Techniques for Secure System Boot

Johansen, Kristian Tjelta

Momcilovic, Igor

Silva, Jonas Lien Sampaio Da

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Abstract

In this paper we are exploring some of the general techniques that can be implemented in order to secure the boot process of a system. The boot process of a system begins when the system is powered on and ends when the operating system is started. The objectives of this paper are as follows:

- Explain and discuss how the different methods for attaining a secure boot process work together.
- Show that it is important to secure the boot process of a system. This is demonstrated by discussing how the different components are vulnerable and through a proof of concept.
- Discuss weaknesses, problems and vulnerabilities with implementations of secure boot processes and how these can be mitigated.

We have found that:

- No single technique can be implemented to secure the whole boot process of a system.
- The security of the boot process is not stronger than the weakest link.
- Each component of the boot process should verify its subsequent component(s), starting with a trusted component.

1 INTRODUCTION

An insecure boot process will lead to an insecure system. This is due to the possibility of malware being launched in the boot process, which can render the system infected, unbeknownst to anti-malware software. We seek to answer how you can secure the boot process of the system.

Secure Boot is a term used for all techniques that help to secure the boot process - from platform initialization to the point where the operating system (OS) is loaded. The term is ambiguous, as it is sometimes used to describe specific implementations, such as *UEFI Secure Boot*. In this paper, we will distinguish between the different implementations and use the term Secure Boot in reference to the general protection of the boot process.

Due to the general complexity and variation on different implementations, we will assume that all systems are Unified Extensible Firmware Interface (UEFI) compliant computers, as per the UEFI [1] and UEFI PI [2] specifications. According to UEFI Forum [1], the UEFI specification "… describes an interface between the operating system (OS) and the platform firmware".

2 THE BOOT PROCESS

The general boot process of a computer consists of three main steps. First, the platform is initialized, this is the Platform Initialization step (PI) as defined in the UEFI PI specification [2]. The PI step starts when the system is powered on. After the platform is initialized in the PI step, the UEFI Boot Loader will load UEFI images[1], such as the OS Loader, which in turn will launch the OS along with its required components.

2.1 PLATFORM INITIALIZATION

The platform initialization is divided into four phases, Security (SEC), Pre-EFI initialization (PEI), Driver Execution Environment (DXE) and Boot Device Selection (BDS)[2].

2.1.1 SEC

When a computer is started it first enters the SEC phase. The SEC phase does the initial initialization of the system, such as delivering power to the components and initializing temporary memory (e.g. CPU cache). The SEC phase also serves as the system's Root of Trust. As we will explore later, some manufacturers choose to implement verification of the PEI in the SEC phase. After the minimum initialization, the phase is completed, and the flow continues to the PEI phase.

2.1.2 PEI

The PEI phase is responsible for a minimal initialization of the hardware, so that it is ready for the DXE phase. The phase consists of the PEI Foundation and PEI modules (PEIM). PEI Foundation is specific to the processor architecture of a specific system and is responsible for executing PEIMs. The PEIMs are vendor-specific initialization modules, for the different hardware components, such as the RAM and chipset. The execution code for the PEI phase is stored on the IBB (Initial Boot Block) implemented by the Original Equipment Manufacturer (OEM).

2.1.3 DXE

The main initialization of the system takes place in the DXE phase. The execution code for the DXE phase is stored on the OBB (OEM Boot Block) implemented by the OEM. DXE, after its initialization, provides services through which UEFI applications can interact with hardware

[1] A UEFI Image is executable code which runs during the boot process. These can be located on PCI cards, system flash or hard disks.

devices. These services provide an abstraction so that UEFI Images does not have to implement specific hardware support. DXE also initializes SMM (System Management Mode), which operates with the highest system privileges, and is used for management tasks such as power management. It is worth taking note of, as it can be exploited in order to create UEFI rootkits, as we will explore in more detail in section 9.

2.1.4 BDS

After all the DXE drivers have been executed in the DXE phase, the boot flow moves into the BDS phase. Here the firmware will implement the UEFI boot manager[2], as defined in the UEFI Specification [1] section 2.1. The goal of the BDS phase is to boot from one of the discovered boot devices.

2.2 UEFI

It is important to note that UEFI is an interface specification, and only an interface specification[3]. It strictly provides a specification that allows the operating system to communicate with the system firmware. This is further restricted to communication regarding the boot process. This is because when the boot is completed, the OS takes control of the hardware, and communicates with it directly, through its own drivers. It is also worth noting that UEFI has evolved from Intel's EFI, therefore some components of the UEFI specification still hold the name EFI instead of UEFI.

2.2.1 UEFI Boot Manager

As briefly mentioned in section 2.1.4, UEFI specifies a boot manager. The boot manager can load UEFI Images, such as UEFI applications and drivers. The drivers can be restricted to the boot process, such drivers are called UEFI Boot Service drivers, and they will exit once the OS Loader calls the *ExitBootServices()* method. UEFI Drivers that are active, also after the boot process, are called UEFI Runtime drivers. Such drivers can be called by the OS. UEFI applications are different from UEFI drivers as their memory and state are unloaded after the image returns from its entry point [3]. The OS Loader is a UEFI application that will transfer the firmware control over to the OS, through the invocation of *ExitBootServices()*.

2.3 OS LOADER

As mentioned in the previous section, the OS Loader is a special UEFI application. The OS Loader is responsible for finding out which operating system to load, loading the operating system, and transferring firmware control over to the operating system kernel [2]. The OS Loader implementations among different operating systems are not homogeneous. For instance, Windows (Vista and later) has a split Boot Manager and operating system loader, where the Boot Manager is "generic and unaware of the specific requirements for each operating system" [4]. The Boot Manager is responsible for finding out which operating system loader should be launched, either by a predefined priority list, or by user input. On the other hand, the operating system loader is responsible for the actual initialization of the Windows OS. A popular OS Loader for Linux that does this differently is the GNU GRUB OS Loader. GNU GRUB works both as a boot manager, and as an operating system loader.

[2] The kernel is the part of the operating system responsible for communicating with firmware, as well as managing resource allocation.

3 ATTACK VECTORS ON THE BOOT PROCESS

Systems without any implementations of Secure Boot techniques will have many exploitable attack vectors in the boot process, these systems were commonplace before UEFI Secure Boot was introduced in 2012[3] and later implemented by original equipment manufacturers (OEM's).

Without securing the boot process it is virtually trivial (as shown in section 10) for an agent with mal intent to exploit this and create malware that resides at a level inaccessible to some anti-malware software, this is called a rootkit (or bootkit).

Malware that has the ability to persist through reboots and has high privilege levels are usually called rootkits. The term rootkit is a general term for this – although bootkits could be a more accurate term as we are describing malware in the boot process.

Rootkits and bootkits are particularly dangerous for a system, as they can attain kernel-level privileges and usually can evade most traditional methods of detecting and removing malware. These are persistent and can in some cases even persist through an OS reset or even hardware (ex: hard disk) change [5].

The reason that UEFI rootkits (bootkits) can evade most traditional methods of detecting and defending against malware, is due to the fact that they are started before the OS. As they are started before the OS, they could change how the OS functions. For example, by injecting malicious kernel drivers which will launch at OS startup, defense processes such as Windows Driver Signature Enforcement would be bypassed [6]. These changes to the kernel could enable false reporting to anti-malware software, so that it is unable to detect the infection.

UEFI rootkits (bootkits) can reside on EFI Partition on a boot hard drive and overwrite some OS Loader code to load the malicious code or write itself down as runtime driver (driver rootkit). This will grant the malware kernel-level privileges, and from this point, it is up to the malware what it wants to do. Some examples are:

- Sniff data from the user
- Encrypt all user data and demand cryptocurrency from the user
- Make the device compliant in a bot network.

The EFI Partition isn't the sole possible host of these types of attacks - other EFI blocks that could be affected by such threats would be:

- Platform initialization components (PEIM)
- Driver execution environment (DXE)
- UEFI drivers and other executables
- OS Loader

Note: The attack specifics of each component are explained more thoroughly in section 3.2.

More advanced anti-malware can detect rootkits on the EFI partition of a connected hard drive, but in theory, it is also possible for malware to exploit other connected chipsets on the device and

[3] UEFI Secure Boot was introduced in the UEFI Specification Version 2.3.1 (Errata C) (released June 2012).

write malicious code to that component – which runs at boot. Components that could source the malware:

- Hard drives, or other persistent data storage. This could be attacked through weaknesses in software and OS, but also through an already infected device or a supply chain attack (worst-case scenario).
- Option ROM on expansion cards, some implementations of UEFI Secure Boot will not authenticate option ROMs because of backward compatibility [7].
- Fallback OS Loaders, such as USB Live boot devices and network booting.

3.1 PHYSICAL-BASED ATTACKS

Physical-based attacks bypass the security that the operating system provides, although Secure Boot can mitigate these attacks. Physical-based attacks are relatively harder for attackers to exploit but also harder to secure against.

3.1.1 "Evil maid" attacks

"Evil maid" attacks are attacks where an attacker has physical access to a system, where they permanently or temporarily add an attack vector to a vulnerable machine – e.g., an evil peripheral device (such as a USB device) or other evil plug-in cards (e.g., PCI card).

These can do something simple as emulating a USB-based "human interface device" (HID) such as a keyboard and running commands as the user. These attacks need to be handled and secured by the operating system and, in many cases, also anti-malware software.

Live boot USBs

Live boot USB can be used to temporarily install a guest operating system.

Disk encryption can be used to encrypt user data from a temporary operating system on the machine.

Option ROM

Plug-in cards can also have might have built-in EFI executables that could be a source of infection.

A common vulnerability on modern chipsets allows unsigned Option ROM to be executed, even with UEFI Secure Boot enabled.

3.1.2 Cold boot attacks

Cold boot is a type of side-channel attack which circumvents the usual security measures to extract sensitive information. A cold boot attack requires temporary physical access to perform a memory dump. This can be done even after a machine has been completely turned off because of *data remanence* of the memory modules; DRAM will remain readable for a period after – up to 90 minutes in some cases [8]. One method involves booting a lightweight operating system from a removable disk (e.g. USB device) and dumping the memory. Another more invasive method, which can be used if it's not possible to boot from USB, is done by removing the memory module and dumping the memory from the said module, this requires a specialized tool.

Cold boot attacks are harder to mitigate as they exploit a hardware weakness rather than a software vulnerability. Disk encryption is not effective against this type of attack, as the attack targets the random-access memory – and cold boot could be used to extract the disk key, in the case that a system doesn't have a TPM.

Some effective countermeasures include secure memory-erasing before shutting down and full memory encryption. Physical barriers like soldering the memory to the board would make an attack harder and more inaccessible, this is common with some laptop manufacturers.

3.2 SPECIFIC COMPONENT ATTACKS

3.2.1 Platform initialization

The platform initialization phase sets up the trusted computing base[4] (TCB) for the rest of the boot process, although low-level and OEM specific - it is a very important foundation to secure the PI. Attacks on the platform initialization could be done with physical access and extensive knowledge of the hardware [9]. For example by overriding the default DXE block, so that UEFI Secure Boot is disabled.

3.2.2 Driver execution environment (DXE)

Attacks targeting this component could be unaffected from UEFI Secure Boot as it is executed alongside the UEFI code block. Infected code blocks in this component would have kernel-level privileges and would be hard to detect and secure against in later phases. With measured boot, it is however possible to detect anomalies in this phase of the boot.

3.2.3 UEFI Drivers

One of the responsibilities of a UEFI implementation is to run EFI executables which include bootloaders, boot service drivers, runtime drivers and EFI executables relating to other system components. *(See 2.2.1)*

Without any security measures, it is possible, through various attack vectors, to infect the system and achieve arbitrary code execution (ACE) by writing or overwriting an EFI image. Such attack vectors could be OS vulnerabilities that grant unauthorized processes write access to the EFI System Partition or "evil maid" attacks. UEFI bootkits are possible by simply writing to the EFI partition: The UEFI bootkit "ESPecter" was recently discovered to be infecting the EFI Partition System (ESP) on Windows machines [6].

Many of these exploits are solved by the UEFI Secure Boot, which must verify and subsequently abort unsigned EFI executables. As the UEFI implementation trusts the TCB from prior phases, it would not mitigate attacks on these.

3.2.4 OS Loader

Attacks on the OS loader are similar to the UEFI Drivers as the OS Loader is, like the drivers, just EFI images – but usually located on an external storage device. These EFI images (bootloader or relevant early runtime drivers) could be overwritten and infected by malware, or by a live boot device in an "evil maid" attack. Microsoft's Early Launch Anti-malware (ELAM) is an attempt to catch malware launched at this stage.

[4] A TCB is a small subset of the firmware, hardware and/or software, on which the security of a system is dependent on.

4 TRUSTED BOOT & MEASURED BOOT

Many of the Secure Boot methods we will explore later, are primarily concerned with the integrity of the system and preventing malware to execute. It is however worth mentioning how we can truly trust that the system has booted in a secure manner. The Trusted Boot (often referred to as Measured Boot) process' primary focus is to allow attestation of the boot process after the OS is loaded [10]. However, it is also possible to use the attestation during the boot process, for example, the OS Loader can use this process to check that the PEI phase can be trusted.

Trusted Boot, as defined by TCG (Trusted Computing Group), has two different specifications. One of them is specific to UEFI platforms and makes use of the TPM (Trusted Platform Module) as the root of trust for storage and reporting. We will focus on this implementation (TCG EFI Platform Specification for TPM Family 1.1 or 1.2), as it is specific to UEFI platforms, and as mentioned in the introduction we assume that all systems are UEFI compliant.

The Trusted Platform Module, or TPM in short, is a standard that defines the specification for a system component, which state is separate from the rest of the system. The TPM can only communicate with the system through the protocols as defined in the specification [11].

The TPM can be implemented as a physical computer-on-chip, as a part of another physical chip or in software. All TPM implementations must have some platform configuration registers (PCR), these are volatile memory registers, which can only be updated using the PCR extend or- Reset functions. The PCRs used by Trusted Boot (PCR index 0-15 [12]) can only be extended and is only reset on TPM reset (reboot). The Root-of-Trust for Measurement (RTM) is the first executed code on the firmware boot block, and it will measure itself into the PCR [11]. The RTM will measure all other components into the PCR using the PCR extend function. This function takes whatever data is in the PCR right now, concatenates it with the new measurement, hashes it and stores it back in the PCR.

Now, why is it useful to have this hash value in the PCR, and what can we use it for? The Hash alone provides little meaningful information, therefore the Trusted Computing Group specifies an Event Log [12]. The event log shall contain one event entry for each measurement made by the RTM. The event entries contain information about which event was measured, the hash value and its index for measurement into the PCR. The Event Log is passed on to the operating system and can therefore not be trusted. As you can see, we need both the PCR (trusted, but little information) and the Event Log (not trusted but provides more information) for the measurements to be of any use.

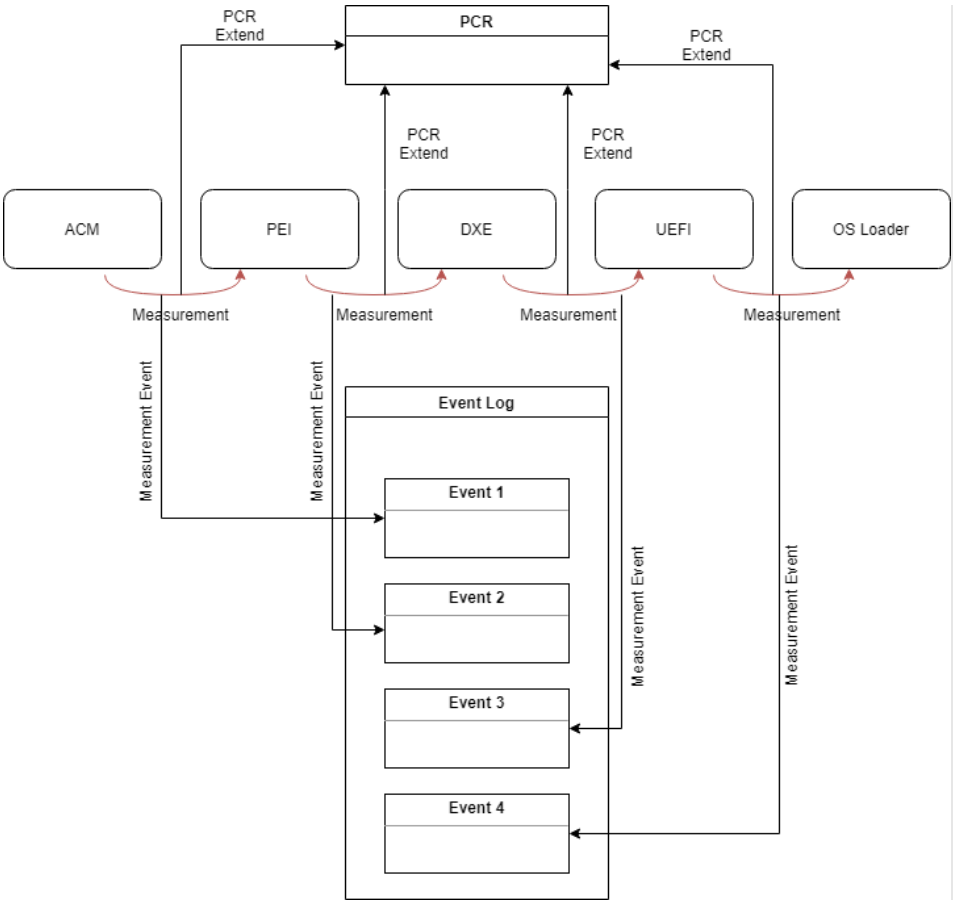

Figure 4:1

Figure 4:1 shows how each component in the boot process can be measured before it is executed. The measurements are concatenated with the current PCR value, hashed and stored back to the PCR. The measurements are also appended to the Event Log. As mentioned, the RTM is the component that does the measurement, it is therefore crucial that we can trust the RTM. A basic implementation could be that the PEI is the RTM, but as discussed in 3.2.1 the PEI cannot be trusted. A better implementation would be to use the ACM (see 5.2) from the SEC phase as the RTM. The figure shows an implementation using Intel TXT ACM as RTM to measure PEI.

Let's look at a use case for Trusted Boot:

- Alice is working for Company Inc.
- Alice has a company laptop PC, with TPM PC-TPM and OS PC-OS.
- Company Inc. is working with classified government data.
- The classified data is stored on server CS.

Alice is working from home and needs to access the data on server CS. The consequences for unauthorized access to the data would be severe, and Company Inc. requires Trusted Boot with remote attestation before an endpoint device can access the data on CS.

1. PC sends a request to CS.
2. CS requests the PCR value from PC-TPM, using the PCR Quote function.
3. PC-TPM replies with a message containing the PCR value, signed with the TPM Attestation Key.
4. CS uses the PC Attestation Public key to verify the hash.
5. CS requests the Event Log.

6. PC-OS replies with the Event Log.
7. CS checks whether the Event Log matches RIM[5], if it does, it has not been tampered with.
8. CS replays the events from the PC Event Log and checks if the hash matches the hash from step 4, if it does, the Event Log – and the computer – can be trusted.
9. PC gets access to the data on CS.

Note that in the real world, the attestation server would most likely be a different host than the server containing the data. In this case, the CS would use the attestation server to authenticate the client.

5 SECURING THE UEFI STARTUP

As the UEFI Secure Boot relies on a trusted foundation, such as the platform initialization and the code block that implements UEFI. Since it implicitly trusts OEM platform firmware to be secure, it makes this foundation a valuable target for attackers. Intel Trusted Execution Technology (Intel TXT) secures this part of the boot process through Intel Boot Guard which trusts immutable microcode embedded on the CPU.

5.1 INTEL TRUSTED EXECUTION TECHNOLOGY

Intel TXT's main goals are to check the authenticity of its platform and OS, to secure and assure a trusted environment for the operating system and to provide the OS additional security capabilities [14]. One of the features we are interested in is Intel Boot Guard, which Intel TXT includes.

5.2 INTEL BOOT GUARD

Intel Boot Guard roots its trust in hardcoded microcode on the CPU called the *Authenticated Code Module Key*, or ACM Key - the Authenticated Code Module (ACM) is verified with this key, this module in turn verifies the Initial Boot Block (IBB) and then the OEM Boot Block (OBB). The IBB's main responsibility is to verify the OBB and initialize and load it into memory.

The ACMs verify the OEM Key Hash which is stored in Field Programmable Fuses[6] (FPF). The OEM Key Hash is used to verify the subsequent components in the platform initialization phase. This means that the IBB is verified by a key set in hardware, and is therefore more secure than implicitly trusting the SEC phase.

5.3 AMD PLATFORM SECURITY PROCESSOR & HARDWARE VALIDATED BOOT

AMD's implementation of technology similar to Intel Boot Guard for securing the whole boot process is called AMD Validated Boot (AMD HVB) and, like Intel's TXT, it is a part of the AMD Secure Boot.

Hardware Validated Boot is a technology to attain a secure boot, it roots its trust in an immutable hardware ROM ("read-only memory") chip called the AMD Platform Security Processor (PSP), which in turn verifies the system's firmware (OBB) [15].

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[5] Reference Integrity Manifest. Contains reference measurements from OEM and the organization. [13] *TCG Reference Integrity Manifest (RIM) Information Model*, T. C. Group, 2020.

[6] FPFs is one-time programmable storage that should be programmed by the OEM making them read-only.

The initial block for AMD PSP is verified against a master key fused on the CPU, contrary to Intel's TXT the AMD PSP does not rely on the Platform Controller Hub (PCH) on the system and gets its primary key directly from the CPU [16]. Intel's implementation uses the PCH to get the primary key, but it's verified against the ACM.

6 UEFI SECURE BOOT

In a nutshell, UEFI Secure Boot is a system that verifies the code being executed from the computer's UEFI firmware is safe, before the code is executed. When something runs before the operating system has begun its loading it would be hard to catch harmful applications, leading to the possibility that the system becomes compromised. This is because it wouldn't matter if you used an antivirus program, the harmful UEFI application/driver could hide itself from the OS, so that it is not possible to detect it, as seen in section 3.

UEFI Secure Boot works with a combination of checksums and signatures that are converted to unintelligible text, in other words, cryptographic text. So, for every program that is being started in the boot process, for example, the OS loader will come with its own signature that must be verified by UEFI Secure Boot before allowing it to execute.

That said you could technically (in most OEM implementations) turn off the UEFI Secure Boot functionality, but this would not be suggested as this can make your system very vulnerable to harmful exploits. This could also be an attack vector if a malicious actor has physical access to your device, and the OS does not require UEFI Secure Boot.

Several vulnerabilities pertaining to disabling and bypassing the UEFI Secure Boot have been discovered in different OEM implementations, allowing for many new attack vectors. This will be further explained in section 9.

6.2 UEFI SECURE BOOT DATABASES

6.2.1 The Allowed Database (db)

db is a database with allowed certificates (X.509) and hashes. (SHA-256). The database is utilized to validate signed UEFI binaries, as well as unsigned binaries through their hash. To update the db, the update must be signed by a KEK, as explained in 6.3.3.

6.2.2 The Forbidden Database (dbx)

dbx on the other hand is the opposite, this is a database with known forbidden certificates (X.509) and hashes (SHA-256). Updates have the same authentication requirements as for updates to db.

Why do we need this database when we already have the allowed database? The db does typically not contain many certificates/hashes, as such, if an image has been signed, and it is later discovered that the image is in fact malicious, if we were to secure the system by removing the signing certificate from the db, all other images signed by this certificate would have to be signed again. This would be a tedious process, and it is much simpler to add the hash of the image to the dbx.

6.3 SAFE UPDATES OF THE DB AND DBX DATABASES

To understand how UEFI Secure Boot can update its databases as safely as possible we need to go through the process step by step.

6.3.1 Storage of the databases

Before your PC is deployed, the OEM will store the UEFI Secure Boot databases (db, dbx and KEK) on the pc. These databases will at the time of manufacturing be stored on the firmware nonvolatile RAM(NV-RAM) [17].

6.3.2 Platform Key (PK)

The reason we have Platform Key (PK) is to make credentials between the system owner and the firmware. The private part of the platform key is used to sign updates to Key Exchange Keys.

The PK is split into two parts, one private key, and one public key. The OEM is responsible for generating the PK, the public part is stored on the platform, and the private part is kept by the OEM [18]. It is also possible for the actual owner of the system to override the OEM PK and enroll their own. Any update to the PK variable has to be signed by the current PK, if there is a current PK. It is also possible for the OEM to implement a platform specific way to clear the current PK and enter UEFI Secure Boot setup mode so that a new PK can be enrolled.

Now, why would one want to override the OEM PK with your own? Starting with Windows 8, Microsoft required OEMs to enable UEFI Secure Boot by default, and also include Microsoft's Key Exchange Key. For users wanting to use another OS, or custom drivers not signed by Microsoft, you would have to either sign the image yourself, or add the vendor's KEK. For both of those operations, you need access to the PK private part. As you do not have the OEM PK private part, you would have to enroll your own. You should however not use the PK for signing images directly, only KEKs should be used for this. This is due to the fact that the PK private part can authenticate updates to the PK variable, and as such a UEFI image that is signed with the PK could tamper with the PK variable programmatically [18].

6.3.3 Key Exchange Keys (KEK)

To ensure that malicious actors cannot feed the databases with certificates and hashes, we got KEK, Key Exchange Keys. The private part is being used to sign updates to the db and dbx database. UEFI Secure Boot is made in a way that it will not allow the databases to update if it's not signed from a KEK. The KEKs can be enrolled by the OEM while the platform is in setup mode (before the PK has been enrolled) [18]. Once the PK is enrolled, altering the KEK database requires an authenticated update, signed by the PK private part, rendering it practically impossible, as the PK should never be on the system and is kept by the OEM.

While the reason for the PK is to have trust between the system owner and the firmware, we got the KEK to make that same trust but between the OS and the firmware. The KEK is simply authorizing modification to the db and dbx databases. If KEK doesn't allow for modification the two databases will not change, at least per the specification.

Now, why do we need the KEKs, when we already have the PK? Imagine this scenario: the system owner (Alice), wish to have two operating systems on her computer (Windows and Ubuntu) which is made by an OEM (Lenovo). The two OS vendors (Microsoft and Canonical) would want to allow different images, and have different forbidden hashes/certificates. If we only had the PK, it would have to sign each update to the databases itself, and Microsoft could for example not add a new forbidden hash, without Alice's approval (or Lenovo if she did not enroll her own PK). This would clearly be inefficient. What about only KEK, and no PK? If the computer came from Lenovo

with only Windows, and Alice would later like to add Ubuntu, Microsoft would have to approve that the Canonical certificate is added as a KEK. Why should Microsoft have to approve which OSes Alice chooses to install? This would not be a good idea.

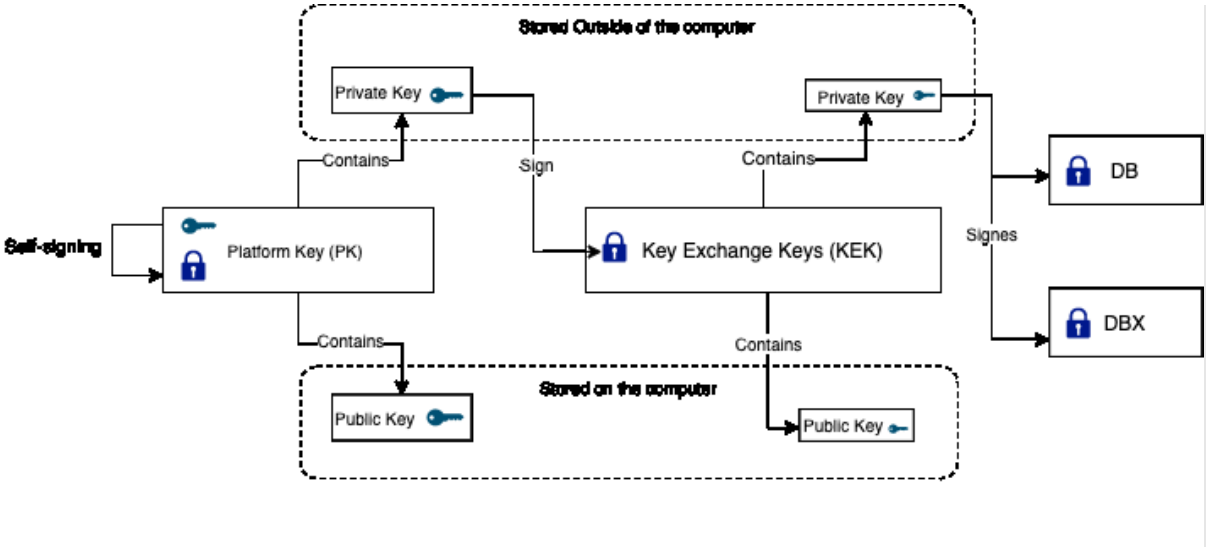


Figure 6:1

6.4 The UEFI Secure Boot verification process

When secure boot is enabled, images are only allowed to execute when all the following conditions are met:

- The signing certificate is not in dbx.
- The image hash is not in dbx.
- The signing certificate is in db OR the image hash is in db.

An image could have multiple signatures. In this case only one signing certificate or image hash has to be in db, but no signing certificates or image hashes can be in dbx. This is for instance beneficial if the same image is used with different OSes and the image developer does not know which OS you have installed. You would only need one of the OSes to run the image. If there is a vulnerability in the image and you have multiple OSes, the first OS to add the image hash to the dbx would veto the others. For example, if you have both RHEL and Ubuntu, and they use the same OS Loader, if Red Hat discovers a vulnerability in the OS Loader, they could add the hash to the dbx. This is a good measure, as the image would otherwise be authorized due to the fact that Canonical still approves the image.

6.5 Passport control analogy

You can think of UEFI Secure Boot like passport control. When a person tries to enter a country then they will be checked if they are allowed into the country. Then check with the passport if it matches the person. The same you can make of the UEFI Secure Boot. If a program wants to execute in the boot process, then the UEFI Secure Boot must check the signature (passport information) with db (allowed countries). If this matches, and is not in dbx (terrorist-list) it will allow the program to execute (enter the country).

If we now imagine that we skip the pass control and let everyman enter the country it would allow whoever to enter and then also terrorist and unwanted people who will maybe cause damage to the country, and we would lose control over the country. The same would happen with the UEFI

Secure Boot. If we would disable this, then it would allow every program that wanted to be executed to run. This would allow many programs that want to harm your computer to attack and make damage. Therefore, as it's important to check everyone who enters a country it's important to have a UEFI Secure Boot to verify every program before it is executed.

7 SECURING THE OS LOADER

As we have explored earlier, the OS loader is responsible for starting the operating system, along with its required drivers, and taking control of the hardware (handed over from UEFI). Without any security mechanisms, any driver could be loaded, including malicious ones. As we have seen in the previous section, it is therefore important that the OS Loader also verifies drivers before they are executed. This has to be handled by the OS Loader and not by UEFI, although the implementations could be functionally similar.

7.1 EARLY LAUNCH ANTI-MALWARE (ELAM)

Windows provides a module called Early Launch Anti-Malware (ELAM), which makes it possible for approved third-party applications to do verifications during the loading of the operating system and provide protection before other third-party software has a chance to run.

Before the kernel launches a driver, ELAM will analyze the driver and give one of four return values:

1. The driver is a good driver.
2. The driver is a bad driver (malicious driver).
3. The driver is an unknown driver, meaning it is unknown to the ELAM.
4. The driver is malicious but critical, meaning the OS is forced to boot with it if it is going to boot at all.

Based on the registry configuration, it will decide whether the driver will be launched or not. By default, *good*, *unknown* and *bad but critical drivers* are allowed to load. This can be changed by a system administrator, from allowing all drivers to more restrictive options (that might block a successful boot). To determine which setting this should be on a particular system, the system owner should do an assessment and weigh the increased risk level up against the impact an incident will have. On first sight, the default setting might sound idiotic, but if a boot-critical system driver is actually infected, would you rather have the system not function at all? This assessment should be done with the broader system landscape in mind, if you for example have remote attestation, you could be certain that you can identify the bad but critical drivers after the system is booted, and access to non-public information can be blocked. However, if the system has valuable sensitive information stored in plain text on the system, and no remote attestation, it would most likely be a better idea to block the bad but critical drivers.

The ELAM measures drivers on these four data points [19]:

- Path to the driver
- Registry path to service
- Certificates related to the driver
- Image hash

7.2 OS INTEGRITY CHECK

A method to further secure the bootloader is to do an integrity check on the startup components, like drivers, files, keys, settings and anti-malware, to see if they are corrupted or infected. On Windows this is called *Trusted Boot*. *See section 8.4*

7.3 MEASURED BOOT

Measured Boot can be used to secure the whole boot process including the OS Loader. The operating system, together with an attestation server, can verify the system's health after booting - and prevent further damage.

See section 4 for more detail on measured boot

8 SECURE BOOT CHAIN & WINDOWS IMPLEMENTATION

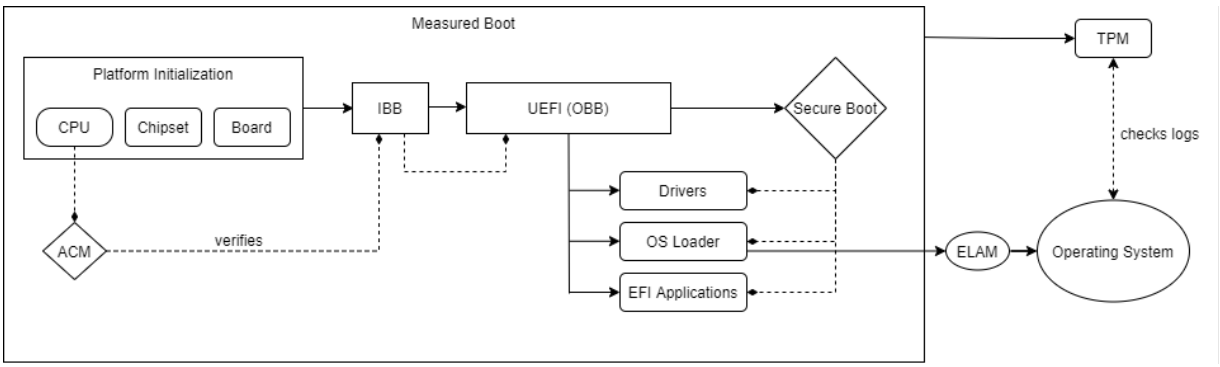


Figure 8:1

This section will summarize and chain these different technologies, as it is used today, to try to attain a secure boot process.

During the SEC phase of the initial boot sequence of a machine, the Intel Boot Guard code is run. As explained in section 5, the boot guard uses its immutable key to verify its way until hitting the OEM boot block (OBB) which in this example implements the UEFI specification flawlessly including the UEFI Secure Boot.

8.1 UEFI

In this stage, if the firmware is successfully verified, the UEFI Secure Boot takes over and checks all EFI drivers and other executables before running them. Some of these drivers are run and then quit, others and runtime drivers and run together with the OS and most importantly the OS Loader (commonly referred to as the bootloader) is verified and run.

On the Windows platform, some additional security checks are set in place related to the boot process: Measured Boot, ELAM and Windows Trusted Boot (see 4.1, 7.1 and 7.2 respectively). These countermeasures, together with UEFI Secure Boot provide a strong defense against early launched malware.

8.2 ELAM

The Early Launch Anti-Malware module is launched before the main Windows operating system is launched (as seen in figure 8:1) and provides hooks for antimalware software to start protecting the operating system before any other third-party software is run. This is an important protection

against rootkits and bootkits on the Windows platform [20]. Windows Defender which is enabled by default on Windows uses ELAM to defend against these types of attacks; other advanced third-party antimalware can also make use of the ELAM hooks and design its defense against early-launched malware.

8.3 Windows Measured Boot

Alongside the whole boot process, *measured boot* is used to log the startup process to the TPM and give information to the operating system about the security of the system after boot. Measured Boot can be used on Windows and be sent to a trusted attestation server to give a report on the system's health, this can be used to quarantine and restrict a machine on a network [20].

In the diagram above (Figure 8:1) we can see a secure boot chain when using measured boot, Intel Boot Guard and UEFI Secure Boot on a system with a TPM.

8.4 Windows Trusted Boot

Windows Trusted Boot is an OS integrity checking stage. Trusted Boot takes over after the UEFI Secure Boot. This checks the integrity of the different components of the Windows OS, like drivers, startup files and ELAM. If any component is corrupted the system refuses to boot, but this system is self-repairing and can restore the components to a satisfactory state [20].

9 Weaknesses in Secure Boot

9.1 Intel Boot Guard

Intel Boot Guard is, as mentioned earlier, a method for verifying and/or measuring the OEM's IBB, which is in turn used for verifying and/or measuring the OBB. In theory, this might sound like a good technique for securing the OEM firmware and verifying that it has not been modified. The problem is not with the specification, but the implementations.

The OEM's public key hash should be stored in hardware using Field Programmable Fuses (FPF). Security researcher Alex Matrosov has shown that not every OEM sets the FPFs[21]. Combine this with the fact that the same OEMs allow unprotected updates of the firmware, an attacker could set the FPFs, blocking the possibility for further firmware updates. As such, a bootkit could be permanently present in the system. The very technology designed for protecting your system, could in reality be helping an attacker maintain control over the system. Some comments as to why the OEMs choose to do this will follow at the end of section 9.2.

9.2 UEFI Secure Boot

In order to bypass the image verification provided by UEFI Secure Boot, an attacker has to gain write access to the SPI flash, where the UEFI firmware is located. This can be done by executing code in System Management Mode (SMM) on the UEFI firmware through a kernel exploit (e.g. through a direct exploit that can elevate its rights to kernel-level or through a signed OS driver with kernel-level privileges) [22]. SMM has read/write access to SPI by default. This can be blocked by SPI write flash protection (PRx), however, very few vendors use this type of protection [21], including Intel – who designed the PRx technology.

The attacker with write access to SPI can then update the UEFI method implementation used by UEFI Secure Boot that verifies images so that it always will return EFI_SUCCESS. This will disable the verification of images before they launch, rendering the following verification process (OS Loader verifies kernel, which verifies OS) useless, as its Root of Trust cannot be trusted.

One can only speculate as to why the OEMs would want to have such weak implementations that allow unauthorized write to SPI, and FPF programming. One reason might be that it allows easier support and firmware updates, easier (and cheaper) both for the developing vendor, and the end-user. Another reason could be that the probability of this threat scenario being utilized by an attacker is deemed unlikely, as it requires a target (firmware) specific attack, and therefore the OEM considers the cost vs benefit unprofitable. A third reason might be that the customers do not care about these vulnerabilities, as they neither understand nor are informed about them, and it would therefore not make sense for the OEM to spend extra time and money in order to secure the system.

9.3 TRUSTED BOOT

In order to launch malware unnoticed by the Trusted Boot and remote attestation, an attacker would have to either (ignoring implementation vulnerabilities):

A. Patch the remote attestation service, so that malicious clients would be marked as trusted.
B. Modify both the TPM PCRs and Event Log before handover to the remote attestation service.
    - This can be done by recording the actual good measurements, and then "replaying" them.
    - Or you can do a masquerade attack, by reporting known-good measurements from another trusted system.
C. Modify the measuring code block in SMM, so that the "good" measurement, expected by the remote attestation service is recorded, rather than the actual "bad" measurements.

Now, if the remote attestation service could be compromised (point A), the protocol would not be the problem, but it could be a possible attack vector.

The TPM PCRs should be safe from intrusion, as per the TPM specification [12], but if the implemented protocol used for attestation does not handle checking of the digital signature provided by the TPM (Attestation Key) a man-in-the-middle attack could be carried out with success. As Jain and Vyas [23] has proved, with the correct protocol implementation;

"A malicious system cannot attest itself unless one or more of the following conditions hold true:

- Certificates can be forged.
- Hardware attacks such as DMA or resetting PCR are possible.
- TPM is broken and private key is retrieved.
- Server's source of entropy is weak and hence it's nonce is predictable"[23].

Point C might then be the most severe vulnerability, as the measuring code runs in SMM, and as we have seen in the previous section, without the right protection in the OEM implementations, an attacker can modify the code running in SMM.

9.4 WINDOWS OS LOADER

An issue that the Secure Boot (Intel TXT & UEFI Secure Boot) doesn't address and also isn't designed to handle - is malware that targets the OS startup process, (e.g., overwriting essential startup files). Antimalware software can usually prevent malicious code to run and persist, but this could be moot if the malware is run before any antimalware software is run.

ELAM (*see sections 7.1 and 8.2*) attempts to address this problem by starting before most first-party and all third-party software then verifying each of their files. Preventing bad drivers to be run – in most cases – ELAM is by default configured to run known bad drivers if they're critical for booting. ELAM will also, by default, allow the execution of unknown drivers. Since ELAM is a relatively simplistic heuristic tool for malware discovery, as described in *section 7.1,* it would be possible for an attacker to change the malware's evaluated signature, making it *unknown*. Making the malware critical for boot would also be a valid method for bypassing the ELAM. Overwriting startup files essential for a successful boot would make ELAM authorize code execution.

Since ELAM is implemented to work in conjunction with antimalware software (AM), it could be possible to attack the specific AM and disable or modify the ELAM protection. By either exploiting [24] the AM or fooling the AM by simulating user input [25].

10 PROOF OF CONCEPT

In this proof of concept, we are going to demonstrate the importance of having the UEFI Secure Boot enabled on your computer. We will prove that without UEFI Secure Boot, an attacker can launch code before the OS is started. We are going to compare an attack on a windows computer that has UEFI secure boot enabled, and one windows computer that has UEFI Secure Boot disabled. All the provided screenshots are from virtual machines.

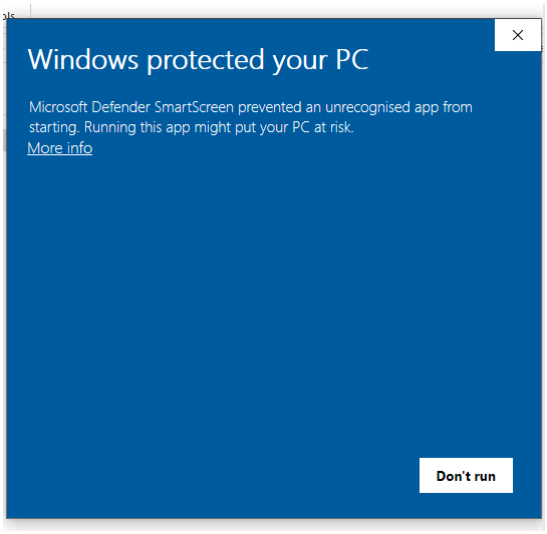
As this is only a proof of concept, the "bootkit" will only display the message:

"**** ALL YOUR SYSTEM BELONG TO OLE-JOHAN DAHL ****"

We will replace the windows boot manager (bootmgfw.efi) with our application as shown in Appendix B. We are using the UEFI development environment GNU-EFI, which is a more lightweight dev-env than EDK2.

The compiled EFI application main.efi (from Appendix B) can be stored on a web server at URL http://attack.er/main.efi. The Batch script from Appendix A will ask for administrator privileges, mount the boot partition, download main.efi, delete bootmgfw.efi, and then copy main.efi to the previous location of bootmgfw.efi. We expect that we will be able to overwrite the boot manager on both systems. We further expect that main.efi will only run on the system without UEFI Secure Boot. The implementations as to what happens when a non-signed EFI application requests to execute is OEM specific, as such we do not know whether the system with UEFI Secure Boot enabled will turn off, enter a recovery mode, etc.

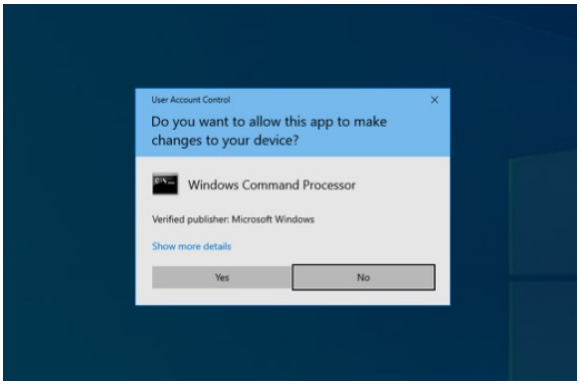
When you launch the *bootkit.bat* file, the following message will appear:



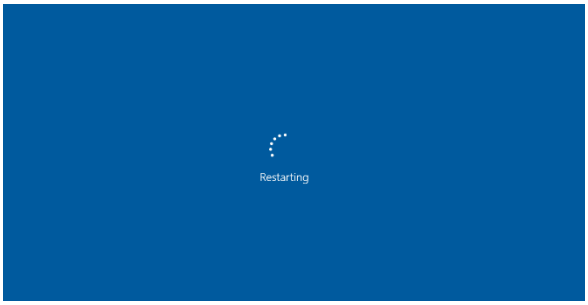
To continue, click **More info** and **Run anyway**.

An empty CMD window will then appear:

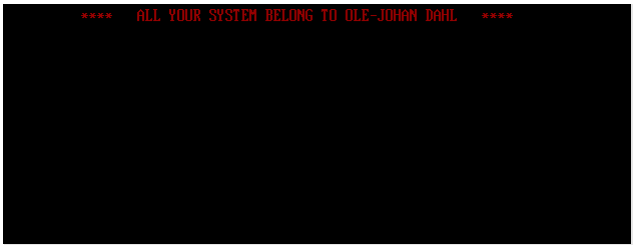
Then Windows UAC will prompt you for administrator privileges:



After confirming, your computer will restart:



And then depending on whether you have UEFI Secure Boot or not, you will get one of the two results:



The screengrab on the left shows the result without UEFI Secure Boot activated, and the screengrab to the right shows the result with UEFI Secure Boot activated. As expected, the machine without UEFI Secure Boot runs our EFI application without further questions, but the machine with UEFI Secure Boot enabled does not launch the application, but instead returns that a Security Violation has occurred. This particular implementation from VMWare then continues to search for other bootable devices.

Now, in the real world you would probably not want to only display this message, but instead initialize malware, and then continue with launching the usual operating system. However, we have proved that it is possible to launch EFI applications before the operating system is started. The security implications from this is, as discussed in section 3, severe. The delivery method would also probably be different, for example to disguise the script bootkit.bat (or application with similar functionality) as a legitimate application, so that a person unaware of the security risk would gladly ignore the warnings from Windows.

11 CONCLUSION

The purpose of this paper was to explore the general techniques that can be implemented to secure the boot process of a system, as well as showing why it's important and discuss problems with these techniques.

We have presented techniques to:

- Assure that the state of the system is trusted after boot with Trusted Boot.
- Secure the PI and UEFI initialization with Intel Boot Guard.
- Secure UEFI with UEFI Secure Boot.
- Secure the OS Loader with ELAM and integrity check.

As we have shown, by tooling these techniques together, you can achieve a secure system boot, although there are some problems with how the techniques are implemented.

As mentioned in the introduction, Secure Boot is a term used for all techniques that help to secure the boot process - from platform initialization to the point where the operating system (OS) is loaded. Earlier in this paper, we establish that a system without any implementation of a secure boot will have many exploitable attack vectors. The proof of concept proves that a system without UEFI Secure boot is vulnerable to bootkits. But with the help of UEFI Secure Boot this particular vulnerability is mitigated.

Securing the OS Loader is also an important step to establishing a safe boot process. The OS Loader is responsible for starting the OS, loading the required drivers and taking control over the hardware. ELAM and integrity checking can prevent the OS loader to load malicious drivers.

In conclusion: no single technique can be implemented to secure a system during the Boot Process. As with other processes, the security is not stronger than the weakest link. Therefore, you must have a secure base, which is expanded recursively through each component verifying its subsequent component(s). Each of these components must implement their own techniques to secure its services. It is also necessary to implement an overarching method to verify that the system boot can actually be trusted.

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13 Appendix A

File: bootkit.bat

```
1 @ECHO OFF
2 IF NOT "%1"=="am_admin" (powershell start -verb runas '%0' am_admin &
exit /b)
3 mountvol b: /s
4 powershell -c "Invoke-WebRequest -Uri 'http://attack.er/main.efi' -
OutFile '%CD%\main.efi'"
5 del B:\EFI\Microsoft\Boot\bootmgfw.efi
6 copy %CD%\main.efi B:\EFI\Microsoft\Boot\bootmgfw.efi
7 shutdown -r -f -t 00
```

14 Appendix B

File: main.c

Compiles to an EFI Application using GNU-EFI.

```
1 #include <efi.h>
2 #include <efilib.h>
3
4 EFI_STATUS efi_main(EFI_HANDLE ImageHandle, EFI_SYSTEM_TABLE
*SystemTable)
5 {
6     // Hooks for accessing UEFI functions
7     ST = SystemTable;
8
9     uefi_call_wrapper(ST->ConOut->ClearScreen, 1, ST->ConOut);
10
11    uefi_call_wrapper(ST->ConOut->SetAttribute, 1, ST->ConOut, EFI_RED);
//Set Text Color
12     ST->ConOut->OutputString(ST->ConOut, L"****   ALL YOUR SYSTEM BELONG
TO OLE-JOHAN DAHL   ****\r");
13
14     while(1);
15
16     return EFI_SUCCESS;
17 }
```