A Practical Analysis of UEFI Threats Against Windows 11

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December 25, 2022
Version: Draft 1.0

Technische Universität Berlin

Electrical Engineering and Computer Science
Institute of Software Engineering and Theoretical Computer Science
Security in Telecommunications (SecT)

Bachelor's Thesis

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Selbständigkeitserklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig und eigenhändig sowie ohne unerlaubte fremde Hilfe und ausschließlich unter Verwendung der aufgeführten Quellen und Hilfsmittel angefertigt habe.

Berlin, den 25. Dezember 2022

Joshua Machauer

Abstract

Firmware attacks are one of the most feared threats in Computer Security. Executing during the boot process, they can already have full control over the system before an operating system and any accompanying antivirus programs are even loaded. With the widespread adaption of standardized Unified Extensible Firmware Interface (UEFI) firmware, these threats have become less machine-dependent, and able to target multiple different systems at once. Their appearances in the wild are still rare as they are stealthy by nature. Through analyses of past threats, we can categorize their attack vectors against Windows and perform our practical analysis. With a deep-dive into the UEFI environment, we learn hands-on about encountered security mechanisms targeting pre-boot attacks, setting our focus on Secure Boot and Trusted Platform Module (TPM)-assisted BitLocker. We were able to achieve system-level privileged execution on Windows 11 by exploiting unrestricted hard drive access to deploy our payload and modify the Windows Registry. With BitLocker enabled, our *BitLogger* was able to decrypt and mount the drive using a keylogged Recovery Key. When BitLocker is misconfigured or our code is part of the trusted measurements, we could sniff the TPM communication to retrieve the VMK. Our thesis shows, that UEFI threats are very powerful, to a point where they discredit all system integrity, making it impossible to put any further trust into the system.

Zusammenfassung

Firmware Attacken sind eine der gefürchtesten Sicherheitsrisiken in der Computersicherheit. Sie werden während des Bootvorgangs ausgeführt und können Kontrolle über das gesamte System erlangen, bevor das Betriebssystem und seine begleitenden Antivirusprogramme geladen worden sind. Mit der zunehmenden Verbreitung von standardisierter Unified Extensible Firmware Interface (UEFI) Firmware sind diese Bedrohungen weniger geräteabhänig geworden und können nun eine Vielzahl von Systemen gleichzeitig adressieren. Das Vorkommnis solcher Attacken ist weiterhin recht selten, da sie von Natur aus schwierig aufzufinden sind. Durch Analysen bisheriger Funde können wir ihre Angriffsvektoren kategorisieren und unsere praktische Analyse durchführen. Wir tauchen in die UEFI-Welt ein, um durch die Implementierung eigener Attacken die Sicherheitsmechanismen des Bootvorgangs besser zu verstehen. Dabei setzen wir unseren Fokus auf Secure Boot und BitLocker unter Verwendung des Trusted Platform Module (TPM). Als Resultat unserer Attacken erreichten wir Codeausführung mit erhöhten Privilegien unter Windows 11. Mittels unbeschränkten Zugriffs auf die Festplatte konnten wir weitere Benutzerebnenprogramme installieren und die Windows Registry modifizieren. Wenn BitLocker aktiv ist, ermöglichte unser *BitLogger* das Entschlüsseln der Festplatten durch einen mitgeloggten Recovery Key. Bei einer Fehlkonfiguration BitLockers oder, wenn unser Schadcode Teil der vertrauten Messungen ist, können wir die TPM-Kommunikation mitlesen, um an den Volume Master Key (VMK) zu gelangen. Unsere Arbeit zeigt, dass UEFI-Bedrohungen sehr mächtig sind und durch sie jegliche Systemintegrität so diskreditiert wird, dass es unmöglich ist dem System weiter zu vertrauen.

Acknowledgement

Contents

1 Introduction

Regardless of the Operating System (OS) installed on a computer, the Platform Firmware (PF) is the very first piece of code that is executed when powering on the system. It performs basic initialization of all platform components and manages the system's resources until the OS takes over. The PF allows for basic system and boot configuration and serves as a means to create a uniform environment for boot applications. After discovering and selecting the appropriate boot device it hands over execution to the bootloader and with that subsequently the control over the entire system.

This process has been previously performed by the Basic Input/Output System (BIOS) and while the term supersedes the underlying implementation, modern systems are mostly UEFI-based, with even backward-compatibility being phased out by Original Equipment Manufacturers (OEMs). Legacy BIOS is dead and UEFI is here to stay.

UEFI, as the successor, addresses the previous BIOS limitations, modernizing the boot process in a standardized fashion, and allowing to fully abstract the underlying hardware while providing mechanisms for extensibility during runtime and in the long-term. UEFI provides a family of specifications with the UEFI specification itself defining the environment and interfaces for boot applications to communicate with the firmware. The UEFI PI specification defines a model for system designers to follow when implementing the PF. Its design focuses on simplifying the collaboration process between different hardware vendors, whose components come together in a system. Dynamic module discovery, dispatch, and inter-module communication allow for the independent development of early boot components. A well-defined storage solution brings it all together in a single firmware image.

The extensibility and abstractions can become a double-edged sword; when threat actors are introduced to the system, as the same concepts apply to software with malicious intent. They can gain control over the system before the OS and its bootloader are executed. The early execution environment can be abused to achieve persistence across reboots and, with access to the firmware image, even across OS installations. They often deploy additional malware further up into the OS environment. Leveraging their privileges, they remain hidden from the OS and its antivirus software. Through abstractions of the underlying hardware, UEFI-based attacks can become platform-independent and target a host of platforms at once.

UEFI threats fall under the category of rootkits. Rootkits are traditionally a collection of software designed to grant a threat actor control over a system. There are different types of rootkits depending on their entry vector and where they reside. They range from User Mode, Kernel Mode over Hypervisors to bootloaders and firmware [1–3]. UEFI threats are of two categories, bootloader rootkits (Bootkits) or firmware rootkits. While bootkits rely on intervening in the process of the PF handing over execution to boot applications, firmware rootkits reside within the firmware image and are executed as part of the PI. Within this thesis we will reserve the standalone term *rootkit* for UEFI firmware rootkits and mostly refer to bootloader rootkits with the term *bootkit*.

Discoveries of UEFI threats are still rather rare occurrences, which may depend more on the fact that they are hard to detect than the amount of them existing. Despite this, recent years have led to more and more being found and analyzed by security researchers. Examples of bootkits are FinSpy, ESPecter, Dreamboot and exemplary rootkits are Mosaicregressor, LoJax, Moonbounce, and CosmicStrand. Given the small sample size, the infection method is often unknown and general information is typically very limited. The attack approaches can be categorized into memory-and storage-based approaches. Memory-based attacks modify boot applications when they are loaded in memory. This allows them to propagate malicious code execution into the OS kernel. Storage-based attacks do not rely on the OS boot process and instead modify the OS's hard drive contents *at rest*.

By performing our own UEFI attacks we look at some infection methods for root- and bootkits, mainly involving physical access. We want to analyze Windows security mechanisms and standard security policies, whether they protect the system and, if so, how. We furthermore focus on storage-based attacks comparable to LoJax and Mosaicregressor, as Windows offers BDE with TPM 2.0 protection to prevent unauthorized access to the hard drive. TPM measurements provide a mechanism to verify system integrity and should be able to pick up malicious code execution such as rootkits and deny hard drive access and stop the system from booting.

Structure

We start off in Chapter 2 by introducing all necessary knowledge about the UEFI environment, defined through the family of UEFI specifications, listing the interface and its implementation. We briefly go over relevant security concepts of the TPM and its interaction with the PF in Chapter 3. This allows us to go over Windows 11's interaction with the UEFI environment as well as relevant security mechanisms in Chapter 4. With this knowledge we then look at analyzes of previously discovered UEFI threats in Chapter 5, categorizing them by their attack vector and threat model. In Chapter 6 we discuss the test setups, we performed our attacks on, consisting of emulation and hardware. We then lay out our practical approach of implementing our own UEFI attacks in Chapter 7, analyzing security mechanisms faced when attempting attacks from the UEFI environment. Chapter 8 describes the results reflected through our attacks. Afterward, we discuss the impact of our findings, the restrictions that apply, as well as potential mitigation techniques in Chapter 9. Chapter 10 concludes the thesis by summarizing the achievements of our attacks and laying out topics of further interest.

2 UEFI/PI

"The UEFI specifications define a new model for the interface between personal-computer OS and PF. [...] Together, these provide a standard environment for booting an OS and running pre-boot applications" [4].

The specifications making up this model are:

- ACPI Specification
- UEFI Specification
- UEFI Shell Specification
- UEFI PI Specification
- UEFI PI Distribution Packaging Specification
- TCG EFI Platform Specification
- TCG EFI Protocol Specification

The Advanced Configuration and Power Interface (ACPI) and the UEFI PI Distribution Packaging Specification are not required to be able to follow this thesis. As for the other specifications, we briefly summarize the relevant content.

2.1 Unified Extensible Firmware Interface (UEFI)

The UEFI specification is a pure interface specification, describing a programmatic interface for boot applications to interact with the PF. It states what interfaces, structures, and abstractions a PF has to offer and implement and what boot applications such as OS loaders may use [5].

It was designed to replace the legacy Boot Firmware BIOS, while also providing backward-compatibility with a Compatibility Support Module (CSM) allowing UEFI firmware to boot legacy BIOS applications [5]. It is aimed to be a complete solution, abstracting all platform features and capabilities in a way that bootloaders require no knowledge about the underlying hardware [6, p. 1.3].

The UEFI interfaces are defined in the `C` programming language. During the boot process, system resources are owned and managed by the UEFI firmware until the OS explicitly assumes control over the system. On the `x64` Central Processing Unit (CPU) architecture the PF hands over the execution in `64-bit` long mode which includes memory protection. Paging is also enabled, and the virtual memory is identity mapped, meaning virtual addresses equal physical addresses, with most regions being marked as read, write, and execute. The CPU is operating in uniprocessor mode and a sufficient amount of stack is available [6, Section 2.3.4].

Since UEFI mainly exists to offer a well-defined boot environment for OS loaders, its services are not required anymore upon OS takeover. A large part of UEFI can thus be unloaded, leaving only a portion of the initially offered services. The remaining runtime services can be used by the OS to configure or update the PF.

2.1.1 Globally Unique Identifier (GUID)

The UEFI environment depends on GUIDs, also known as Universally Unique Identifiers (UUIDs), to uniquely identify a variety of things, such as protocols, files, and hard drive partitions. GUIDs are 128-bit long, statistically unique identifiers that can be generated on demand and without a centralized authority, statistically guaranteeing that there will be no duplicates on a system that combines hard- and software from multiple vendors [7].

2.1.2 GUID Partition Table (GPT)

Partitions allow a disk to be distinctly separated into logical disks, allowing for each to be formatted with a different file system. Prior to UEFI disks have been partitioned using the Master Boot Record (MBR) partition table, supporting up to four different partitions. The MBR is stored within the first sector, also optionally containing 424 bytes of bootable code through which the BIOS boots [6, Section 13.3.1]. UEFI is still backwards compatible with MBR partitioned disks and contained on each disk, but UEFI does not execute the boot code. The MBR is used in two different ways by the UEFI environment, either as a legacy MBR or a protective MBR. With the legacy MBR, UEFI uses the partitions defined in the MBR partition table, whereas the protective MBR only has one partition spanning the entire disk. The protective partition is for legacy devices and, in practice, GPT partitioning is used to separate the disk. For this, UEFI defines two OS types used in MBR partition entries. One identifies the ESP, the partition UEFI boots from, within the legacy MBR partition table and the other indicates that a protective partition is used [6, Section 5]. [6, Section 5] defines the GPT disk layout. With the GPT format, Logical Block Address (LBA) are 64-bit instead of 32-bit, enabling support for drives with up to 9400000000 Terra Byte (TB) of storage, whereas MBR is limited to 2 TB. This is accompanied by allowing more than four partitions, with Windows supporting up to 128 [8]. GUIDs are used to identify partitions and partition types, but also offer a human-readable partition name. GPT also has a primary and a backup partition table for redundancy purposes. The primary table follows the MBR sector and the backup is at the end of the disk.

2.1.3 EFI System Partition (ESP)

The ESP can reside on any media that is supported by the UEFI firmware. It has to be formatted in File Allocation Table (FAT)32 [6, Section 13.3] and must contain an EFI root directory [6, Section 13.3.1.3]. All UEFI applications that are to be launched directly by the UEFI firmware have to be located in sub-directories below the EFI directory [6, Section 13.3.1.3]. Drivers and indirectly loaded applications have no storage restrictions. Vendors are to use vendor-specifically named sub-directories within the EFI directory. Fixed disks have no restrictions on the amount of ESPs present, whereas removable media is only allowed to have one ESP, so that boot behavior is deterministic. In general, the ESP is identified by a specific GUID, but implementations are allowed to support accordingly structured FAT partitions. Since there is no limitation on the amount of ESPs, boot applications can share the drive with their OS, or can be accumulated in a single system-wide ESP [6, Section 13.3.3].

2.1.4 UEFI Images

UEFI images are files containing executable code. They use a subset of the Portable Executable 32-Bit (PE32)+ file format with a modified header signature. The format comes with relocation tables, making it possible for the images to be executed in place or to be loaded at non-pre-determined memory addresses. They support multiple CPU architectures such as IA, ARM, RISC-V, and x86. There are three different subtypes of executables: applications, boot, and runtime drivers. They mainly differ in their memory type and how it behaves. Loading and transferring execution are two separate steps; so that security policies can be applied before executing a loaded image [6, Section 2.1.1].

Applications are always unloaded when they return from execution, while drivers are only unloaded when they return an error code. This allows drivers to install their offered functionality upon initial execution and function calls can jump back into the driver image where the function body remains loaded. Boot drivers are unloaded when an OS loader application transitions to runtime by taking over the memory management through the call of the boot service function `ExitBootServices()`, while runtime drivers remain loaded and are translated into the virtual memory mapping. OS loaders only return execution in error cases.

2.1.5 Protocols and Handles

Protocols are created and discovered dynamically and provide a mechanism to enable an extension of firmware capabilities over time [9, Section 3.6]. They are C structures and may contain services, in the form of function pointers, or other data structures. They are identified by GUIDs and stored in a single global database implemented by the firmware [5]. This database is called the handle database, a handle describes a logical grouping of one or more protocols [9, Section 3.6]. Handles are unique per session and should not be saved across reboots [5]. Multiple instances of a protocol identified by the same GUID can exist on different handles, offering the same service on different devices.

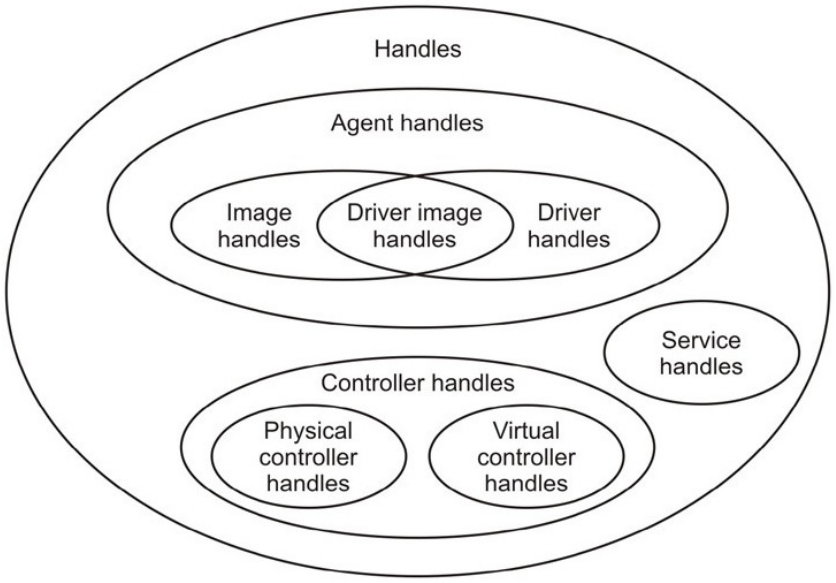


Fig. 2.1.: Handle types (taken from [9, Figure 3])

[9] explains the categories of handles that are formed by the type of protocols that are grouped. Figure 2.1 shows these categories.

Image handles are handles of UEFI images loaded into memory, as they support the Loaded Image Protocol, giving access to information about the image in memory. This includes the image's address, size, memory type, origin, and optional load options.

Driver handles group the UEFI Driver Model protocols (Driver Binding Protocol, the two Component Name Protocols, and the two Driver Diagnostics Protocols).

Driver image handles are the UEFI Driver Model protocols installed onto images loaded in memory.

Agent handles is a term used in the UEFI Driver Model, they describe tracked consumers of other protocols.

Controller/Device handles are interchangeably used to refer to physical and virtual devices that offer Input/Output (I/O) abstraction protocols. Physical device handles support the Device Path Protocol for generic path/location information [6, Section 10.2].

Service handles are used for generic hardware-unrelated abstractions.

2.1.6 UEFI Driver Model

[6, Section 2.5] describes the UEFI Driver Model. It is designed to simplify the implementation process of device drivers by moving common device management and discovery functionality into the firmware. This leaves drivers with the responsibility to offer only interfaces for installation and removal.

An UEFI platform is assumed to consist of one or more CPUs to be connected to one or more core chipsets. The core chipsets produce host bus controllers which offer initial I/O abstractions like the Peripheral Component Interconnect (PCI) Root Bridge I/O Protocol. Bus drivers can be connected to these host bus controllers to discover and create child controllers, these can either be further buses or devices. This forms a tree of buses with devices as leaves. Devices can be keyboards, mice, monitors, etc. (for user in-and output) or hard drives, network adapters, etc. (boot devices) [6, Section 2.5].

Device drivers are very similar to bus drivers, but they do not create new device handles, they instead offer abstractions built upon existing bus driver I/O abstractions. A driver following the UEFI Driver Model is not allowed to interact with any hardware in its entry point and instead installs protocols on its own image handle. It is required to install the Driver Binding Protocol, and it may additionally install configuration or diagnostic-related protocols. The Loaded Image

Protocol also offers a field where a driver can provide a function through which it can be unloaded. Runtime drivers usually register a notification function that is triggered when an OS loader calls `ExitBootServices()`, allowing them to translate any allocated memory to their virtual addresses [6, Section 2.5.2].

The firmware will try to connect device drivers to a controller by using the driver's instance of the Driver Binding Protocol and call the `Supported()` function on a controller handle. The device driver then checks whether it supports the controller. This could be, for example, looking for specific I/O protocols, that it will want to use later and abstract further. If the driver supports the device, the firmware will call the `Start()` function of the Driver Binding Protocol to have the driver install its offered protocols on the controller handle. The firmware connection process can be done recursively as the newly installed device driver might now fulfill the requirements for another driver. If a driver needs to be uninstalled from a specific controller, the firmware can call the `Stop()` method of the Driver Binding Protocol function on the controller handle. An example of this would be another device driver wanting to exclusively manage a controller. To support this functionality, all consumers of a protocol are tracked in the form of agent handles [6, Section 2.5.4].

The part of the firmware that will connect the device drivers is typically the UEFI boot manager. This allows for fast startup, where it may choose to connect only drivers related to a certain boot device [6, Section 2.5.6].

2.1.7 Systemtable

```
typedef
EFI_STATUS
(EFIAPI *EFI_IMAGE_ENTRY_POINT)(IN EFI_HANDLE ImageHandle,
                                IN EFI_SYSTEM_TABLE *SystemTable);
```

Listing 2.1: UEFI Image Entry Point

Listing 2.1 shows the entry point of UEFI images, when they are loaded it is the only part that is *linked*, the rest of the communication has to be discovered programmatically through the UEFI System Table. It serves as the entrance door into the UEFI environment, providing access to the generic boot and runtime services, as well as system configuration information [9, Section 3.3]. The Loaded Image Protocol instance provides an interface to hand over optional load options to an image [5].

Figure 2.2 shows the system table. The functionality of the system table is only available in its entirety during boot as the boot services and structures are eventually unloaded; when the OS takes over control.

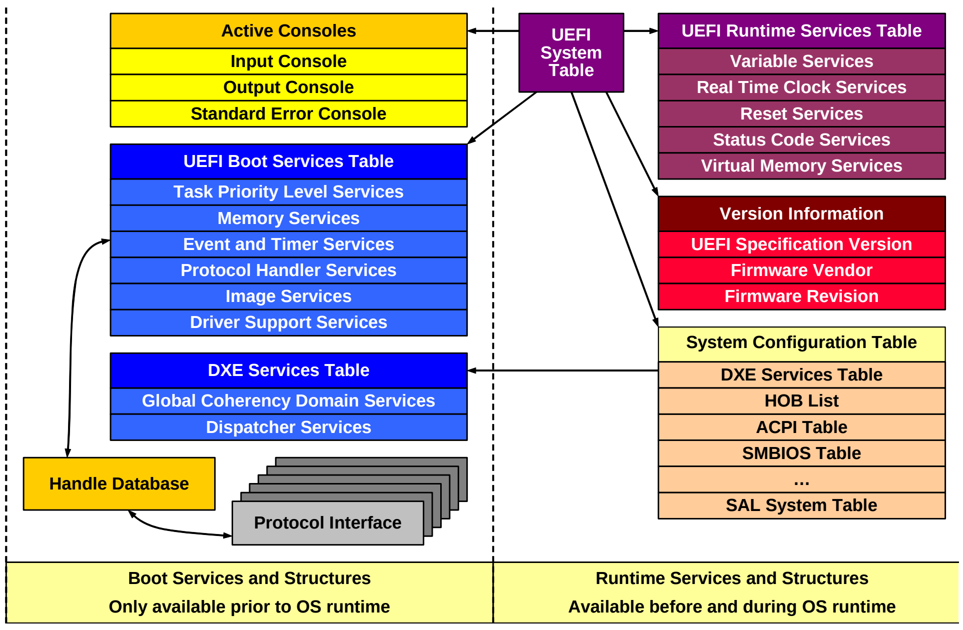


Fig. 2.2.: UEFI System Table (taken from [10, Vol 2, Figure 2-5])

2.1.7.1. Boot Services

UEFI applications must use boot service functions to access devices and allocate memory. They are available until an OS loader takes over control with `ExitBootServices()`. [6, Section 7] splits the boot services into five categories:

Event, Timer, and Task Priority Services used to create, close, signal, wait for, and check events. Setting timers and raising or restoring task priority levels.

Memory Allocation Services to allocate and free pools or whole pages of memory, as well as retrieve the UEFI managed memory map.

Protocol Handler Services used to install, uninstall, and retrieve protocol instances, as well as abstractions related to the UEFI Driver Model.

Image Services to load, unload, and start images. Images can also use these to transfer execution back to the firmware or with `ExitBootServices()` assume control over the system

Miscellaneous Services offer basic memory manipulation, checksum calculation, watchdog timers, and monotonic counters.

2.1.7.2. Runtime Services

The runtime services only offer minimal functionality for the OS to communicate with the PF during runtime.

Variable Services used to query, get, and set variables.

Time Services used to get and set time as well as a system wake-up timer.

Virtual Memory Services relate to enabling virtual memory and translating memory addresses.

Miscellaneous Runtime Services offer a way to reset the system, a monotonic counter, and capsule services. Capsules allow the OS to pass data to the firmware, like firmware and driver updates.

2.1.8 Variables

UEFI variables are key/value pairs used to store arbitrary data passed between the UEFI firmware and UEFI applications. The data type has to be known beforehand and as such is specified for variables defined in UEFI. The storage implementation is not specified by UEFI, but it must support non-volatility, to retain after reboots, or temper resistance if demanded. Variables are defined by a vendor GUID, a name, and attributes. Attributes include their scope (boot, runtime, non-volatile), whether writes require authentication or result in appending data instead of overwriting [6, Section 8.2]. Architecturally defined UEFI variables are called Globally Defined Variables where the vendor GUID has the value `EFI_GLOBAL_VARIABLE` [6, Section 3.3].

2.1.9 Boot Manager

The UEFI boot manager is a firmware component executed after the platform is completely initialized. It decides which UEFI drivers or applications are loaded and when. The boot behavior is configured through architecturally defined Non-volatile RAM (NVRAM) global variables [6, Section 3.1]. Each load option entry for a driver or application resides in a variable following the naming scheme of `Driver####` or `Boot####` respectively, where `#` stands for a hexadecimal digit forming a four-digit number, requiring leading zeros. If a firmware implementation allows for the creation of new load options they can then be added to the ordered lists `DriverOrder` and `BootOrder`. These reference the load options and dictate the order in which they are processed. Driver load options are processed before the boot load options, there also exists the `BootNext` variable to override the boot options once. A general depiction of the UEFI boot flow is depicted in Figure 2.3. Implementations usually allow for an interactive menu, where users can modify the boot order or boot single entries manually [6, Section 3.1.1]. Boot options are generally first attempted to be loaded through the `LoadImage()` boot service. If the device path of a boot option only points to a device instead to the file on a device, it attempts to load a default boot application with the Simple File System Protocol [6, Section 3.1.2]. For x64 it uses the default path `\EFI\BOOT\BOOTX64.EFI` [6, Section 3.5].

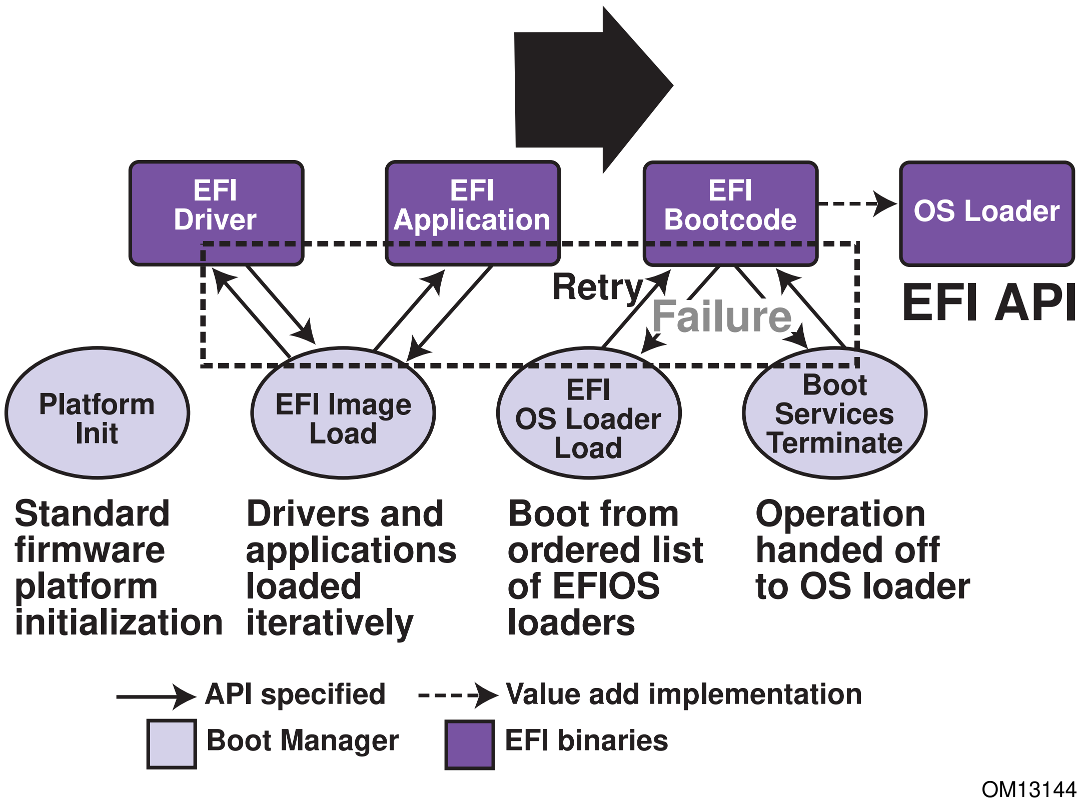


Fig. 2.3.: UEFI Boot Sequence (taken from [6, Figure 2-1])

2.1.10 Security

UEFI offers security mechanisms restricting what is allowed to modify and be modified on a system. This involves authentication of ownership over the platform.

2.1.10.1. Secure Boot

Secure Boot provides a secure hand-off from the firmware to 3rd party applications used during the boot process, located on insecure media [11] [6, Sections 32.2 and 32.5.1]. It assumes the firmware to be a trusted entity and all 3rd party software to be untrusted, this includes images from hardware vendors in the PCI option Read-Only Memorys (ROMs), bootloader from OS vendors, and tools such as the UEFI shell [11]. Digital signatures, embedded within the UEFI images, can be used to authenticate the origin and/or integrity [6, Section 32.2]. This is done through asymmetric signing. Component providers must sign their executables with their private keys and publish the public keys. The public keys are stored in a signature Data Base (DB) and the signed executable can be verified against the database before execution. Multiple signatures can be embedded within the same image [6, Section 32.2.2]. The signatures are created by first calculating a hash over select parts of the executable and then signing it with a private key. The output of this hashing is called a digest and the algorithm for obtaining the digest is defined in [12]. Secure Boot also disallows legacy booting through the CSM.

Secure Boot is managed through three components: a Platform Key (PK), one or more Key Exchange Key (KEK), and the signature DBs.

Platform Key The PK establishes a trust relationship between the platform owner and firmware, the public half is enrolled into the firmware. The private half represents platform ownership, as it can be used to change or delete the PK as well as enroll or modify KEKs.

Key Exchange Key The KEK establishes a trust relationship between OS and firmware, as its private half is used to modify the signature Data Bases (DBs).

Signature Data Bases Signature DBs contain image hashes and certificates, to either allow or deny execution of associated images.

Internally, these are all implemented by authenticated variables, residing in tamper-resistant non-volatile storage [6, Section 32.3]. The PK is a simple variable where the KEK and DB are implemented through signature list data structures [6, Section 32.4.1]. The variable services can be used to append entries or to read and write the list as a whole [6, Sections 32.3.5 and 32.5.3]. The variables are part of the Globally Defined Variables, for each variable, there also exists a variant reserved for default entries. These can be used by an OEM to supply platform-defined values, used for example during Secure Boot initialization by a user. Their contents can be copied to their live versions, to then be used during Secure Boot operation. The current state of Secure Boot is communicated with a secure variable, which the OS can probe [6, Section 3.3].

Users, who are physically present, may disable Secure Boot as well as enroll default or custom keys via an interactive menu [6, Section 3.3].

2.1.10.2. Firmware Management

The Firmware Management Protocol provides a boot abstraction for authenticated updating and management of the PF [6, Section 23]. The runtime services `QueryCapsuleCapabilities()` and `CapsuleUpdate()` may be used by the OS to pass updates to the firmware in a persistent manner, so that they can be processed on subsequent boots [6, Section 23.3]. OEMs also often provide their own ways to process firmware updates, for example via dedicated Universal Serial Bus (USB) ports, which allow processing of firmware updates upon boot. As these are entirely dictated by the platform designer, it is not possible to make vendor-independent assessments about their security.

2.1.10.3. User Identity Policies

UEFI enables a system to have multiple users with varying levels of privileges. This may restrict their ability to enroll other users or to boot from select drives [6, Section 36.1.2]. A trusted environment must be maintained for the integrity of the security identification, by restricting which drivers are loaded and securing the storage of drivers [6, Section 36.1.4].

2.2 UEFI Platform Initialization (PI)

[10] defines an implementation of the PI process and the UEFI environment, as well as a scalable PI firmware storage and interface solution, which together form the basis for the development of UEFI firmware images. As such the following describes the rules of play for UEFI rootkits.

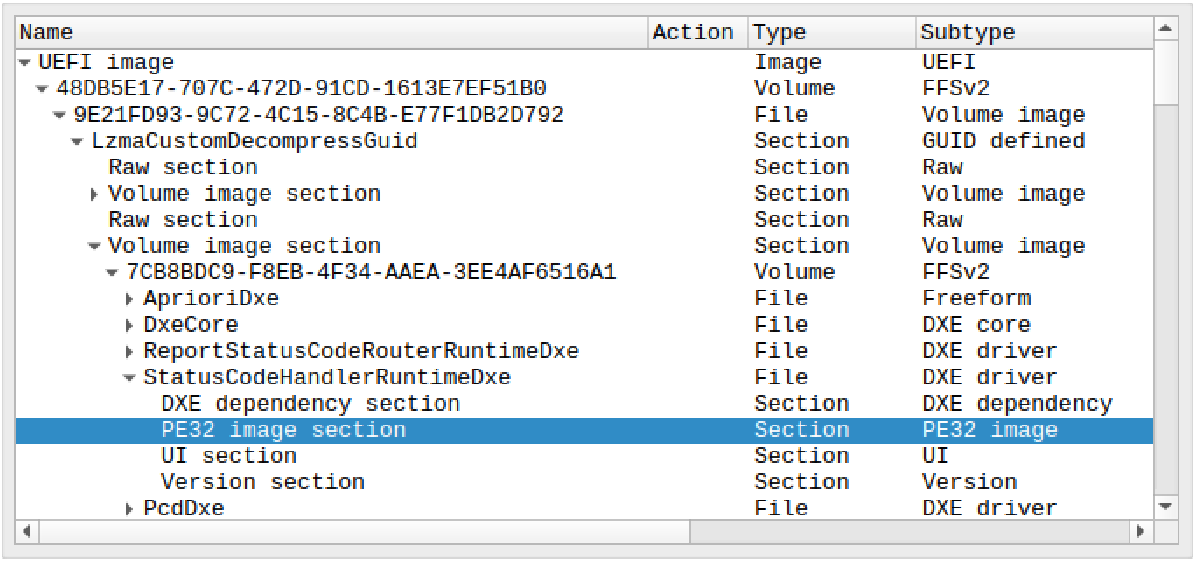
2.2.1 PI Firmware Images

[10, Vol. 3, 2] defines the firmware storage design. A *Firmware Image* is stored in one or more non-volatile physical storage devices called Firmware Devices (FDs), which are most commonly flash devices [10, Vol. 3, 2.1]. Flash memory often offers the ability to restrict read and write properties differently depending on the storage region [10, Vol. 3, 2.1.1]. UEFI variables may reside in a region that remains read- and writable during the whole operation of a system, whereas the code storage may only be writable during the initial PI phases. Firmware images might be split over multiple physical FDs, but may also be in-turn logically split into Firmware Volumes (FVs). FVs are comparable to hard drive volumes as they also are formatted with a file system, usually, the PI Firmware File System (FFS) format defined in [10, Vol. 3, 2.2]. The PI FFS is a flat file system consisting of a single list of files without any directory structure. Parsing the volume is done by iterating over all files one by one. Files contain code or data in the form of sections. Sections split a file into discrete parts with the section type dictating its content. File types impose restrictions on which types of sections a file may or may not contain. The full list of file types defined in the PI specification is listed in the appendix in Table A.1. File sections are organized in trees, with encapsulation as well as leaf sections. Together with the file section type `EFI_SECTION_FIRMWARE_VOLUME_IMAGE` which contains an entire PI FV image, this makes up for the FFS's lack of a directory structure. The full list of section types is given in the appendix in Table A.2.

Figure 2.4 shows a firmware image opened in the UEFITool, an editor for firmware images conforming to the PI specification [13]. The highlighted bar is on the executable section of a DXE driver.

2.2.2 PI Architecture Firmware Phases

[10] defines a multiphase architecture of the Platform Initialization that can be used by system designers to implement Platform Firmware. It is designed to be very extensible and to simplify the process of independent hardware vendors working together when combining their software



```
Name                                              Action  Type       Subtype
▾ UEFI image                                              Image      UEFI
  ▾ 48DB5E17-707C-472D-91CD-1613E7EF51B0                  Volume     FFSv2
    ▾ 9E21FD93-9C72-4C15-8C4B-E77F1DB2D792                File       Volume image
      ▾ LzmaCustomDecompressGuid                          Section    GUID defined
          Raw section                                     Section    Raw
        ▸ Volume image section                            Section    Volume image
          Raw section                                     Section    Raw
        ▾ Volume image section                            Section    Volume image
          ▾ 7CB8BDC9-F8EB-4F34-AAEA-3EE4AF6516A1          Volume     FFSv2
            ▸ AprioriDxe                                  File       Freeform
            ▸ DxeCore                                     File       DXE core
            ▸ ReportStatusCodeRouterRuntimeDxe            File       DXE driver
            ▾ StatusCodeHandlerRuntimeDxe                 File       DXE driver
                DXE dependency section                    Section    DXE dependency
                PE32 image section                        Section    PE32 image
                UI section                                Section    UI
                Version section                           Section    Version
            ▸ PcdDxe                                      File       DXE driver
```

Fig. 2.4.: Open Virtual Machine Firmware (OVMF) opened in the UEFITool

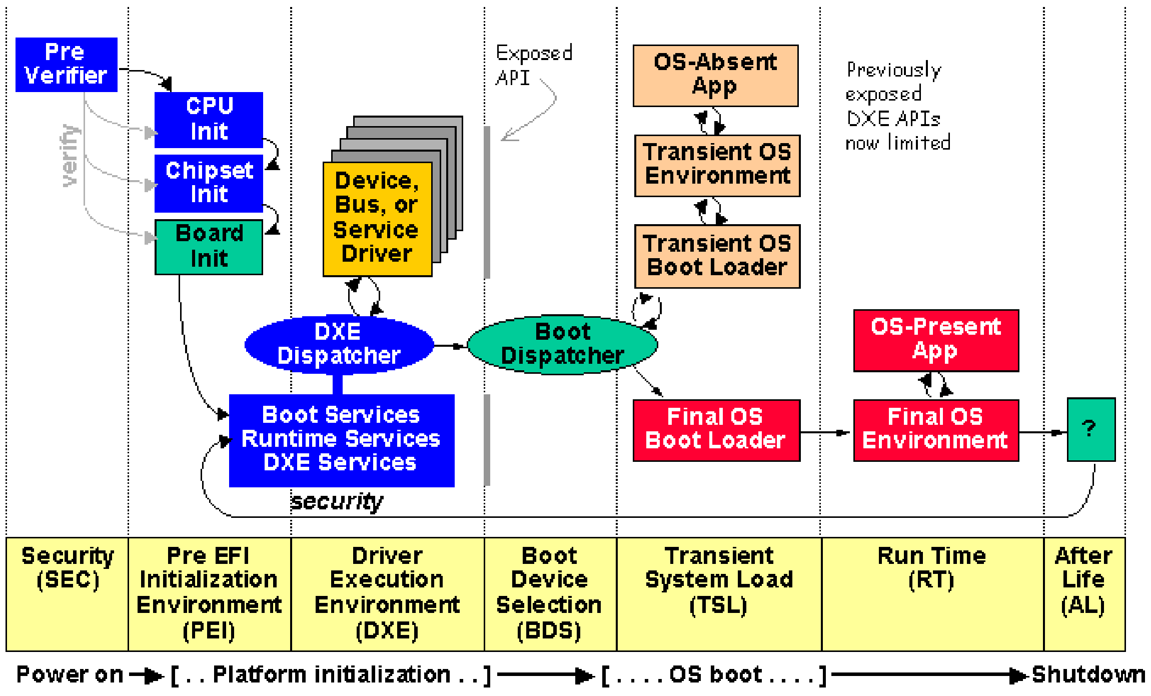
into a single PF. The proposed PI architecture phases are depicted in Figure 2.5. They are not entirely distinct, and system designers may choose to implement phases differently.

2.2.2.1. Security (SEC)

The SEC phase is the first phase performed during platform initialization. Under its responsibilities fall the handling of all platform restart events, setting up a temporary memory, and establishing the system's root of trust. It serves as the foundation for all security operations on which inductive security designs rely to build a chain of trust by having a module verify the integrity of its subsequent module. For this, the SEC phase may verify the integrity of the PEI foundation before transferring execution to it. As this is very specific to how the platform is implemented, the SEC phase is only specified in the form of basic requirements that it needs to meet before handing over execution to the PEI phase. When it transfers execution, it passes information about the current state of the system, including the location and size of the temporary stack, Random Access Memory (RAM), and Boot Firmware Volume (BFV). It can also optionally pass protocols for the PEI phase to use.

2.2.2.2. Pre-EFI Initialization (PEI)

The PEI phase configures the system to meet the minimum requirements for the DXE. Its job is the initialization of all system hardware requiring to be initialized beforehand, as well as the initialization of permanent memory, which is later described in Hand-off Blocks (HOBs) to



Pre Verifier
verify
CPU Init
Chipset Init
Board Init
Device, Bus, or Service Driver
Exposed API
DXE Dispatcher
Boot Dispatcher
Boot Services Runtime Services DXE Services
security
OS-Absent App
Transient OS Environment
Transient OS Boot Loader
Previously exposed DXE APIs now limited
OS-Present App
Final OS Boot Loader
Final OS Environment
?
Security (SEC)
Pre EFI Initialization Environment (PEI)
Driver Execution Environment (DXE)
Boot Device Selection (BDS)
Transient System Load (TSL)
Run Time (RT)
After Life (AL)
Power on
[. . Platform initialization . .]
[. . . . OS boot . . . .]
Shutdown

Fig. 2.5.: PI Architecture Firmware Phases (taken from [10, Figure 2-1])

be passed off to the DXE phase [10, Vol. 1, 2.1]. The PEI phase is architecturally a stripped-down version of the DXE phase, as it offers the same extensibility through modules supplied by the different OEMs responsible for the component initialization. As the PEI's environment is still very restricted and the main memory only initialized towards the end of the phase, more complex processing is to be done in the DXE. Even though the implementation of the PEI phase is the most hardware dependent, the core functionality of the PEI is common to all processor architectures and offered through the PEI foundation [10, Vol. 1, 2.2]. It is the module initially invoked by the SEC phase and responsible for dispatching further Pre-EFI Initialization Modules (PEIMs) and offering an inter-module communication through the management of PEIM-to-PEIM Interfaces (PPIs) [10, Vol. 1, 2.5]. The PEI foundation implements a PEI dispatcher, who iterates over PEIMs found in FVs, to evaluate their Dependency Expressiaboveons (DEPEXs). DEPEXs are logical combinations of PPIs that must be present before loading a PEIM. Loading PEIMs results in the installation of new PPIs and the discovery of additional FVs. This leads to previously unfulfilled DEPEXs to now be fulfilled and the dispatcher loading these PEIMs on their next evaluation. This process is repeated until no more PEIMs can be dispatched. The foundation then invokes the *DXE IPL PPI*, which loads the DXE foundation into memory, to then transfer execution [10, Vol. 1, 2.6]. The BFV containing the PEI foundation, initially discovered by the SEC phase, and any additionally discovered FVs are also passed off to the DXE in the form of HOBs.

While the PEI phase has many architecturally required PPIs that modules have to implement, the PI also defines optional PPIs, one of which is the *Security PPI*. It is used to maintain the chain of trust by offering the chance for platform builders to authenticate or log PEIMs before they are executed [10, Vol. 1, 6.3.6].

2.2.2.3. Driver Execution Environment (DXE)

The DXE phase is responsible for finalizing the initialization of all platform components, as well as implementing UEFI, the UEFI environment, and its system abstractions as they are defined in [6]. As mentioned earlier, the DXE phase is architecturally similar to the PEI phase, as it also has a foundation with a dispatcher, extensible modules in the form of DXE drivers, and uses UEFI protocols for inter-module communication [10, Vol. 2, 2.1]. The DXE foundation is only dependent on the list of HOBs it receives from the previous phase, allowing it to be used with the PEI phase or different implementations. This also makes it possible to unload the previous stage, freeing up its memory [10, Vol. 2, 9.1]. The DXE foundation produces the UEFI boot and runtime services as well as additional DXE services and offers them through the UEFI system table to its DXE drivers as it can be seen in Figure 2.2 [10, Vol. 2, 2.2.1]. DXE drivers are very similar to UEFI images as they even share the same entry point signature. They also come in boot and runtime variants [10, Vol. 2, 11.2.3]. The implementation of the UEFI system table services is done by DXE drivers, who provide architectural protocols for the DXE foundation to consume [10, Vol. 2, 12.1]. Thus, the foundation has to provide the most basic services, required to load and execute DXE drivers, on its own. DXE drivers implementing architectural protocols are called early drivers, as they cannot assume that all UEFI system table services are already available to them and as they do not follow the UEFI driver model [10, Vol. 2, 11.2.1]. To guarantee that some architectural drivers are loaded before others, an *a priori* file can be used. When an *a priori* file is present on a FV, it is read to provide a deterministic order of drivers, which are to be executed before the dispatcher starts its regular DXE driver discovery and DEPEX evaluation on the rest of the architectural drivers [10, Vol. 2, 10.3]. DXE drivers, which follow the UEFI driver model, have an empty DEPEX, as installing the Driver Binding Protocol to its image handle does not require any architectural protocols. They are still only dispatched after all architectural protocols have been installed [10, Vol. 2, 11.2.2]. The dispatcher also makes use of the two Security Architectural Protocols to authenticate each DXE driver to decide whether to execute it [10, Vol. 2, 10.13].

When the DXE dispatcher is unable to load any new drivers it transfers execution to the BDS Architectural Protocol [10, Vol. 2, 2.4]. This indicates the advancement into the BDS phase, but not simultaneously the end of the DXE phase [10, Vol. 2, 2.1]. The two phases work together until the OS takes control of the system with the call to `ExitBootServices()`.

2.2.2.4. Boot Device Selection (BDS)

The BDS phase consists of the implementation of the BDS Architectural Protocol. It implements the UEFI boot manager policy as defined in [6, Section 3] and summarized in Section 2.1.9. When discovering additional FVs the DXE dispatcher is invoked through the DXE services. Execution may also be returned to the DXE phase when not enough drivers were initialized to successfully boot from a device [10, Vol. 2, 12.2].

2.2.2.5. Transient System Load (TSL)

The TSL phase consists of the UEFI OS bootloader performing its necessary actions in preparation for assuming control over the system by calling `ExitBootServices()` and transferring execution to the OS kernel [14, Section 2.3]. The DXE phase and all boot services are unloaded.

2.2.2.6. Runtime (RT)

The RT phase offers only minimal functionality via the remaining runtime services while the OS owns the system [14, Section 2.3].

2.2.2.7. Afterlife (AL)

The AL phase facilitates drivers storing the system state during the shutdown, sleep, hibernation, and restart events [14, Section 2.3].

2.2.3 Security

The PI specification defines PPIs and DXE protocols which can be used to validate images when loading them. During the PEI phase, the *PEI Guided Section Extraction PPI* can be used to authenticate file sections, while the *Security PPI* implements the policy response to the authentication result. The DXE phase has counterparts in the form of the Guided Section Extraction Protocol and the Security Architectural Protocol. The policy response may be the locking of flash upon authentication failure or attestation logging [10, Vol. 2, Section 12.9.1]. It also has the architectural protocol Security2 Architectural Protocol, which implements Secure Boot validation, Trusted Computing Group (TCG) measured boot; and User Identity policy for image loading. The implementation of the boot service `LoadImage()` has to use these protocols in accordance with the rules defined in [10, Vol. 2, Section 12.9.2]. The Security2 protocol is invoked on every loaded image, with the Security protocol being invoked afterward on images loaded through the Firmware Volume Protocol. When the Security2 protocol is not installed it uses the Security protocol regardless of the image's origin.

2.2.3.1. Hardware Validated Boot

Secure Boot relies on the firmware as its root of trust. Hardware validated boot shifts the root of trust out of the firmware image into a smaller part in the hardware, in hopes to reduce the size of the attack vector. This part performs validation of the Initial Boot Block (IBB) before handing over execution to the firmware image [11].

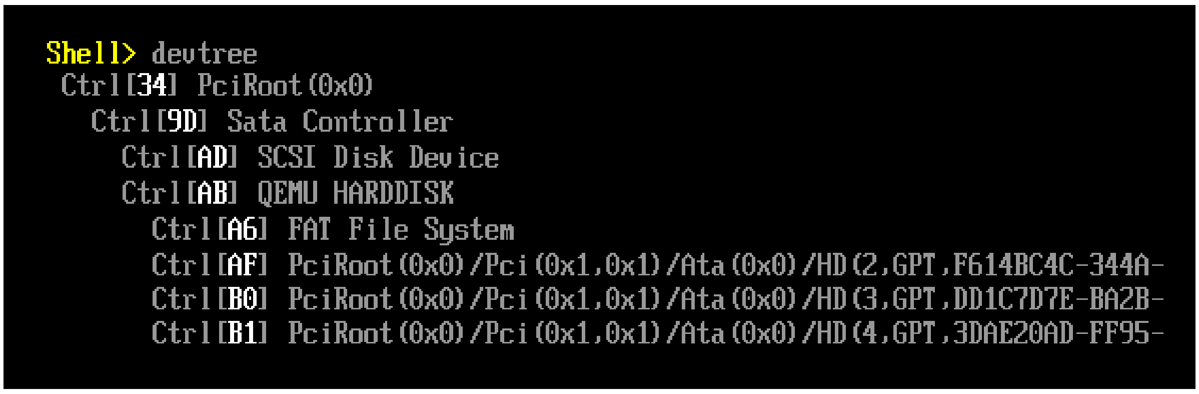
2.2.3.2. Firmware Protection

The PI specification defines an *End of DXE Event*, which indicates the introduction of third-party software execution to the platform. Up until this point, it is assumed that the entire system software is under the control of the platform manufacturer. Drivers may react to this event by locking critical system resources, using the System Management Mode (SMM) related services [10, Vol. 2, 5.1.2.1]. The SMM is a secure execution environment, achieved by isolation from the rest of the system, through the CPU [10, Vol. 4, Section 1.3]. The PI reference implementation also makes use of this event to lock the device that stores the firmware image [15].

2.3 UEFI Shell

Part of the family of UEFI specifications is a shell specification that defines a feature-rich UEFI shell application to interact with the UEFI environment [16, Section 1.1]. It offers commands relating to boot and general configuration, device and driver management, file system access, networking [16, Section 5.1], and scripting [16, Section 4]. A shell application may already be part of the boot options but can always be supplied in the default boot path of removable media.

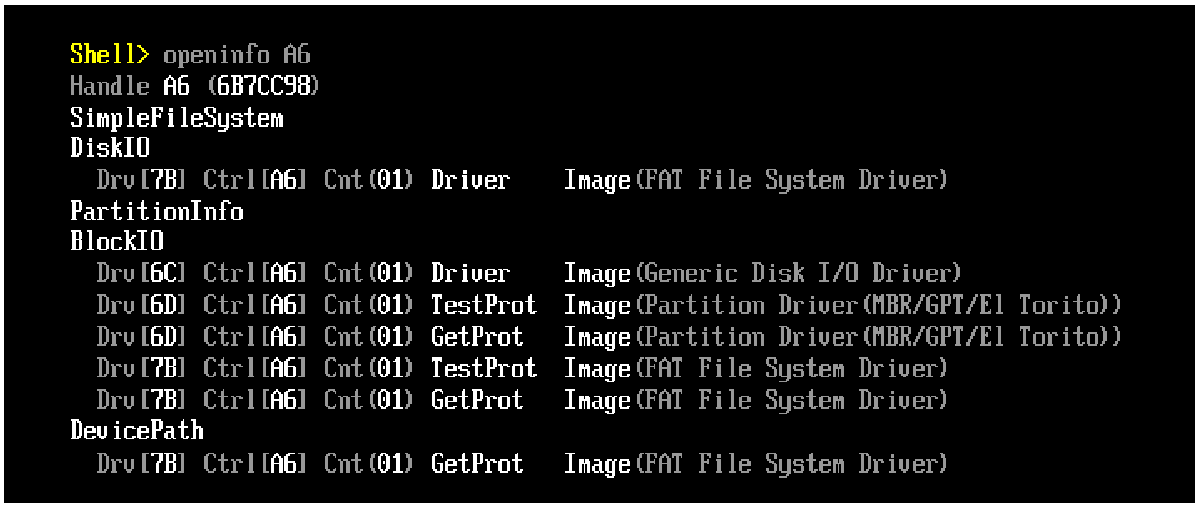
The UEFI shell is a great tool to visualize the UEFI environment. With the devtree command, for example, we can see the tree of all handles complying with the UEFI driver model. This also serves as a great reference on how device paths are formed. Figure 2.6 shows the output of devtree cropped to show a GPT formatted hard drive and its logical partitions. When the firmware discovers a block device it is also required to search for a partition table and create a device handle for each partition. Device drivers abstracting file systems can then be connected to a partition handle and check whether a supported file system format type is present. The first partition listed in Figure 2.6 as a *FAT File System* is the ESP of this drive.



```
Shell> devtree
 Ctrl[34] PciRoot(0x0)
   Ctrl[9D] Sata Controller
     Ctrl[AD] SCSI Disk Device
     Ctrl[AB] QEMU HARDDISK
       Ctrl[A6] FAT File System
       Ctrl[AF] PciRoot(0x0)/Pci(0x1,0x1)/Ata(0x0)/HD(2,GPT,F614BC4C-344A-
       Ctrl[B0] PciRoot(0x0)/Pci(0x1,0x1)/Ata(0x0)/HD(3,GPT,DD1C7D7E-BA2B-
       Ctrl[B1] PciRoot(0x0)/Pci(0x1,0x1)/Ata(0x0)/HD(4,GPT,3DAE20AD-FF95-
```

Fig. 2.6.: Shortened UEFI shell output of devtree

With openinfo we can see the group of protocols that a handle represents. Figure 2.7 shows the output when querying the handle of an ESP. Since this ESP is installed in a logical partition, an instance of the Partition Information Protocol is present. The command also lists the agent handles of each protocol and how the protocol was accessed. `TestProt` is often used in the `Supported()` function of a driver, while `GetProt` is then used to open the protocol for consumption within the `Start()` function.



```
Shell> openinfo A6
Handle A6 (6B7CC98)
SimpleFileSystem
DiskIO
  Drv[7B] Ctrl[A6] Cnt(01) Driver    Image(FAT File System Driver)
PartitionInfo
BlockIO
  Drv[6C] Ctrl[A6] Cnt(01) Driver    Image(Generic Disk I/O Driver)
  Drv[6D] Ctrl[A6] Cnt(01) TestProt  Image(Partition Driver(MBR/GPT/El Torito))
  Drv[6D] Ctrl[A6] Cnt(01) GetProt   Image(Partition Driver(MBR/GPT/El Torito))
  Drv[7B] Ctrl[A6] Cnt(01) TestProt  Image(FAT File System Driver)
  Drv[7B] Ctrl[A6] Cnt(01) GetProt   Image(FAT File System Driver)
DevicePath
  Drv[7B] Ctrl[A6] Cnt(01) GetProt   Image(FAT File System Driver)
```

Fig. 2.7.: Shortened UEFI shell output of openinfo

2.4 EDK II

EFI Development Kit (EDK) II, maintained by *TianoCore*, is an open-source implementation of UEFI, offering a modern, feature-rich, cross-platform firmware development environment for the UEFI and PI specifications [17]. It serves as the build tool for all types of modules defined in the PI and UEFI specification and supports the generation of PF images, option-ROMs, and bootable media, hence we also use EDK II to generate the binaries for our attacks. On top of implementing the PI and UEFI specifications, it defines helpful libraries and protocols that can be used to simplify the development process. With events that require policy-defined reactions, it often already offers well-defined interfaces for a platform designer to pick up on. The build process is flexible, as it can use different compilers such as GCC and MSVC.

TianoCore also offers a lot of material to learn about developing applications, drivers, firmware, and a general understanding of the UEFI ecosystem.

Trusted Platform Module (TPM) 3

With the TPM the TCG specifies a system component designated for security-related functions, providing the ability to establish trust in a system [18]. Its implementation can be accomplished through dedicated hardware or by using the CPU's isolated SMM [19, Section 9.3]. Asides from generating and securely storing cryptographic keys, the TPM can be used for system integrity measurements. Boot code is measured into the TPM by the PF, providing evidence over the initialization process and making it possible to detect deviations [18].

3.1 Platform Configuration Registers (PCRs)

[19] defines PCRs to store the system integrity measurements. The registers can only be modified in two ways: either through a complete TPM reset or by extending their values. Extending a PCR is done by concatenating the hashed measurements together with the current PCR values to form the new contents, as depicted in Equation 3.1. This creates a chain of measurements where from one diverging measurement on, all subsequent PCR extensions result in entirely different values.

$$PCR[i]_{(new)} = Hash(PCR[i]_{(old)} \,||\, Hash(Measurement)) \tag{3.1}$$

The TPM is a passive system component, relying on the host processor to perform measurements and extend the PCRs. The measurement chain starts with a point called the Core Root of Trust for Measurement (CRTM), consisting of the first instructions executed to establish a chain of trust. A root of trust in a system is an element that must be trusted as its behavior is non-verifiable [19]. [20, p. 3.2.2] requires this chain to start in an immutable portion of the PI process, the Static Root of Trust for Measurement (SRTM). [20, p. 3.2.3.1] defines the PF to be composed of a Boot Block and the UEFI firmware, the Boot Block consists of the SEC and PEI phase as well as the IBB. The Boot Block forms the SRTM, while the UEFI firmware is only part of the chain of trust by being measured from the SRTM. The Root of Trust for Measurement (RTM) can either start with the SRTM measuring itself or a Hardware-Core Root of Trust for Measurement (H-CRTM) measuring the SRTM. It falls under the responsibility of the PF to perform the integrity measurements [20]. Different parts of the boot process are measured into separate PCRs. Figure 3.1 shows a high-level measurement flow. Table 3.1 on 25 shows PCR indexes relevant to this thesis and the type of measurements performed to extend them.

Interaction with the TPM is done via a well-defined interface. For external chips, this is done over hardware buses such as Low Pin Count (LPC) or Serial Peripheral Interface (SPI). TCG specifies the TCG2 Protocol for the UEFI environment, providing an abstracted communication interface independent of the underlying implementation.

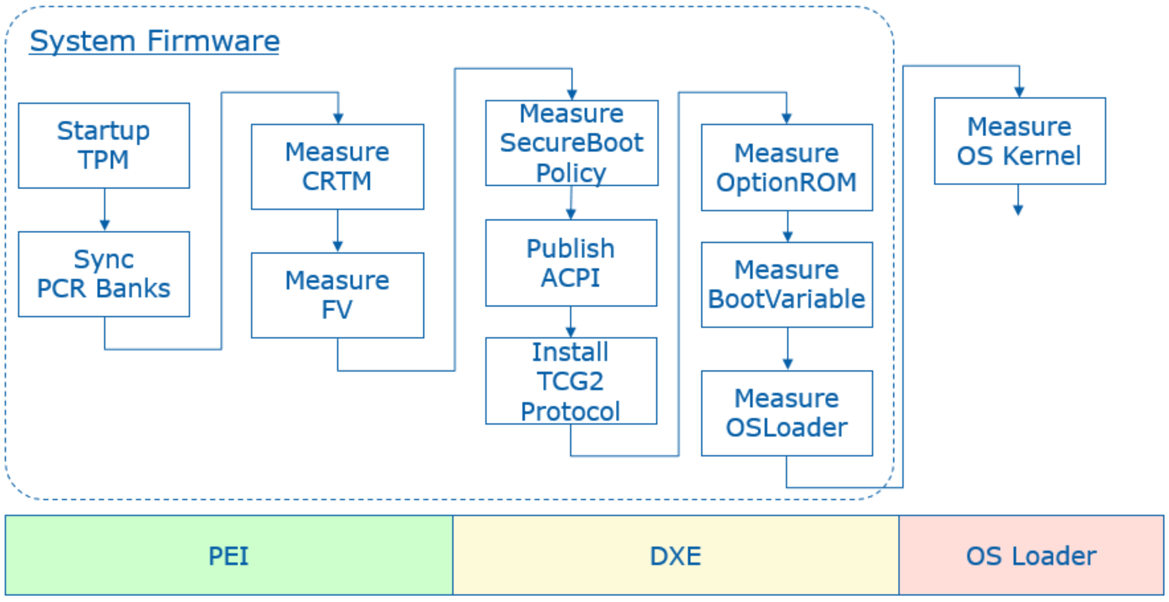


Fig. 3.1.: PF Measurement Flow (taken from [21, Figure 3])

PCR Index	Measurements
0	SRTM, BIOS, Host Platform Extensions, Embedded Option-ROMs, and PI Drivers
1	Host Platform Configuration
2	UEFI driver and application Code
3	UEFI driver and application Configuration and Data
4	UEFI Boot Manager Code (usually the MBR) and Boot Attempts
5	Boot Manager Code Configuration and Data (for use by the Boot Manager Code) and GPT/Partition Table
6	Host Platform Manufacturer Specific
7	Secure Boot Policy
8	First NTFS boot sector (volume boot record)
9	Remaining NTFS boot sectors (volume boot record)
10	Boot Manager
11	BitLocker Access Control

Tab. 3.1.: PCR Usage (taken from [20, Table 1] and [22, Table 9-2])

3.2 Sealing/Unsealing

The chain of measurements can be used to attest that the system is in a trusted state. The TPM can be given data, for example, a cryptographic key, in a state that is assumed to be trusted. This state is reflected by the current PCRs, consisting of the collection of lead-up measurements. The TPM then seals the data with a policy that describes which PCR indexes to use and/or proof of authentication through a Personal Identification Number (PIN) or passphrase. The data can then only be unsealed on subsequent boots when the system is in the same trusted state that it was in when the data was sealed. Any modification of the boot code will be reflected in a deviation of PCR values leaving the TPM unable to unseal the data [23, Section 3.3.6].

Windows 11

4

Windows 11 is, at the time of writing, the latest iteration in the line of desktop OSs from Microsoft. It is built upon the foundation of Windows 10 and, as such, shares many security settings and policies with its predecessor [24]. Simultaneously, it raises the requirements of hardware-related security features. It does not support legacy BIOS anymore, requires the PF to conform to at least UEFI version 2.3.1 and to be capable of Secure Boot. It also requires the presence of a TPM version 2.0 [25].

4.1 UEFI

To be able to analyze UEFI threats against Windows 11 it is important to understand how Windows interacts with the UEFI environment.

4.1.1 Installation

The interaction with UEFI begins with the installation process and the partitioning of the hard drive Windows is installed onto. When the Windows Installer is launched, it creates at least four GPT partitions on the target hard drive: the EFI System Partition (ESP), a recovery partition, a partition reserved for temporary storage, and the boot partition containing the system files. Two copies of the *Windows Boot Manager* bootmgfw.efi are placed on the ESP, one under EFI\Boot\bootx64.efi for the default boot behavior (i.e., booting from the installed hard drive) and one under EFI\Microsoft\Boot\bootmgfw.efi alongside boot resources such as the Boot Configuration Data (BCD). The path of the latter boot manager is saved in a boot load option variable entry `Boot####`, which is then added to the `BootOrder` list variable. The boot load option contains optional data consisting of a GUID identifying the Windows Boot Manager entry in the BCD. The BCD, as its name suggests, contains arguments used to configure various steps of the boot process [26, Section 12]. The boot partition is the primary Windows partition. It is formatted with the NTFS file system containing the Windows installation. This is also the location of the final step of the Windows UEFI boot process, Windload.efi, the application responsible for loading the kernel into memory [26, 12. The Windows OS Loader].

4.1.2 Boot

Now that we have established the basic structure of the Windows UEFI boot environment, we can discuss the boot process. The Windows boot process begins after the UEFI Boot Manager launches the Windows Boot Manager, which starts by retrieving its executable path and the BCD entry GUID from the boot load options. Then it loads the BCD and accesses its entry. It loads its own executable into memory for integrity verification [26, Section 12] if not disabled in the BCD. Depending on what hibernation status is set within the BCD, it may launch the Winresume.efi application, which reads the hibernation file and resumes the kernel execution [26, Section 12]. On a full boot, it checks the BCD for boot entries. If the entry points to a BitLocker encrypted drive, it attempts decryption. If this fails a recovery prompt is displayed, otherwise the system proceeds to load the OS loader Windload.efi which maps the kernel image ntoskernl.exe into memory. After a call to `ExitBootServices()` it transfers execution to the kernel [26, Section 12].

4.1.3 Runtime

During runtime Windows uses the variable services to communicate with the PF and even exposes these to application developers. It also supports firmware and option-ROM updates via the capsule delivery services.

4.2 Registry

A crucial part of the whole Windows ecosystem is the *Registry*. It is a system database containing the information required to boot, what drivers to load, general system-wide configuration as well as application configuration [27, Section 1]. The Registry is a hierarchical database containing keys and values, whereas keys can contain other keys or values, forming a tree-like structure. Values store data through various data types. It is comparable to a file system structure with keys behaving like directories and values behaving like files [26, Section 10]. At the top level it has 9 different keys [26, Section 10]. Normally Windows users are not required to change Registry values directly and instead interact with it through applications providing setting abstractions. Although some more advanced options may not be exposed and can be accessed through the regedit.exe application which provides a graphical user interface to traverse and modify the Registry [26, Section 10]. It also supports importing and exporting registry keys along their subkeys and contained values. Internally, the registry is not a single large file but instead a set of files called hives. Each hive contains one tree that is mapped into the Registry as a whole. There is no one-to-one mapping of a registry root key to a hive file, the BCD file, for example, is also a hive file and is mapped into the Registry under HKEY_LOCAL_MACHINE\BCD00000000 [26, Section 10]. Some hives even reside entirely in memory as a means of offering hardware configuration through the Registry Application Programming Interface (API).

4.3 Security

Figure 4.1 gives an overview of the security within the Windows startup process, with *Secure Boot* starting the process and *Trusted Boot* eventually taking over. We do not cover *Measured Boot* in this thesis.

4.3.1 Secure Boot

Devices shipping with Windows 11 must-have Secure Boot enabled by default [25]. Windows-certified devices generally must allow users to enroll custom keys and signature DBs (to allow execution of non-Windows bootloaders). Additionally, a user should be able to completely disable secure boot. Windows offers two signature DBs: the *Microsoft Windows Production PCA 2011* required for the Windows boot process and the *Microsoft Corporation UEFI Certificate Authority (CA) 2011*, which is reserved for third party executables signed at Microsoft's discretion after a manual review [28]. Microsoft advises to only allow other third party UEFI applications if necessary and even mandates the exclusion of DBs other than *Microsoft Windows Production PCA 2011* on Secured-core Personal Computers (PCs) [3].

4.3.2 Trusted Boot

Trusted Boot picks up where Secure Boot left off and maintains the code integrity chain through the kernel into the Windows startup process. Kernel Mode Code Integrity (KMCI) verifies the digital signature of Windows boot components, including boot drivers, startup files, and the Early-Launch Antimalware (ELAM) driver [29]. ELAM provides anti-malware software developers an interface to be initialized early in the boot process, before other third-party components, to monitor the subsequent boot process [30]. [31] gives a detailed walkthrough of the trusted boot process.

Microsoft can also leverage hardware virtualization features called Virtualization Secure Mode (VSM) for Virtualization Based Security (VBS). This enables Hypervisor-protected Code Integrity (HVCI) where the Code Integrity (CI) checks are taken out of the kernel environment and are now performed from within the isolated hypervisor-based security environment [32].

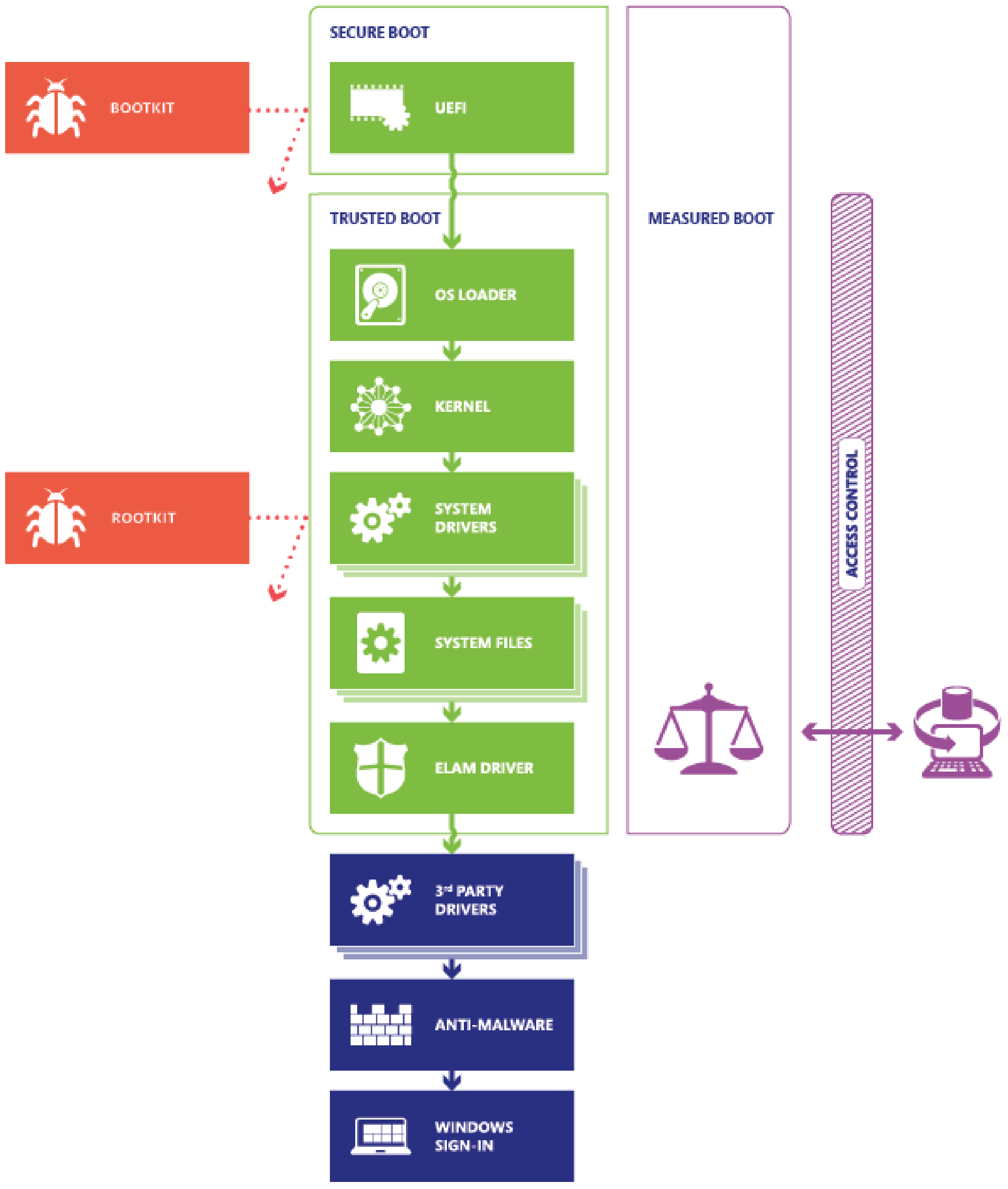


Fig. 4.1.: Windows startup process (taken from [3])

The term *Device Guard* was formerly used to promote the two security-related features HVCI and Windows Defender Application Control (WDAC) (restricts execution of user-level applications). Microsoft has since retired the term to prevent confusion, as there is no direct dependency between the two [33].

4.3.3 BitLocker Drive Encryption (BDE)

Windows is only able to enforce security policies when it is active, leaving the system vulnerable when accessed from outside the OS environment [22, Section 9]. Windows uses BitLocker, an integrated Full Volume Encryption (FVE), aimed to protect system files and data from unauthorized access while at rest [34]. It also serves as a mechanism to verify boot integrity when used in combination with a TPM [22, Section 9]. The en- and decryption of the volume is done by a filter driver beneath the NTFS driver as depicted in Figure 4.2.

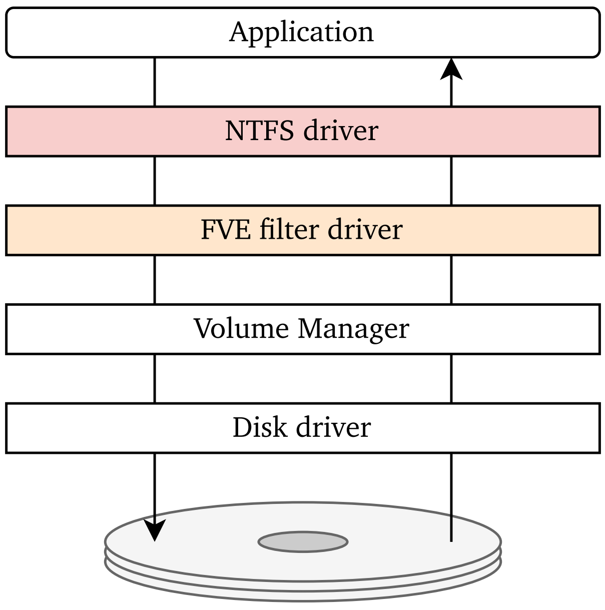


Fig. 4.2.: BitLocker Volume Access Driver Stack (inspired by [22, Figure 9-24])

The NTFS driver translates file and directory access into block-wise operations on the volume. The filter driver then receives these block operations, encrypting blocks on write and decrypting blocks on read, while they pass through it. This results in en- and decryption, which is entirely transparent to the NTFS driver, making the underlying volume appear decrypted [22, Section 9]. The encryption of each block is done using a modified version of the Advanced Encryption Standard (AES)128 and AES256 cipher [22, Section 9]. A Full Volume Encryption Key (FVEK) is used in combination with the block index as input for the algorithm, resulting in an entirely different output for two blocks with identical data [22, Section 9]. The FVEK is encrypted with a Volume Master Key (VMK), which is, in turn, encrypted with multiple protectors. These encrypted versions of the VMK are stored together with the encrypted FVEK in an unencrypted metadata portion at the beginning of the BitLocker protected volume [22, Section 9]. The VMK can be encrypted by the following protectors:

Startup key The Startup key can be stored on removable media such as an USB stick and serves as a physical proof of ownership. The removable media contains a `.bek` file that is named with a GUID corresponding to the BitLocker metadata entry, as it is possible to have multiple startup keys for the same volume [35, Section 2.6], [36].

TPM When a TPM is used to seal the VMK, BitLocker can ensure the integrity of early boot components and boot configuration, as the unseal operation fails upon modification of the boot flow. The TPM can, in combination with the PCR values, use a startup key, a pin, or both to seal the VMK [37]. The collection of PCR indexes used to instruct the TPM when initially sealing the VMK is called a *validation profile*. The validation profile is optionally configurable through Windows group policy settings, and PCR11 is always required, as its contents measure the BitLocker Access Control. Windows configures BitLocker with a default validation profile of `{0, 2, 4, 11}` [38]. BitLocker can also use Secure Boot for integrity validation, where it *binds to PCR7* instead of using the PCRs `{0, 2, 4}`, resulting in the validation profile `{7, 11}` [39]. The PF measures the Secure Boot state and configuration, such as trusted keys, into PCR7 [39], following the rules stated in [40]. *Binding of PCR7* is only possible when Secure Boot is configured to use the *Microsoft Windows Production PCA 2011* signature DB. Any additional DBs will prevent the binding process and cause BitLocker to revert to the default validation profile [41].

Recovery key When BitLocker is activated it always generates a recovery key serving as an additional protector to whatever primary method is selected. This allows users to recover their data when, for example, the TPM fails to unseal the VMK or the startup key is lost. The recovery key can be added to the user's Microsoft account or get stored in any unencrypted media. It consists of 48 digits divided into 8 blocks, each block is converted into a 16-bit value making up a 128-bit key [35, Section 2.4].

User key When BitLocker is used without a TPM, the VMK can be encrypted with the use of a user-supplied password with a maximum length of 49 characters [35, Section 2.7].

Clear key BitLocker can also be suspended when a user, for example, wants to update their PF. The VMK is then encrypted with an unprotected 256-bit key stored on the volume [35, Section 2.5].

5 Past Threats

Before we implement our own UEFI attacks, we first take a look at how past UEFI threats are structured. The threats discussed range from actual attacks found in the wild and analyzed by security researchers, over attacks that have been implemented for similar research purposes, to tools that enable system owners a more advanced control over their systems.

Approach	**Bootkit**	**Rootkit**
Storage-based	**ours**	VectorEDK Mosaicregressor LoJax **ours**
Memory-based	Efiguard ESPecter Dreamboot FinSpy	MoonBounce CosmicStrand

5.1 Infection

The infection is the most important part of an attack, as it dictates when, in what environment, and with what privileges the UEFI payload is executed.

5.1.1 Bootkit

Bootkits use the UEFI Boot manager to gain execution on a system. There are a variety of methods using different mechanisms of the boot process. FinSpy backs up and replaces the Windows Boot Manager bootmgfw.efi on the ESP [42]. ESPecter patches the entry point of the Windows Boot Manager bootmgfw.efi and its copy bootx64.efi in the default boot path, so it executes malicious code upon launch [43]. Dreamboot and EFIGuard are more proof-of-concept than real attacks and suggest being booted into using removable media, but they are also able to be added to the default boot path on an ESP, or generally added as their own new boot entry [44]. They are both applications, which launch the Windows Boot Manager through its boot entry upon execution [44, 45].

5.1.2 Rootkit

Firmware rootkits have been rarer and how exactly the firmware images were infected is not often known. VectorEDK uses OEM's software tooling to generate a firmware update utility on a bootable USB stick that can then be inserted with physical access to the system [46].

LoJax infection method comes with the signed kernel driver from the program RWEverything. RWEverything is a legitimate tool that can be used to query hardware-related information on a system. LoJax uses the driver to read and write to memory mapped I/O, as well as PCI configuration registers. It leverages this to find the SPI flash mapping, to dump the firmware image. It then removes previously packaged NTFS drivers and adds its payload. Reflashing the modified image relies on the platform to be either misconfigured or of an older kind that has a race condition exploit. The SPI flash is secure by a BIOS control register, which has a BIOS Write Enable bit and BIOS Lock Enable bit. The locking mechanism has to be correctly implemented by firmware designers through SMM interrupts. When writing to the BIOS Write Enable bit, while the BIOS is enabled, the operation initially succeeds but is then reverted by a SMM interrupt routine. This could either be incorrectly implemented or exploited through race conditions using multi-processing or multi-threading existing on older hardware. When one thread constantly sets the Write Enable bit to 1 and the other tries to perform write operations on the SPI flash, the firmware image will eventually be overwritten [47].

MosaicRegressor and LoJax add their payload in the form of DXE drivers to a firmware volume [47, 48], as these are automatically executed by the DXE dispatcher. MoonBounce and CosmicStrand instead patch existing files in the firmware image. MoonBounce patches the DXE Core [49], while CosmicStrand patches an existing DXE driver [50]. While both approaches could fundamentally be done in the form of an added DXE driver, it does make the detection harder.

5.2 Approach

We can categorize the threats by their attack vector. Rootkits and bootkits do not seem to have distinct approaches, as they both start their execution in the UEFI environment prior to the Windows boot process. We found that their approach can mainly be divided into storage-based and memory-based attacks. Storage-based attacks mostly gain execution in the operating system environment by writing their payload into the Windows installation and modifying configuration data on the disk. These attacks are often performed offline before any parts of the operating system are executed. Memory-based attacks instead hook into the operating system's boot process to execute malicious code alongside the operating system in memory. For storage-based attacks, we were only able to find examples of rootkits [47, 48, 51], whereas memory-based attacks were performed by both root- and bootkits [42–45, 49, 50]. There is no technical limitation as we show in Section 7.1.1 when we implement our own storage-based bootkit, but more likely a general preference for memory-based attacks, as they are more sophisticated. Storage-based attacks face more restrictions such as BitLocker and code integrity checks.

5.2.1 Storage-based

Storage-based attacks need file-based access to the Windows installation to modify its content. The primary partition is NTFS formatted and, due to the UEFI specification only mandating compliant firmware to support FAT12, FAT16 and FAT32 [6, Section 13.3.1.1], NTFS drivers are delivered as part of the attack. MosaicRegressor and Lojax seem to use VectorEDK's leaked NTFS driver [47, 48]. LoJax deploys its payload under the file path C:\Windows\SysWOW64\autoche.exe and then modifies the registry entry HKEY_LOCAL_MACHINE\SYSTEM\C
Manager\BootExecute, so that their payload is executed instead of the original executable [47]. MosaicRegressor simply deploys its payload in the Windows startup folder [48], whose contents, as its name suggests, are executed upon Windows startup.

5.2.2 Memory-based

It seems to be unique to ESPecter to patch out the integrity self-check of the Windows Boot Manager, as it is the only bootkit to change the bootloader on disk instead of in-memory [43]. FinSpy and Dreamboot when executed, load bootmgfw.efi into memory and apply patches before transferring execution [42, 45]. EFIGuard loads an additional UEFI driver which is able to hook the boot service `LoadImage()`. When the function is called to load bootmgfw.efi, it patches the bootloader in memory [44]. MoonBounce applies its patches from within an `ExitBootServices()` hook [49].

The general approach is the same for all memory-based attacks. They propagate malicious code execution further up in the boot chain by hooking each image of the boot process as it is loaded into memory, i.e., from bootmgfw.efi to Winload.efi to ntoskernel.exe, the kernel image.

EFIGuard and ESPecter patch the kernel to disable Windows Driver signing, allowing them to install further kernel drivers [43, 44]. While FinSpy and Dreamboot deploy payloads executed with elevated privileges [42, 45]. MoonBounce and CosmicStrand map code directly into the kernel space [49, 50].

6 Test Setup

We perform our attacks against Windows 11 on three different setups. Even though all three UEFI firmware are PI specification compliant, there is still a lot of freedom for OEMs when implementing the PF. The Security in Telecommunications chair has mainly been focusing on Advanced Micro Devices (AMD) hardware security in the past, leading to our test setups missing Intel-based machines.

6.1 QEMU

Our main development setup is an emulated environment using the Quick Emulator (QEMU) [52] together with the OVMF image from EDK II using version `edk2-stable202208`. For Secure Boot, we generate our own PK and use the *Microsoft Corporation KEK CA 2011* and the two signature DBs *Microsoft Windows Production PCA 2011* and *Microsoft Corporation UEFI CA 2011* provided by Microsoft. Depending on whether we want to force PCR7 binding we can leave out or include *Microsoft Corporation UEFI CA 2011*. For BitLocker and to fulfill Windows 11's general requirement of a present TPM 2.0, we use swtpm, a TPM emulated in software [53]. Accessing the firmware image with this setup is done through simple file access.

6.2 Lenovo Ideapad 5 Pro-16ACH6

Our first hardware setup is a Lenovo Ideapad 5 Pro-16ACH6, an AMD-based laptop with an AMD Ryzen 9 5900H [54]. It supports Microsoft Device Guard and PCR7 binding when Secure Boot is enabled using the default keys. We can read and write the firmware image with physical hardware access by opening the device and using an SPI chip clip on top of the SPI chip on the mainboard, as shown in Figure 6.1. The SPI chip clip is connected to a programmer and can be managed with the Linux utility flashrom.

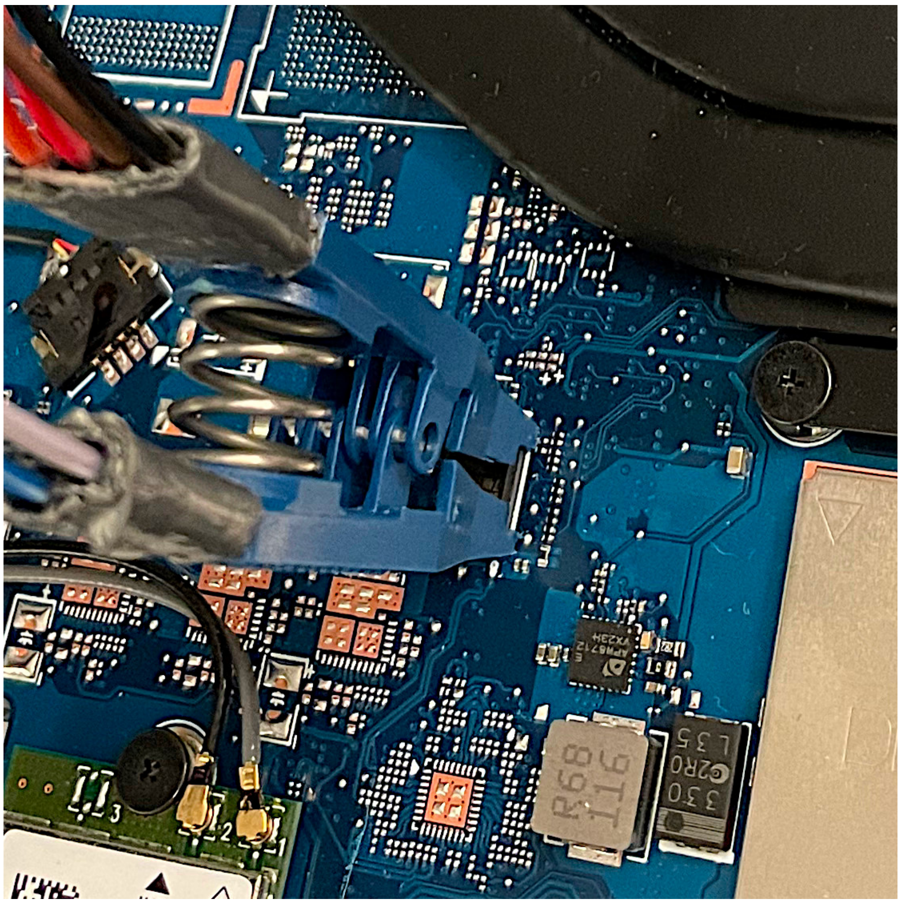


Fig. 6.1.: Lenovo Ideapad flash memory accessed with an SPI chip clip

6.3 ASRock A520M-HVS

Our second hardware setup is a desktop PC with an AMD-based ASRock A520M-HVS motherboard. We use the latest firmware image as of writing, which is version 2.30. This setup also supports PCR7 binding when Secure Boot is enabled using the default keys. The SPI flash chip on the main board is disabled and instead an EM100 SPI flash emulator is attached. When the system thinks it is accessing the SPI flash chip, it is instead communicating with the emulator. Additionally, by dual-booting into Linux, we can use flashrom to communicate with the SPI chip directly for read and write access. The Linux distribution of our choice, Ubuntu, uses a so-called Lockdown Mode when Secure Boot is enabled. This blocks direct access to the SPI chip [55], but can be disabled while Secure Boot remains enabled [56].

Attacks

7

We implement our storage-based UEFI attacks in the form of a bootkit and a rootkit and test them against our setups using three different escalating levels of security. The first attack uses standard Windows security policies that are to be expected after a fresh manual installation, i.e., Secure Boot and BitLocker are disabled. For the second attack, we enable Secure Boot and for the third attack, we enable Windows BDE using a TPM to protect the VMK.

7.1 Neither Secure Boot nor BitLocker Enabled

We start by implementing a baseline attack, which we can use to test against Secure Boot and BitLocker and further build upon. The implementation in the form of a bootkit and a rootkit both share the same approach and core functionality. The general approach of our attack is to access the Windows installation from within the UEFI environment and gain elevated code execution by modifying its contents.

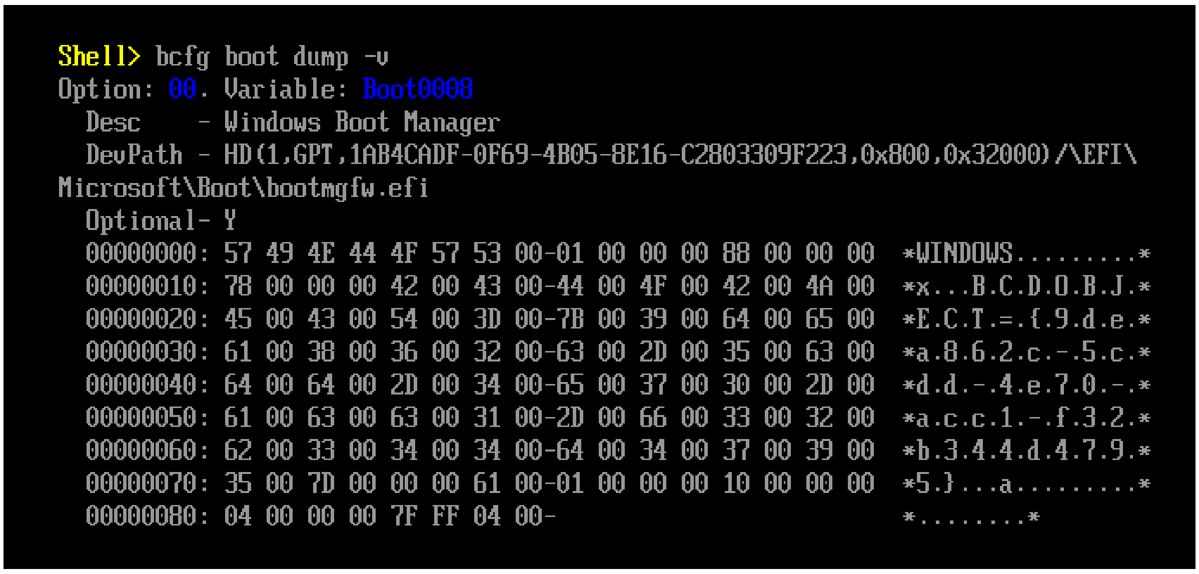
7.1.1 Bootkit

We start with the description of the bootkit approach.

7.1.1.1. Infection

We have two ways to infect a system: we can either use a bootable medium such as a CD-ROM or a USB stick with an UEFI application installing the bootkit, or we can use a Windows executable. Booting into the installer application requires either the firmware implementation or the boot order to prefer booting from the removable media over booting Windows directly. This can be forced during the boot process when accessing the interactive firmware menu at startup, given that it is not password protected. Installation from Windows requires admin privileges to mount and modify the ESP.

The installation process is identical for both options. We access the ESP and create a copy of the Windows Boot Manager located under EFI\Microsoft\Boot\bootmgfw.efi. We then replace the original with our bootkit as well as drop all resources required by the bootkit on the ESP. Now that our bootkit is in place of the Windows Boot Manager; when the UEFI Boot Manager selects the boot load option for the Windows Boot Manager, it will cause our bootkit to be executed. Figure 7.1 shows a dump of the Windows boot entry using the UEFI shell command bcfg. The entry contains the device path including the file path and optional data.



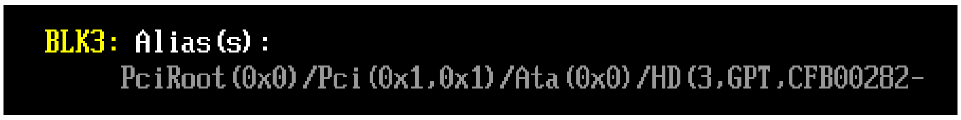
```
Shell> bcfg boot dump -v
Option: 00. Variable: Boot0008
  Desc    - Windows Boot Manager
  DevPath - HD(1,GPT,1AB4CADF-0F69-4B05-8E16-C2803309F223,0x800,0x32000)/\EFI\
Microsoft\Boot\bootmgfw.efi
  Optional- Y
  00000000: 57 49 4E 44 4F 57 53 00-01 00 00 00 88 00 00 00  *WINDOWS.........*
  00000010: 78 00 00 00 42 00 43 00-44 00 4F 00 42 00 4A 00  *x...B.C.D.O.B.J.*
  00000020: 45 00 43 00 54 00 3D 00-7B 00 39 00 64 00 65 00  *E.C.T.=.{.9.d.e.*
  00000030: 61 00 38 00 36 00 32 00-63 00 2D 00 35 00 63 00  *a.8.6.2.c.-.5.c.*
  00000040: 64 00 64 00 2D 00 34 00-65 00 37 00 30 00 2D 00  *d.d.-.4.e.7.0.-.*
  00000050: 61 00 63 00 63 00 31 00-2D 00 66 00 33 00 32 00  *a.c.c.1.-.f.3.2.*
  00000060: 62 00 33 00 34 00 34 00-64 00 34 00 37 00 39 00  *b.3.4.4.d.4.7.9.*
  00000070: 35 00 7D 00 00 00 61 00-01 00 00 00 10 00 00 00  *5.}...a.........*
  00000080: 04 00 00 00 7F FF 04 00-                          *........*
```

Fig. 7.1.: Windows boot entry, part of the UEFI shell output of bcfg

7.1.1.2. File Access

The most important step for a storage-based approach is gaining access to the Windows installation from within the UEFI environment. Since UEFI does not require the firmware to come with an NTFS driver, our attack has to come with its own. EDK II does not provide one, but we can use the open source NTFS driver ntfs-3g from Tuxera [57]. It was ported to the UEFI environment by *pbatard* [58]. Using EDK II to compile it, we receive a .efi executable image.

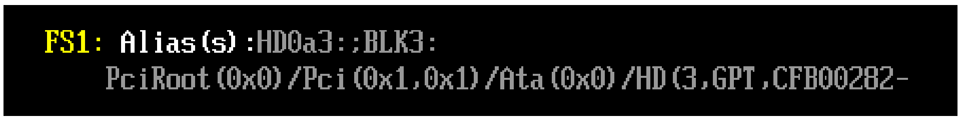
We can use the UEFI shell and its file system-related commands to test the NTFS driver's capabilities. When booting into the UEFI shell we are greeted with a screen displaying the UEFI specification version the firmware supports and a list of default mappings for file systems and block devices. These mappings are created by the shell to provide a short name that can be used interchangeably with a longer device path when issuing commands [16, Section 3.7.2]. They are designed to be consistent across reboots as long as the hardware configuration stays the same and are comparable to Windows partition letters [16, Appendix A]. Figure 7.2 shows the mapping of a partition containing a Windows installation. As there is no NTFS driver present yet, it is only displayed as a block device.



```
BLK3: Alias(s):
        PciRoot(0x0)/Pci(0x1,0x1)/Ata(0x0)/HD(3,GPT,CFB00282-
```

Fig. 7.2.: Mapping of the Windows partition

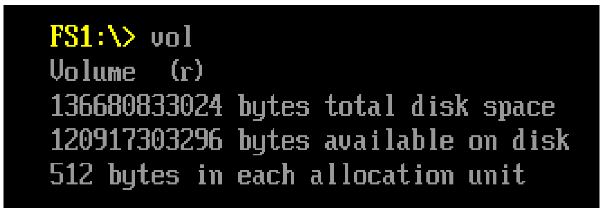
We can enter the mapping name of the file system containing our NTFS driver to use it as our current working directory and load the driver using the load command. The command is executed successfully, and the driver is now listed when querying the currently loaded drivers with the command drivers. We can now instruct the default mappings to be reset with the map -r command, to receive an updated list including the file systems now provided through the NTFS driver. Figure 7.3 also shows us that the new file system now sits on top of a device that previously was listed only as a block device.



```
FS1: Alias(s):HD0a3::BLK3:
      PciRoot(0x0)/Pci(0x1,0x1)/Ata(0x0)/HD(3,GPT,CFB00282-
```

Fig. 7.3.: Mapping of the mounted Windows partition

As done before we now type the mapping name of the new file systems, to check the root directories' contents with ls until we find the partition containing the Windows installation and then enter vol to check the access rights. This reveals that the file system is currently read-only, as shown in Figure 7.4. Upon debugging the NTFS driver, it appears to be that the driver falls back to read-only when it encounters a file that indicates that the Windows system is in hibernation mode. We can remove this fallback from the NTFS driver's code and recompile.



```
FS1:\> vol
Volume  (r)
136680833024 bytes total disk space
120917303296 bytes available on disk
512 bytes in each allocation unit
```

Fig. 7.4.: Volume Information of the Windows File System

On the ASRock test setup as described in Section 6.3, we noticed that the firmware already shipped with a read-only NTFS driver included. In the case of our rootkit, we would be able to remove this driver by modifying the firmware image, but we can implement a solution that applies to both types of UEFI payload. We can change the NTFS driver to install its Simple File System Protocol under a GUID different from the regular `gEfiSimpleFileSystemProtocolGuid`. This enables us to install two instances of the Simple File System Protocol alongside each other on the same controller. The alternative GUID can then be searched for by our root- and bookit, to retrieve our specific protocol instance with write access. The driver also has to open the protocols it uses without demanding exclusive ownership over them. This prevents the NTFS driver from being denied access when trying to open a protocol that is already in exclusive ownership [6, Section 7.3], which would be a likely occurrence as file system drivers are encouraged to get exclusive control over their block device [6, Section 13.5].

We now know that provided we get to load the NTFS driver, we can read and write the files of a Windows installation. Thus we drop the driver together with the bootkit onto the ESP as part of our infection process. When our bootkit is executed, we use the Loaded Image Protocol of our own image handle to retrieve the source device handle from which our bootkit was loaded from [6, Section 9.1]. As both files reside within the same volume, we can use this handle to call the boot services `LoadImage()` and `StartImage` to execute the driver. Since the driver conforms to the UEFI driver model, we also need to connect the driver to a device representing the Windows partition using the Driver Binding Protocol. We can do this by retrieving all protocol instances and iterating over all controllers, to connect them recursively. This way the driver can assume controller over all NTFS formatted volumes and install an instance of the Simple File System Protocol on their handles.

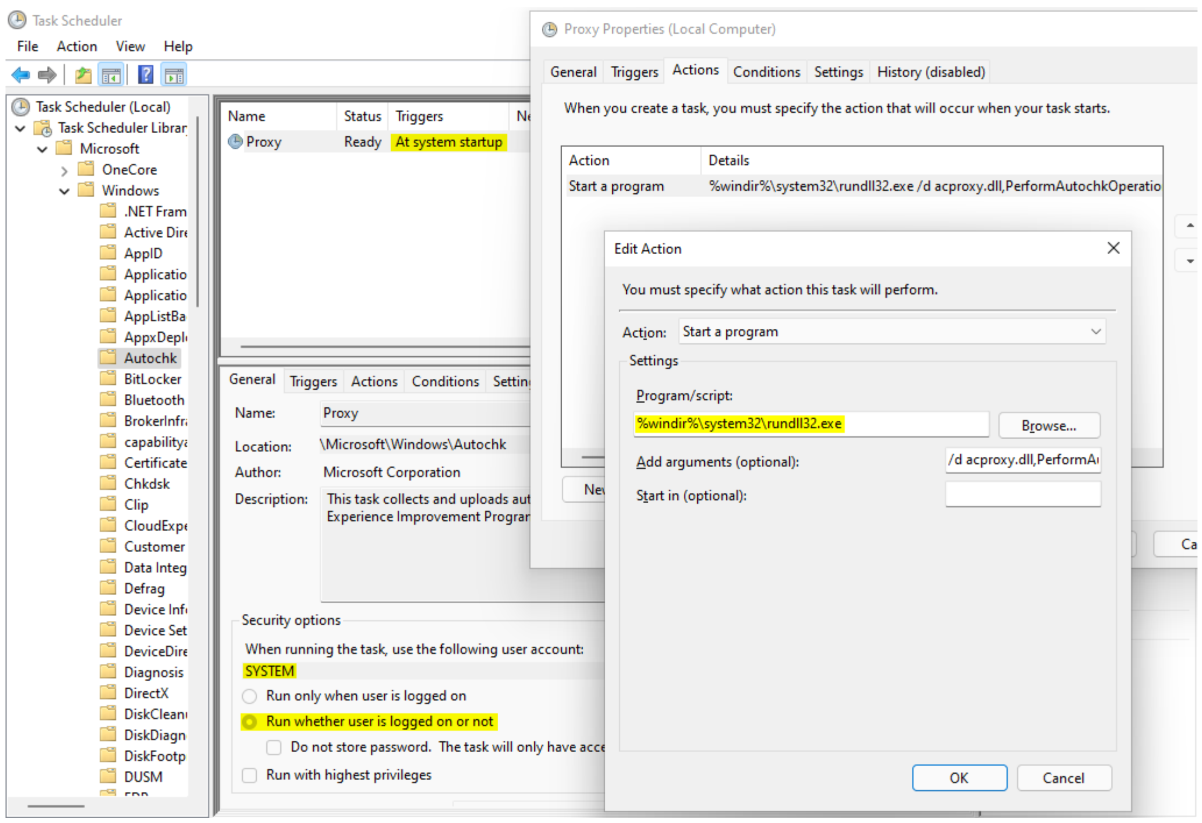
7.1.1.3. Payload Deployment

Before we can deploy our payload we first need to read it into memory. `LoadImage()` is reserved to be used for UEFI images. Non-executable files are read directly with the Simple File System Protocol. The ESP's device handle can be used with the boot service `HandleProtocol()` to retrieve its instance of the Simple File System Protocol. A call to `OpenVolume()` results in an instance of the File Protocol representing the root folder of the volume [6, Section 13.4]. The root directory can then be used to open and read our payload with an absolute path.

We need the device handle of the volume containing the Windows installation to perform the write operation. We can use the boot service `LocateHandleBuffer()` to receive an array of all handles that support the Simple File System Protocol, this includes volumes such as the Windows recovery partition or the ESP we just used. We can iterate over all handles and search for the Windows folder to identify the correct volume.

Now the question arises as to where we write our payload; our goal here is automatic and elevated execution. *MosaicRegressor* writes its payload to the Windows startup folder, a folder whose contents are automatically executed at system startup. The programs within the startup folder are unfortunately not automatically run at an elevated level, so this is not a suitable target location. We also cannot trivially overwrite or modify executables that are part of the Windows startup process, as KMCI will verify their code integrity before execution.

Our approach is to use the *Task Scheduler*. The Task Scheduler is a Windows service responsible for managing the automatic execution of background tasks [26, Section 10]. Tasks are performed on certain triggers, which may be time-based (periodically or at a specific time) or event-based, for example on user logon or system boot [59]. A task can perform various actions upon invocation [60]. We will focus on command execution. Most tasks will simply execute other programs as their action. This execution is performed under a specified security context [61]. The idea is to have a task, that performs its action with a high privilege level, execute our payload. Our task-of-choice is called Proxy and can be found under the Autochk folder. Its properties are depicted in Figure 7.5.


Task Scheduler

File Action View Help

Task Scheduler (Local)
Task Scheduler Librar
Microsoft
OneCore
Windows
.NET Fram
Active Dire
AppID
Applicatio
Applicatio
AppListBa
AppxDepl
Autochk
BitLocker
Bluetooth
BrokerInfr
capability
Certificate
Chkdsk
Clip
CloudExpe
Customer
Data Integ
Defrag
Device Inf
Device Set
DeviceDire
Diagnosis
DirectX
DiskClean
DiskDiagn
DiskFootp
DUSM

Name	Status	Triggers	N
Proxy	Ready	At system startup	

General Triggers Actions Conditions Settin

Name: Proxy

Location: \Microsoft\Windows\Autochk

Author: Microsoft Corporation

Description: This task collects and uploads aut Experience Improvement Progra

Security options

When running the task, use the following user account:

SYSTEM

( ) Run only when user is logged on

(●) Run whether user is logged on or not

[ ] Do not store password. The task will only have acce

[ ] Run with highest privileges

Proxy Properties (Local Computer)

General Triggers Actions Conditions Settings History (disabled)

When you create a task, you must specify the action that will occur when your task starts.

Action	Details
Start a program	%windir%\system32\rundll32.exe /d acproxy.dll,PerformAutochkOperatio

Edit Action

You must specify what action this task will perform.

Action: Start a program

Settings

Program/script:

%windir%\system32\rundll32.exe

Add arguments (optional): /d acproxy.dll,PerformA

Start in (optional):

Fig. 7.5.: Proxy Task shown using the Task Scheduler Configuration Tool

The Proxy task is triggered at system startup (with a 30-minute delay) and its action is to start the program rundll32.exe with the options `/d acproxy.dll,PerformAutochkOperations`. This causes rundll32.exe to load the acproxy.dll Dynamically Linked Library (DLL) into memory and invoke its exported function `PerformAutochkOperations()` [62]. The function name as well as the task name suggest the performed action relates to the Windows utility autochk which verifies the integrity of NTFS file systems [63]. Under security options, we can see that the task is executed using the built-in *SYSTEM* account. This task is therefore the perfect candidate to run our payload.

The Task Scheduler bookkeeps its active tasks in the Windows registry under the path HKLM\SOFTWARE\Micros
NT\CurrentVersion\Schedule\TaskCache. The tasks are grouped by four subkeys: Boot, Logon, Plain, and Maintenance. The entries under these subkeys consist only of a GUID. This GUID references the task descriptors that are saved using task master keys, which are located under HKLM\SOFTWARE\Microsoft\Windows NT\CurrentVersion\Schedule\TaskCache\Tasks [26, Section 10]. A secondary copy of the task descriptors exists within the regular file system under %windir%\system32\Task, stored in the form of Extensible Markup Language (XML) files.

We can use the Task Scheduler Configuration Tool to modify the Proxy task on a system under our control, changing the executable path as well as removing the delay configured in its trigger. We can save the output of whoami /all into a file to verify the privileges our payload is executed with. The whoami command shows the current user and privileges [64]. After manually triggering the task through the configuration tool, we can see in Listing 7.1, that our payload was run from the *nt authority\system* user account, which is the most privileged system account [65].

```
User Name SID
=================== ========
nt authority\system S-1-5-18
```

Listing 7.1: Snippet of whoami /all invoked by the Proxy task

Using the Windows registry editor reged.exe we can navigate to the task descriptor store and search for the task master key belonging to our task. We can then export the task master key and import it on our victim's system as part of our attack. By importing an entire registry key, instead of modifying a single value of an existing registry key, the victim's registry key maintains its integrity, as with a full overwrite the registry key's hash value is also changed. We can use a Linux utility called chntpw To import the key. The tool's primary purpose is to reset the password of local Windows user accounts [66]. It does this by editing the hive files of a Windows installation and as such the author also offers a standalone registry editor called reged. We can test the Linux tool when dual-booting Linux and Windows. For now, we place our payload manually in the Windows installation and then boot into Linux, where we can open the HKEY_LOCAL_MACHINE/SOFTWARE hive in reged and import our modified registry key. This overwrites the task descriptor and, when booting into Windows, our payload is executed.

Our UEFI payload now needs to perform the registry modification from within the UEFI environment. For this, we port the reged utility so that our bootkit can use it. The tool is already written in C, facilitating an easy porting process. The porting process boils down to providing semantically equivalent definitions for all external functions the program links against. These functions are mostly C standard library and Linux kernel related. Declarations and macros are still supplied by the local compiler's system headers. We can often use UEFI equivalent functions and wrap them to match the required signature. EDK II offers a lot of libraries implementing commonly used abstractions that we can use. Memory allocation like `malloc()` and `free()` can be mapped to the `MemoryAllocationLib`. Memory manipulation like `memset` and `memcpy` to `BaseMemoryLib`. Basic string manipulation like `strcmp()` and `strlen()` to `BaseLib`. Function calls related to standard input and output such as opening, reading, and writing the hive file, are more complex and have to be mapped to the UEFI protocols Simple File System Protocol and File Protocol. Luckily the author of reged used distinct functions to access the hive file and the registry file, making it possible to create the UEFI port and keep the original source code unmodified.

We also make a change to the import behavior, as the name of a task master key is the task's GUID. This may differ from device to device, thus we cannot import a key into its exact path. We instead iterate over the subkeys of the target's parent key and then match for the name value to find the right key.

Now that we modified the Windows installation to execute our payload upon boot, we need to transfer execution from the bootkit to the original Windows Boot Manager. Loading the original application is inspired by how the UEFI boot manager processes boot options. This includes relaying the `LoadOptions` and `ParentHandle` of the Loaded Image Protocol from the bootkit's image handle to the Windows Boot Manager's image handle.

7.1.2 Rootkit

Performing the attack in the form of a rootkit is very similar and mainly differs in the infection process. We now compile the UEFI payload as a DXE driver instead of a regular UEFI application. When it is placed in a DXE volume it is automatically loaded by the DXE dispatcher iterating over the FV, loading drivers and resolving dependencies. The core functionality of our UEFI payload is identical with the exception that we do not have to manually load the NTFS driver anymore and that accessing the Windows payload is now done through the BDS Protocol defined in the [10, Section 3.4.1], instead of Simple File System Protocol. There are no traditional file names in a FFS, so we have to search for files using their GUIDs, they are defined within the EDK II module file.

7.1.2.1. Infection

Infection with the rootkit has a much higher entry barrier, as it requires read and write access to the firmware image. Chapter 6 lists how we access the firmware images on our target systems, which mainly rely on physical access. In Chapter 5 we show that software exploits also exist, with *VectorEDK* exploiting the OEM firmware update mechanisms and *LoJax* using direct access to the SPI chip. Other ways of infection include intercepting the manufacturer's firmware deployment and having them deploy infected images or stealing private keys to make infected images appear legitimate.

When we are in possession of the image, we need to insert our payload into a DXE volume and redeploy the modified image. We can do this using the previously mentioned UEFITool, where we navigate to a DXE volume, identified by containing DXE drivers. On our Lenovo Ideapad 5 Pro-16ACH6 system, the firmware image does not contain enough free space to allow for the addition of our payload. By deleting network drivers, which are not used as Windows is not booted via a network in our attacks, we can debloat the firmware image and insert our drivers.

Our UEFI payload in the form of .efi executable images cannot be directly inserted with UEFITool, because of the FFS file sectioning mentioned in Section 2.2.1. DXE drivers have three mandatory sections: the PE32 executable section, composed of the .efi file content, a version section, and the DEPEX section [10, Vol. 3, 2.1.4.1.4]. For our UEFI payload to be generated as a sectioned FFS file using EDK II, we need our drivers to be packaged as part of a FV. We can add our files to the build process of the OVMF package in EDK II. The build process generates intermediary .ffs files, which are the sectioned files.

For our Windows payload, we can use a special EDK II module type that takes binary files as input. The generated result is a sectioned file of type `EFI_FV_FILETYPE_FREEFORM`. This type puts no restrictions on the contained file sections [10, Vol. 3, 2.1.4.1.7]. The output contains only one file section of type `EFI_SECTION_RAW` consisting of the binary payload.

Now that we have sectioned files corresponding to all our resources used in the attack we can import these into the target image with UEFITool. Redeploying the modified image concludes our infection process.

7.2 Secure Boot Enabled

Our second attack is performed with Secure Boot enabled. We assume that the signature DBs of allowed images does not contain our image's hashes and that the interactive UEFI setup menu is password protected. Otherwise, we could simply turn off Secure Boot.

7.2.1 Bootkit

The interactive menu being password-protected makes the likelihood of infection via booting into our installer smaller. We now solely rely on the boot order/firmware policy to prefer removable media. Even if this was to be the case, we promptly see that Secure Boot already denies the execution of the installer when trying to boot it. When using our Windows installer we observe the same denial for the bootkit itself. The Windows Boot Manager boot option pointing to our bootkit is now denied execution. If we were to have overwritten the standard boot entry of the hard drive EFI\Boot\bootx64.efi, a copy of the Windows Boot Manager, Windows would now be rendered unbootable.

7.2.2 Rootkit

In Section 2.2.3 we discussed how the PI specification defines the usage of its two security architectural protocols, with them being required to be invoked on every call to `LoadImage()`, and that the Security2 Architectural Protocol is responsible for the implementation of Secure Boot authentication. As `LoadImage()` is used internally within the DXE dispatcher the security protocol invocations also apply to our rootkit's DXE drivers when being loaded. We also discussed in subsubsection 2.1.10.1 that Secure Boot relies on the firmware image as its root of trust, where Secure Boot is inherently unable to verify the behavior of the PI process.

Now, these two seem to be conflicting, but when we deploy our rootkit it is unaffected by Secure Boot and executes just like before. When we look at the reference implementation in EDK II, we can see why: Listing 7.2 shows a snippet of the function that is used to implement the Security2 Architectural Protocol. It shows that the image origin dictates which policy is being applied. The standard policy for images from a Firmware Volume (FV) (`IMAGE_FROM_FV`) is to always allow execution. This aligns with what the UEFI specification says about the Secure Boot Firmware Policy: "The firmware may approve UEFI images for other reasons than those specified here. For example: whether the image is in the system flash [...]" [6, p. 32.5.3.2]. This behavior was reproducible on all our test setups. Even if the PF were to apply Secure Boot authentication to

DXE drivers, as long as the root of trust of authentication is established within the firmware image it can be patched as all code within the firmware image is modifiable.

```
switch (GetImageType(File))
{
case IMAGE_FROM_FV:
    Policy = ALWAYS_EXECUTE;
    break;

case IMAGE_FROM_OPTION_ROM:
    Policy = PcdGet32(PcdOptionRomImageVerificationPolicy);
    break;

case IMAGE_FROM_REMOVABLE_MEDIA:
    Policy = PcdGet32(PcdRemovableMediaImageVerificationPolicy);
    break;

case IMAGE_FROM_FIXED_MEDIA:
    Policy = PcdGet32(PcdFixedMediaImageVerificationPolicy);
    break;

default:
    Policy = DENY_EXECUTE_ON_SECURITY_VIOLATION;
    break;
}
```

Listing 7.2: Policy Selection in DxeImageVerificationHandler (EDK II reference implementation of Security2 Architectural Protocol)

7.3 BitLocker Enabled

Our final attack is against systems with BDE using a TPM 2.0, without additional PIN or startup key, for key protection. With this the Windows boot partition is encrypted, while the ESP remains unencrypted, thus BitLocker does not affect the bootkit infection process. When Secure Boot is enabled in combination with BitLocker, it has the same effects, as observed in Section 7.2. It also dictates which validation profile Windows uses to configure BitLocker, as mentioned in Section 4.3.3. We perform our attack against both validation profiles, starting with `{0, 2, 4, 11}`. This means either Secure Boot is disabled or PCR7 is not bound.

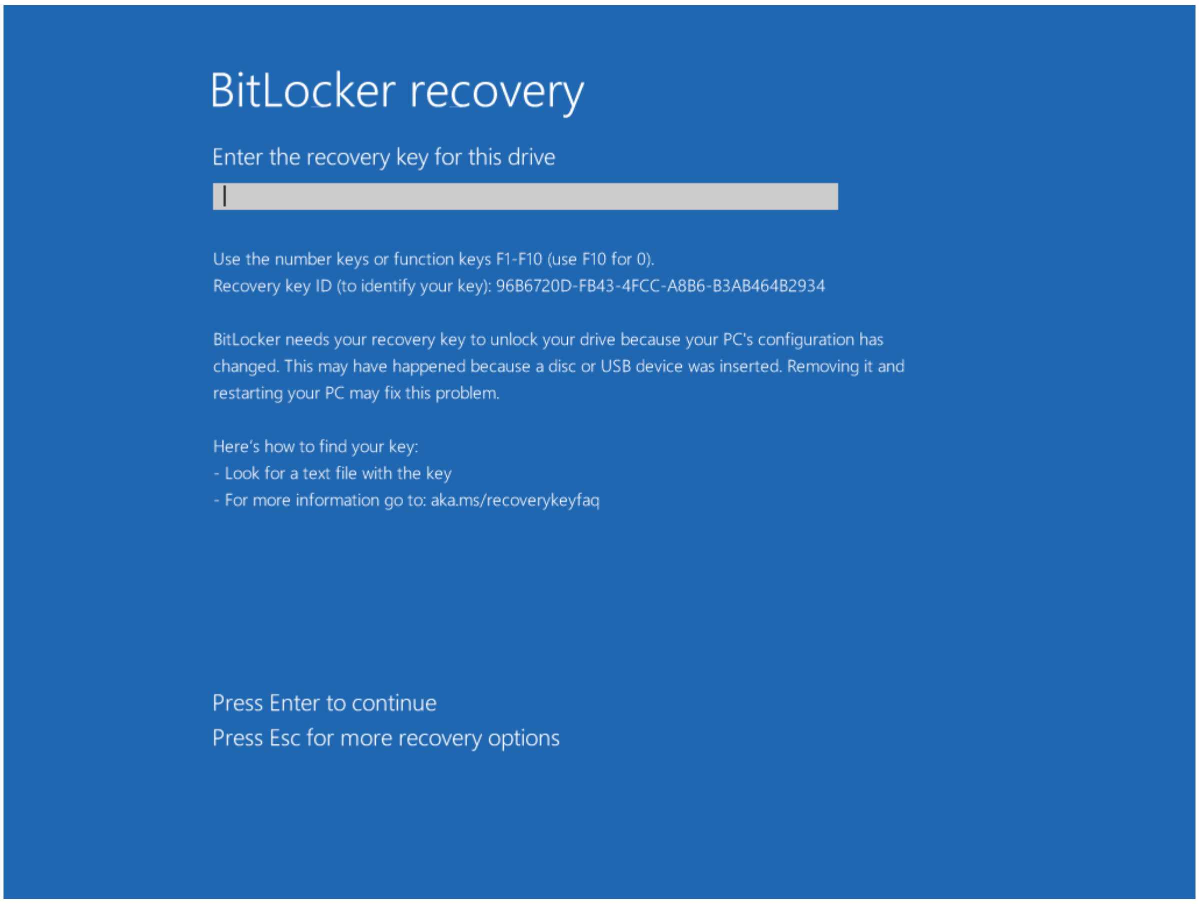
The validation profile `{7, 11}`, used when BitLocker uses Secure Boot for integrity validation, is covered in Section 7.3.4.

Due to the boot- and rootkit still sharing their core functionality we keep the approach abstract and refer to them with the expression UEFI payload, not to be confused with our Windows payload that is deployed into the Windows installation. We start by assuming that the infection is performed after BitLocker has already been fully set up; and cover the scenario that a user enables BitLocker while being infected at the end in Section 7.3.4.

7.3.1 Infection

When booting with our previous UEFI payload, the NTFS driver is unable to recognize any file system structure on the Windows boot partition, due to the FVE. This results in an inability to further deploy the Windows payload on the target system. Additionally, during the execution of the Windows Boot Manager, the BitLocker recovery prompt, shown in Figure 7.6, interrupts the regular boot process requiring the drive's recovery key for decryption before being able to continue booting. This happens due to TPM's PCR values differing from what was initially used to seal the VMK. The rootkit is measured into PCR0 and the bootkit into PCR2. This leaves the Windows bootloader unable to retrieve the unencrypted VMK from the TPM and as a result unable to decrypt the Windows installation [26, Section 12].

BitLocker discovers the deviation in the boot flow, via the TPM measurements, and blocks our UEFI attack from accessing the Windows installation. But how do users react to this? After all, it is asking them to enter their recovery key to resume the boot process and not to throw out their motherboard. There are a few options for a user to proceed: they either trust the system and enter their recovery key, they mistrust the operating system, or they mistrust the entire system. If they were to mistrust the whole system, they could take the hard drive out of the system and use the recovery key on a trusted system to recover data, being careful not to accidentally boot from the drive. This would deny both our rootkit and bootkit any further


BitLocker recovery

Enter the recovery key for this drive

Use the number keys or function keys F1-F10 (use F10 for 0).
Recovery key ID (to identify your key): 96B6720D-FB43-4FCC-A8B6-B3AB464B2934

BitLocker needs your recovery key to unlock your drive because your PC's configuration has changed. This may have happened because a disc or USB device was inserted. Removing it and restarting your PC may fix this problem.

Here's how to find your key:
- Look for a text file with the key
- For more information go to: aka.ms/recoverykeyfaq

Press Enter to continue
Press Esc for more recovery options

Fig. 7.6.: BitLocker Recovery Prompt

access to any sensitive data. If they were to mistrust the OS, or they were to have neglected to properly back up their recovery key, they might perform a fresh installation of Windows. In the case of our bootkit this would get rid of the threat, but the rootkit remains within the firmware image and would be part of the chain of trust for the fresh installation.

7.3.2 BitLogger

When the user enters their recovery key, the Windows Boot Manager uses the recovery key to decrypt the VMK in the metadata entry that was encrypted using the recovery key when BitLocker was set up. It then proceeds to access the BitLocker encrypted drive containing the Windload.efi OS loader. This all still happens during the UEFI boot environment, before ExitBootServices is called, as this is done within Windload.efi. Unfortunately, we remain unable to access the Windows installation during this, as BitLocker only ever decrypts read operations in memory, leaving the drive fully encrypted at all times. If we were to acquire the recovery key, we could use it to decrypt the VMK, then the FVEK, and in turn the drive ourselves.

This can be achieved by logging the keystrokes a user performs when they enter their recovery key into the recovery prompt. Since the Windows Boot Manager is executed in the UEFI boot environment, it has to use UEFI protocols instead of Windows drivers to access the hardware. This includes user input via the keyboard. UEFI offers two protocols for this purpose: the Simple Text Input Protocol and the Simple Text Input Ex Protocol. We can quickly determine which of these is used by the Windows Boot manager by adding a simple `Print()` statement to the implementation in the EDK II source code of the OVMF image. This change is also already enough to trigger the recovery prompt by invalidating the PCR measurements. A keystroke during the recovery prompt now shows us that the Simple Text Input Ex Protocol is being used. The protocol structure is listed in Listing A.13. The Windows Boot Manager uses the `ReadKeyStrokeEx()` function to retrieve the latest pending key press. The protocol also offers the `WaitForKeyEx()` event, signaling when keystrokes are available. Execution can be blocked until this event is emitted with the `WaitForEvent` boot service. The protocol also allows users to register and unregister a callback function to react upon user input. An exemplary use of the `ReadKeyStrokeEx()` is given below in Listing 7.3.

```
EFI_STATUS EFIAPI EntryPoint(IN EFI_HANDLE ImageHandle,
                             IN EFI_SYSTEM_TABLE *SystemTable)
{
    gBS = SystemTable->BootServices;

    EFI_SIMPLE_TEXT_INPUT_EX_PROTOCOL *SimpleTextInEx;

    gBS->HandleProtocol(SystemTable->ConsoleInHandle,
                        &gEfiSimpleTextInputExProtocolGuid,
                        (VOID **)&SimpleTextInEx);

    UINTN EventIndex;
    gBS->WaitForEvent(1, &SimpleTextInEx->WaitForKeyEx, &EventIndex);

    EFI_KEY_DATA KeyData;
    SimpleTextInEx->ReadKeyStrokeEx(SimpleTextInEx, &KeyData);

    // do something with key press

    return EFI_SUCCESS;
}
```

Listing 7.3: Example of using `HandleProtocol()` to retrieve an instance to the Simple Text Input Ex Protocol to use its `ReadKeyStrokeEx()` function to wait for and read a pending key press

We can intercept the `ReadKeyStrokeEx()` function call by using a technique called function hooking. There are various ways of doing this, for example, patching a jump instruction at the beginning of the target function to detour the execution flow. UEFI protocol hooking does not require such an invasive and processor architecture-dependent technique. When we take a closer look at how protocols are returned to their user we can see why. The UEFI boot services offer two functions, `HandleProtocol()` and `OpenProtocol()`, which can be used to retrieve a protocol instance. `HandleProtocol()` is a simplified abstraction of `OpenProtocol()` and is implemented by the latter internally. `OpenProtocol()` offers many additional options such as exclusivity and notifying consumers when a protocol is being uninstalled [6, Section 7.3].

Listing 7.3 shows how `HandleProtocol()` can be used to receive the Simple Text Input Ex Protocol instance installed on the active console input device [6, Section 4.3]. The input parameters are a device handle, the GUID identifying the protocol and the address of a pointer to the protocol structure. When calling `HandleProtocol()`, the value of the pointer is modified to point to the corresponding protocol instance. The protocol instance itself is previously allocated by a driver and installed onto the device handle in `Start()` function of their Driver Binding Protocol. The driver assigns the function fields with functions residing in the driver's image. This is why a driver's image needs to remain loaded even after initial execution. The important fact about this process is that a driver installs only one protocol instance per device handle and every protocol user receives the same address to the same protocol instance, given they use the same device handle. The function interfaces of `HandleProtocol()` and `OpenProtocol()` would generally allow for the return of allocated memory containing a copy of the protocol's content, but the implementers of drivers, managing multiple devices, are encouraged to keep track of private data. Private data is necessary to manage a device, but not part of the protocol interface. The struct defining the private data contains the public protocol instance so that it is possible to calculate the address of the private data, using the protocol instance's address. The protocol instance address is subtracted by the offset of the protocol within the private struct [9, Section 8]. In Listing 7.4 we show an example of retrieving private data through the public protocol interface. This keeps the protocol interface limited to public functionality. The UEFI boot services are not aware of the size of the private data when managing protocol instances and therefore cannot make copies spanning the entire data. On top of that, the private data likely contains information about the device state, as changes in the state would have to occur in each protocol user's instance to remain in a synchronous state.

```
typedef struct
{
    UINTN Signature;
    EFI_DISK_IO_PROTOCOL DiskIo;
    EFI_BLOCK_IO_PROTOCOL *BlockIo;
} PRIVATE_DATA;
```

```

#define PRIVATE_DATA_FROM_THIS(This) \
    ((PRIVATE_DATA *)((CHAR8 *)(This) - OFFSET_OF(PRIVATE_DATA, DiskIo)))

EFI_STATUS EFIAPI DiskIoReadDisk(IN EFI_DISK_IO_PROTOCOL *This,
                                 IN UINT32 MediaId,
                                 IN UINT64 Offset,
                                 IN UINTN BufferSize,
                                 OUT VOID *Buffer)
{
    PRIVATE_DATA *Private = PRIVATE_DATA_FROM_THIS(This);

    Private->BlockIo->ReadBlocks(...);
}
```

Listing 7.4: Example of a driver using private data in the implementation of the Disk I/O Protocol

Since our UEFI payload is executed before the Windows Boot Manager, we can query all Simple Text Input Ex Protocol instances and change each function pointer of `ReadKeyStrokeEx()` to point to our function hook. When the Windows Boot Manager later receives the protocol instance and calls `ReadKeyStrokeEx()` our hook is called instead of the original function. The hook has to be implemented in memory, which remains loaded until the Windows Boot Manager uses `ReadKeyStrokeEx()`. We can do this using a boot driver, as its image remains loaded until `ExitBootServices()` is called. We also have to save the original function address, so that we can call it later. To associate where we took the original from, we store it together with a pointer to the protocol instance. Multiple different drivers could offer the same protocol, resulting in different function implementations being called depending on the device. When our hook is called we start by identifying which original function needs to be called using the protocol instance that is used as the first argument of the `ReadKeyStrokeEx()` function signature. We then call the original to read the pending keystroke, keeping track of the keystrokes (separately for each protocol instance), before returning the key data to the caller. We coin this BitLocker-specific keylogger *BitLogger*. A simplified version of how the hooking process works can be seen in Listing 7.5;

```
EFI_STATUS EFIAPI ReadKeyStrokeExHook(IN EFI_SIMPLE_TEXT_INPUT_EX_PROTOCOL *This,
                                      OUT EFI_KEY_DATA *KeyData);
{
    SimpleTextInputExHook *Hook = GetHookFromProtocol(This);
    Hook->ReadKeyStrokeExOriginal(This, KeyData);

    // log keystrokes
}
```

```

VOID HookSimpleTextInEx()
{
    gBS->LocateHandleBuffer(ByProtocol, &gEfiSimpleTextInputExProtocolGuid,
                            NULL, &HandleCount, Handles);

    gHooks = AllocatePool(HandleCount * sizeof(SimpleTextInputExHook));

    for (UINTN i = 0; i < HandleCount; ++i)
    {
        EFI_SIMPLE_TEXT_INPUT_EX_PROTOCOL *SimpleTextInEx;
        status = gBS->HandleProtocol(Handles[i],
                                     &gEfiSimpleTextInputExProtocolGuid,
                                     (VOID **)&SimpleTextInEx);

        SimpleTextInputExHook *Hook = &gHooks[gHookCount++];
        Hook->SimpleTextInEx = SimpleTextInEx;
        Hook->ReadKeyStrokeExOriginal = SimpleTextInEx->ReadKeyStrokeEx;

        SimpleTextInEx->ReadKeyStrokeEx = ReadKeyStrokeExHook;
    }
}
```

Listing 7.5: Simplified example of hooking the Simple Text Input Ex Protocol

We want to use the recovery key programmatically, so we cannot simply log all key presses in chronological order and evaluate them by hand later. The BitLocker recovery prompt has a few rules and does not allow the user to simply enter any possible combination of digits. Each entered block is checked for validity before allowing the cursor to advance to another block. This also applies when moving the cursor backward to a previously entered block, while incomplete blocks are not evaluated. A block passes the validity check when it is divisible by 11 [22, Section 9], while this is also a requirement applying to the recovery key, no further checks regarding the general correctness are done unless a complete key is entered. The cursor can be used to increment and decrement the current digit by using the up and down arrow keys. Because of this and validity checks when trying to move the cursor out of a block, we have to implement internal tracking of the cursor movement. The recovery prompt in Figure 7.6 also tells us that the function keys (F1-F10) are accepted as input, with F10 mapping to zero, so we have to log these key presses as well.

7.3.3 Dislocker

To make use of the recovery key we can use an open source software called *Dislocker*, which implements the Filesystem in Userspace (FUSE) interface to offer mounting a BitLocker encrypted partitions under Linux, supporting read and write access [67].

In Section 4.3.3 we discussed how the BitLocker filter driver integrates into Windows. To integrate Dislocker into UEFI, we start by analyzing how the UEFI NTFS driver works. We can start by checking the EDK II module file of the driver. Among the source files and libraries required to build a module, the file also declares which (protocol) GUIDs the driver consumes and produces [68]. A snippet of the *protocols section* is listed in Listing 7.6.

```
[Protocols]
  gEfiDiskIoProtocolGuid
  gEfiDiskIo2ProtocolGuid
  gEfiBlockIoProtocolGuid
  gEfiBlockIo2ProtocolGuid
  gEfiSimpleFileSystemProtocolGuid
  gEfiUnicodeCollationProtocolGuid
  gEfiUnicodeCollation2ProtocolGuid
  gEfiDevicePathToTextProtocolGuid
```

Listing 7.6: Protocols section of NTFS driver's module file

We can ignore the last three protocols as they are not directly involved in media access. The Simple File System Protocol is produced by the driver, as it installs the protocol onto handles of devices it supports. So the only relevant protocols it consumes are the Disk I/O Protocol and the Block I/O Protocol, as well as their respective asynchronous counterparts marked by the trailing 2. We will ignore the asynchronous protocols, as they only serve to further abstract their synchronous version [6, Sections 13.8 and 13.10]. The same can be said for the Disk I/O Protocol, as it abstracts the Block I/O Protocol to offer an offset-length driven continuous access to the underlying block device [6, Section 13.7]. The Block I/O Protocol is only used directly to retrieve volume size and block size, as well as read the first block to determine whether the volume is formatted using NTFS.

The source code analysis shows that the file-wise access the driver offers through Simple File System Protocol and the Simple File System Protocol is multiple abstraction layers built on top of block-wise access to the underlying media through the Block I/O Protocol. To imitate the BitLocker filter driver in Figure 4.2, which en- and decrypts each block as it passes through, we hook the Block I/O Protocol functions `ReadBlocks()` and `WriteBlocks()`. Their signatures are given in the appendix in Listing A.9. This allows for our hooks to create a layer where we can perform Dislocker operations on blocks passing through. A diagram of the volume access protocol stack with our Dislocker hook layer can be seen in Figure 7.7. Each read operation is decrypted before being passed upwards and each write operation is encrypted before being written to disk.

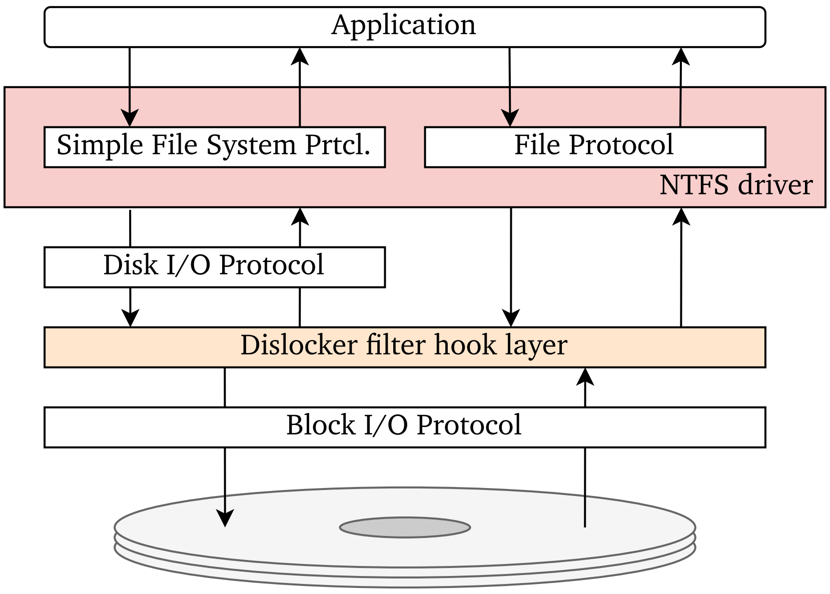


Fig. 7.7.: Dislocker Volume Access Protocol Stack

When we look at the Dislocker source code, we find that Dislocker offers two main functions, `dislock()` and `enlock()`, each taking offset-length parameters, comparable to the Disk I/O Protocol abstraction. `dislock()` is implemented to read from the underlying volume using `pread`, before decrypting the data and handing it to the caller. `enlock()` encrypts the data before it writes it to the disk using `pwrite`. The two functions directly access the volume and are not implemented as simple de- and encryption algorithms performed on data in memory, because some sectors of a volume are not encrypted (BitLocker metadata) or are mapped to different sectors. In our hooked `ReadBlocks` and `WriteBlocks` functions, we simply call `dislock()` and `enlock()` respectively and have the Dislocker implementation call the original `ReadBlocks` and `WriteBlocks` functions through `pread` and `pwrite` when it needs to access the underlying volume. This way, Dislocker can choose which blocks to perform its operations on, as well as freely remap underlying sectors. The general hooking process is depicted in Listing 7.7.

```
EFI_STATUS EFIAPI ReadBlocksHook(IN EFI_BLOCK_IO_PROTOCOL *This,
                                 IN UINT32 MediaId,
                                 IN EFI_LBA Lba,
                                 IN UINTN BufferSize, OUT VOID *Buffer)
{
    BlockIoHook *Hook = GetHookFromProtocol(This);
    int Read = dislock(Hook->dis_ctx, Buffer, Lba * This->Media->BlockSize, BufferSize);
    return Read == BufferSize ? EFI_SUCCESS : RETURN_PROTOCOL_ERROR;
}

EFI_STATUS EFIAPI WriteBlocksHook(IN EFI_BLOCK_IO_PROTOCOL *This,
                                  IN UINT32 MediaId,
                                  IN EFI_LBA Lba,
                                  IN UINTN BufferSize, IN VOID *Buffer)
{
    BlockIoHook *Hook = GetHookFromProtocol(This);
    int Read = enlock(Hook->dis_ctx, Buffer, Lba * This->Media->BlockSize, BufferSize);
    return Read == BufferSize ? EFI_SUCCESS : RETURN_PROTOCOL_ERROR;
}

ssize_t pread(int fd, void *buf, size_t nbytes, off_t offset)
{
    BlockIoHook *Hook = GetHookDataFromIndex(fd);
    Hook->ReadBlocksOriginal(hook->protocol,
                             BlockIo->Media->MediaId,
                             offset / Hook->BlockIo->Media->BlockSize,
                             nbytes, buf);
    return nbytes;
}

ssize_t pwrite(int fd, const void *buf, size_t nbytes, off_t offset)
{
    BlockIoHook *Hook = GetHookDataFromIndex(fd);
    Hook->WriteBlocksOriginal(hook->protocol,
                              BlockIo->Media->MediaId,
                              offset / Hook->BlockIo->Media->BlockSize,
                              nbytes, (void *)buf);
    return nbytes;
}
```

Listing 7.7: Simplified example of hooking the Block I/O Protocol

For the previous two attacks the timing of deploying the payload did not matter, as long as it was done before Windows loads the HKLM\SOFTWARE registry hive, thus simply performing the deployment as soon as the UEFI payload is executed was an option, as this happens before any Windows boot related actions are performed. With BitLocker, we have to deploy after *BitLogger* was able to obtain the recovery key. We then initialize Dislocker with the recovery key, to enable the transparent Block I/O Protocol hook layer. We then need to reconnect all Driver Binding Protocol instances to all controllers to trigger a (re-)evaluation. The BitLocker encrypted drive now appears unencrypted to the driver, allowing it to install its Simple File System Protocol instance on the device. From here we simply perform our attack, as developed in Section 7.1, to deploy the Windows payload and import our modified registry key. After doing this we need to disable the Dislocker hook layer again, as otherwise, Windows is unable to boot and instead attempts Windows recovery.

Windows recovery causes the recovery environment to show a second recovery prompt, but now outside the UEFI environment with their own device drivers. This recovery environment is located on the unencrypted NTFS partition created during installation. It is also accessible when pressing the escape key during the initial UEFI environment's recovery prompt. We want to prevent the user from switching environments, as our *BitLogger* would not be able to obtain the recovery key. In our `ReadKeyStrokeEx` hook, we can suppress the user's escape keystroke and return a different key to the Windows Boot Manager.

If we were to attack Windows 10 we would be done now, but Windows 11 will show the recovery prompt every boot. Windows 10 seems to automatically reseal the VMK with the new PCR values, whereas Windows 11 does not, so our UEFI payload keeps invalidating the PCR values. We can add a few calls to the BitLocker management tool `manage-bde` [69] within our Windows payload, deleting the old TPM protector and adding a new one. Now our UEFI payload is part of the measurements and considered trusted, and subsequent boots do not trigger the BitLocker recovery prompt anymore.

7.3.4 BitLocker Access without Recovery Key

When BitLocker uses a validation profile that does not include PCR values where our UEFI payload is measured into or the TPM protector already included our UEFI payload when the VMK was sealed, the TPM's unseal operation yields the Windows Boot Manager the unencrypted VMK, despite our UEFI payload being executed. This is the case for our rootkit when BitLocker uses Secure Boot for integrity validation and PCR7 is bound. The validation profile `{7, 11}` is used, while our rootkit is part of the measurements in PCR0.

The recovery prompt is not triggered, and we are unable to receive a recovery key and cannot initialize Dislocker. In the case we caused the TPM protector update following the *BitLogger* attack, we could simply save the recovery key in an unencrypted region of the drive. This is not necessary as we are now in a position where we can gain access to the drive without the recovery key.

Under these circumstances, execution of our UEFI payload does not influence the outcome of the interaction between the Windows boot manager and the TPM when unsealing the encrypted VMK. This allows us to be a spectator of the process without interrupting it. [70, 71] have proven the viability of sniffing the TPM communication directly off the hardware bus. Similarly, we can sniff the communication hooking the TCG2 Protocol, which is used to abstract the TPM communication in the UEFI environment. The `SubmitCommand()` function is used to request the unseal operation from the TPM. We can hook this function and filter for the correct command submission using the header structures of the request and response. We then extract the unencrypted VMK from the command response, as already done in [71]. The VMK can then be simply passed to Dislocker for the initialization of our hook layer.

8 Results

We were able to implement UEFI attacks in the form of a UEFI firmware rootkit and a UEFI bootloader rootkit (bootkit). Both were able to deploy Windows-level payload from within the UEFI environment using an NTFS driver. We were able to modify the Windows Registry by porting the Linux utility reged to UEFI. Through the manipulation of a Task Scheduler master registry key, we were able to have our Windows payload executed with the privileges of the built-in local system account. The execution happens at system boot before login.

We showed that the attack using our rootkit is unaffected by Secure Boot, as Secure Boot relies on the PF as its root of trust. This leaves Secure Boot unable to verify the behavior of the PI, including our rootkit. As Secure Boot's threat model consists of the hand-over process from the platform firmware to UEFI images, the attack through our bootkit is successfully mitigated.

When the target system uses BDE with a TPM 2.0 and the default validation profile `{0, 2, 4, 11}`, both our root-and bootkit trigger the BitLocker recovery prompt protecting the hard drive from unauthorized access and stopping the boot process. We also show that Windows, giving the user the ability to override the TPM's security reaction by entering the recovery key, allows us to overcome BDE. Our *BitLogger* was able to log the entered keystrokes to obtain the recovery key. We were then able to use the recovery key with our UEFI port of Dislocker to mount the encrypted drive, allowing us to repeat our initial attack of deploying a payload and modifying the registry.

In the case of our UEFI payload being part of the TPM measurements used to encrypt the VMK or when a validation profile is used that does not include the measurements of our payload. We showed that this is the case when Secure Boot is enabled and PCR7 is bound. Binding is possible when Secure Boot only uses Microsoft's signature DB required to boot Windows. BitLocker then uses a validation profile of `{7, 11}`, leaving out PCR0 where our rootkit is measured into. This provides us a chance to sniff the communication between the TPM and the Windows Boot Manager to retrieve the unencrypted VMK for use with Dislocker, making it possible for our rootkit to gain access to the system without requiring any prior knowledge or additional user input.

Discussion 9

The biggest takeaway of our attacks is, that counter-intuitively BitLocker-protected Windows 11 installations are likely less secure against UEFI rootkits when Secure Boot is enabled compared to when it is disabled. We disprove Microsoft's statements that "Windows is secure regardless of using TPM profile `{0, 2, 4, 11}` or profile `{7, 11}`" [41] and that "Secure boot ensures that the computer's pre-boot environment loads only firmware that is digitally signed by authorized software publishers." [72]. Excluding PCR0 in the validation profile and relying solely on Secure Boot for integrity validation is a flawed approach, as this is not part of Secure Boot's threat model. On the contrary, Secure Boot relies on the firmware as its root of trust, meaning it is not able to validate the behavior of the PI process. Its purpose is to enforce authentication when the PF interacts with UEFI images outside the firmware image. Microsoft also states "When this policy [*Allow Secure Boot for integrity validation*] is enabled and the **hardware is capable** of using Secure Boot for BitLocker scenarios, the *Use enhanced Boot Configuration Data validation profile* group policy setting is ignored" [72], which might refer to Hardware Validated Boot. Hardware Validated Boot moves the root of trust out of the firmware image into hardware and together with Secure Boot would be a sufficient way to replace the early boot component measurements of the TPM for BitLocker. But as we have shown, the policy does not require Hardware Validated Boot. Microsoft's decision to use Secure Boot for integrity validation leaves a lot of systems more vulnerable than they should be. Any attacker with read and write access to the firmware image can gain control over such a system. This is especially easy for attackers with physical access, with a stolen laptop being a prime candidate for the attack. We cannot even argue for Microsoft doing this out of a trade-off between security and convenience. It is true that leaving out PCR0 does significantly reduce the chance of the TPM being unable to unseal the VMK after a firmware update, making validation profiles containing PCR0 more prone to false positives in comparison. It is also the case that Secure Boot does not enforce its authentication and policies on code that is measured into PCR0. If Microsoft were to have intentionally made this trade-off, Secure Boot should not be the deciding factor on whether to leave out PCR0 or not. A validation profile that maintains a similarly reduced security, compared to `{7, 11}`, for systems without Secure Boot would have been `{2, 4, 11}`. With this profile, only measurements of the TPM regarding code that Secure Boot reigns over, are used for BitLocker, and PCR0 would have also been left out for convenience. Microsoft's decision, instead, causes different levels of security across systems with and without Secure

Boot, with systems using Secure Boot being at the short end of the stick. Secure Boot effectively leads to a hidden degradation of security.

As a result, we advise overriding the default validation profile settings when using BitLocker. For additional security, PCR0 should always be included.

9.1 Recovery Key as Security Override

Even when BitLocker correctly picks up on an integrity violation, the security advantage still highly depends on the user's reaction to the recovery prompt. While BitLocker protects in scenarios where the system owner is not present by preventing unauthorized access to the hard drive, we argue that the significance of the recovery prompt's appearance is dismissed by providing the system owner an immediate ability to override the security reaction with a recovery key. This leaves the burden of security enforcement to the user. It is now their responsibility to be aware of the security-related implications of the recovery prompt and to act accordingly upon them. We can look at how the user is influenced in their decision. Taking a closer look at the recovery prompt in Figure 7.6, we see that the message suggests a configuration change might have caused the prompt to appear. It is hinting to the user, that the removal of a disk or a USB stick might fix the issue. The rest is only about helping the user to find their recovery key to enter.

When taking appropriate precautions the hard drive should be removed from the system and inserted into a trustworthy system. From here the recovery key can be used to fulfill its namesake, recovering data from the drive. Entering the recovery key into the recovery prompt is not data recovery but an overriding of a security mechanism. A user presumably assumes to have encountered the recovery prompt through a false positive, a firmware update without prior BitLocker suspension, boot configuration-related changes etc. When there is no reasonable assumption for the user to have encountered the recovery prompt they should not enter the recovery key. After all the inherent problem is that the system's integrity has been violated, in what fashion is now unverifiable. It leaves the system in a state where no further trust should be put into it. A distinction about whether a false positive or malicious code has caused the recovery prompt is not possible. It is also the only time a user has a chance to react correctly, as their decision to further put trust into an infected system, causes from hereinafter that malicious code will be part of the root of trust.

Microsoft's decision to allow this security override created a dangerous precedent, especially since they do not display any warnings about the inherent danger. Instead of a recovery prompt, the user should have been made aware of the inherent loss of system integrity instead of normalizing the security override. Any future adjustments to provide more user awareness within the recovery prompt; can be manipulated by an attacker, as by definition the appearance of the prompt signals that there is no more system integrity. It is already possible to easily modify the message and Uniform Resource Locator (URL) displayed by the recovery prompt, as these can be configured through group policies [73], that are read from the BCD hive [74]. Even if the recovery prompt were to be removed in the future, phishing attacks could still replicate the prompt.

An attack that willingly triggers the BitLocker recovery prompt generally risks raising suspicion, which may lead to investigations and being discovered. It is somewhat of a last-ditch effort, that relies on social engineering and may be compared to phishing.

9.2 Mitigations

Enabling Hardware Validated Boot should prevent the execution of any malicious code within the firmware image. Using the TPM with additional authentication mechanisms like a PIN or USB also adds to the security against an attacker trying to gain access to a system without the owner's interaction, preventing the stolen laptop scenario, even if only `{7, 11}` is used. When the owner is present to enter the PIN into an infected system, it, unfortunately, does not provide any additional security. It is always beneficial to use a password to protect the interactive firmware menu, so Secure Boot cannot be disabled and booting into malicious removable media is prevented. System designers can also make access to the (SPI) flash more complicated, so an attacker will have more trouble modifying the firmware image.

10 Conclusion

Our practical analysis of UEFI threats against Windows 11 showed that enabling Secure Boot when using BitLocker comes with a hidden reduction in security. Microsoft misuses Secure Boot in an attempt to provide platform firmware integrity validation, where the TPM already offers a perfectly fine solution. With such a misconfigured BitLocker validation profile our rootkit was able to sniff the communication between the Windows Boot Manager and TPM without introducing side effects. Through interception of the *unseal* command, we gained access to the unencrypted BitLocker VMK, to decrypt the hard drive and deploy further payload in the Windows installation. By then modifying the Windows registry our payload was executed with privileges of the local system account.

Microsoft also has set a dangerous precedent by offering the user a mechanism to override the security reaction to integrity violations in an inherently untrustworthy system. In the case of a correctly configured BitLocker validation profile, the code of our root- or bootkit measured into the TPM cause the *unseal* operation to fail and the Windows Boot Manager to trigger a recovery prompt. The burden of security enforcement is now left to the user and when they decide to put further trust into the system and enter their recovery key, our *BitLogger* can record the performed keystrokes to decrypt the hard drive.

Future Work

Investigations into the RTM being established by the SRTM measuring itself could reveal flaws further up in the implementation of the measurement chain.

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List of Acronyms

ACPI	Advanced Configuration and Power Interface
AES	Advanced Encryption Standard
AL	Afterlife
AMD	Advanced Micro Devices
API	Application Programming Interface
BCD	Boot Configuration Data
BDE	BitLocker Drive Encryption
BDS	Boot Device Selection
BF	Boot Firmware
BFV	Boot Firmware Volume
BIOS	Basic Input/Output System
CA	Certificate Authority
CI	Code Integrity
CPU	Central Processing Unit
CRTM	Core Root of Trust for Measurement
CSM	Compatibility Support Module
DB	Data Base
DEPEX	Dependency Expressiaboveon
DLL	Dynamically Linked Library
DXE	Driver Execution Environment
EDK	EFI Development Kit
EFI	Extensible Firmware Interface
ELAM	Early-Launch Antimalware
ESP	EFI System Partition
FAT	File Allocation Table
FD	Firmware Device
FFS	Firmware File System
FUSE	Filesystem in Userspace
FV	Firmware Volume
FVE	Full Volume Encryption
FVEK	Full Volume Encryption Key
GPT	GUID Partition Table
GUID	Globally Unique Identifier

H-CRTM	Hardware-Core Root of Trust for Measurement
HOB	Hand-off Block
HVCI	Hypervisor-protected Code Integrity
I/O	Input/Output
IBB	Initial Boot Block
KEK	Key Exchange Key
KMCI	Kernel Mode Code Integrity
LBA	Logical Block Address
LPC	Low Pin Count
MBR	Master Boot Record
NTFS	New Technology File System
NVRAM	Non-volatile RAM
OEM	Original Equipment Manufacturer
OS	Operating System
OVMF	Open Virtual Machine Firmware
PC	Personal Computer
PCI	Peripheral Component Interconnect
PCR	Platform Configuration Register
PE32	Portable Executable 32-Bit
PEI	Pre-EFI Initialization
PEIM	Pre-EFI Initialization Module
PF	Platform Firmware
PI	Platform Initialization
PIN	Personal Identification Number
PK	Platform Key
PPI	PEIM-to-PEIM Interface
QEMU	Quick Emulator
RAM	Random Access Memory
ROM	Read-Only Memory
RT	Runtime
RTM	Root of Trust for Measurement
SEC	Security
SMM	System Management Mode
SPI	Serial Peripheral Interface
SRTM	Static Root of Trust for Measurement
TB	Terra Byte
TCG	Trusted Computing Group
TPM	Trusted Platform Module
TSL	Transient System Load

UEFI	Unified Extensible Firmware Interface
URL	Uniform Resource Locator
USB	Universal Serial Bus
UUID	Universally Unique Identifier
VBS	Virtualization Based Security
VMK	Volume Master Key
VSM	Virtualization Secure Mode
WDAC	Windows Defender Application Control
XML	Extensible Markup Language

Appendix A

A.1 System Table

```
typedef struct
{
    EFI_TABLE_HEADER Hdr;
    CHAR16 *FirmwareVendor;
    UINT32 FirmwareRevision;
    EFI_HANDLE ConsoleInHandle;
    EFI_SIMPLE_TEXT_INPUT_PROTOCOL *ConIn;
    EFI_HANDLE ConsoleOutHandle;
    EFI_SIMPLE_TEXT_OUTPUT_PROTOCOL *ConOut;
    EFI_HANDLE StandardErrorHandle;
    EFI_SIMPLE_TEXT_OUTPUT_PROTOCOL *StdErr;
    EFI_RUNTIME_SERVICES *RuntimeServices;
    EFI_BOOT_SERVICES *BootServices;
    UINTN NumberOfTableEntries;
    EFI_CONFIGURATION_TABLE *ConfigurationTable;
} EFI_SYSTEM_TABLE;
```

Listing A.1: System Table

A.1.1 Boot Services

```
typedef struct
{
    EFI_TABLE_HEADER Hdr;
    EFI_RAISE_TPL RaiseTPL;
    EFI_RESTORE_TPL RestoreTPL;
    EFI_ALLOCATE_PAGES AllocatePages;
    EFI_FREE_PAGES FreePages;
    EFI_GET_MEMORY_MAP GetMemoryMap;
    EFI_ALLOCATE_POOL AllocatePool;
    EFI_FREE_POOL FreePool;
    EFI_CREATE_EVENT CreateEvent;
    EFI_SET_TIMER SetTimer;
    EFI_WAIT_FOR_EVENT WaitForEvent;
    EFI_SIGNAL_EVENT SignalEvent;
    EFI_CLOSE_EVENT CloseEvent;
    EFI_CHECK_EVENT CheckEvent;
    EFI_INSTALL_PROTOCOL_INTERFACE InstallProtocolInterface;
    EFI_REINSTALL_PROTOCOL_INTERFACE ReinstallProtocolInterface;
    EFI_UNINSTALL_PROTOCOL_INTERFACE UninstallProtocolInterface;
    EFI_HANDLE_PROTOCOL HandleProtocol;
    VOID *Reserved;
    EFI_REGISTER_PROTOCOL_NOTIFY RegisterProtocolNotify;
    EFI_LOCATE_HANDLE LocateHandle;
    EFI_LOCATE_DEVICE_PATH LocateDevicePath;
    EFI_INSTALL_CONFIGURATION_TABLE InstallConfigurationTable;
    EFI_IMAGE_LOAD LoadImage;
    EFI_IMAGE_START StartImage;
    EFI_EXIT Exit;
    EFI_IMAGE_UNLOAD UnloadImage;
    EFI_EXIT_BOOT_SERVICES ExitBootServices;
    EFI_GET_NEXT_MONOTONIC_COUNT GetNextMonotonicCount;
    EFI_STALL Stall;
    EFI_SET_WATCHDOG_TIMER SetWatchdogTimer;
    EFI_CONNECT_CONTROLLER ConnectController;
    EFI_DISCONNECT_CONTROLLER DisconnectController;
    EFI_OPEN_PROTOCOL OpenProtocol;
    EFI_CLOSE_PROTOCOL CloseProtocol;
    EFI_OPEN_PROTOCOL_INFORMATION OpenProtocolInformation;
    EFI_PROTOCOLS_PER_HANDLE ProtocolsPerHandle;
    EFI_LOCATE_HANDLE_BUFFER LocateHandleBuffer;
    EFI_LOCATE_PROTOCOL LocateProtocol;
    EFI_INSTALL_MULTIPLE_PROTOCOL_INTERFACES InstallMultipleProtocolInterfaces;
    EFI_UNINSTALL_MULTIPLE_PROTOCOL_INTERFACES UninstallMultipleProtocolInterfaces;
    EFI_CALCULATE_CRC32 CalculateCrc32;
    EFI_COPY_MEM CopyMem;
    EFI_SET_MEM SetMem;
    EFI_CREATE_EVENT_EX CreateEventEx;
} EFI_BOOT_SERVICES;
```

Listing A.2: Boot Services

A.1.2 Runtime Services

```
typedef struct
{
    EFI_TABLE_HEADER Hdr;
    EFI_GET_TIME GetTime;
    EFI_SET_TIME SetTime;
    EFI_GET_WAKEUP_TIME GetWakeupTime;
    EFI_SET_WAKEUP_TIME SetWakeupTime;
    EFI_SET_VIRTUAL_ADDRESS_MAP SetVirtualAddressMap;
    EFI_CONVERT_POINTER ConvertPointer;
    EFI_GET_VARIABLE GetVariable;
    EFI_GET_NEXT_VARIABLE_NAME GetNextVariableName;
    EFI_SET_VARIABLE SetVariable;
    EFI_GET_NEXT_HIGH_MONO_COUNT GetNextHighMonotonicCount;
    EFI_RESET_SYSTEM ResetSystem;
    EFI_UPDATE_CAPSULE UpdateCapsule;
    EFI_QUERY_CAPSULE_CAPABILITIES QueryCapsuleCapabilities;
    EFI_QUERY_VARIABLE_INFO QueryVariableInfo;
} EFI_RUNTIME_SERVICES;
```

Listing A.3: Runtime Services

A.2 Protocols

A.2.1 Loaded Image Protocol

```
typedef struct
{
  UINT32 Revision;
  EFI_HANDLE ParentHandle;
  EFI_SYSTEM_TABLE *SystemTable;
  EFI_HANDLE DeviceHandle;
  EFI_DEVICE_PATH_PROTOCOL *FilePath;
  VOID *Reserved;
  UINT32 LoadOptionsSize;
  VOID *LoadOptions;
  VOID *ImageBase;
  UINT64 ImageSize;
  EFI_MEMORY_TYPE ImageCodeType;
  EFI_MEMORY_TYPE ImageDataType;
  EFI_IMAGE_UNLOAD Unload;
} EFI_LOADED_IMAGE_PROTOCOL;

extern EFI_GUID gEfiLoadedImageProtocolGuid;
extern EFI_GUID gEfiLoadedImageDevicePathProtocolGuid;
```

Listing A.4: Loaded Image Protocol

A.2.2 Driver Binding Protocol

```
typedef EFI_STATUS(EFIAPI *EFI_DRIVER_BINDING_SUPPORTED)(
    IN EFI_DRIVER_BINDING_PROTOCOL *This,
    IN EFI_HANDLE ControllerHandle,
    IN EFI_DEVICE_PATH_PROTOCOL *RemainingDevicePath OPTIONAL);

typedef EFI_STATUS(EFIAPI *EFI_DRIVER_BINDING_START)(
    IN EFI_DRIVER_BINDING_PROTOCOL *This,
    IN EFI_HANDLE ControllerHandle,
    IN EFI_DEVICE_PATH_PROTOCOL *RemainingDevicePath OPTIONAL);

typedef EFI_STATUS(EFIAPI *EFI_DRIVER_BINDING_STOP)(
    IN EFI_DRIVER_BINDING_PROTOCOL *This,
    IN EFI_HANDLE ControllerHandle,
    IN UINTN NumberOfChildren,
    IN EFI_HANDLE *ChildHandleBuffer OPTIONAL);

struct _EFI_DRIVER_BINDING_PROTOCOL
{
    EFI_DRIVER_BINDING_SUPPORTED Supported;
    EFI_DRIVER_BINDING_START Start;
    EFI_DRIVER_BINDING_STOP Stop;
    UINT32 Version;
    EFI_HANDLE ImageHandle;
    EFI_HANDLE DriverBindingHandle;
};

extern EFI_GUID gEfiDriverBindingProtocolGuid;
```

Listing A.5: Driver Binding Protocol

A.2.3 Simple File System and File Protocol

A.2.3.1. Simple File System Protocol

```
typedef EFI_STATUS(EFIAPI *EFI_SIMPLE_FILE_SYSTEM_PROTOCOL_OPEN_VOLUME)(
    IN EFI_SIMPLE_FILE_SYSTEM_PROTOCOL *This,
    OUT EFI_FILE_PROTOCOL **Root);

struct _EFI_SIMPLE_FILE_SYSTEM_PROTOCOL
{
  UINT64 Revision;
  EFI_SIMPLE_FILE_SYSTEM_PROTOCOL_OPEN_VOLUME OpenVolume;
};

extern EFI_GUID gEfiSimpleFileSystemProtocolGuid;
```

Listing A.6: Simple File System Protocol

A.2.3.2. File Protocol

```
struct _EFI_FILE_PROTOCOL
{
  UINT64 Revision;
  EFI_FILE_OPEN Open;
  EFI_FILE_CLOSE Close;
  EFI_FILE_DELETE Delete;
  EFI_FILE_READ Read;
  EFI_FILE_WRITE Write;
  EFI_FILE_GET_POSITION GetPosition;
  EFI_FILE_SET_POSITION SetPosition;
  EFI_FILE_GET_INFO GetInfo;
  EFI_FILE_SET_INFO SetInfo;
  EFI_FILE_FLUSH Flush;
  EFI_FILE_OPEN_EX OpenEx;
  EFI_FILE_READ_EX ReadEx;
  EFI_FILE_WRITE_EX WriteEx;
  EFI_FILE_FLUSH_EX FlushEx;
};
```

Listing A.7: File Protocol

A.2.4 Disk I/O Protocol

```
typedef EFI_STATUS(EFIAPI *EFI_DISK_READ)(
      IN EFI_DISK_IO_PROTOCOL *This,
      IN UINT32 MediaId,
      IN UINT64 Offset,
      IN UINTN BufferSize,
      OUT VOID *Buffer);

typedef EFI_STATUS(EFIAPI *EFI_DISK_WRITE)(
      IN EFI_DISK_IO_PROTOCOL *This,
      IN UINT32 MediaId,
      IN UINT64 Offset,
      IN UINTN BufferSize,
      IN VOID *Buffer);

struct _EFI_DISK_IO_PROTOCOL
{
   UINT64 Revision;
   EFI_DISK_READ ReadDisk;
   EFI_DISK_WRITE WriteDisk;
};

extern EFI_GUID gEfiDiskIoProtocolGuid;
```

Listing A.8: Disk I/O Protocol

A.2.5 Block I/O Protocol

```
typedef EFI_STATUS(EFIAPI *EFI_BLOCK_RESET)(
    IN EFI_BLOCK_IO_PROTOCOL *This,
    IN BOOLEAN ExtendedVerification);

typedef EFI_STATUS(EFIAPI *EFI_BLOCK_READ)(
    IN EFI_BLOCK_IO_PROTOCOL *This,
    IN UINT32 MediaId,
    IN EFI_LBA Lba,
    IN UINTN BufferSize,
    OUT VOID *Buffer);

typedef EFI_STATUS(EFIAPI *EFI_BLOCK_WRITE)(
    IN EFI_BLOCK_IO_PROTOCOL *This,
    IN UINT32 MediaId,
    IN EFI_LBA Lba,
    IN UINTN BufferSize,
    IN VOID *Buffer);

typedef EFI_STATUS(EFIAPI *EFI_BLOCK_FLUSH)(
    IN EFI_BLOCK_IO_PROTOCOL *This);

struct _EFI_BLOCK_IO_PROTOCOL
{
    UINT64 Revision;
    EFI_BLOCK_IO_MEDIA *Media;
    EFI_BLOCK_RESET Reset;
    EFI_BLOCK_READ ReadBlocks;
    EFI_BLOCK_WRITE WriteBlocks;
    EFI_BLOCK_FLUSH FlushBlocks;
};

extern EFI_GUID gEfiBlockIoProtocolGuid;
```

Listing A.9: Block I/O Protocol

A.2.6 Boot Device Selection (BDS) Architectural Protocol

```
typedef VOID(EFIAPI *EFI_BDS_ENTRY)(
    IN EFI_BDS_ARCH_PROTOCOL *This);

struct _EFI_BDS_ARCH_PROTOCOL
{
    EFI_BDS_ENTRY Entry;
};

extern EFI_GUID gEfiBdsArchProtocolGuid;
```

Listing A.10: BDS Architectural Protocol

A.2.7 Firmware Volume2 Protocol

```
typedef EFI_STATUS(EFIAPI *EFI_FV_READ_FILE)(
    IN CONST EFI_FIRMWARE_VOLUME2_PROTOCOL *This,
    IN CONST EFI_GUID *NameGuid,
    IN OUT VOID **Buffer,
    IN OUT UINTN *BufferSize,
    OUT EFI_FV_FILETYPE *FoundType,
    OUT EFI_FV_FILE_ATTRIBUTES *FileAttributes,
    OUT UINT32 *AuthenticationStatus);

typedef EFI_STATUS(EFIAPI *EFI_FV_READ_SECTION)(
    IN CONST EFI_FIRMWARE_VOLUME2_PROTOCOL *This,
    IN CONST EFI_GUID *NameGuid,
    IN EFI_SECTION_TYPE SectionType,
    IN UINTN SectionInstance,
    IN OUT VOID **Buffer,
    IN OUT UINTN *BufferSize,
    OUT UINT32 *AuthenticationStatus);

struct _EFI_FIRMWARE_VOLUME2_PROTOCOL
{
    EFI_FV_GET_ATTRIBUTES GetVolumeAttributes;
    EFI_FV_SET_ATTRIBUTES SetVolumeAttributes;
    EFI_FV_READ_FILE ReadFile;
    EFI_FV_READ_SECTION ReadSection;
    EFI_FV_WRITE_FILE WriteFile;
    EFI_FV_GET_NEXT_FILE GetNextFile;
    UINT32 KeySize;
    EFI_HANDLE ParentHandle;
    EFI_FV_GET_INFO GetInfo;
    EFI_FV_SET_INFO SetInfo;
};

extern EFI_GUID gEfiFirmwareVolume2ProtocolGuid;
```

Listing A.11: BDS Protocol

A.2.8 Simple Text Input Protocol

```
typedef struct
{
  UINT16 ScanCode;
  CHAR16 UnicodeChar;
} EFI_INPUT_KEY;

typedef EFI_STATUS(EFIAPI *EFI_INPUT_RESET)(
      IN EFI_SIMPLE_TEXT_INPUT_PROTOCOL *This,
      IN BOOLEAN ExtendedVerification);

typedef EFI_STATUS(EFIAPI *EFI_INPUT_READ_KEY)(
      IN EFI_SIMPLE_TEXT_INPUT_PROTOCOL *This,
      OUT EFI_INPUT_KEY *Key);

struct _EFI_SIMPLE_TEXT_INPUT_PROTOCOL
{
  EFI_INPUT_RESET Reset;
  EFI_INPUT_READ_KEY ReadKeyStroke;
  EFI_EVENT WaitForKey;
};

extern EFI_GUID gEfiSimpleTextInProtocolGuid;
```

Listing A.12: Simple Text Input Protocol

A.2.9 Simple Text Input Ex Protocol

```
typedef struct
{
    UINT16 ScanCode;
    CHAR16 UnicodeChar;
} EFI_INPUT_KEY;

typedef EFI_STATUS(EFIAPI *EFI_INPUT_READ_KEY_EX)(
    IN EFI_SIMPLE_TEXT_INPUT_EX_PROTOCOL *This,
    OUT EFI_KEY_DATA *KeyData);

typedef EFI_STATUS(EFIAPI *EFI_SET_STATE)(
    IN EFI_SIMPLE_TEXT_INPUT_EX_PROTOCOL *This,
    IN EFI_KEY_TOGGLE_STATE *KeyToggleState);

typedef EFI_STATUS(EFIAPI *EFI_KEY_NOTIFY_FUNCTION)(
    IN EFI_KEY_DATA *KeyData);

typedef EFI_STATUS(EFIAPI *EFI_REGISTER_KEYSTROKE_NOTIFY)(
    IN EFI_SIMPLE_TEXT_INPUT_EX_PROTOCOL *This,
    IN EFI_KEY_DATA *KeyData,
    IN EFI_KEY_NOTIFY_FUNCTION KeyNotificationFunction,
    OUT VOID **NotifyHandle);

typedef EFI_STATUS(EFIAPI *EFI_UNREGISTER_KEYSTROKE_NOTIFY)(
    IN EFI_SIMPLE_TEXT_INPUT_EX_PROTOCOL *This,
    IN VOID *NotificationHandle);

struct _EFI_SIMPLE_TEXT_INPUT_EX_PROTOCOL
{
    EFI_INPUT_RESET_EX Reset;
    EFI_INPUT_READ_KEY_EX ReadKeyStrokeEx;
    EFI_EVENT WaitForKeyEx;
    EFI_SET_STATE SetState;
    EFI_REGISTER_KEYSTROKE_NOTIFY RegisterKeyNotify;
    EFI_UNREGISTER_KEYSTROKE_NOTIFY UnregisterKeyNotify;
};

extern EFI_GUID gEfiSimpleTextInputExProtocolGuid;
```

Listing A.13: Simple Text Input Ex Protocol

A.2.10 TCG2 Protocol

```
typedef EFI_STATUS(EFIAPI *EFI_TCG2_HASH_LOG_EXTEND_EVENT)(
    IN EFI_TCG2_PROTOCOL *This,
    IN UINT64 Flags,
    IN EFI_PHYSICAL_ADDRESS DataToHash,
    IN UINT64 DataToHashLen,
    IN EFI_TCG2_EVENT *EfiTcgEvent);

typedef EFI_STATUS(EFIAPI *EFI_TCG2_SUBMIT_COMMAND)(
    IN EFI_TCG2_PROTOCOL *This,
    IN UINT32 InputParameterBlockSize,
    IN UINT8 *InputParameterBlock,
    IN UINT32 OutputParameterBlockSize,
    IN UINT8 *OutputParameterBlock);

typedef EFI_STATUS(EFIAPI *EFI_TCG2_GET_ACTIVE_PCR_BANKS)(
    IN EFI_TCG2_PROTOCOL *This,
    OUT UINT32 *ActivePcrBanks);

typedef EFI_STATUS(EFIAPI *EFI_TCG2_SET_ACTIVE_PCR_BANKS)(
    IN EFI_TCG2_PROTOCOL *This,
    IN UINT32 ActivePcrBanks);

struct tdEFI_TCG2_PROTOCOL
{
    EFI_TCG2_GET_CAPABILITY GetCapability;
    EFI_TCG2_GET_EVENT_LOG GetEventLog;
    EFI_TCG2_HASH_LOG_EXTEND_EVENT HashLogExtendEvent;
    EFI_TCG2_SUBMIT_COMMAND SubmitCommand;
    EFI_TCG2_GET_ACTIVE_PCR_BANKS GetActivePcrBanks;
    EFI_TCG2_SET_ACTIVE_PCR_BANKS SetActivePcrBanks;
    EFI_TCG2_GET_RESULT_OF_SET_ACTIVE_PCR_BANKS GetResultOfSetActivePcrBanks;
};

extern EFI_GUID gEfiTcg2ProtocolGuid;
```

Listing A.14: TCG2 Protocol

A.2.11 Security Architectural Protocols

A.2.11.1. Security Architectural Protocol

```
typedef EFI_STATUS(EFIAPI *EFI_SECURITY_FILE_AUTHENTICATION_STATE)(
    IN CONST EFI_SECURITY_ARCH_PROTOCOL *This,
    IN UINT32 AuthenticationStatus,
    IN CONST EFI_DEVICE_PATH_PROTOCOL *File);

struct _EFI_SECURITY_ARCH_PROTOCOL
{
  EFI_SECURITY_FILE_AUTHENTICATION_STATE FileAuthenticationState;
};

extern EFI_GUID gEfiSecurityArchProtocolGuid;
```

Listing A.15: Security Architectural Protocol

A.2.11.2. Security2 Architectural Protocol

```
typedef EFI_STATUS(EFIAPI *EFI_SECURITY2_FILE_AUTHENTICATION)(
    IN CONST EFI_SECURITY2_ARCH_PROTOCOL *This,
    IN CONST EFI_DEVICE_PATH_PROTOCOL *File OPTIONAL,
    IN VOID *FileBuffer,
    IN UINTN FileSize,
    IN BOOLEAN BootPolicy);

struct _EFI_SECURITY2_ARCH_PROTOCOL
{
    EFI_SECURITY2_FILE_AUTHENTICATION FileAuthentication;
};

extern EFI_GUID gEfiSecurity2ArchProtocolGuid;
```

Listing A.16: Security2 Architectural Protocol

A.2.12 Firmware Management Protocol

```
typedef EFI_STATUS(EFIAPI *EFI_FIRMWARE_MANAGEMENT_PROTOCOL_GET_IMAGE_INFO)(
    IN EFI_FIRMWARE_MANAGEMENT_PROTOCOL *This,
    IN OUT UINTN *ImageInfoSize,
    IN OUT EFI_FIRMWARE_IMAGE_DESCRIPTOR *ImageInfo,
    OUT UINT32 *DescriptorVersion,
    OUT UINT8 *DescriptorCount,
    OUT UINTN *DescriptorSize,
    OUT UINT32 *PackageVersion,
    OUT CHAR16 **PackageVersionName);

typedef EFI_STATUS(EFIAPI *EFI_FIRMWARE_MANAGEMENT_PROTOCOL_GET_IMAGE)(
    IN EFI_FIRMWARE_MANAGEMENT_PROTOCOL *This,
    IN UINT8 ImageIndex,
    OUT VOID *Image,
    IN OUT UINTN *ImageSize);

typedef EFI_STATUS(EFIAPI *EFI_FIRMWARE_MANAGEMENT_PROTOCOL_SET_IMAGE)(
    IN EFI_FIRMWARE_MANAGEMENT_PROTOCOL *This,
    IN UINT8 ImageIndex,
    IN CONST VOID *Image,
    IN UINTN ImageSize,
    IN CONST VOID *VendorCode,
    IN EFI_FIRMWARE_MANAGEMENT_UPDATE_IMAGE_PROGRESS Progress,
    OUT CHAR16 **AbortReason);

struct _EFI_FIRMWARE_MANAGEMENT_PROTOCOL
{
  EFI_FIRMWARE_MANAGEMENT_PROTOCOL_GET_IMAGE_INFO GetImageInfo;
  EFI_FIRMWARE_MANAGEMENT_PROTOCOL_GET_IMAGE GetImage;
  EFI_FIRMWARE_MANAGEMENT_PROTOCOL_SET_IMAGE SetImage;
  EFI_FIRMWARE_MANAGEMENT_PROTOCOL_CHECK_IMAGE CheckImage;
  EFI_FIRMWARE_MANAGEMENT_PROTOCOL_GET_PACKAGE_INFO GetPackageInfo;
  EFI_FIRMWARE_MANAGEMENT_PROTOCOL_SET_PACKAGE_INFO SetPackageInfo;
};

extern EFI_GUID gEfiFirmwareManagementProtocolGuid;
```

Listing A.17: Firmware Management Protocol

A.2.13 Partition Information Protocol

```
typedef struct
{
  UINT32 Revision;
  UINT32 Type;
  UINT8 System;
  UINT8 Reserved[7];
  union
  {
    MBR_PARTITION_RECORD Mbr;
    EFI_PARTITION_ENTRY Gpt;
  } Info;
} EFI_PARTITION_INFO_PROTOCOL;

extern EFI_GUID gEfiPartitionInfoProtocolGuid;
```

Listing A.18: Partition Information Protocol

A.3 Firmware File Types

Name	Value	Description
EFI_FV_FILETYPE_RAW	0x01	Binary data
EFI_FV_FILETYPE_FREEFORM	0x02	Sectioned data
EFI_FV_FILETYPE_SECURITY_CORE	0x03	Platform core code used during the SEC phase
EFI_FV_FILETYPE_PEI_CORE	0x04	PEI Foundation
EFI_FV_FILETYPE_DXE_CORE	0x05	DXE Foundation
EFI_FV_FILETYPE_PEIM	0x06	PEI module (PEIM)
EFI_FV_FILETYPE_DRIVER	0x07	DXE driver
EFI_FV_FILETYPE_COMBINED_PEIM_DRIVER	0x08	Combined PEIM/DXE driver
EFI_FV_FILETYPE_APPLICATION	0x09	Application
EFI_FV_FILETYPE_MM	0x0A	Contains a PE32+ image that will be loaded into MMRAM in MM Traditional Mode.
EFI_FV_FILETYPE_FIRMWARE_VOLUME_IMAGE	0x0B	Firmware volume image
EFI_FV_FILETYPE_COMBINED_MM_DXE	0x0C	Contains PE32+ image that will be dispatched by the DXE Dispatcher and will also be loaded into MMRAM in MM Tradition Mode.
EFI_FV_FILETYPE_MM_CORE	0x0D	MM Foundation that support MM Traditional Mode.
EFI_FV_FILETYPE_MM_STANDALONE	0x0E	Contains a PE32+ image that will be loaded into MMRAM in MM Standalone Mode.
EFI_FV_FILETYPE_MM_CORE_STANDALONE	0x0F	MM Foundation that support MM Tradition Mode and MM Standalone Mode.
EFI_FV_FILETYPE_OEM_MIN... EFI_FV_FILETYPE_OEM_MAX	0xC0-0xDF	OEM File Types
EFI_FV_FILETYPE_DEBUG_MIN... EFI_FV_FILETYPE_DEBUG_MAX	0xE0-0xEF	Debug/Test File Types
EFI_FV_FILETYPE_FFS_MIN... EFI_FV_FILETYPE_FFS_MAX	0xF0-0xFF	Firmware File System Specific File Types
EFI_FV_FILETYPE_FFS_PAD	0xF0	Pad File For FFS

Tab. A.1.: Firmware File Types (taken from [10, Vol. 3, Table 3-3])

A.4 Firmware File Section Types

Name	Value	Description
`EFI_SECTION_COMPRESSION`	`0x01`	Encapsulation section where other sections are compressed.
`EFI_SECTION_GUID_DEFINED`	`0x02`	Encapsulation section where other sections have format defined by a GUID.
`EFI_SECTION_DISPOSABLE`	`0x03`	Encapsulation section used during the build process but not required for execution.
`EFI_SECTION_PE32`	`0x10`	PE32+ Executable image.
`EFI_SECTION_PIC`	`0x11`	Position-Independent Code.
`EFI_SECTION_TE`	`0x12`	Terse Executable image.
`EFI_SECTION_DXE_DEPEX`	`0x13`	DXE Dependency Expression.
`EFI_SECTION_VERSION`	`0x14`	Version, Text and Numeric.
`EFI_SECTION_USER_INTERFACE`	`0x15`	User-Friendly name of the driver.
`EFI_SECTION_COMPATIBILITY16`	`0x16`	DOS-style 16-bit EXE.
`EFI_SECTION_FIRMWARE_VOLUME_IMAG`	`0x17`	PI Firmware Volume image.
`EFI_SECTION_FREEFORM_SUBTYPE_GUI`	`0x18`	Raw data with GUID in header to define format.
`EFI_SECTION_RAW`	`0x19`	Raw data.
`EFI_SECTION_PEI_DEPEX`	`0x1B`	PEI Dependency Expression.
`EFI_SECTION_MM_DEPEX`	`0x1C`	Leaf section type for determining the dispatch order for an MM Traditional driver in MM Traditional Mode or MM Standalone driver in MM Standalone Mode.

Tab. A.2.: Firmware File Section Types (taken from [10, Vol. 3, Table 3-4])