From BIOS to UEFI

Understanding the Modern Firmware Attack Surface

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VRIJE UNIVERSITEIT AMSTERDAM

Hardware Security Guest Lecture – Dec 12, 2025

Who Am I

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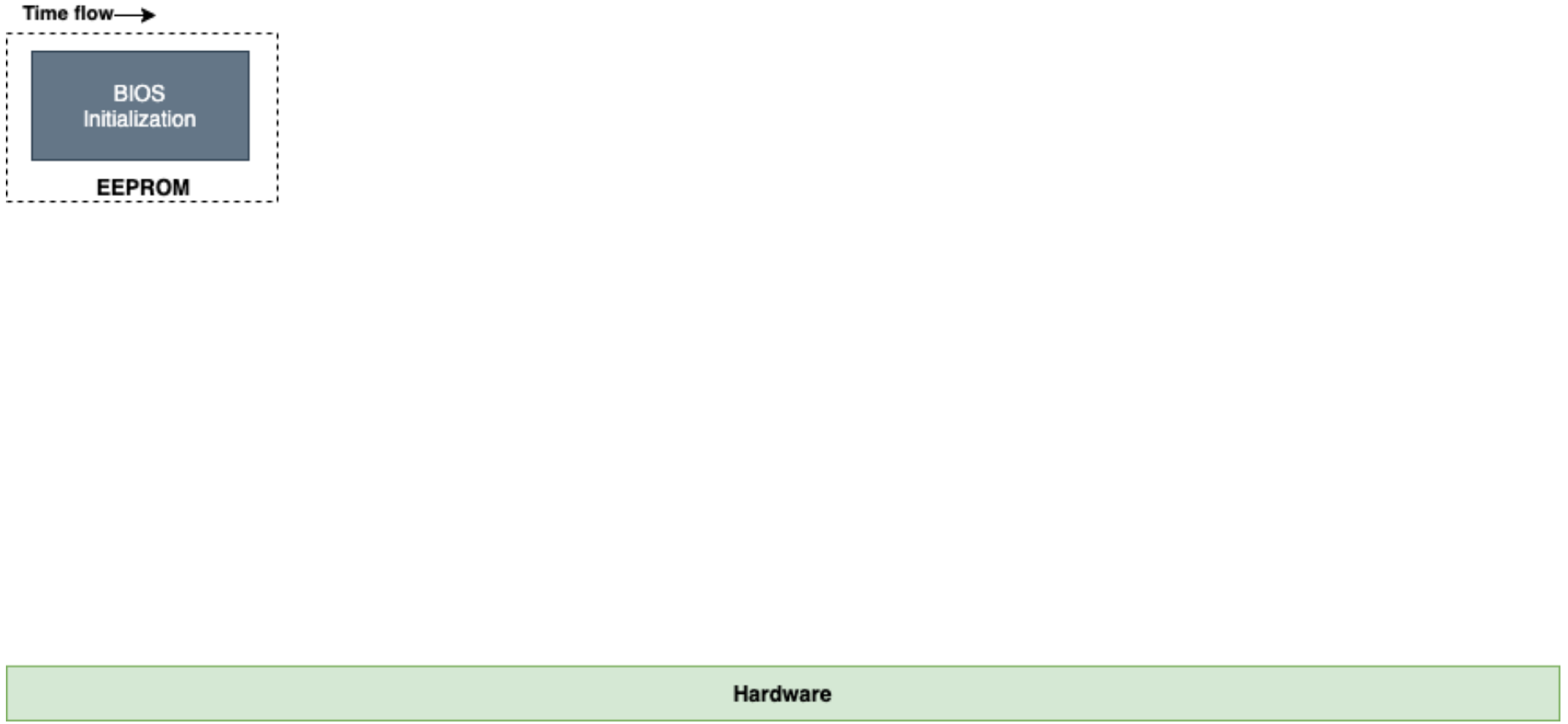
- PhD Candidate @ Vrije Universiteit Amsterdam
- Security Researcher, HyperDbg lead maintainer
- UEFI, hypervisor and PCI Express security
- Previous work: Intel Thunderbolt vulnerability research (thunderspy.io), sandbox escapes (Chrome, Firefox, Microsoft Office, Adobe)
- More info: bjornweb.nl

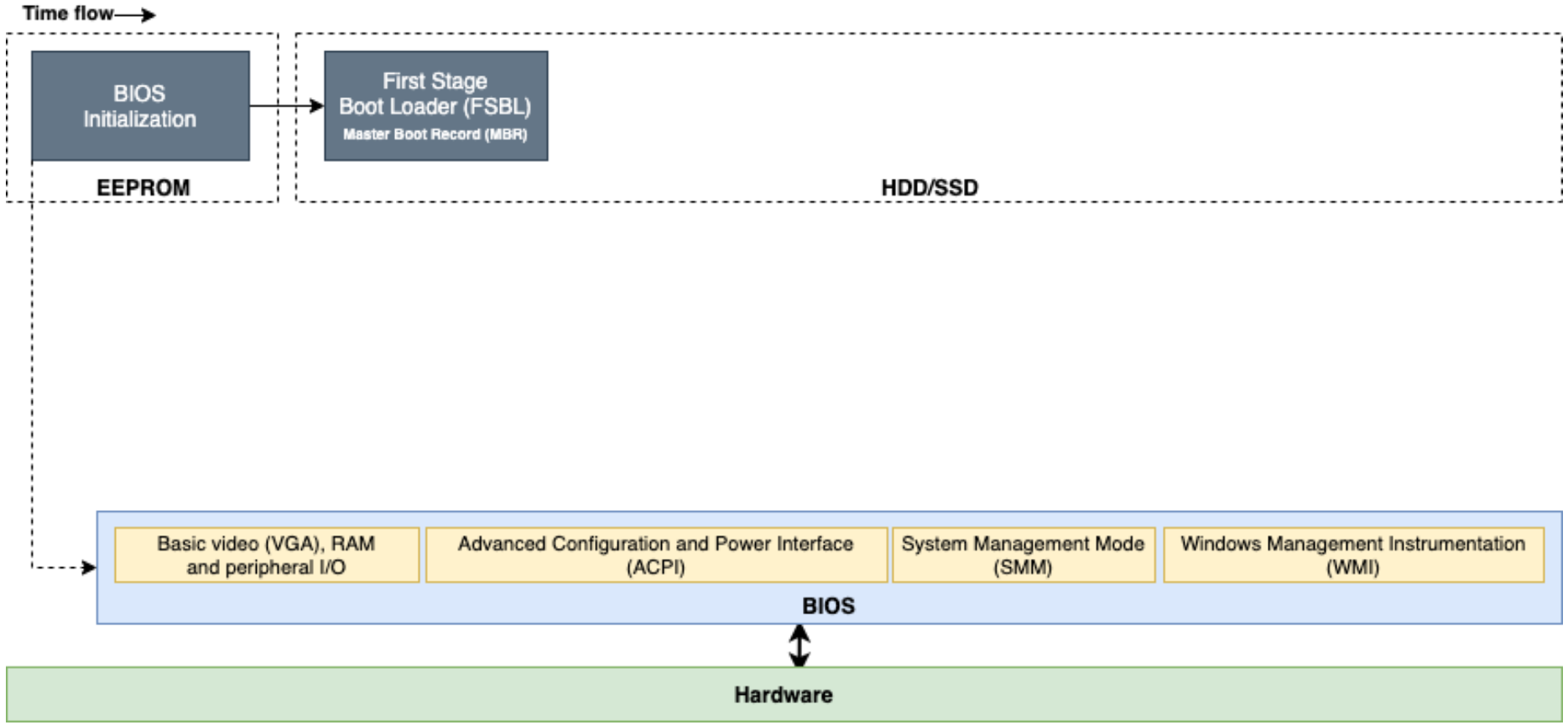
Background – BIOS Booting (MBR)

Legacy Boot



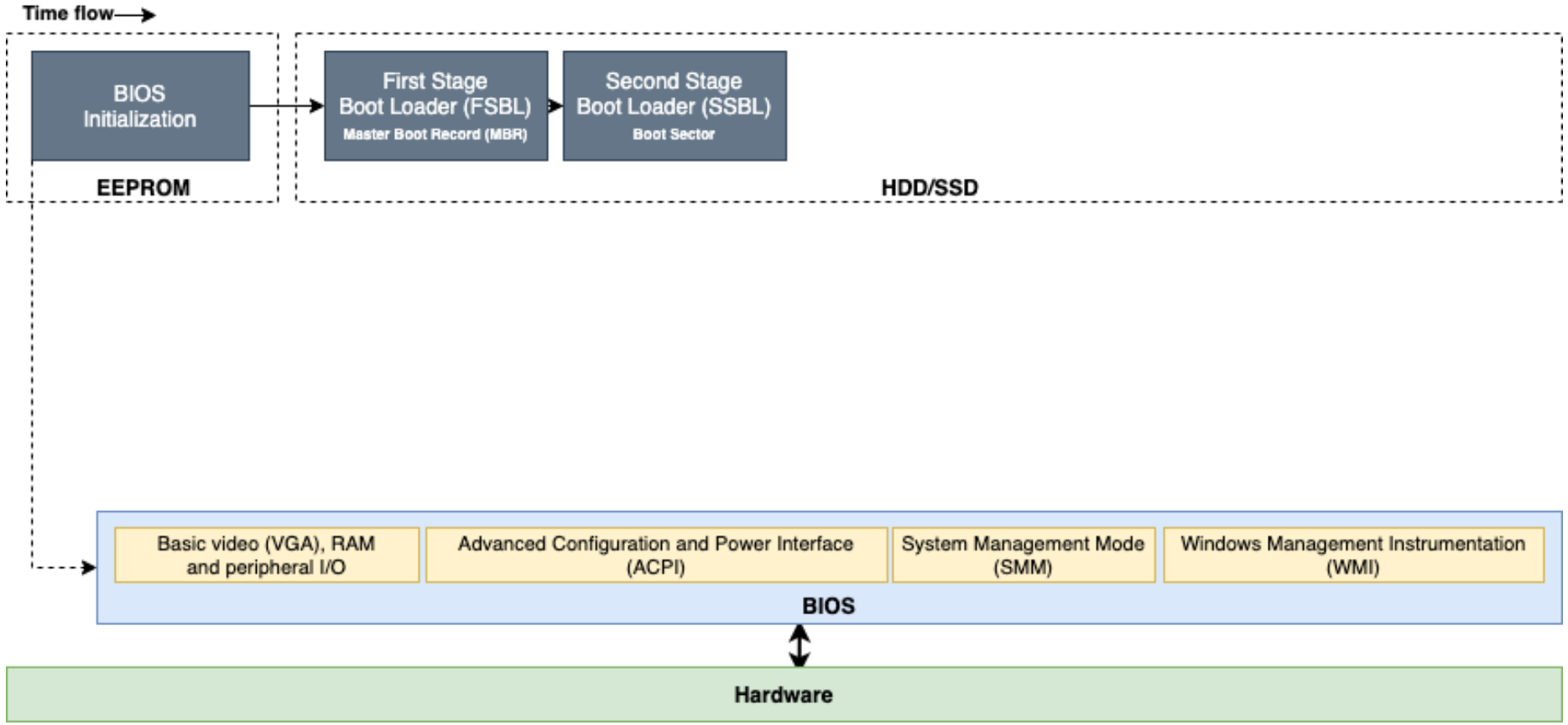
- CPU is powered on, loads Basic Input/Output System (BIOS)

Legacy Boot



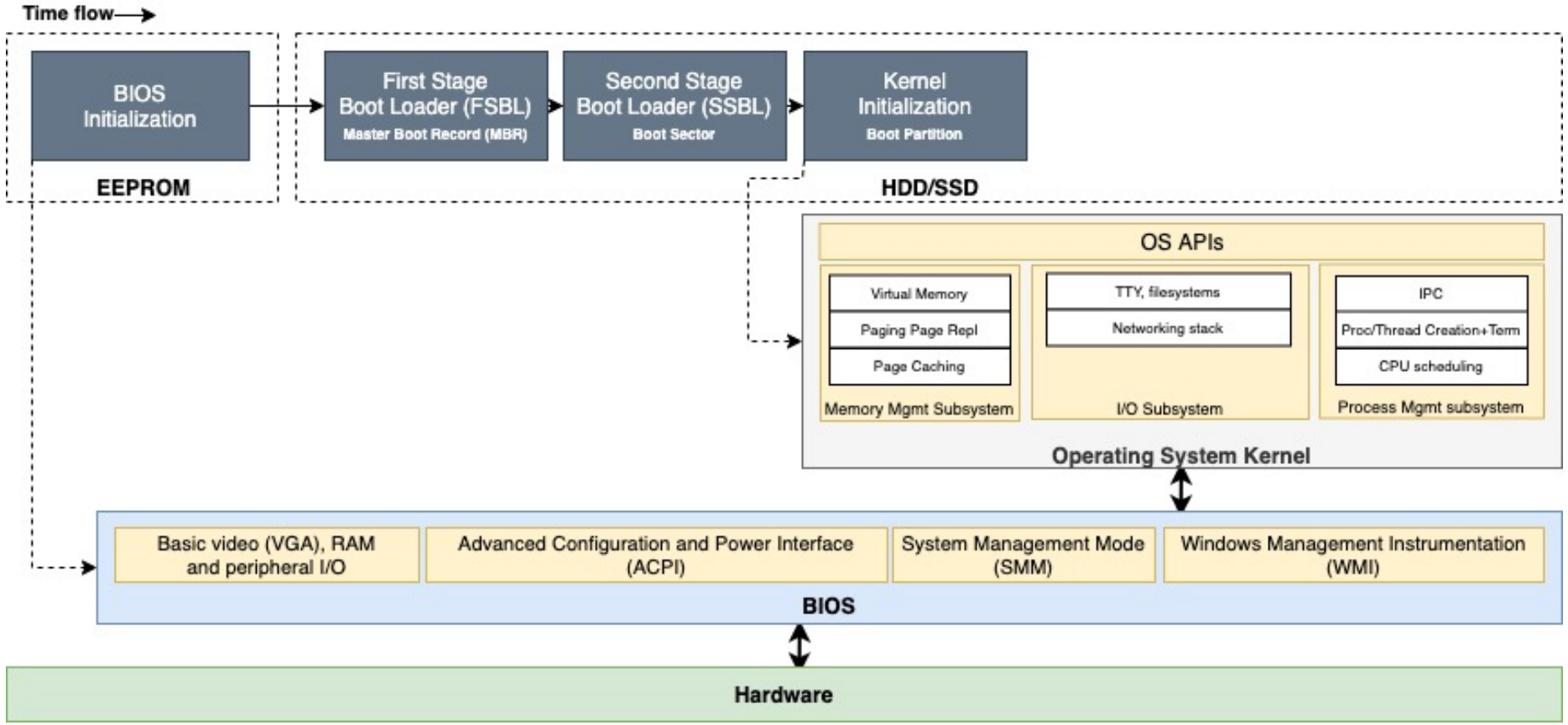
- BIOS
  - Performs basic hardware initialization (e.g. RAM, GPU, storage) and testing (Power On Self Test)
  - Enumerates hardware capabilities and provides basic abstractions to OS, including ACPI, SMM, WMI
  - Loads Master Boot Record (MBR), executes embedded First Stage Boot Loader (e.g. GRUB/NTLDR)

Legacy Boot



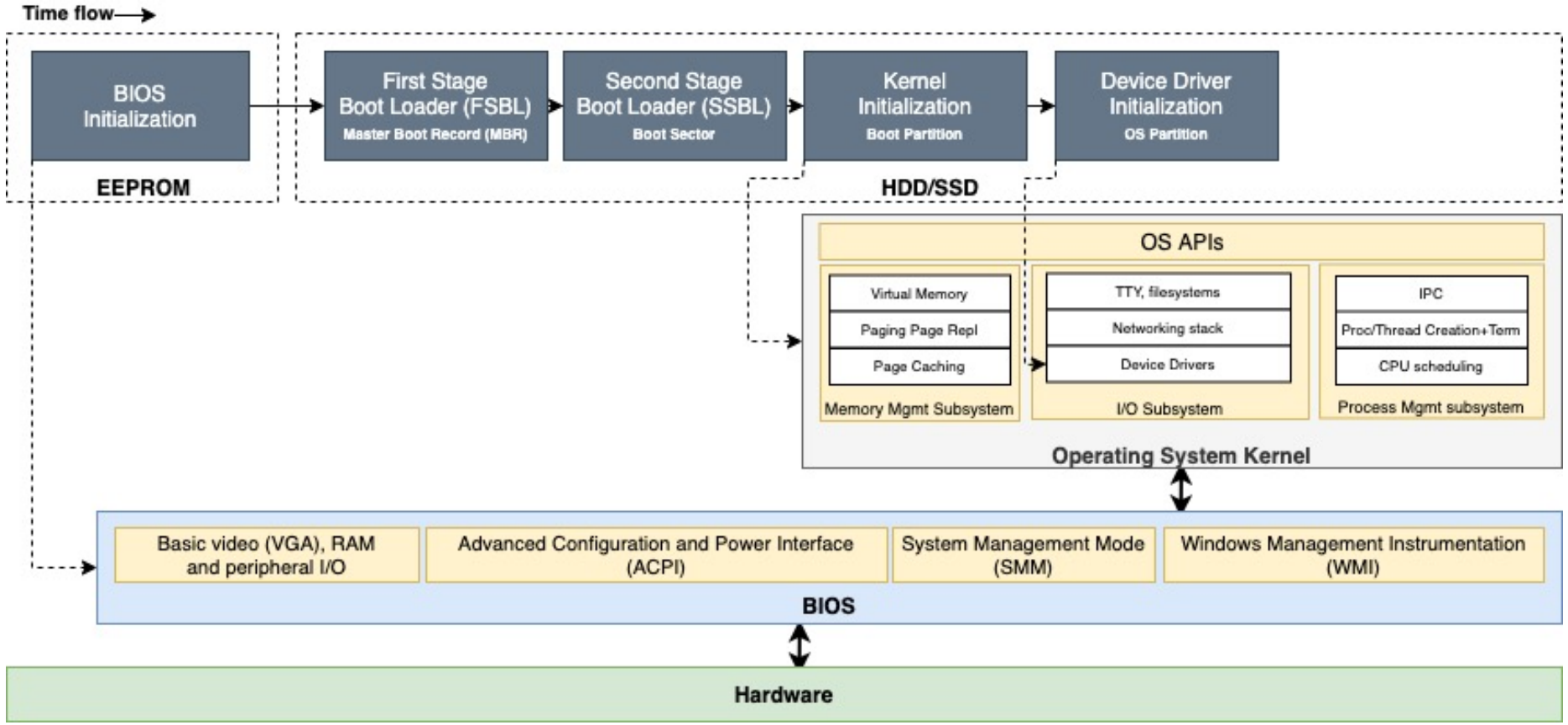
- First Stage Boot Loader
  - Mounts filesystem on first bootable partition
  - Loads SSBL into RAM (e.g. second stage GRUB/NTLDR)

Legacy Boot



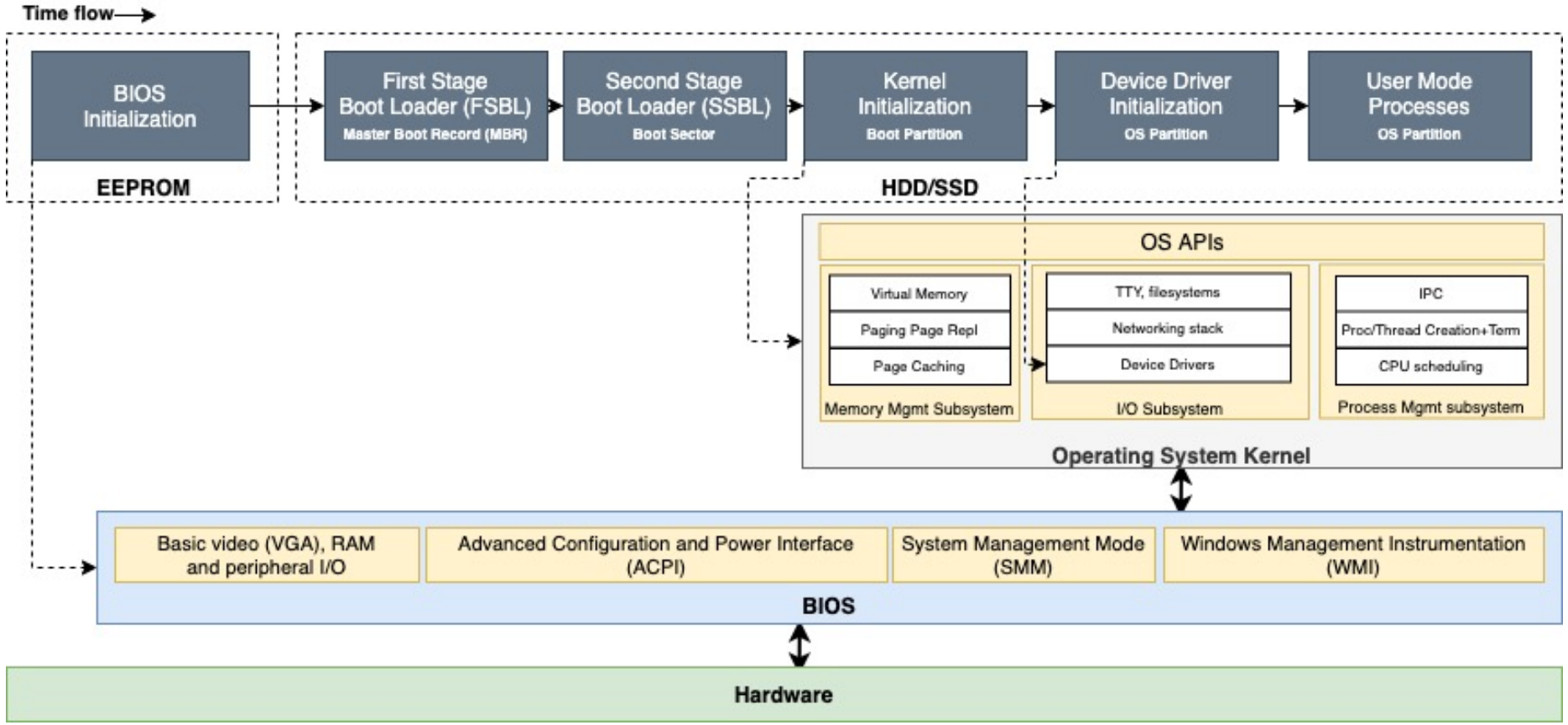
- Second Stage Boot Loader
  - Mounts OS filesystem, loads kernel into RAM, executes kernel

Legacy Boot



- Operating System kernel
  - Initializes memory management, I/O, process management subsystems
  - Loads device drivers, enabling full peripheral functionality

Legacy Boot



- Operating System kernel
  - Launches user mode processes

Legacy Boot – Limitations

- First BIOS implementations date from 1970's
- Legacy technology renders code base difficult to maintain
  - 16-bit "real mode" x86 assembly
  - Typically limited to 1 MB EEPROM
  - MBR imposes inflexible and resource-constrained boot process
    - FSBL limited to 440 bytes, need to resort to SSBL for further system initialization
    - Partition table limited to 4 partitions
    - Uses 32-bits for logical block addressing, limiting storage to 2 TB (16 TB using "Advanced Format")
  - Monolithic architecture complicates adding new hardware support
  - Single-threaded code preventing parallelizing hardware initialization, leading to extended boot times
  - **No security:** boot process can be hijacked by malicious code

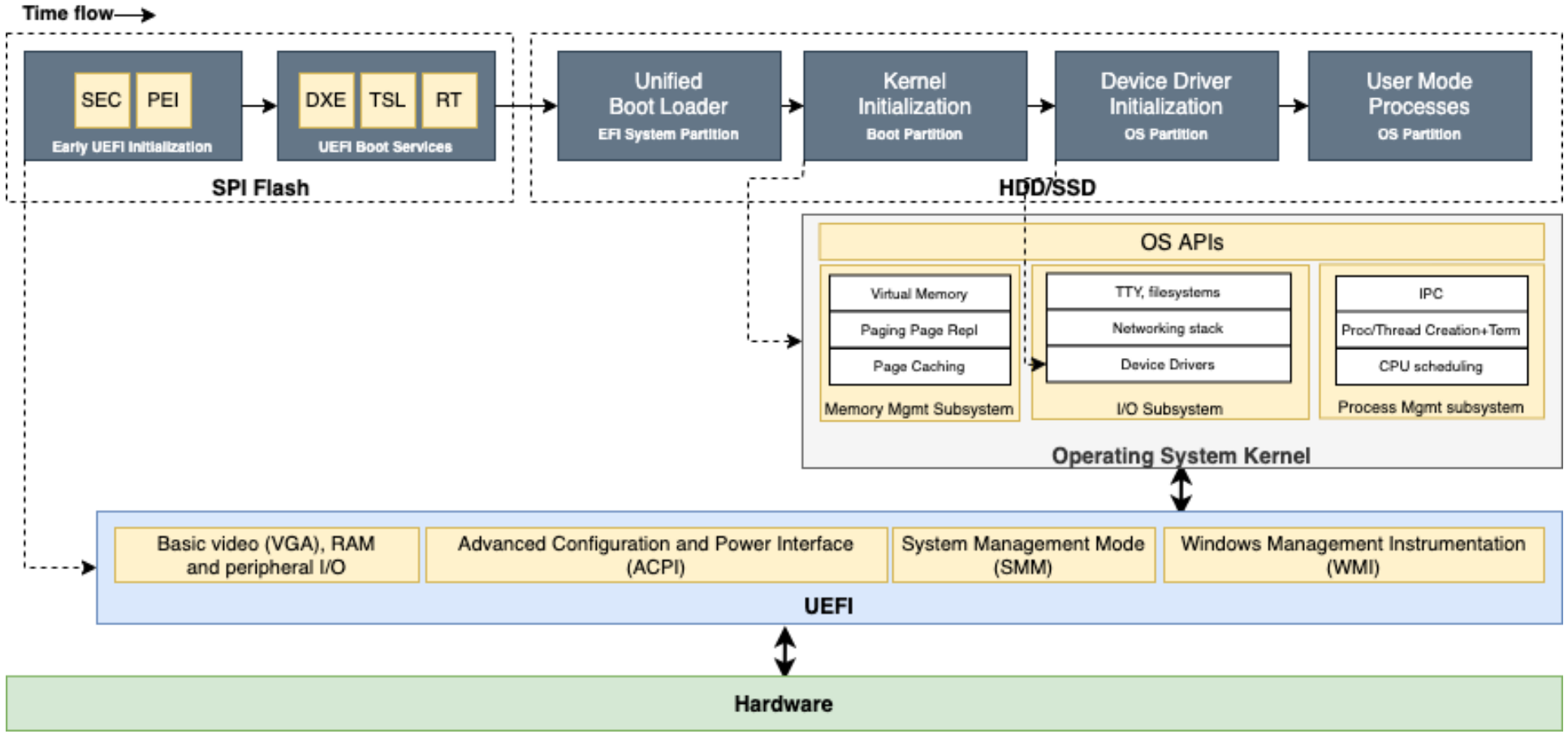
Background – UEFI Booting

UEFI Boot

Unified Extensible Firmware Interface (UEFI)

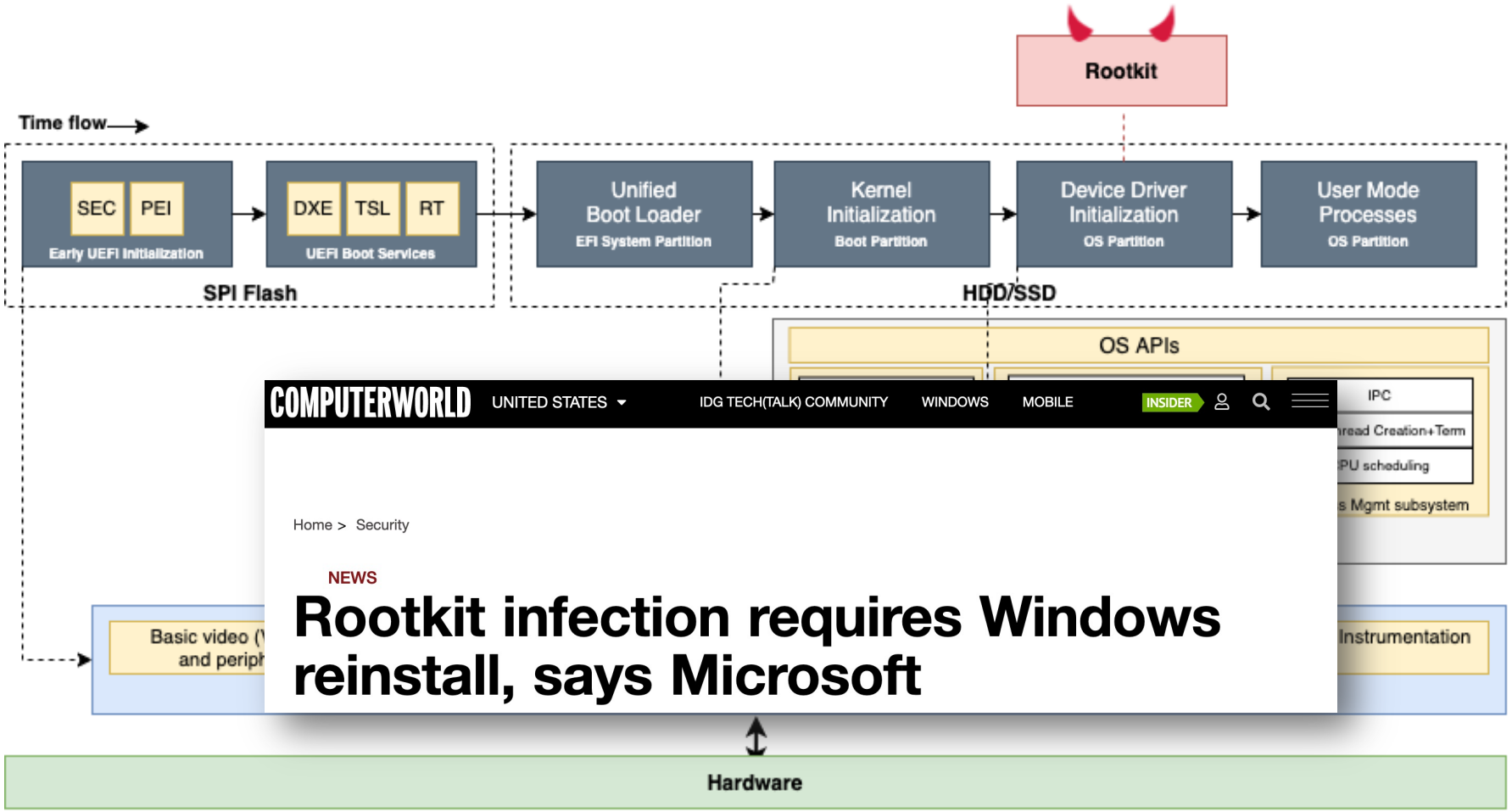
- Early versions developed exclusively by Intel (2000). Contributed to UEFI Forum and subsequently adopted by
  - Apple, for Intel Macs (2006 – today)
  - x86 OEM/ODMs (2011 – today)
  - Recent ARM and PowerPC implementations available, but not commonly used
- Stored on SPI flash, typically up to 64 MB
- GUID Partition Table (GPT) boot alleviates most MBR limitations
  - Unified boot loader binary stored on FAT32-formatted EFI System Partition (ESP)
  - Partition table enables up to 128 partitions
  - Uses 64 bits for logic block addressing – storage addressable up to 9.4 ZB
- Boot stages
  - Security Phase (SEC): Minimal assembly to initialize microcode and co-processors (Intel ME, AMD PSP, TPM)
  - Pre-EFI Initialization (PEI): Basic hardware initialization + POST, ACPI sleep/resume handling
  - Driver Execution Environment (DXE): initialize boot time device drivers
  - Transient System Load (TSL): Load user-selected boot loader from ESP
  - Runtime (RT): UEFI hands over control to OS boot loader
- Note: often still referred to as “BIOS” in vendor documentation, literature

UEFI Boot



What about security?

UEFI Boot – Attack Vectors



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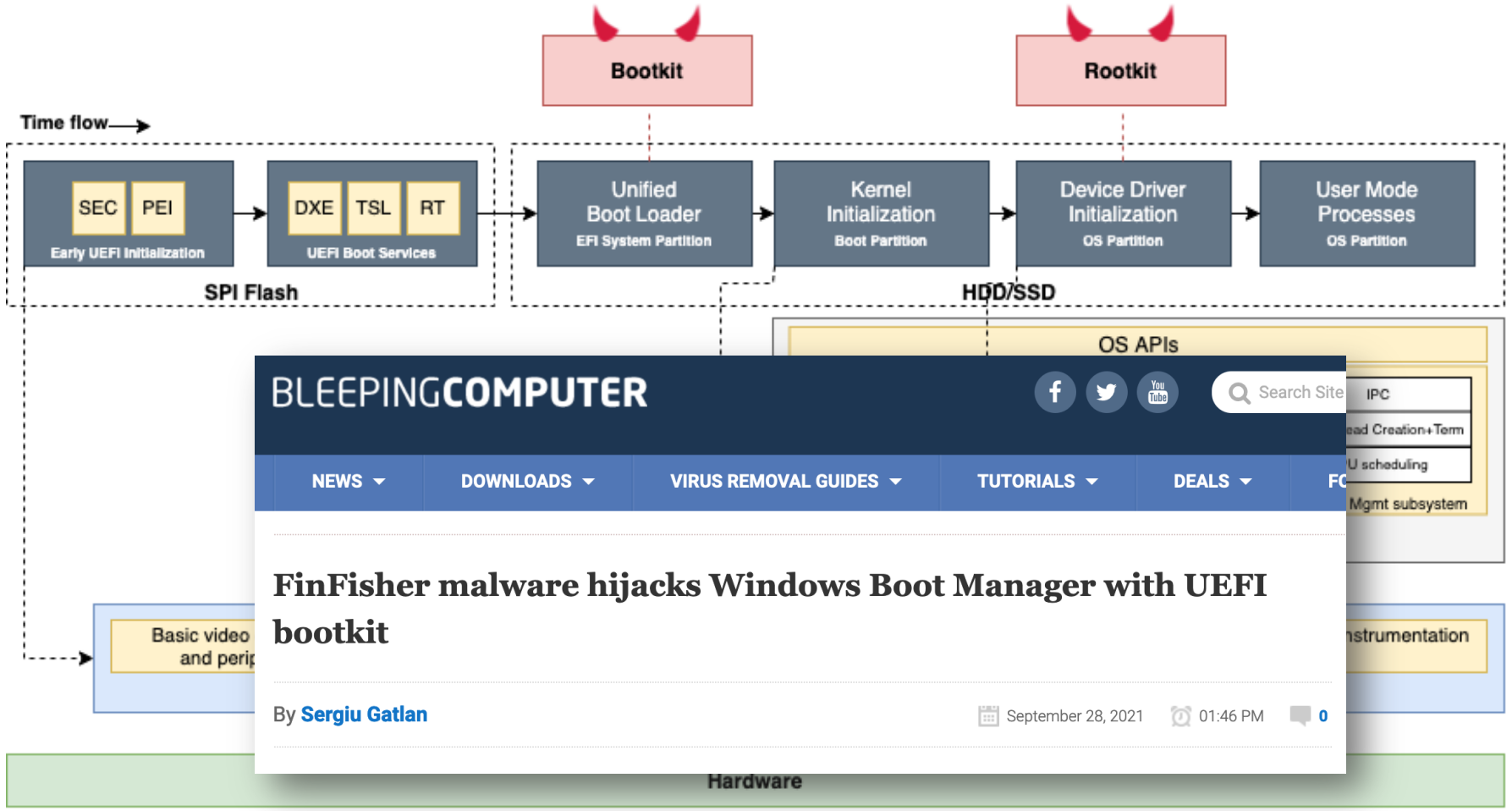
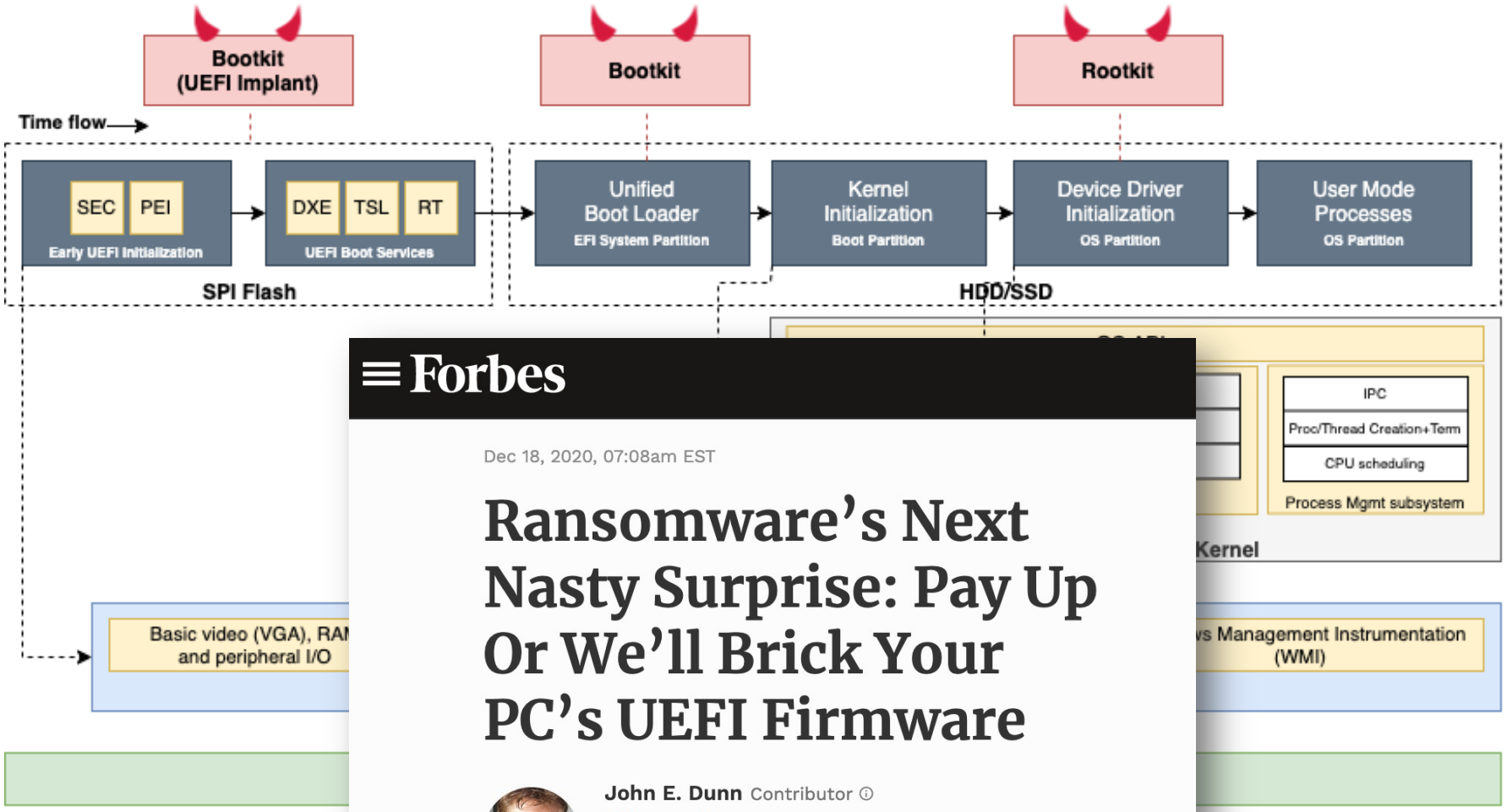


UEFI Boot – Attack Vectors



Forbes

Dec 18, 2020, 07:08am EST

Ransomware's Next Nasty Surprise: Pay Up Or We'll Brick Your PC's UEFI Firmware

John E. Dunn Contributor ⓘ

Cybersecurity

Trying to explain cybersecurity woes and why they matter

Addressing UEFI Boot Attack Vectors

- **Verified Boot / Boot Guard**
  - Protects against malicious firmware implants
  - Cryptographically verifies UEFI integrity
- **Driver signing**
  - Ensures driver authenticity (originates from device vendor) and integrity (tamper-resistance)
  - OS vendors require device vendors to submit drivers for evaluation
    - Linux (kernel.org): submit code for functional + security review
    - Windows: semi-blackbox testing through WHQL program
  - Upon passing verification
    - Linux: distribution vendors sign pre-compiled driver binaries
    - Windows: Microsoft signs driver's commercial release certificate; device vendor signs driver using private key to latter certificate
- **Secure Boot**
  - Protects against malicious, unsigned code early in boot process
  - Cryptographically verifies boot chain: OS bootloader, kernel, drivers

Secure Boot: A Closer Look

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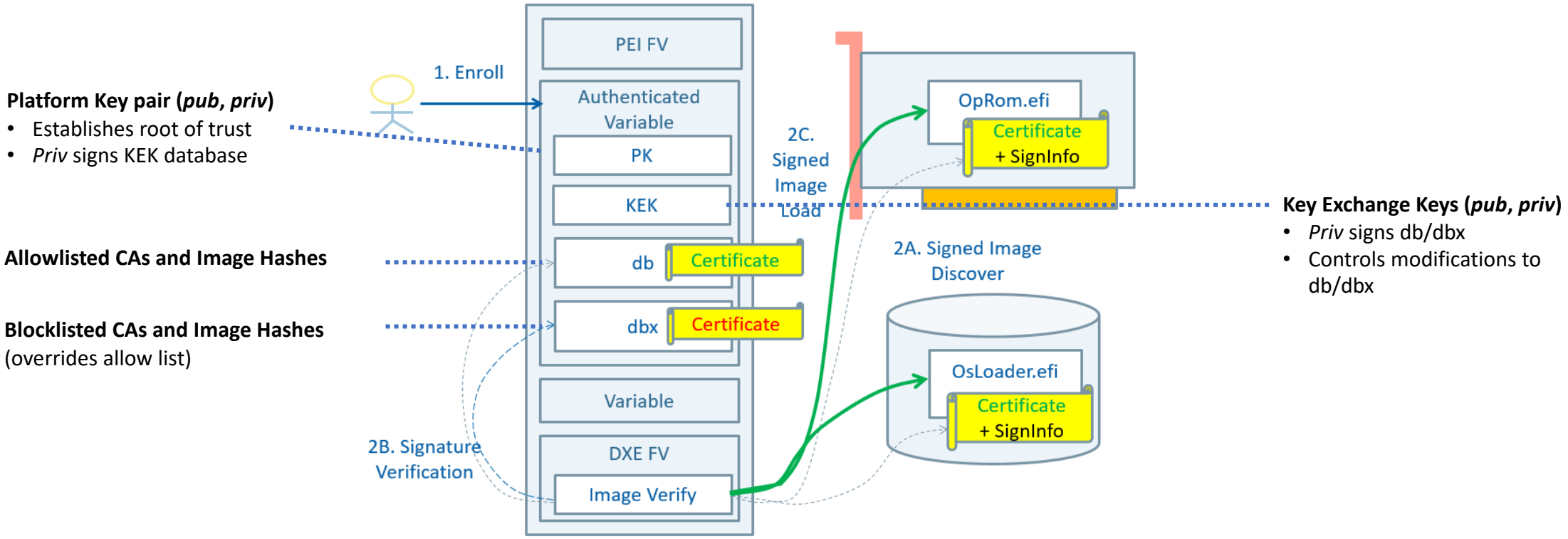

[Based on "Understanding the UEFI Secure Boot Chain" – TianoCore/EDK2]

Secure Boot: A Closer Look

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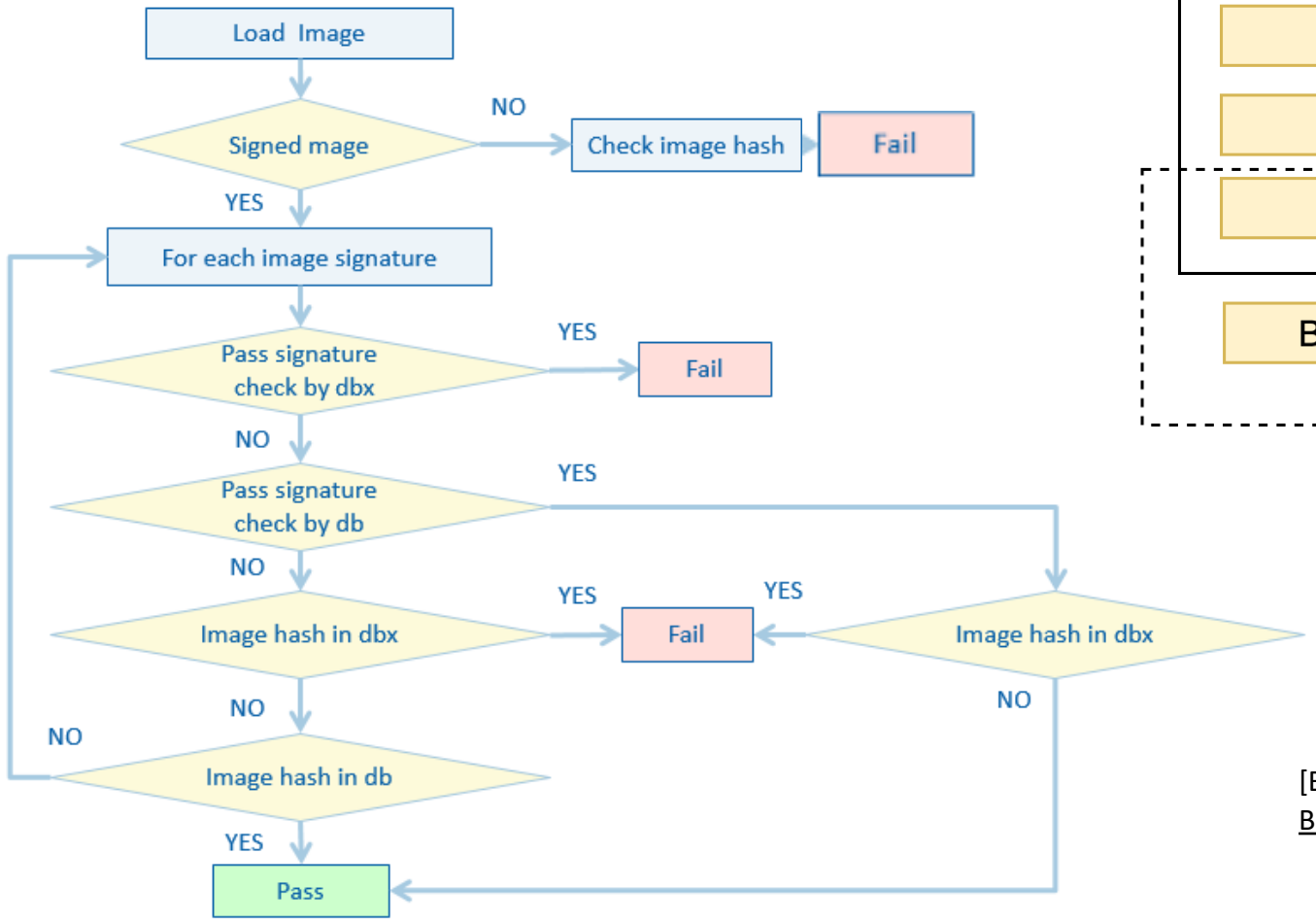

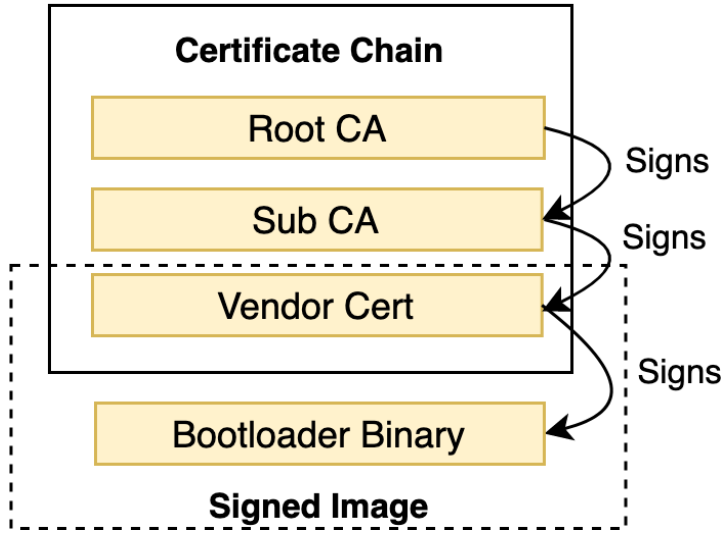

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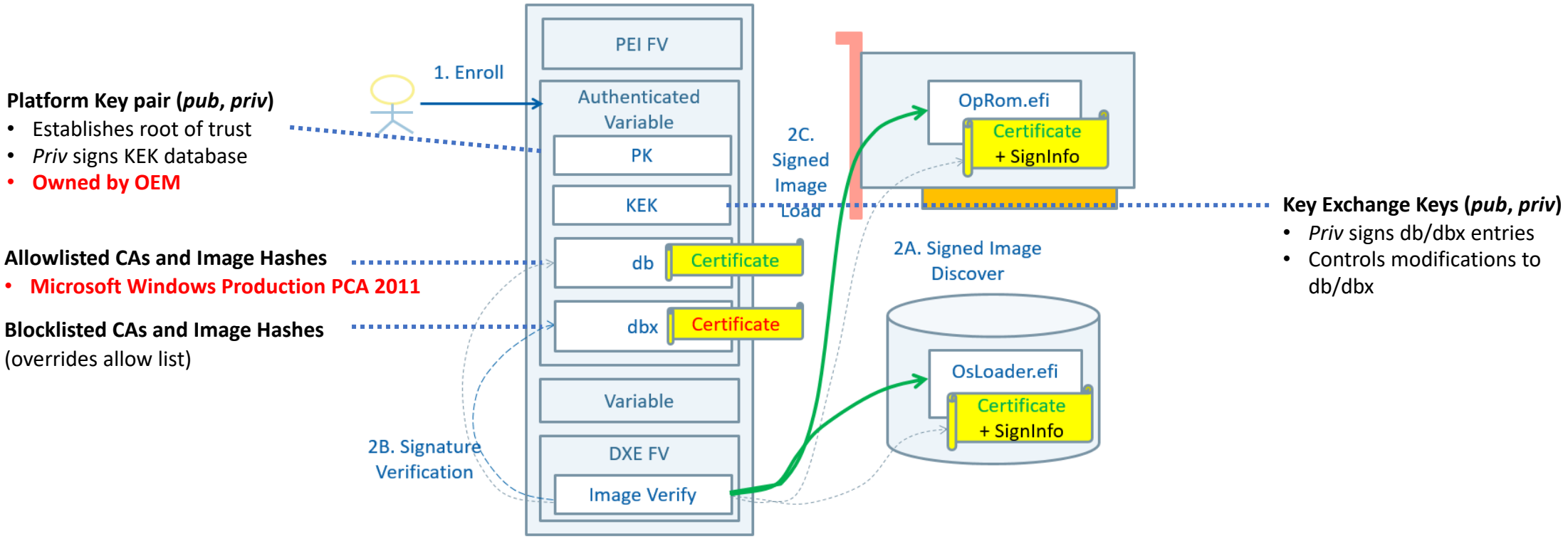
Secure Boot: A Closer Look

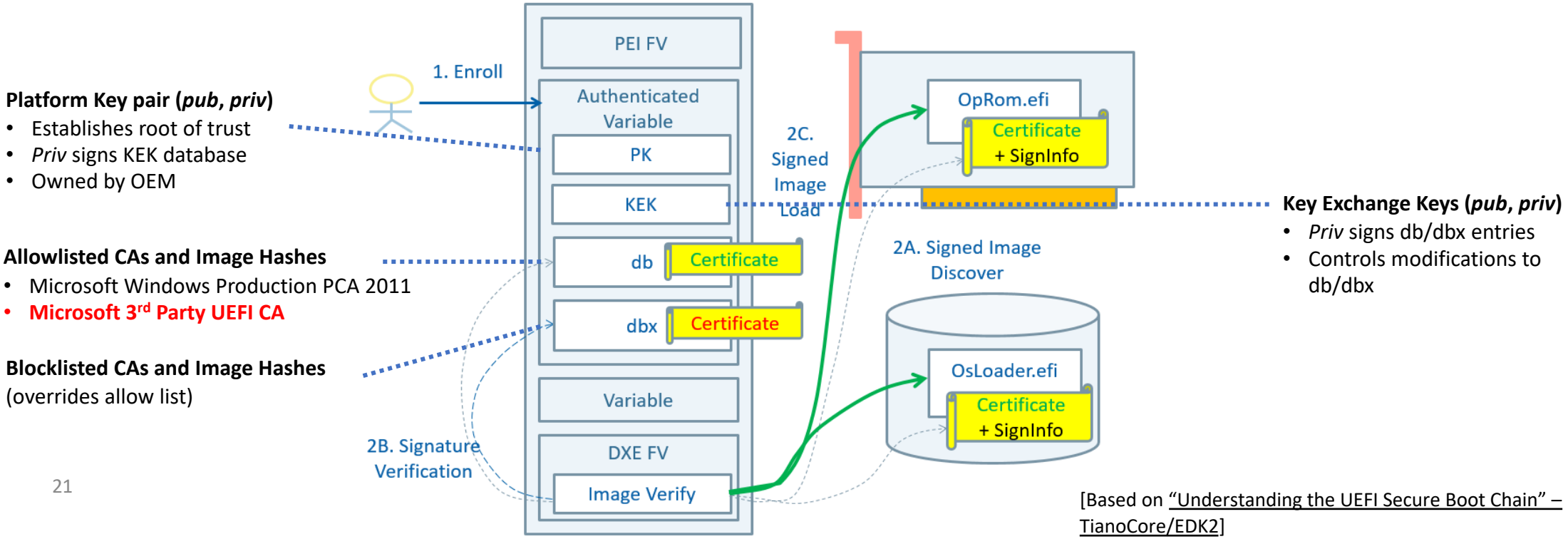
- Secure Boot trust model similar to WebPKI, but with significant exceptions
  - OEM-controlled PK; Root CAs exclusively controlled by Microsoft
- Raises concerns on Secure Boot chain ownership



[Based on "Understanding the UEFI Secure Boot Chain" – TianoCore/EDK2]

Secure Boot: A Closer Look

- Recent UEFI implementations enable user-replaceable PK
- Secondary Microsoft Root CA signs third party boot loaders
  - Red Hat: SHIM first stage boot loader
    - Used to chainload e.g. GRUB2, systemd-boot, EFI Stub
    - Enables users to self-sign boot loaders + drivers using “Machine Owner Key” (MOK)
  - Anti-malware and imaging solutions, e.g. live USB flash drive environment



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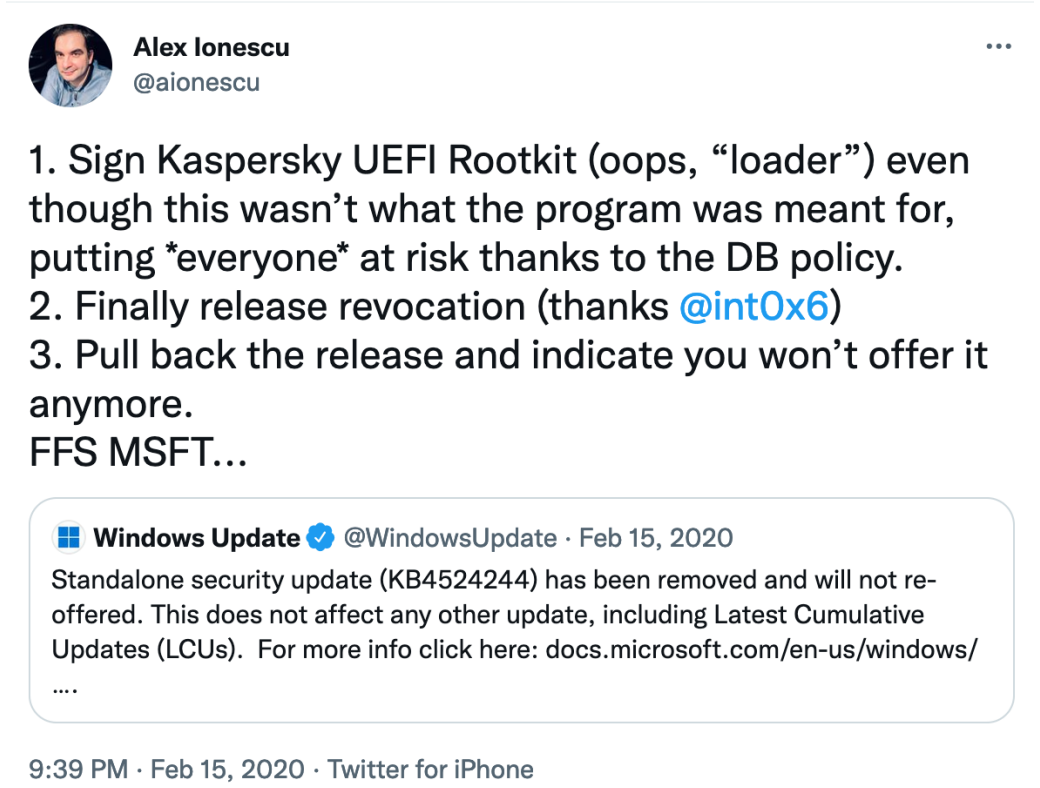
Secure Boot: How Secure is It?

- Boot chain security relies on
  - Root and subordinate CAs ensuring appropriate key management practices
  - Root and subordinate CAs signing only trustworthy binaries



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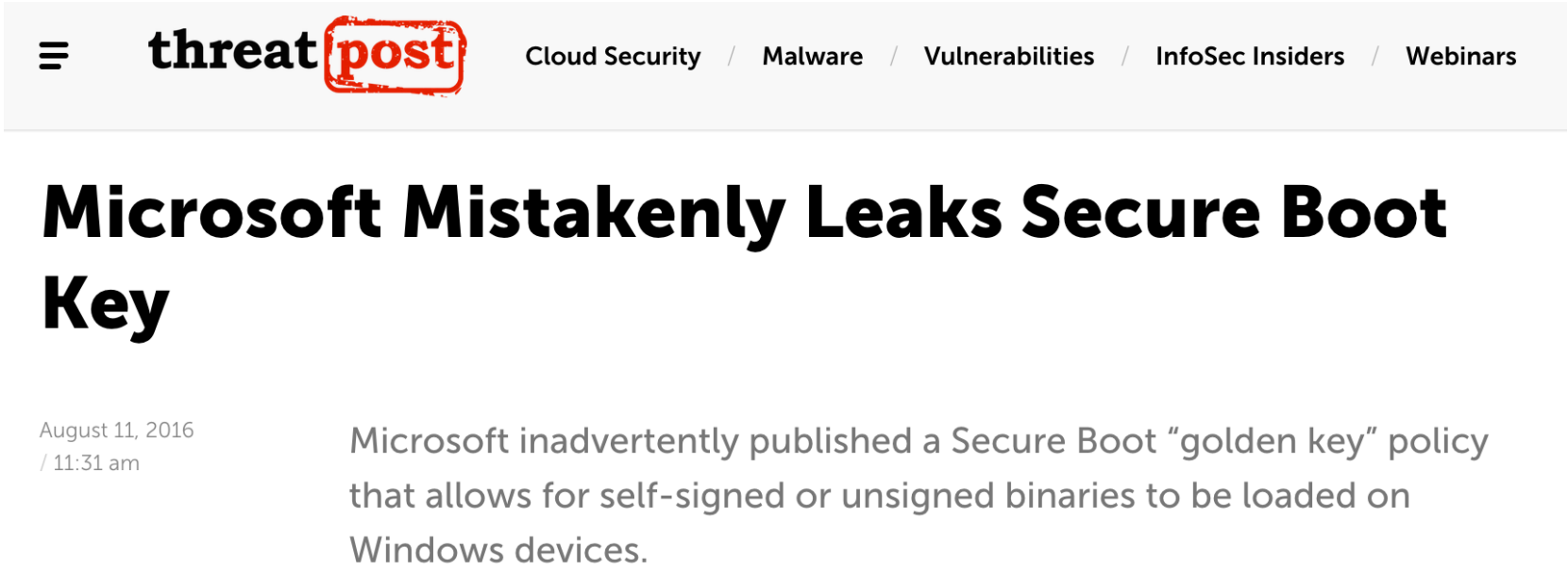

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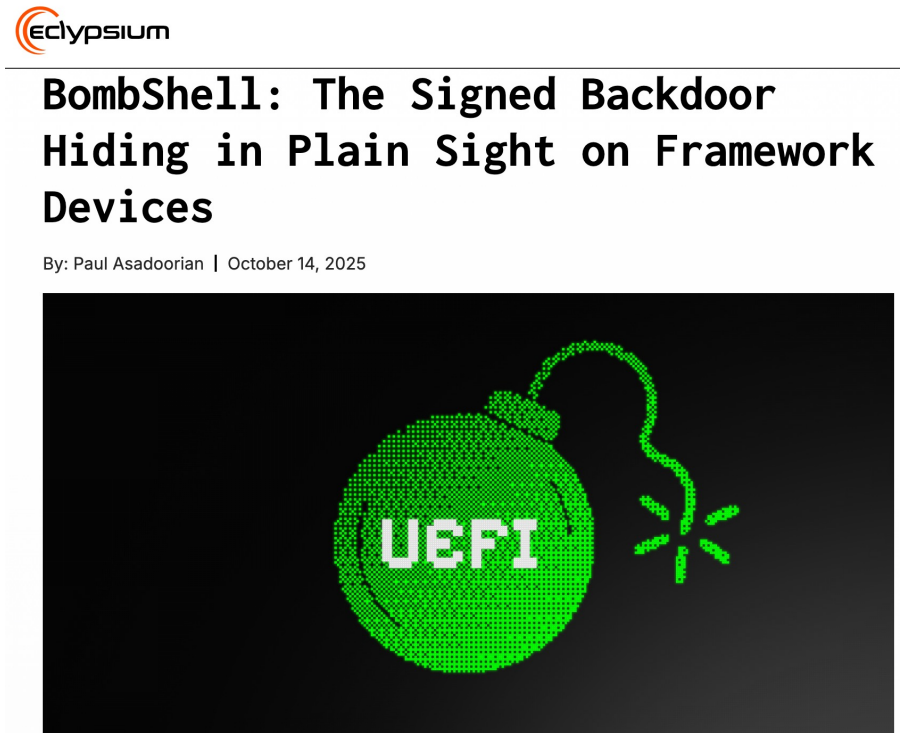
"BootHole" vulnerability in the GRUB2 bootloader opens up Windows and Linux devices using Secure Boot to attack. All operating systems using GRUB2 with Secure Boot must release new installers and bootloaders.



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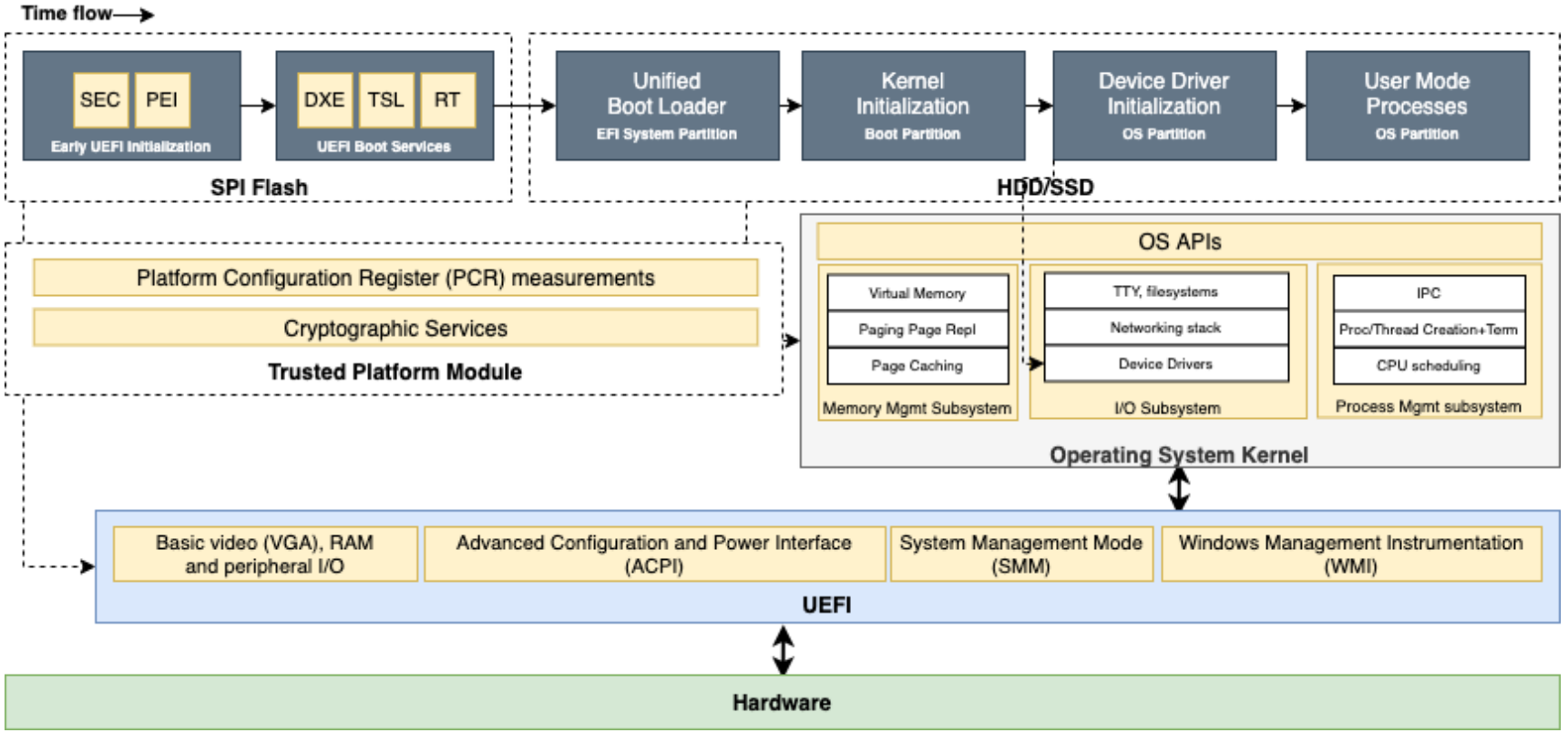
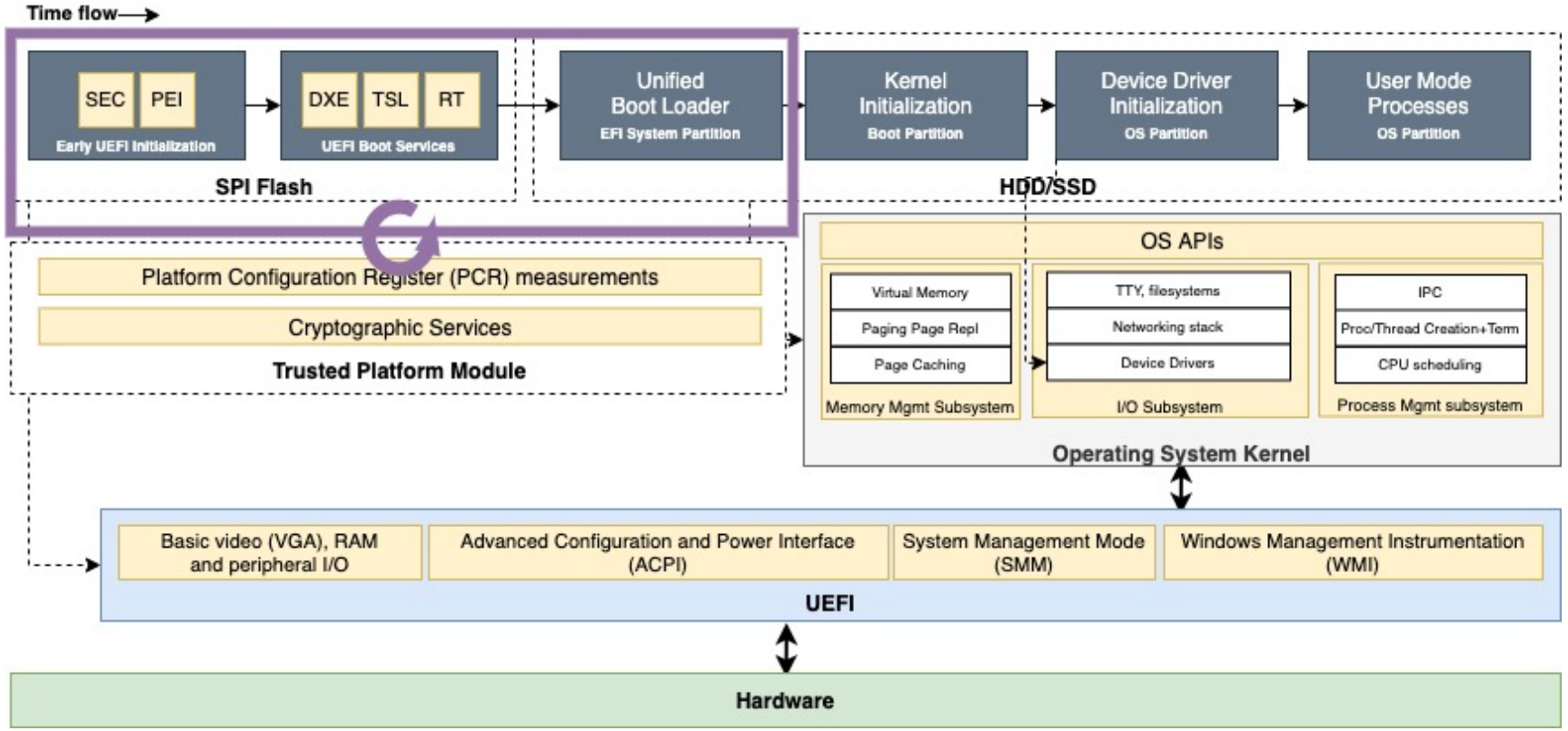
  - Signed binaries verifying any subsequently chainloaded binaries
  - Signed binaries not introducing vulnerabilities of their own
  - If all fails, CAs timely identifying affected public keys/binaries; OEMs distributing dbx updates

Measured Boot: Essentials (1)



- Requires autonomous, distinct agent that continuously monitors boot process

Measured Boot: Essentials (2)



- Typical x86 approach employs TPM
  - Learns about known good state, i.e. “one-time” setup that computes hash over UEFI image, UEFI config, bootloader and other boot-related parameters.
  - Stores state as PCR tuple. Continuously computes PCR on each boot cycle – e.g.

    $PCR[11]_n = SHA256(PCR[11]_{n-1} \,\#\, ValueToExtendWith)$
  - Common use case: PCR changes ⇔ boot chain modified

Measured Boot: Platform Configuration Registers (1)

0	Firmware	UEFI Boot Component	Core system firmware executable code	UEFI TPM event log
1	Firmware	UEFI Boot Component	Core system firmware data/host platform configuration; typically contains serial and model numbers	UEFI TPM event log
2	Firmware	UEFI Boot Component	Extended or pluggable executable code; includes option ROMs on pluggable hardware	UEFI TPM event log
3	Firmware	UEFI Boot Component	Extended or pluggable firmware data; includes information about pluggable hardware	UEFI TPM event log
4	Firmware	UEFI Boot Component	Boot loader and additional drivers; binaries and extensions loaded by the boot loader	UEFI TPM event log
5	Firmware	UEFI Boot Component	GPT/Partition table	UEFI TPM event log
7	Firmware	UEFI Boot Component	SecureBoot state	UEFI TPM event log

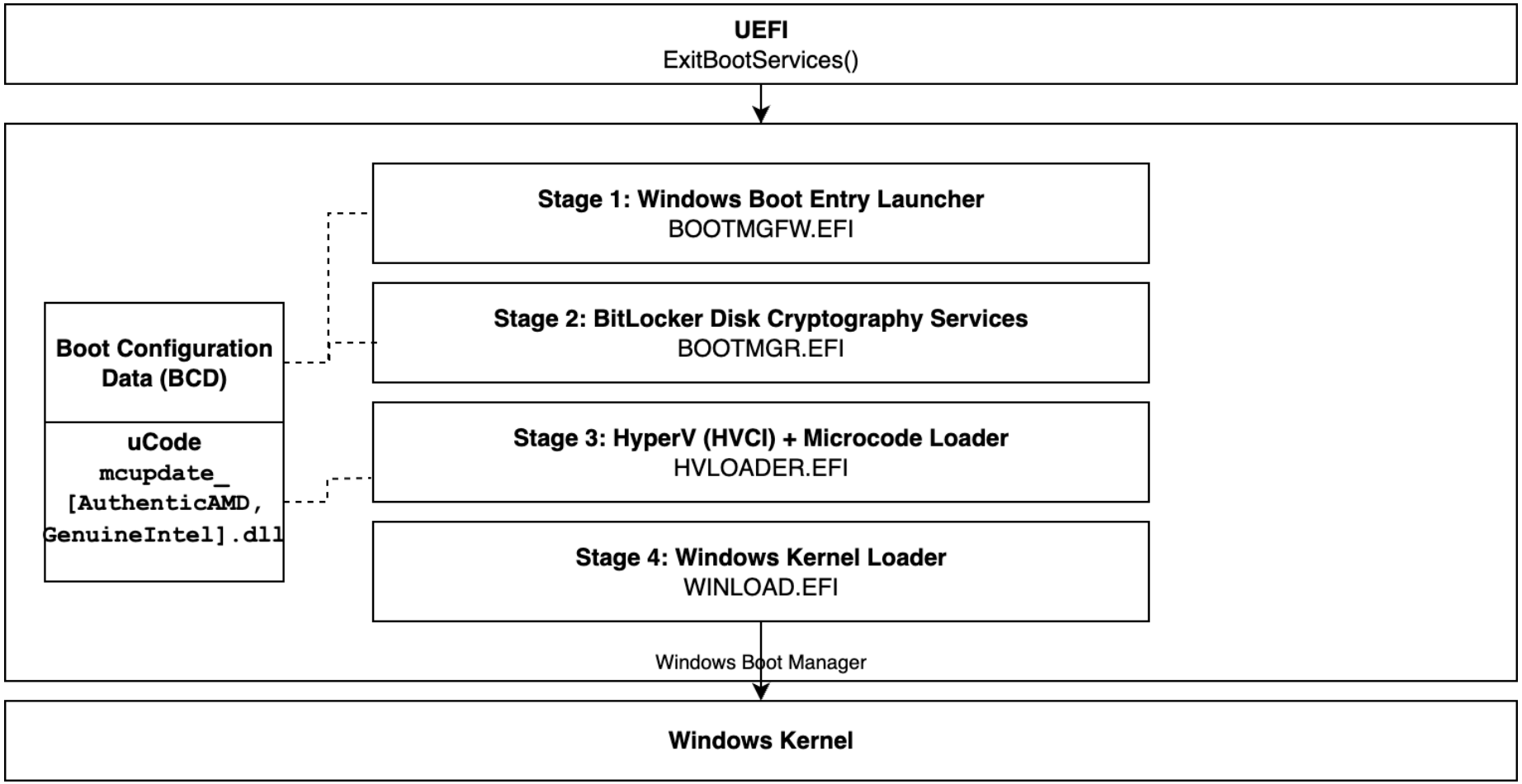
["PC Client Specific Platform Firmware Profile Specification 2.0", Trusted Computing Group]

Measured Boot: Platform Configuration Registers (2)

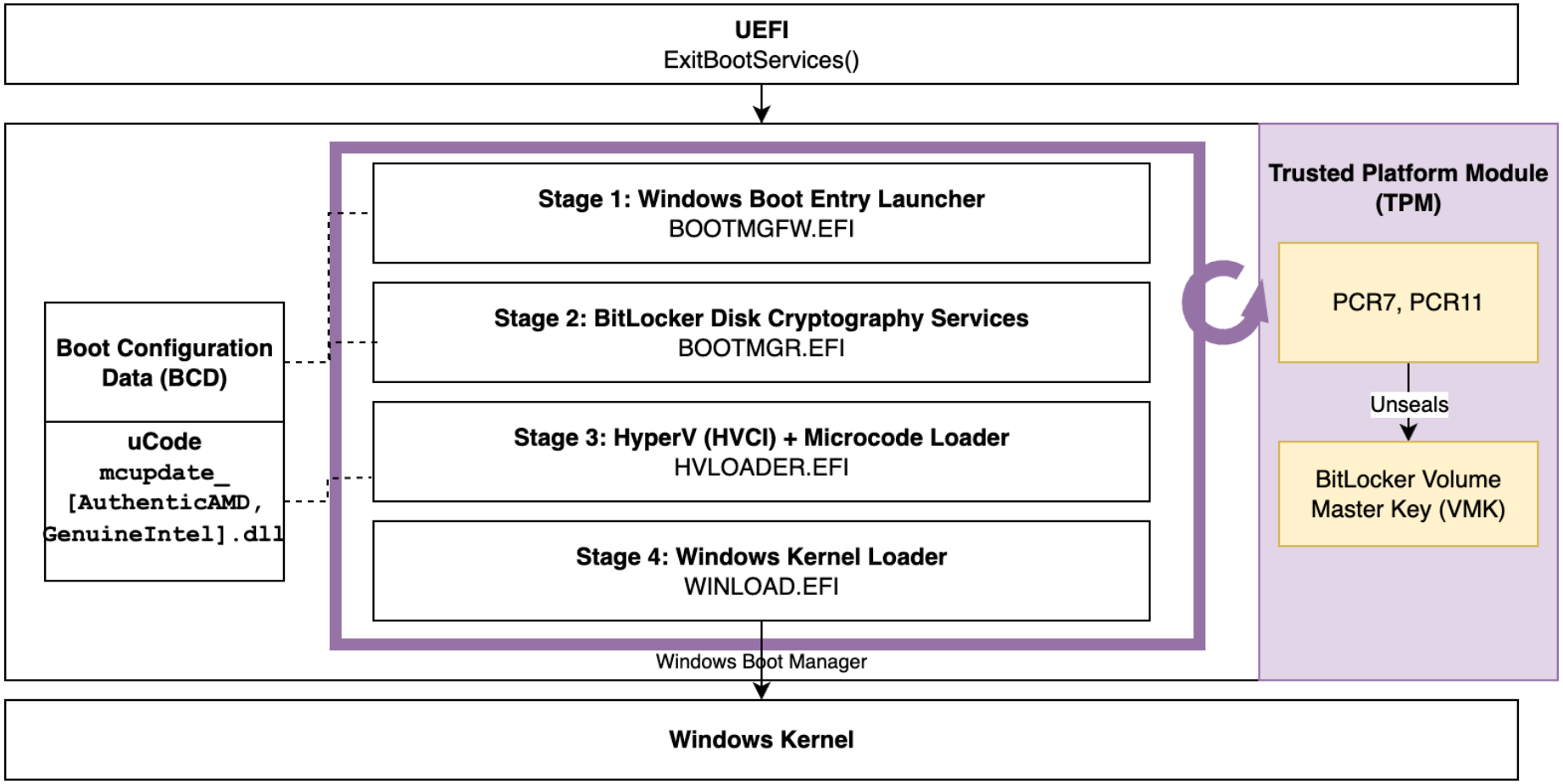
8	`grub` 🍲	UEFI Boot Component	Commands and kernel command line	UEFI TPM event log
9	`grub` 🍲	UEFI Boot Component	All files read (including kernel image)	UEFI TPM event log
	Linux kernel 🫘	Kernel	All passed initrds (when the new `LOAD_FILE2` initrd protocol is used)	UEFI TPM event log
10	IMA 📐	Kernel	Protection of the IMA measurement log	IMA event log
11	`systemd-stub` 🚀	UEFI Stub	All components of unified kernel images (UKIs)	UEFI TPM event log
	`systemd-pcrphase` 🚀	Userspace	Boot phase strings, indicating various milestones of the boot process	Journal (for now)
12	`systemd-stub` 🚀	UEFI Stub	Kernel command line, system credentials and system configuration images	UEFI TPM event log
13	`systemd-stub` 🚀	UEFI Stub	All system extension images for the initrd	UEFI TPM event log
14	`shim` 🔑	UEFI Boot Component	“MOK” certificates and hashes	UEFI TPM event log

[“PC Client Specific Platform Firmware Profile Specification 2.0”, Trusted Computing Group]

Measured Boot: Windows Boot Chain (3)



Measured Boot: Windows Boot Chain (4)



Measured Boot: How Secure Is It?

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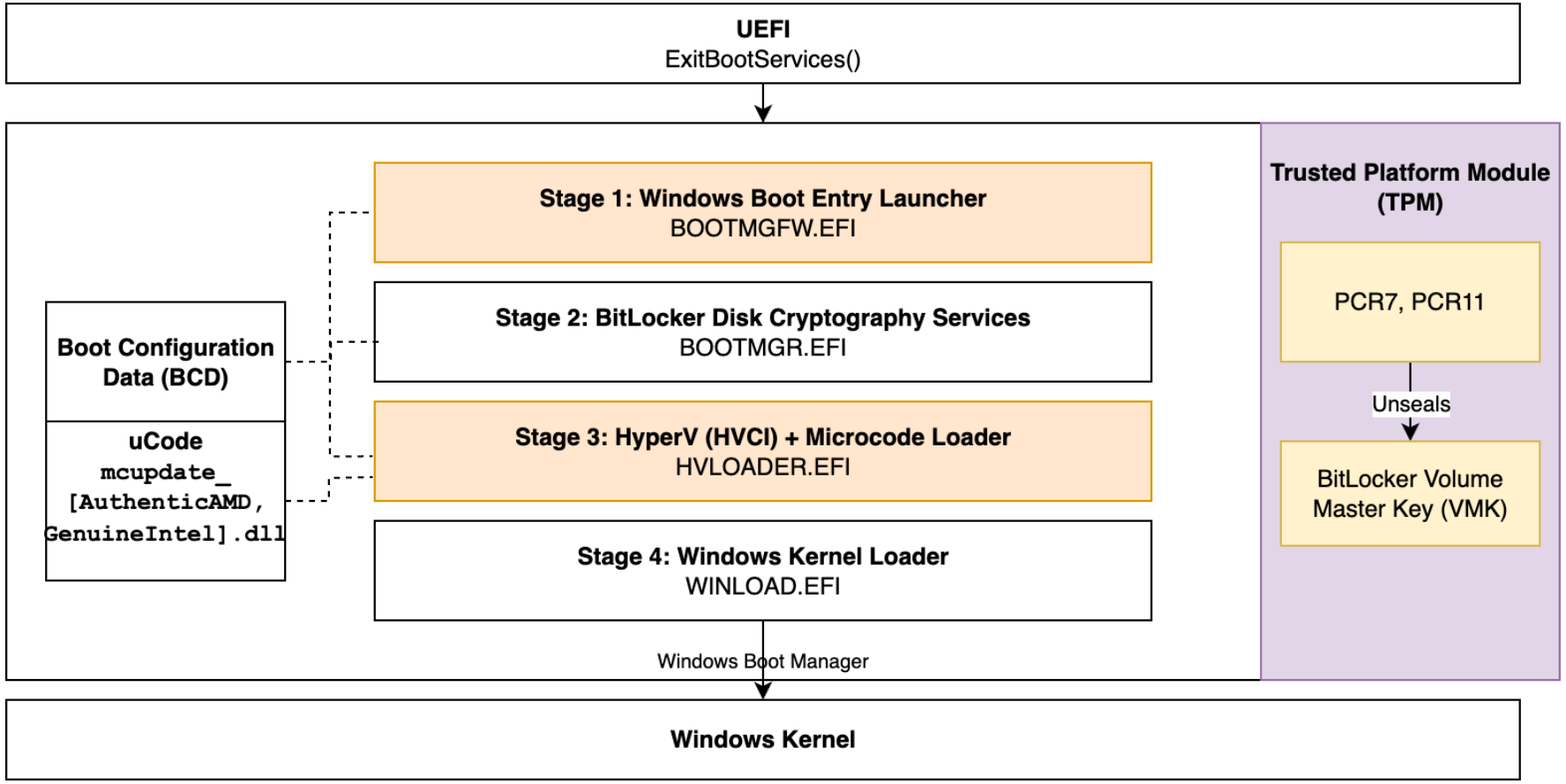


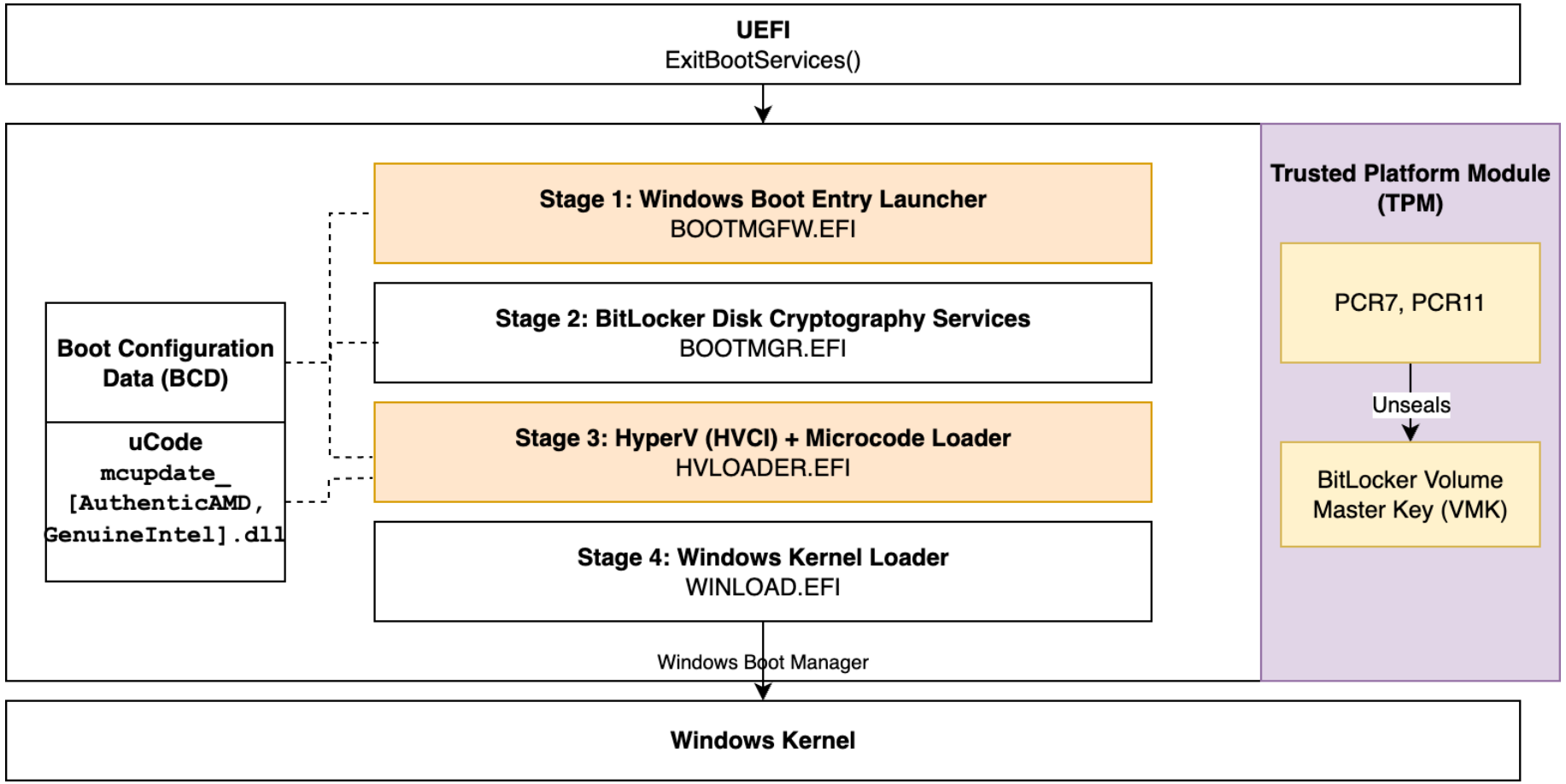
- Black Lotus (2023)
  - APT-sponsored bootkit campaign; exploits Windows bootloader 0-day (“Baton Drop”)
  - Disables BitLocker measured boot through OS runtime privilege escalation
  - More details in bonus slides

Conclusion

- From BIOS to UEFI: transition from legacy, inflexible, insecure BIOS/MBR booting to modern UEFI with richer functionality and scalability
- Modular architecture, larger firmware space, faster parallelized initialization, GPT support, and robust extensibility
- Strong, but not flawless boot-time security mitigations
  - Secure Boot as strong as weakest link in 1) PKI-based trust hierarchy, and 2) chainloaded binaries
  - Measured Boot conceptually strong, implementation-wise a work in progress
  - Verified Boot remains unchallenged… or does it?

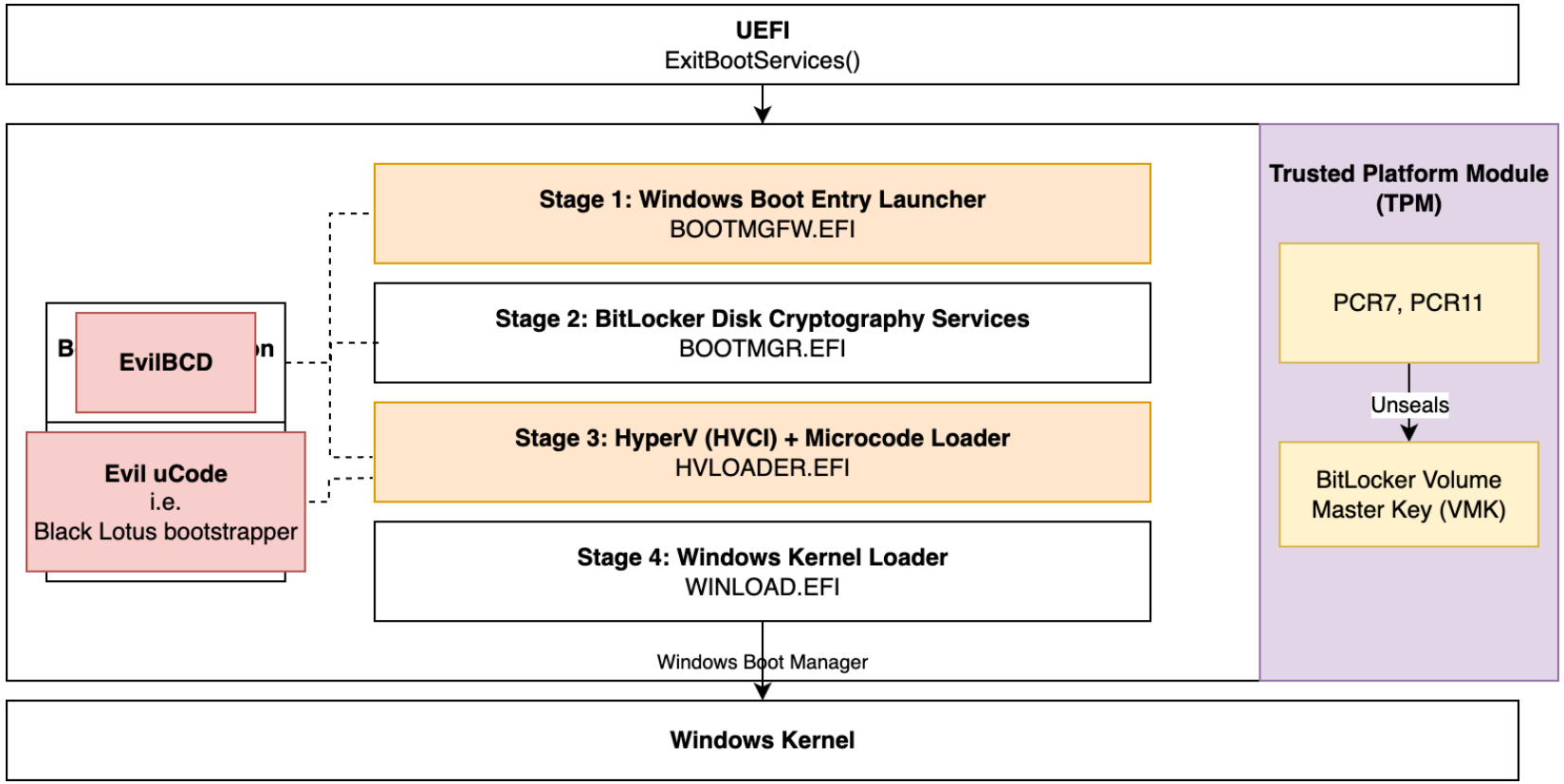
Bonus slides – Black Lotus (2023)

Black Lotus (1): Entry Point



- Baton Drop (CVE-2022-21894)
  - Bootmgfw BCD parser vulnerability: `truncatememory` allows limiting accessible PA range
  - Microsoft issues WBM update, but does not revoke trust through DBX

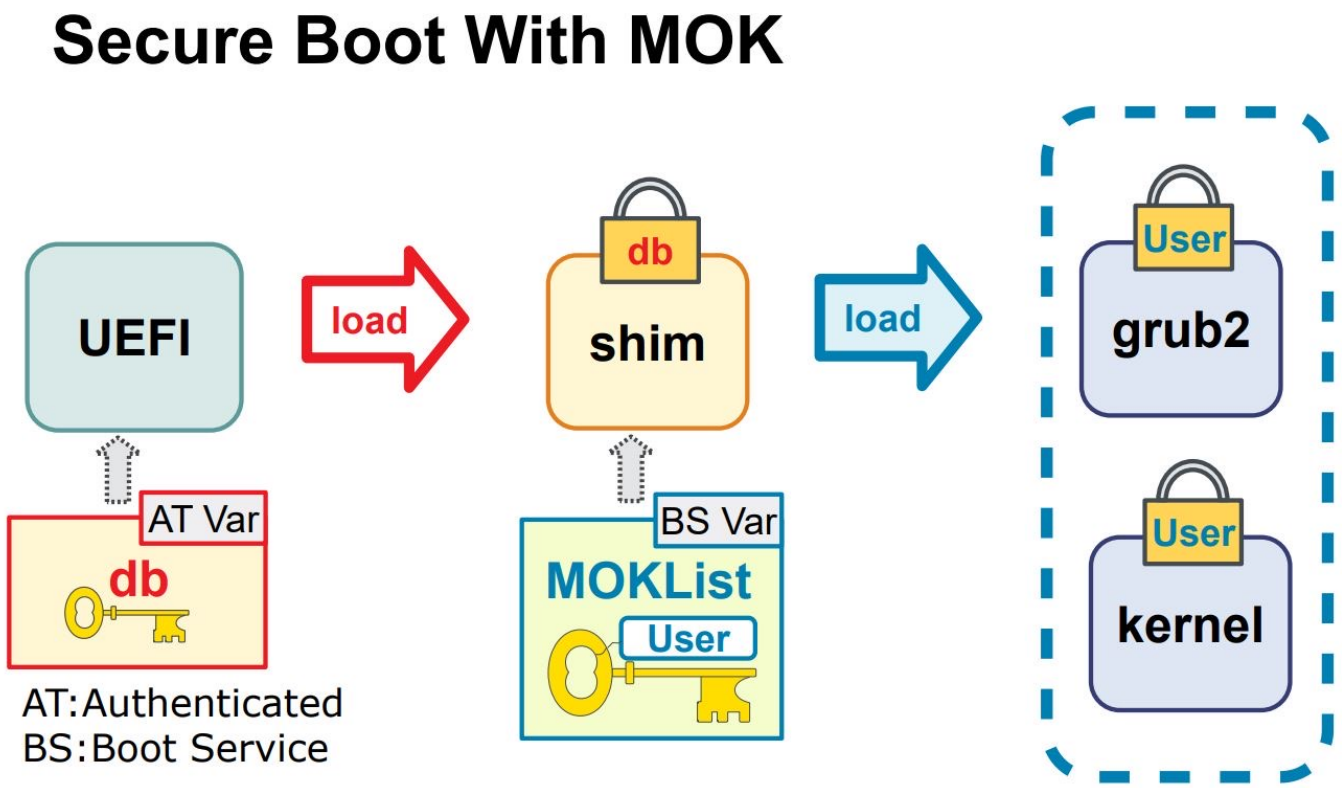
Black Lotus (2): Attack Flow



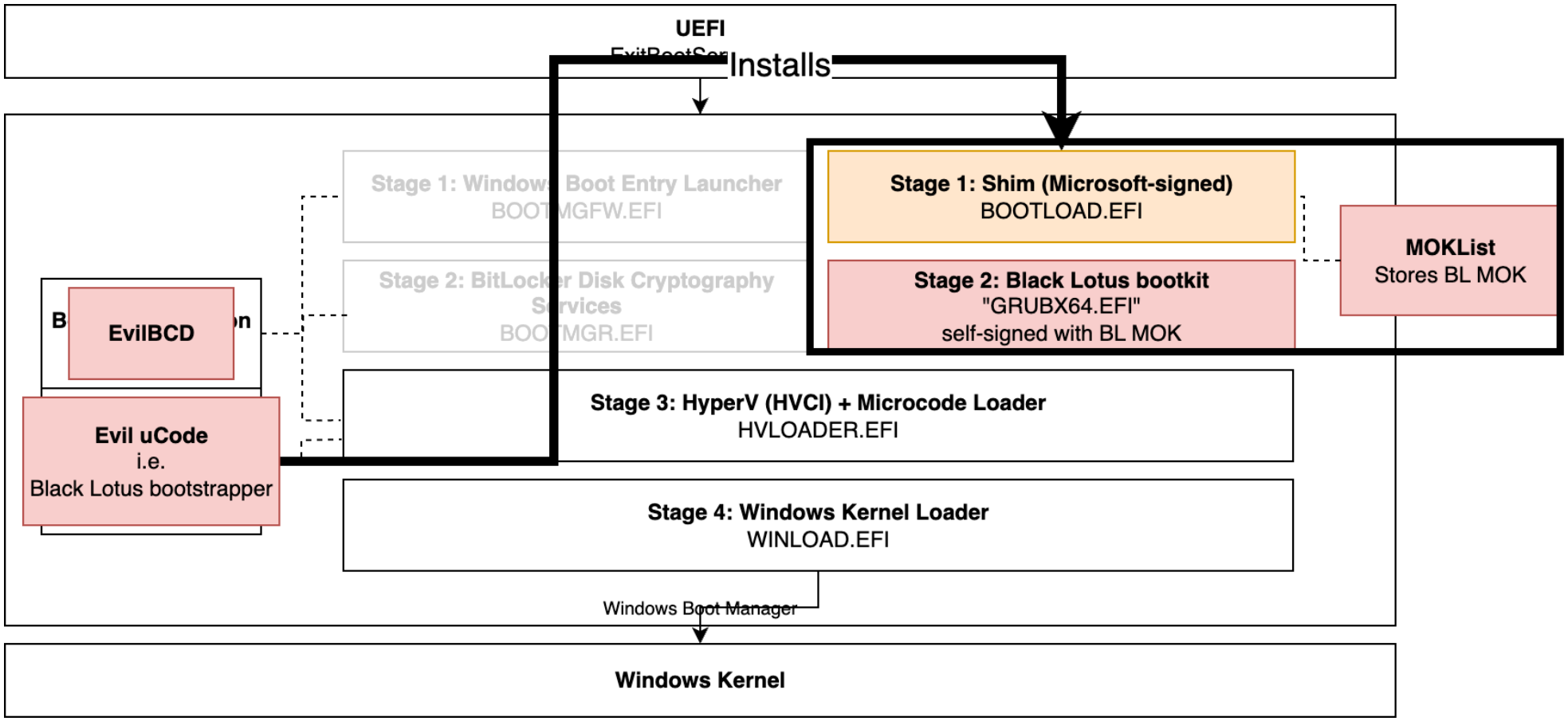
- **Black Lotus Dropper**: at Windows runtime (e.g. browser drive-by-download w/privesc, supply chain attack, social eng), installs **EvilBCD** and **Evil uCode**
- WBM Secure Boot policy stored at 0x10000000
- **EvilBCD** sets `truncatememory` = 0x10000000, effectively disabling Secure Boot, and thus enabling `testsigning`, `nointegritychecks`

Pit stop: Shim

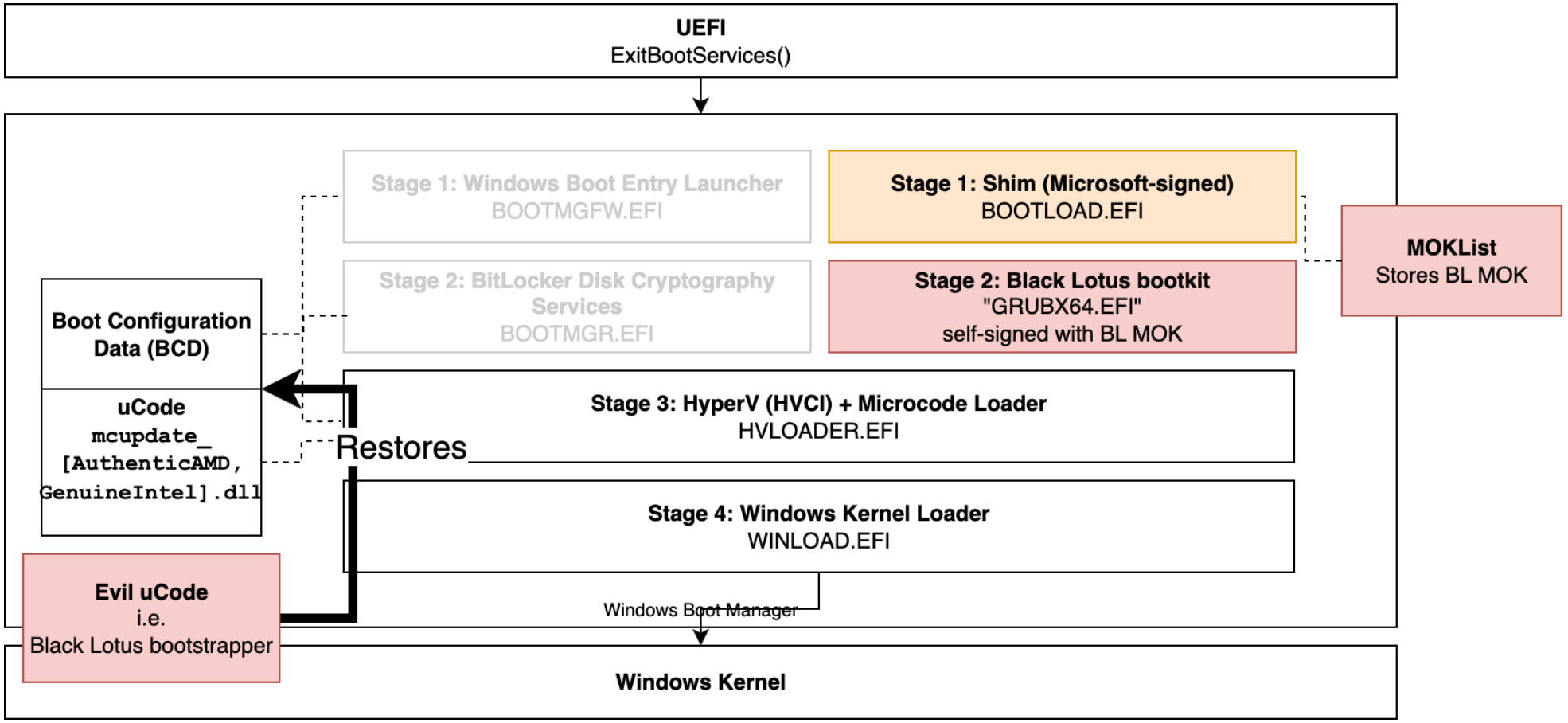
- Red Hat: SHIM first stage boot loader
  - Used to chainload e.g. GRUB2, systemd-boot, EFI Stub
  - Enables users to self-sign boot loaders + drivers using “Machine Owner Key” (MOK)



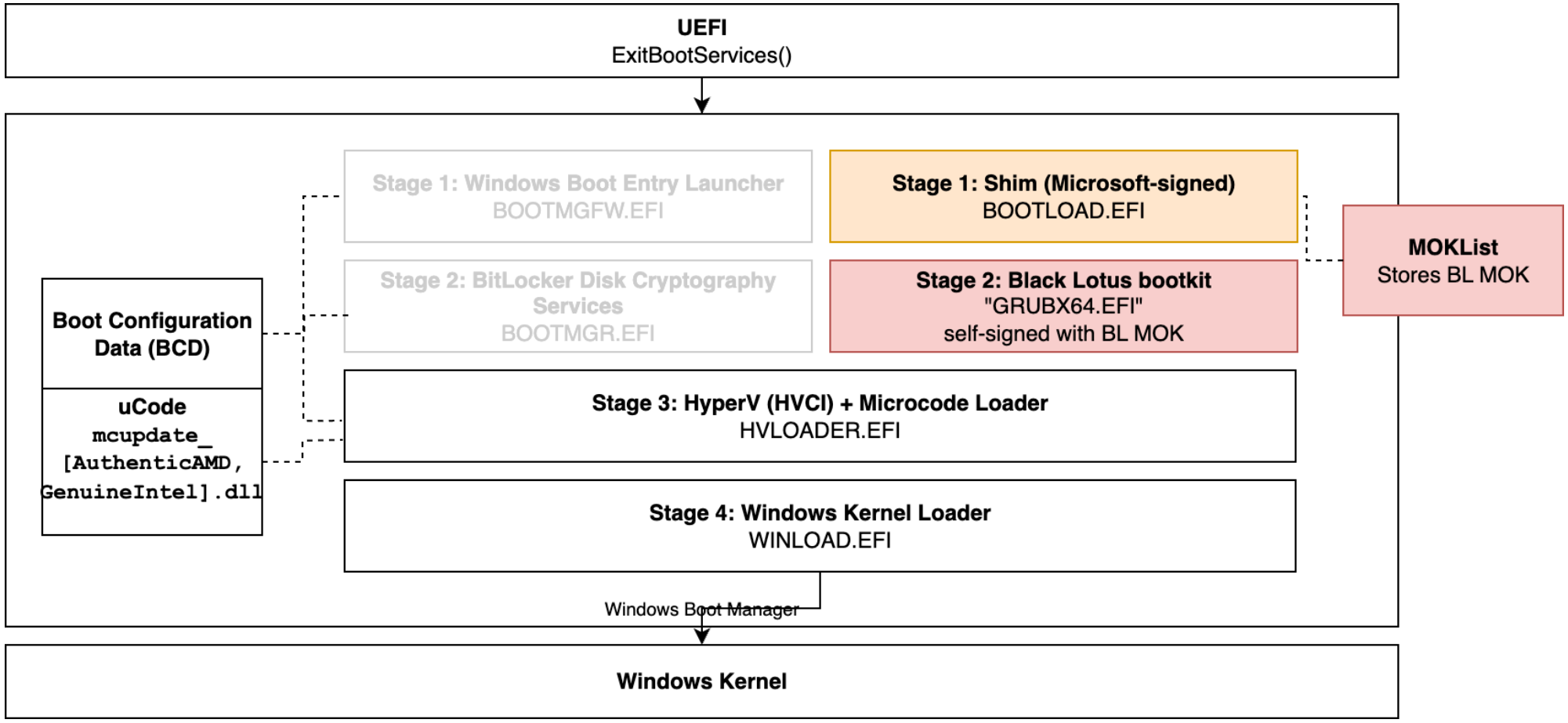
Black Lotus (3): Persistence



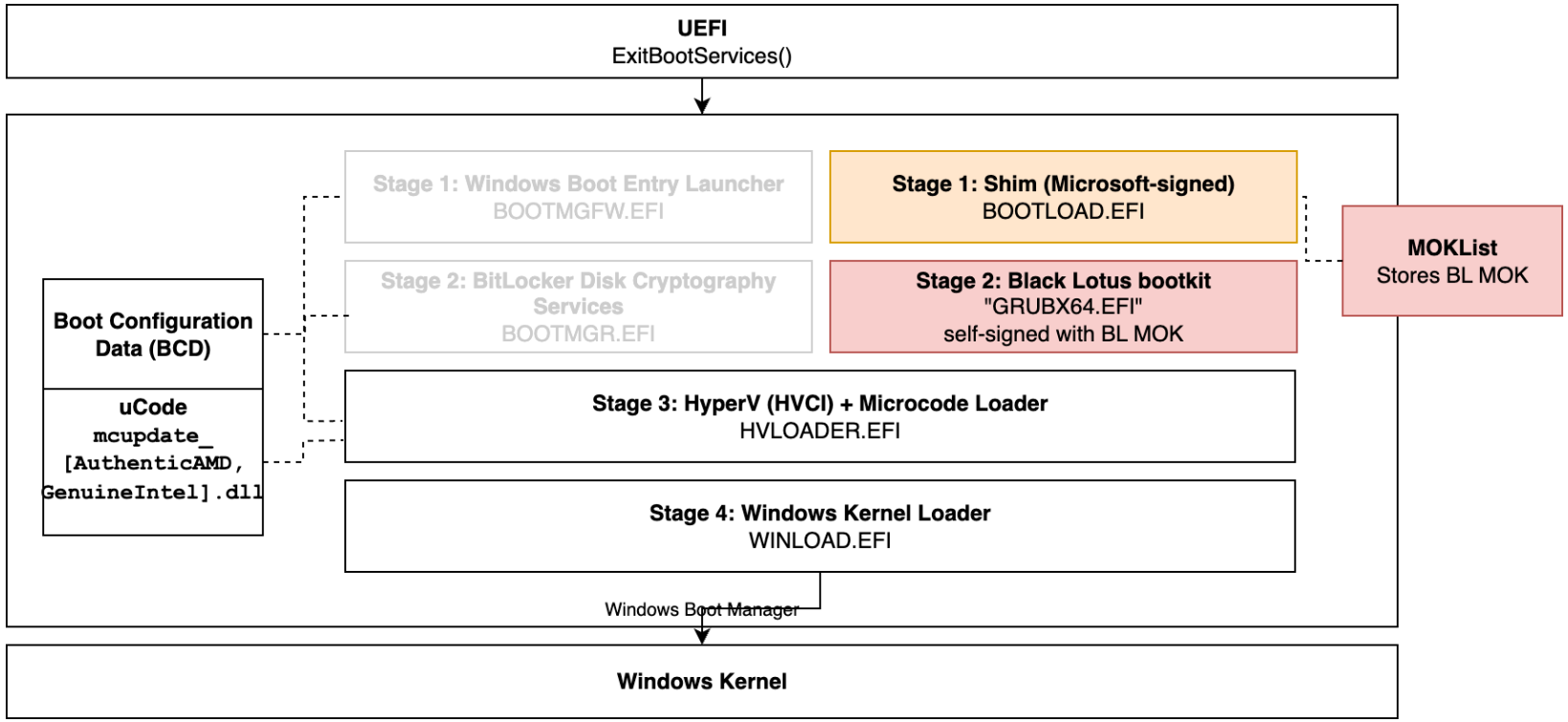
Black Lotus (4): Clean Up



Black Lotus (5): Compromised Boot Chain

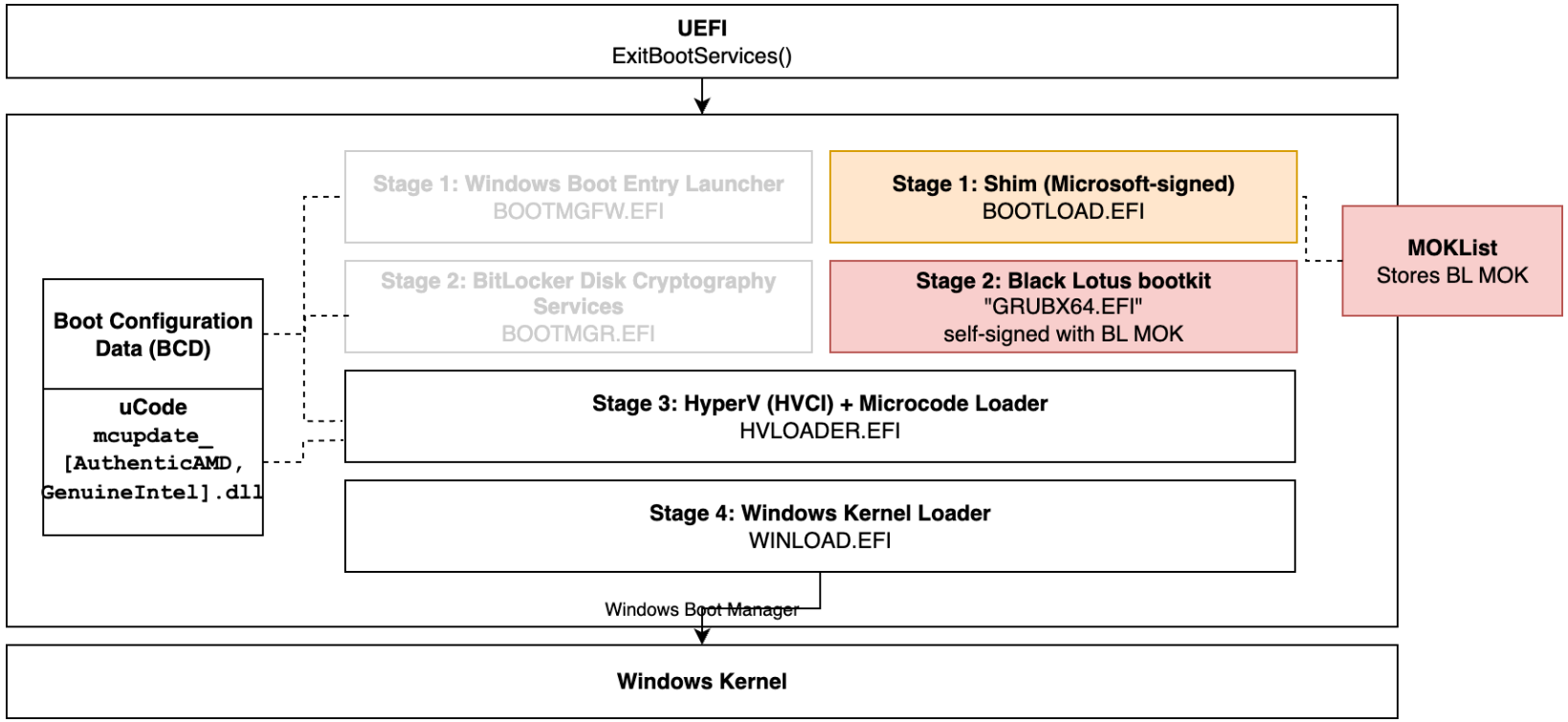


Black Lotus (6): Compromised Boot Chain



- But… what about TPM's PCR measurements?
  - As part of first stage, Black Lotus dropper simply disables BitLocker measured boot through `DisableKeyProtectors`

Black Lotus (7): Compromised Boot Chain



- But… what about TPM's PCR measurements?
  - As part of first stage, Black Lotus dropper simply disables BitLocker measured boot through `DisableKeyProtectors`
- Windows kernel-based C&C agent allows further system compromise