Lock Enable (BLE)** ⇒ if it is set to 1, it generates an SMI routine to run just in case the BWE goes from 0 to 1.

- Of course, there should be a SMM handler in order to prevent setting the BWE to 1.
- What could happen if SMI events were blocked? 😬
- The **SMM BIOS write protection (SMM_BWP)**, which protects the entire BIOS area, is not enabled. 😞
ADVANCED MALWARES

chipsec_main.py -m common.spi_lock
• SPI Protect Range registers protect the flash chip against writes.
• They control Protected Range Base and Protected Range Limit fields, which set regions for Write Protect Enable bit and Read Protect Enable bit.
• If the Write Protect Enable bit is set, so regions from flash chip that are defined by Protected Range Base and Protected Range Limit fields are protected.
• However, SPI Protect Range registers DO NOT protect the entire BIOS and NVRAM.
• In a similar way to BLE, the HSFSS.FLOCKDN bit (from HSFSTS SPI MMIO Register) prevents any change to Write Protect Enable bit. Therefore, malware can’t disable the SPI protected ranges for enabling access to the 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)
```
ADVANCED MALWARES

- **Top Swap Mode**, which is enabled by BUC.TS in Root Complex range, is a feature that allows fault-tolerant update of the BIOS boot-block.

- Therefore, when Top Swap Configuration and swap boot-block range in SPI are not protected or even locked, any malware could force an execution redirect of the reset vector to backup bootblock because CPU will fetch the reset vector at 0xFFFFEFFFF0 instead of 0xFFFFF0 address.

- **SMRR (System Management Range Registers)** blocks the access to SMRAM (range of DRAM that is reserved by BIOS SMI handlers) while CPU is not in SMM mode, preventing it to execute any SMI exploit on cache.
ADVANCED MALWARES

```python
running module: chipsec.modules.common.smrr

Module: CPU SMM Cache Poisoning / System Management Range Registers

OK. SMRR range protection is supported

Checking SMRR range base programming.
[00] Type = 4 << SMRR memory type
[12] PhysBase = CF800 << SMRR physical base address

OK so far. SMRR range base is programmed

Checking SMRR range mask programming.
[12] PhysMask = FF800 << SMRR address range mask

OK so far. SMRR range is enabled

Verifying that SMRR range base & mask are the same on all logical CPUs.

CPU0: SMRR_PHYSBASE = 00000000CF800004, SMRR_PHYSMASK = 00000000FF800800
CPU1: SMRR_PHYSBASE = 00000000CF800004, SMRR_PHYSMASK = 00000000FF800800
CPU2: SMRR_PHYSBASE = 00000000CF800004, SMRR_PHYSMASK = 00000000FF800800
CPU3: SMRR_PHYSBASE = 00000000CF800004, SMRR_PHYSMASK = 00000000FF800800
CPU4: SMRR_PHYSBASE = 00000000CF800004, SMRR_PHYSMASK = 00000000FF800800
CPU5: SMRR_PHYSBASE = 00000000CF800004, SMRR_PHYSMASK = 00000000FF800800
CPU6: SMRR_PHYSBASE = 00000000CF800004, SMRR_PHYSMASK = 00000000FF800800
CPU7: SMRR_PHYSBASE = 00000000CF800004, SMRR_PHYSMASK = 00000000FF800800

OK so far. SMRR range base/mask match on all logical CPUs

Trying to read memory at SMRR base 0xCF800000.
PASSED: SMRR reads are blocked in non-SMM mode

PASSED: SMRR protection against cache attack is properly configured
```
CONCLUSION

- Most security professionals have been facing problems to understand how to analyze malicious drivers because the theory is huge and not easy.

- Real customers are not aware about ring -2 threats and they don’t know how to update systems’ firmwares.

- All protections against implants are based on integrity (digital certificate and signature). However, what would it happen whether algorithms were broken (QC - quantum computation)?
THANK YOU FOR ATTENDING MY TALK!

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