TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Computer Science Institute of Systems Architecture, Operating Systems Group

TRUSTED COMPUTING

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Lecture Goals

Goal: Understand principles of:

- Authenticated booting, relation to (closed) secure booting
- Remote attestation
- Sealed memory
- Dynamic root of trust, late launch
- Protection of applications from the OS
- Point to implementation variants (TPM, SGX, TrustZone)

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Lecture Non-Goals

Non-Goal:

- Deep discussion of cryptography
- Lots of details on TPM, TCG, TrustZone, SGX, ...
  → Read the documents once needed

Terminology

- Secure Booting
- Measured / authenticated Booting
- (Remote) Attestation
- Sealed Memory
- Late Launch / dynamic root of trust
- Trusted Computing (Group)
- Trusted Computing Base
- **Beware of terminology chaos!**

Trusted Computing …

Trusted Computing Base (TCB):

- Set of all components *(hardware, software, procedures)* that must be relied upon to enforce a security policy

Trusted Computing (Technology):

- Particular technology, often comprised of authenticated booting, remote attestation, and sealed memory

Trusted Computing Group (TCG):

- Consortium behind a specific trusted computing standard

Key Goals of Trusted Computing

- Prevent certain software from running
- Which computer system do I communicate with?
- Which stack of software is running …
  - … in front of me?
  - … on my server somewhere?
- Restrict access to certain secrets to certain software
- Protect an application against the OS

Usage Examples (1)

Digital Rights Management (DRM):

- Vendor sells content
- Vendor creates key, encrypts content with it
- Client downloads encrypted content, stores it locally
- Vendor sends key, but wants to ensure that only specific software can use it
- Has to work also when client is offline
- **Vendor does not trust the client**

Usage Examples (2)

Virtual machine by cloud provider:

- Client rents compute and storage (virtual machine)
- Client provides its own operating system (OS)
- Needs to ensure that provided OS runs
- Needs to ensure that provider cannot access data
- **Customer does not trust cloud provider**

Usage Examples (3)

Industrial Plant Control:

- Remote operator sends commands, keys, …
- Local technicians occasionally run maintenance / selftest software, install software updates, …
- **Local technicians are not trusted**

Usage Examples (4)

Anonymity Service:

- Provides anonymous communication over internet (e.g., one node in mix cascade)
- Law enforcement can request introduction of surveillance functionality (software change)
- **Anonymity-service provider not trusted**

Trusted Computing Terminology

Measuring:

- Process of obtaining metrics of platform characteristics
- Example: Hash code of software

Attestation:

- Vouching for accuracy of (measured) information

Sealed Memory:

- Binding information to a (software) configuration

Notation: Hashes and Keys

Hash: H(M)

- Collision-resistant hash function **H** applied to content **M**

Asymmetric key pair: $\mathbf{E_{pair}}$ consisting of $\mathbf{E_{priv}}$ and $\mathbf{E_{pub}}$

- Asymmetric private/public key pair of entity **E**, used to either conceal (encrypt) or sign some content
- $\mathbf{E_{pub}}$ can be published, $\mathbf{E_{priv}}$ must be kept secret

Symmetric key: E

- Symmetric key of entity **E**, must be kept secret ("secret key")

Notation: Result of Operations

Digital Signature: $\{M\}E_{priv}$

- E_{pub} can be used to verify that **E** has signed **M**
- E_{pub} is needed and sufficient to check signature

Concealed Message: $\{M\}E_{pub}$

- Message **M** concealed (encrypted) for **E**
- E_{priv} is needed to unconceal (decrypt) **M**

Identification of Software

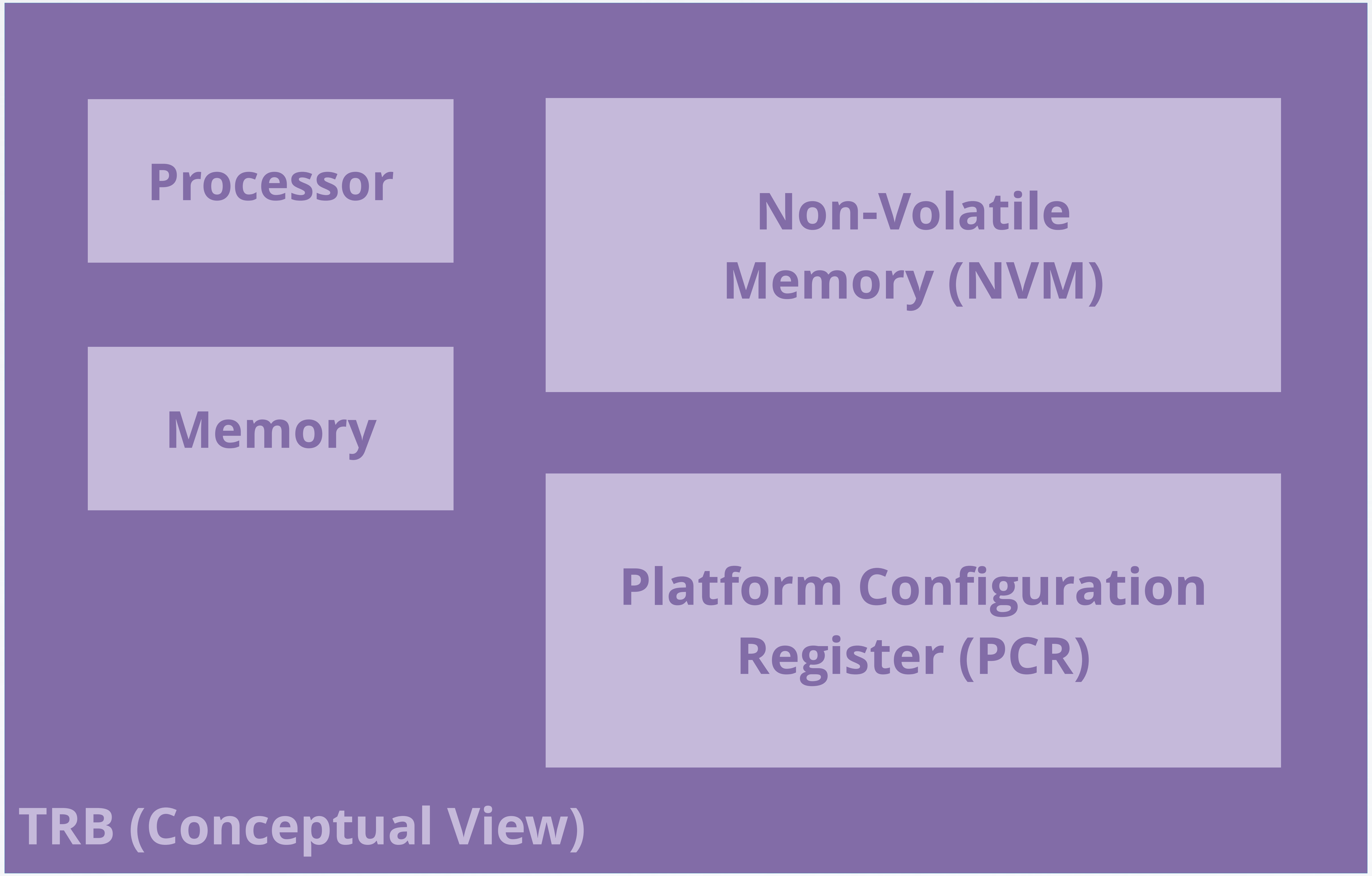
Example: program vendor FooSoft (FS)

Software identity **ID** must be known

Two ways to identify software:

- By hash: $\mathbf{ID_{Program} = H(Program)}$
- By signature: $\mathbf{\{Program, ID_{Program}\}FS_{priv}}$
  - Signature must be available (e.g., shipped with program)
  - Use $\mathbf{FS_{pub}}$ to check signature
  - $\mathbf{(H(Program), FS_{pub})}$ can serve as $\mathbf{ID_{Program}}$

Tamper-Resistant Black Box (TRB)



Secure Booting (“Burn in the OS")

OS stored in read-only memory (flash)

Hash H(OS) in TRB NVM, preset by manufacturer:

- Load OS code, compare **H(loaded OS code)** to preset **H(OS)**
- Abort if different

Public key FS_{pub} in TRB NVM, preset by manufacturer:

- Load OS code, check signature of loaded OS code using **FS_{pub}**
- Abort if check fails

Authenticated Booting ("Choose your OS")

Steps:

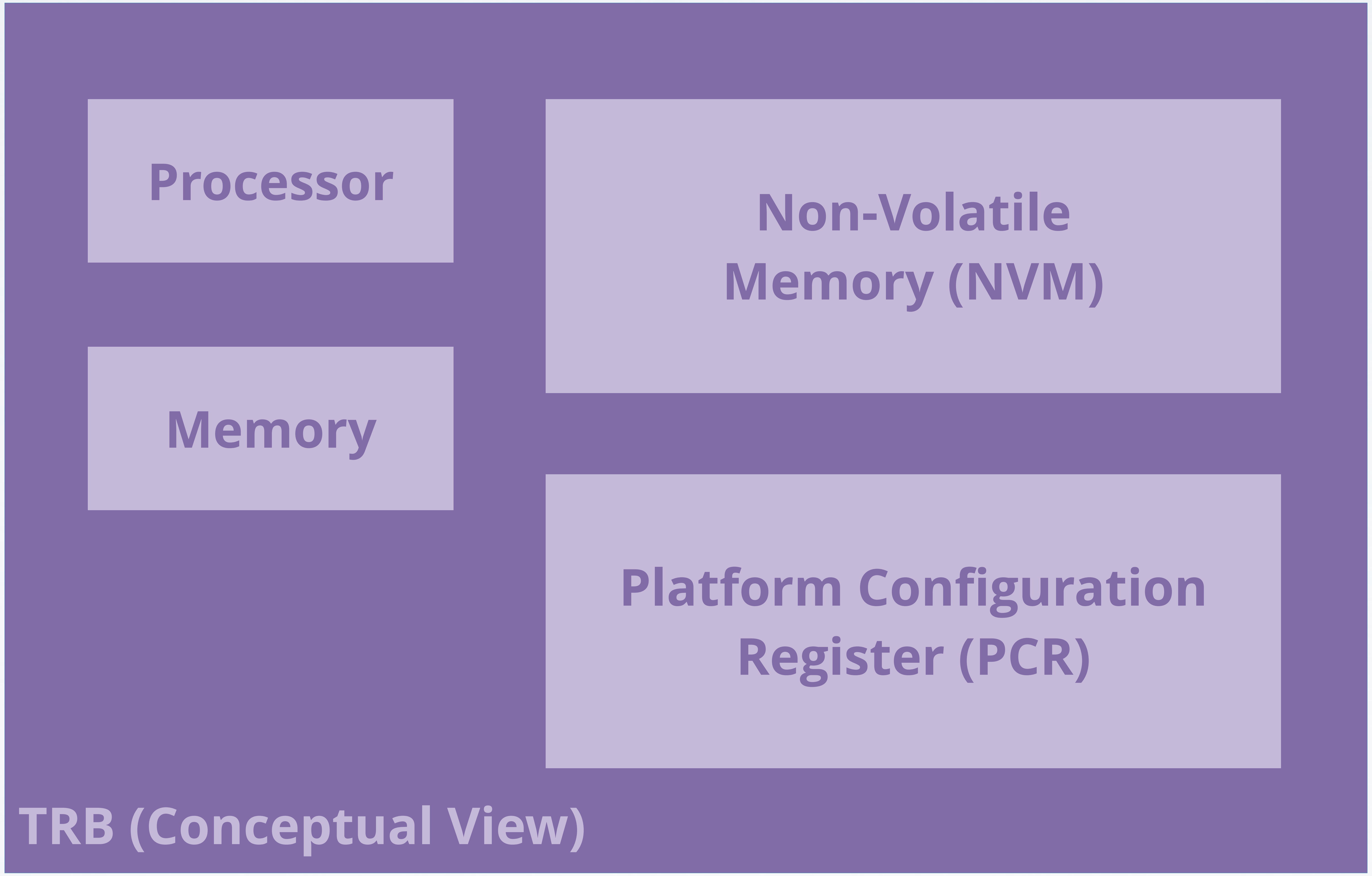
1) Preparation by OS and TRB vendors
2) Booting & measuring
3) Remote attestation

OS Identity and Certification

1a) Preparation by OS vendor:

- Certifies: **{**„a valid OS“, **H(OS)}OSVendor$_{\mathbf{priv}}$**
- Publishes identifiers: **OSVendor$_{\mathbf{pub}}$** and **H(OS)**

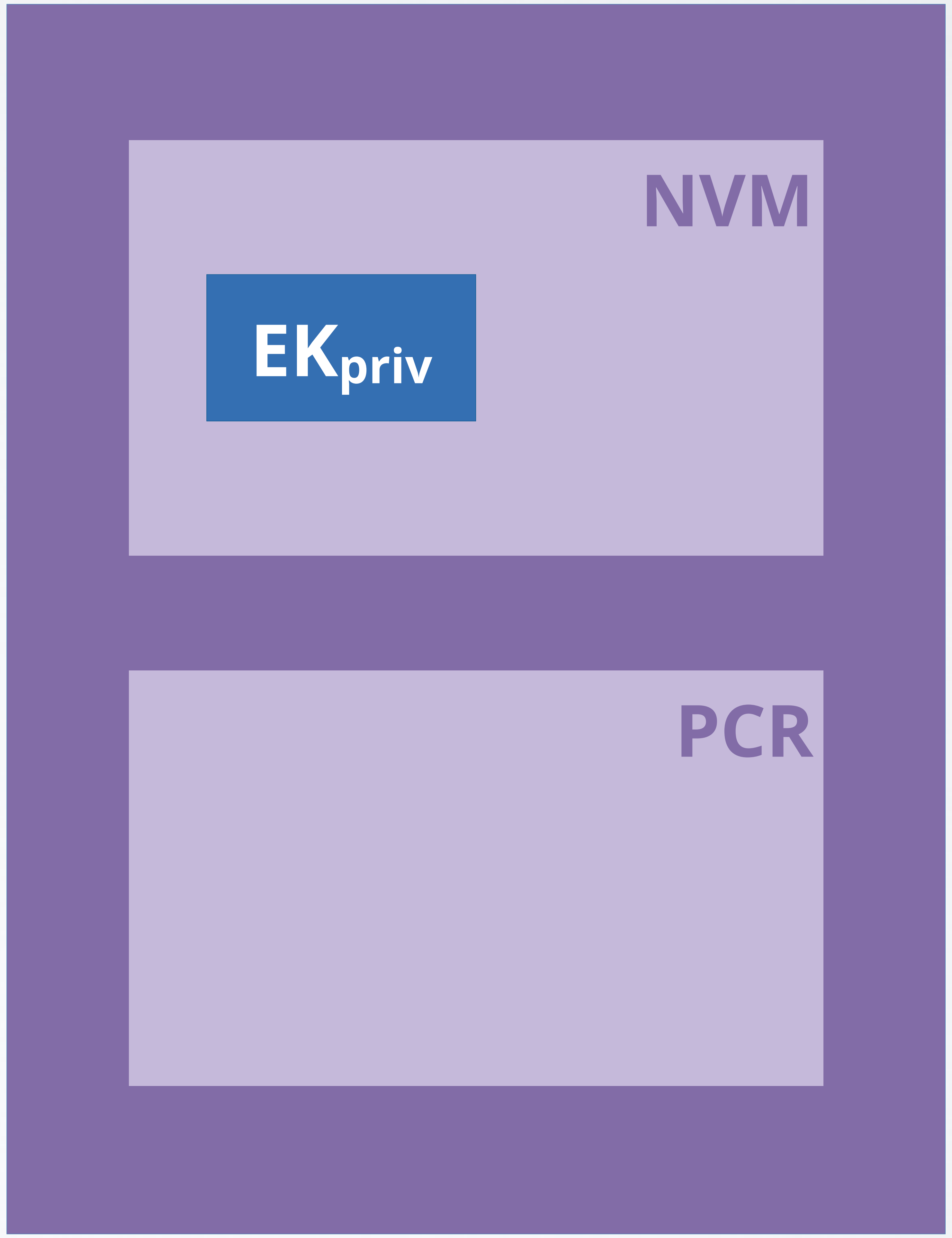
Tamper-Resistant Black Box (TRB)



TRB Initialization

1b) Preparation by TRB vendor:

- TRB generates "Endorsement Key" pair: $\mathbf{EK_{pair}}$
- TRB Stores $\mathbf{EK_{priv}}$ in TRB NVM
- TRB publishes $\mathbf{EK_{pub}}$
- TRB vendor certifies: {"a valid EK", $\mathbf{EK_{pub}}$}$\mathbf{TRBVendor_{priv}}$

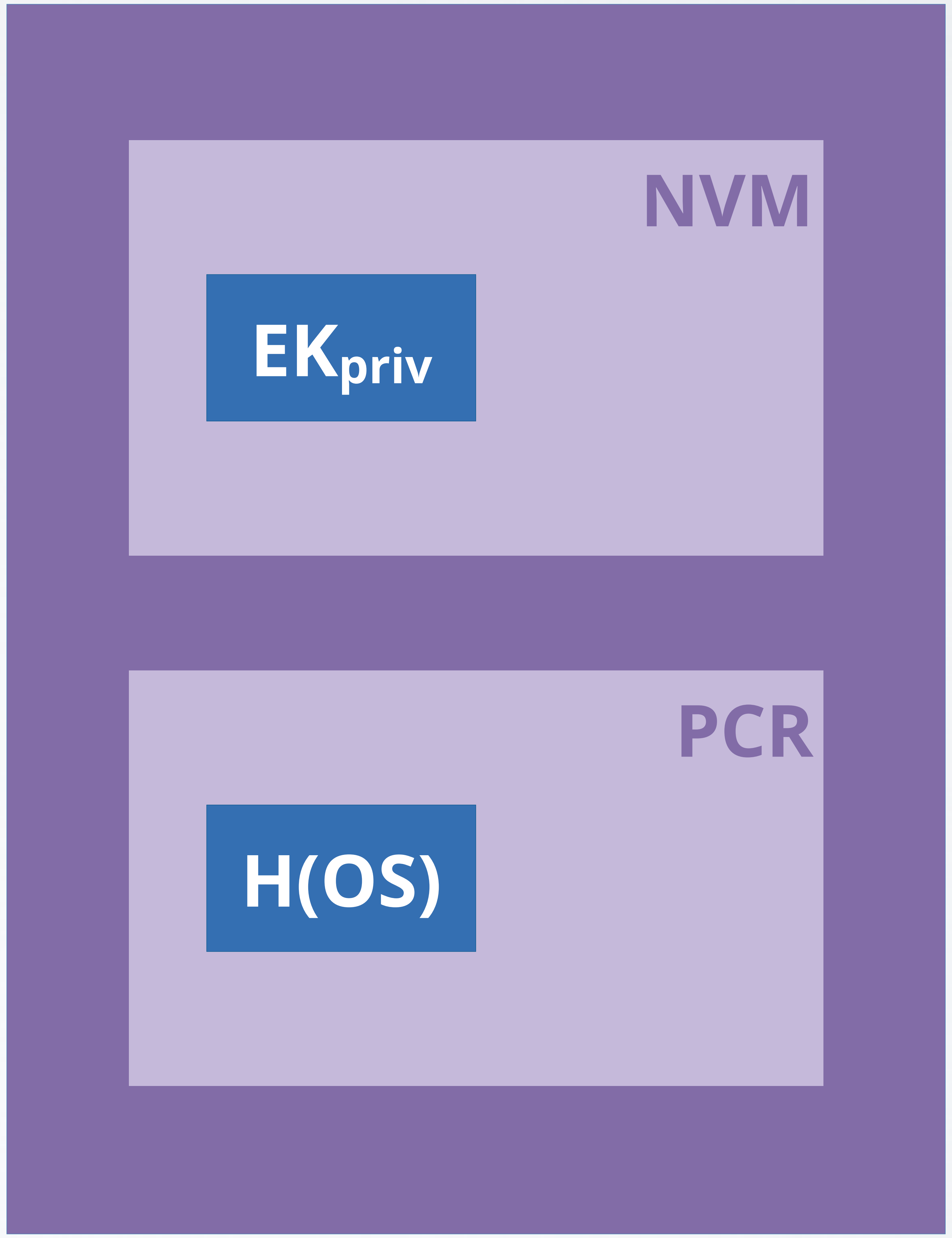


Authenticated Booting

2) Booting & measuring:

- TRB resets
- TRB computes ("measures") hash **H(OS)** of loaded OS
- Records **H(OS)** in platform configuration register **PCR**

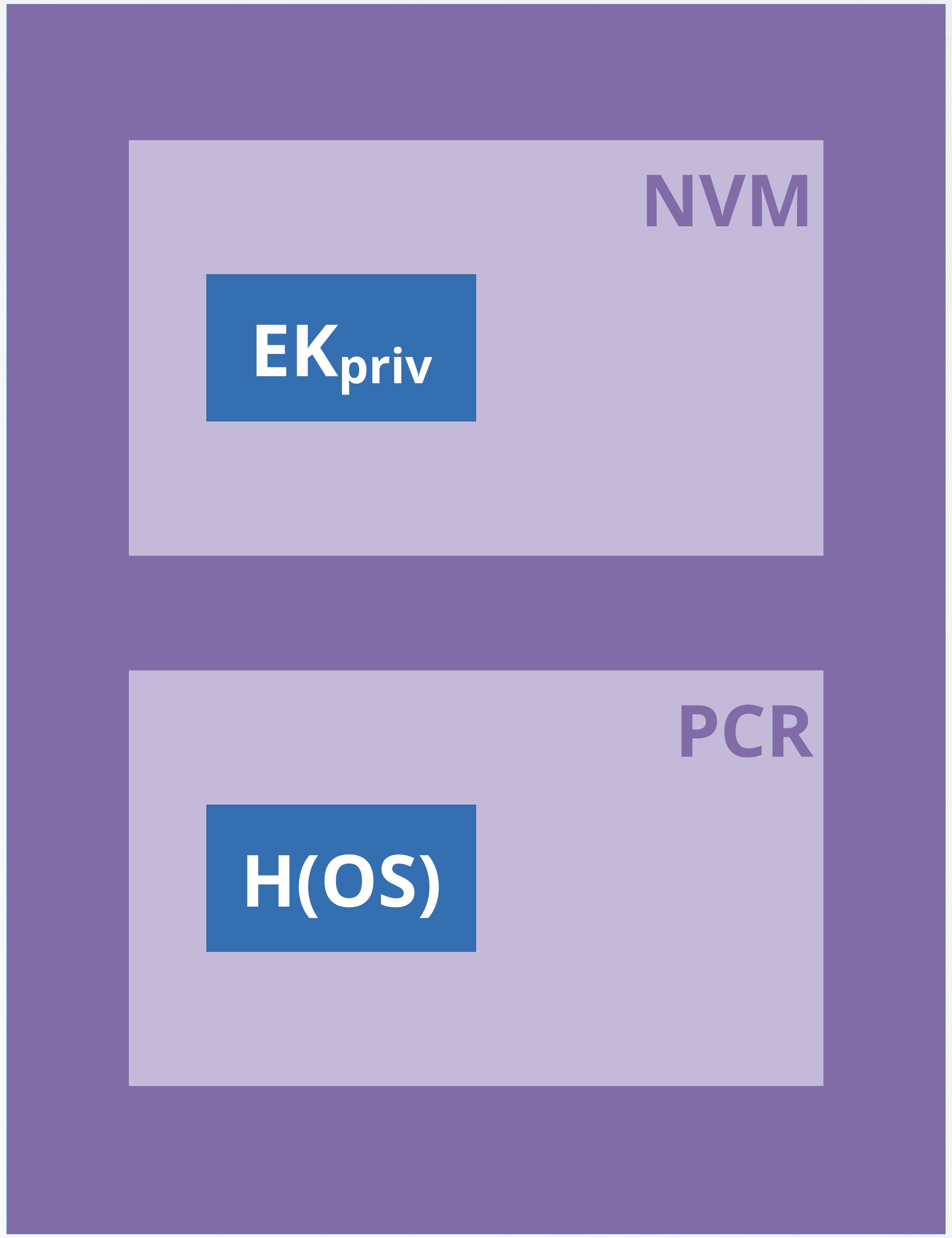
- **Note: PCR** not directly writable, more on this later



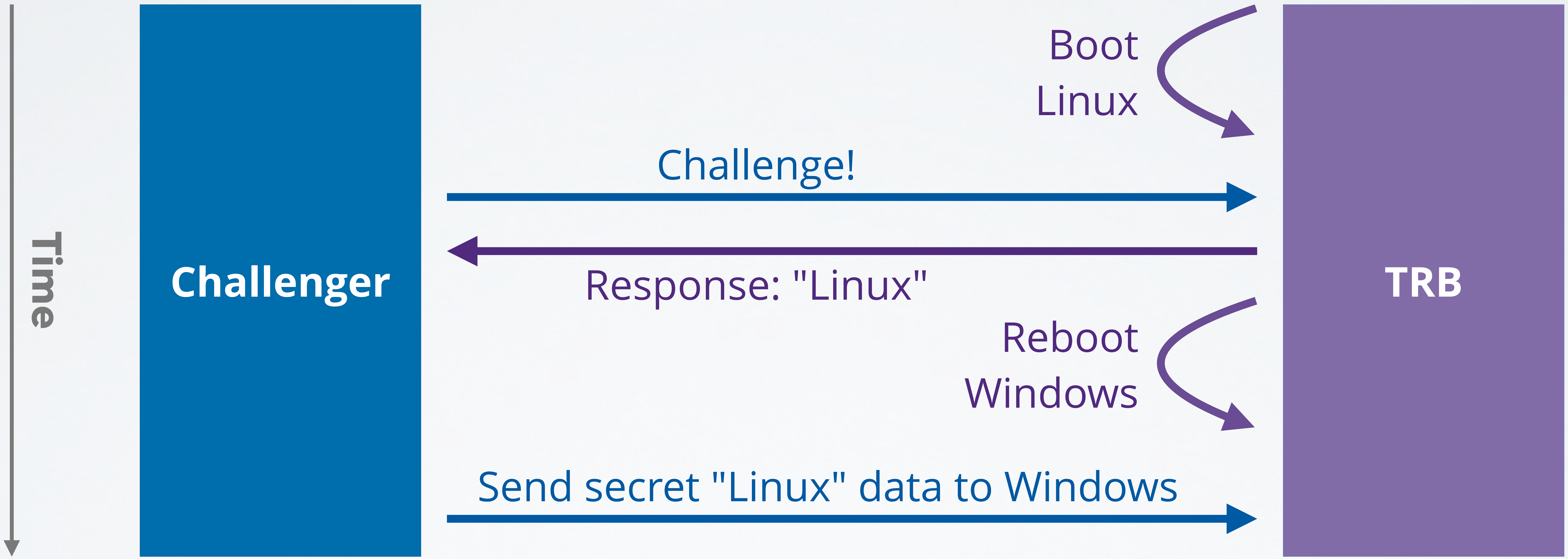
Remote Attestation (Simplified)

3) Remote Attestation:

- Remote computer sends "challenge": **NONCE**
- TRB signs **{NONCE, PCR}EK_{priv}** and sends it to "challenger"
- Challenger checks signature, decides if OS identified by **H(OS)** in reported signed **PCR** is OK



Problem



Problem: Time-of-check, time-of-use (TOCTOU) attack possible

Solution: Create new key pair for protecting data until next reboot

Booting (Considering Reboot)

At each boot, TRB does the following:

- Computes **H(OS)** and records it in **PCR**
- Creates two key pairs for the booted, currently active OS:
  - **ActiveOSAuthK$_{pair}$** /* for authentication (signing) */
  - **ActiveOSConK$_{pair}$** /* for concealing (encryption) */
- TRB certifies:
  {ActiveOSAuthK$_{pub}$, ActiveOSConK$_{pub}$, H(OS)}EK$_{priv}$
- Hands over to booted OS, to be used like "session keys"

Attestation (Considering Reboot)

Remote Attestation:

- Challenger sends: **NONCE**
- Currently booted, active OS generates response:
{ActiveOSConK$_{pub}$, ActiveOSAuthK$_{pub}$, H(OS)}EK$_{priv}$
{NONCE}ActiveOSAuthK$_{priv}$

Client sends data over secure channel:

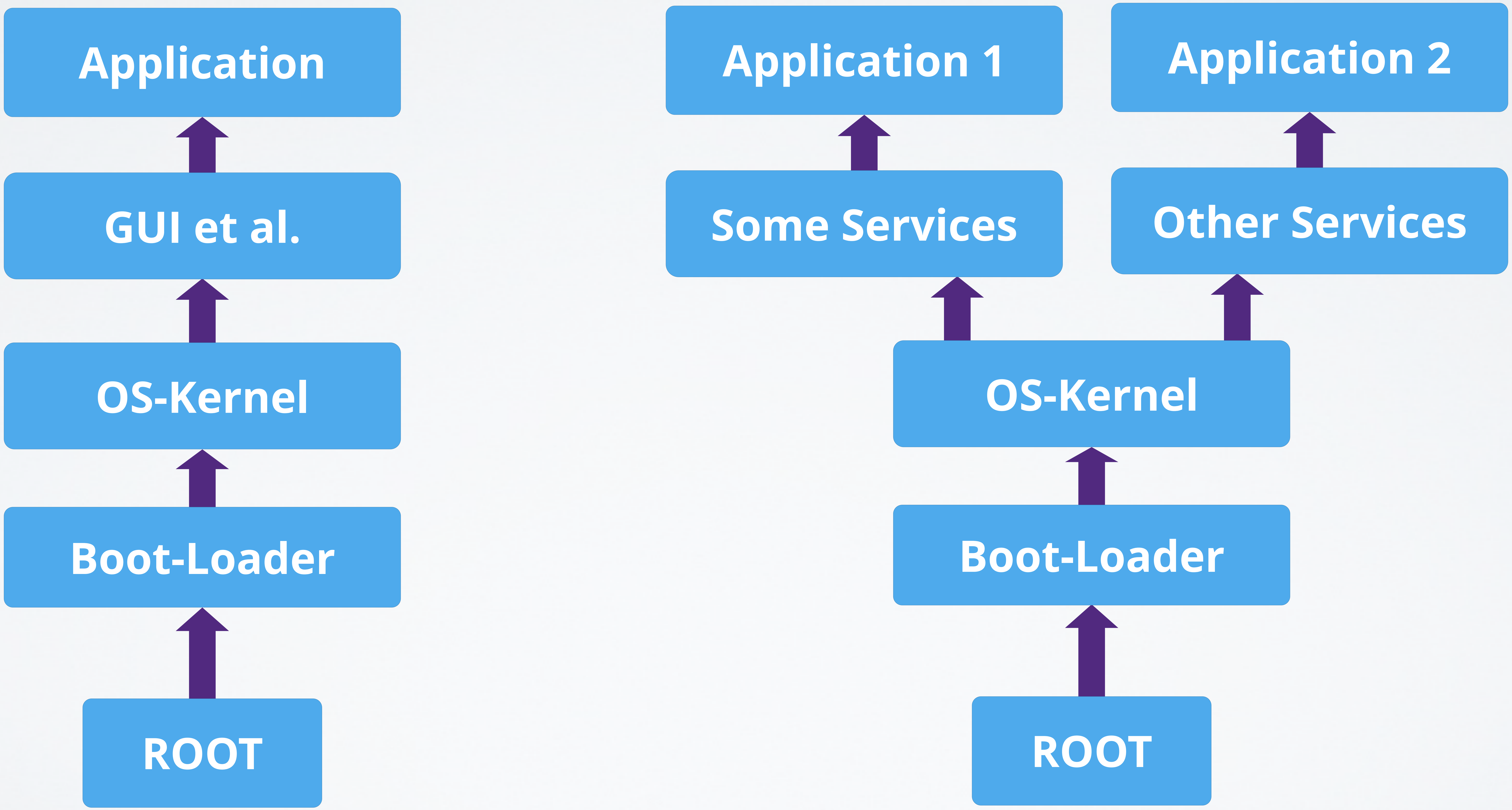
- {data for active OS}**ActiveOSConK$_{pub}$**

Assumptions

Authenticated booting and **remote attestation** as presented are secure, if:

1) TRB can protect **EK_{priv}, PCR**
2) OS can protect "Active OS" keys
3) Rebooting destroys content of:
    - PCR
    - “Active OS keys” in memory

Software Stacks and Trees



Software Stacks and Trees

Two Concerns:

- Very large Trusted Computing Base (TCB) for booting (including device drivers, etc.)
- Remote attestation of one process (leaf in tree)

Software Stacks and Trees

Extend operation:

$$\mathbf{PCR_n = H(PCR_{n-1} \mid\mid new\ component)} \qquad [PCR_0=0]$$

Software Stack:

- 1 PCR value $\mathbf{PCR_n}$ after **n** components have been measured

Software "Tree":

- 1 PCR value $\mathbf{PCR_n}$ for each leaf at end of a branch of length **n**
- Needs multiple PCRs (1 per branch) that share state from **Root** to $\mathbf{PCR_{OS}}$, then diverge to leafs at $\mathbf{PCR_{App1}}$, $\mathbf{PCR_{App}}$, **...**

Software Stacks and Trees

Key pairs per level of tree:

- OS controls applications → generate additional key pair per application
- OS certifies:
  - **{Application 1, App1K_{pub}}ActiveOSAuth$_{priv}$**
  - **{Application 2, App2K_{pub}}ActiveOSAuth$_{priv}$**

Late Launch/Dynamic Root of Trust

Problem: huge software to boot system

Solution: late launch

- Use arbitrary software to start system and load all software
- Provide specific instruction to enter “secure mode”
  - Put hardware in secure state (stop all processors, I/O, …)
  - Measure “root of trust” software and record into PCR
- **AMD (skinit):** hashes arbitrary "secure loader" and start it
- **Intel (senter):** starts boot code (must be signed by Intel)

The Need for Trusted Storage

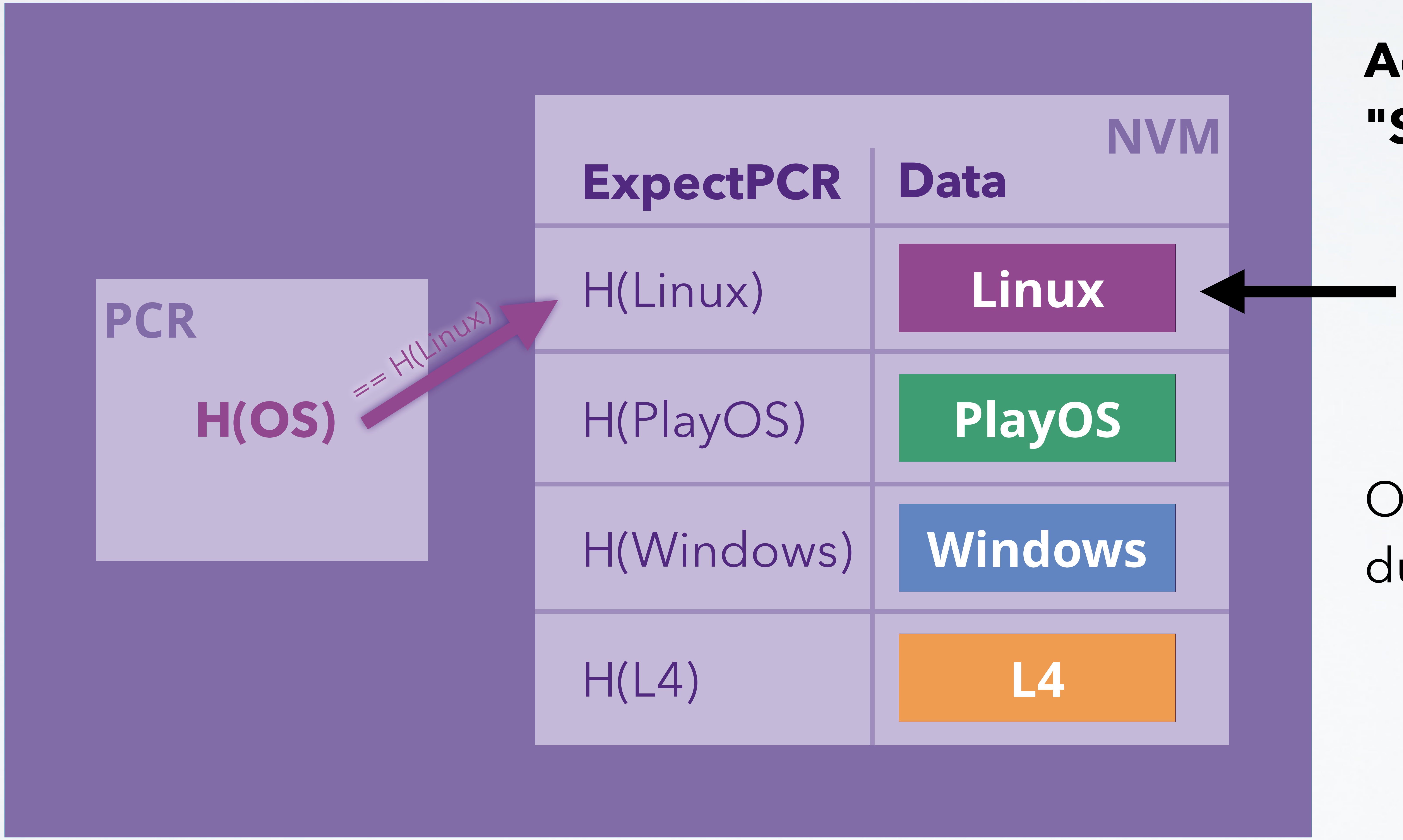
Use case from earlier example:

- Send data over secure channel after remote attestation
- Bind that data to software configuration via TRB

Problem: How to work with this data when offline?

- Must store data for time after reboot
- For example for DRM: bind decryption key for downloaded movie to specific machine with specific OS

Sealed Memory Principle

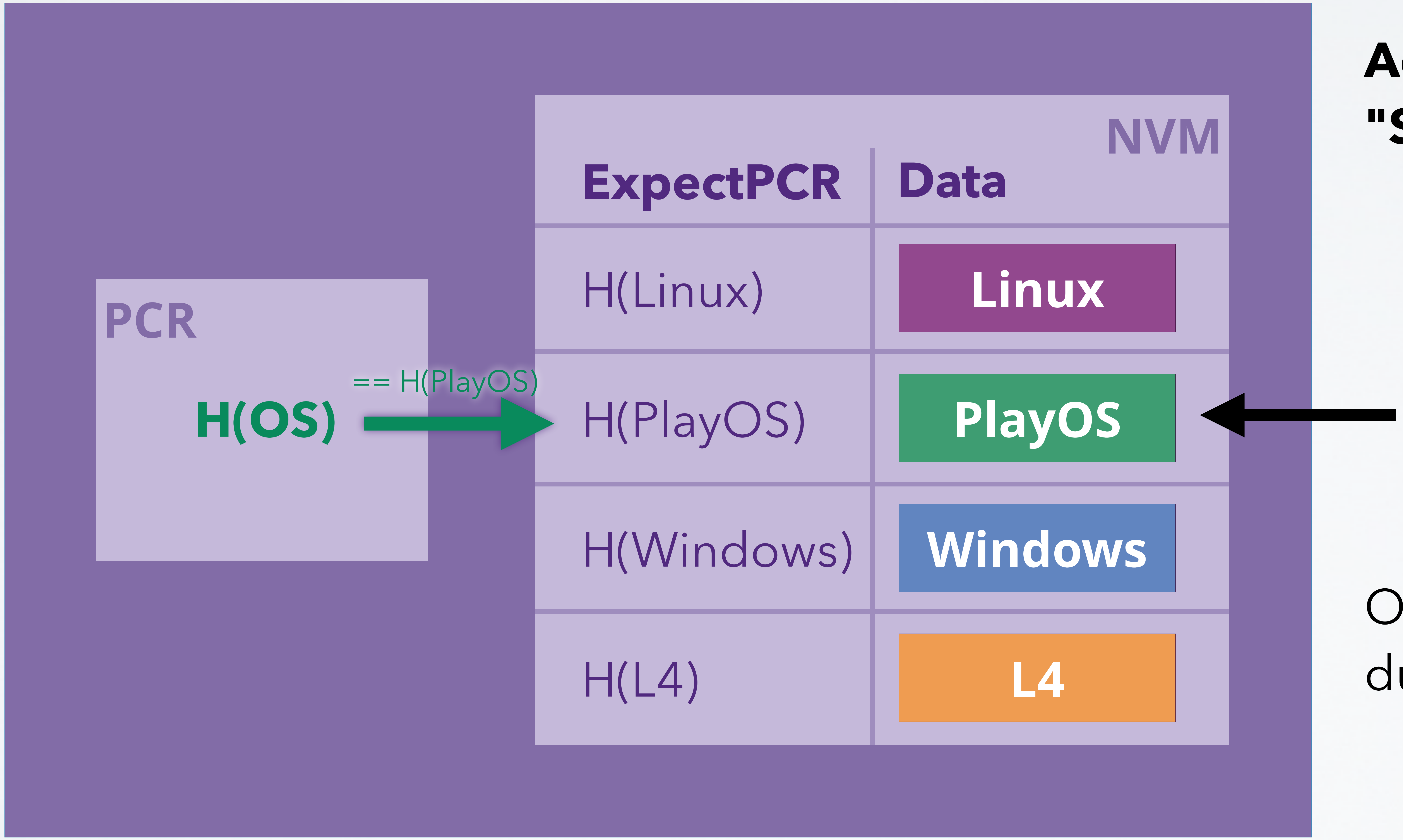


Add/remove/read/write "Sealed Memory" slots

Can be accessed by currently active OS

Other slots inaccessible due to PCR mismatch

Sealed Memory Principle



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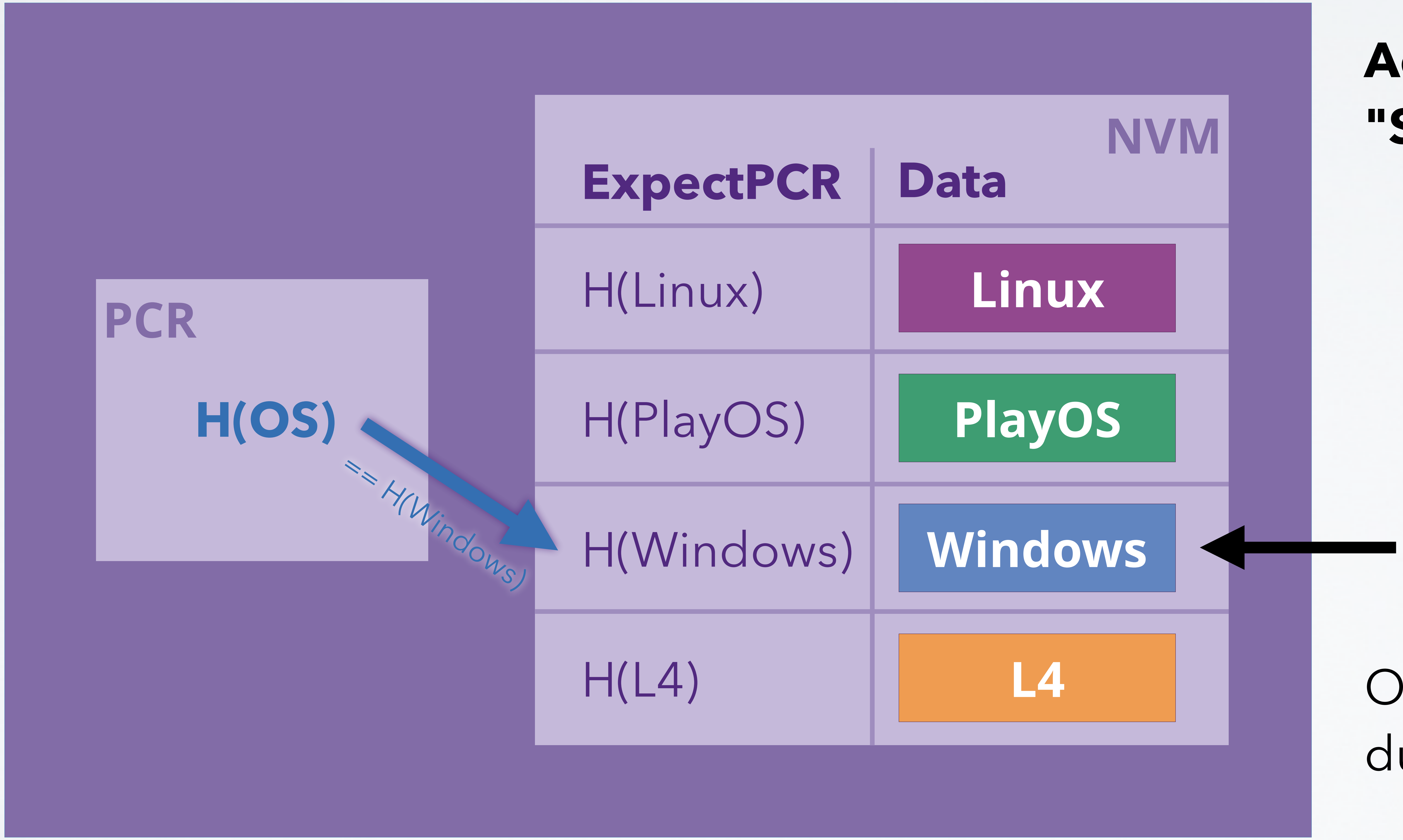

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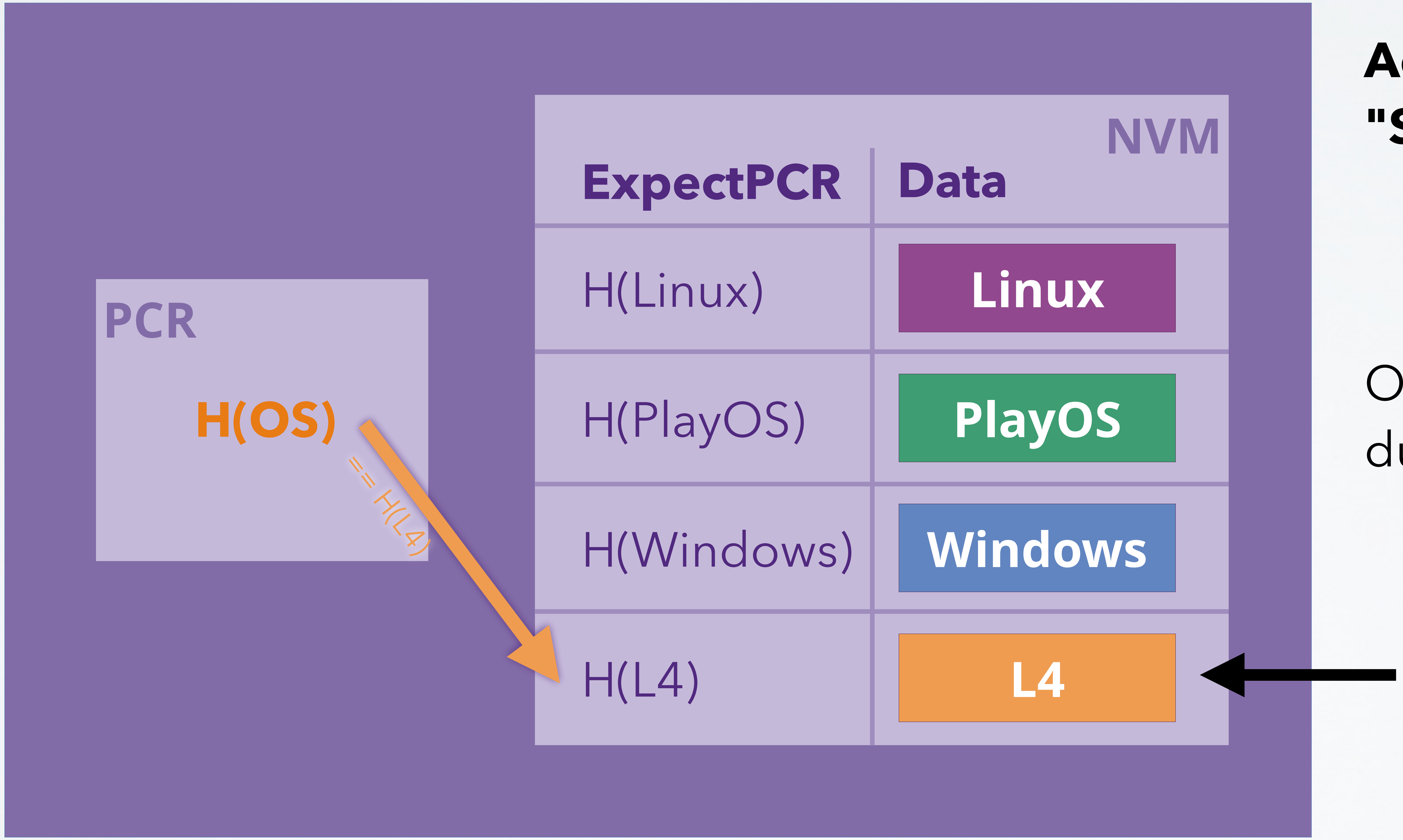


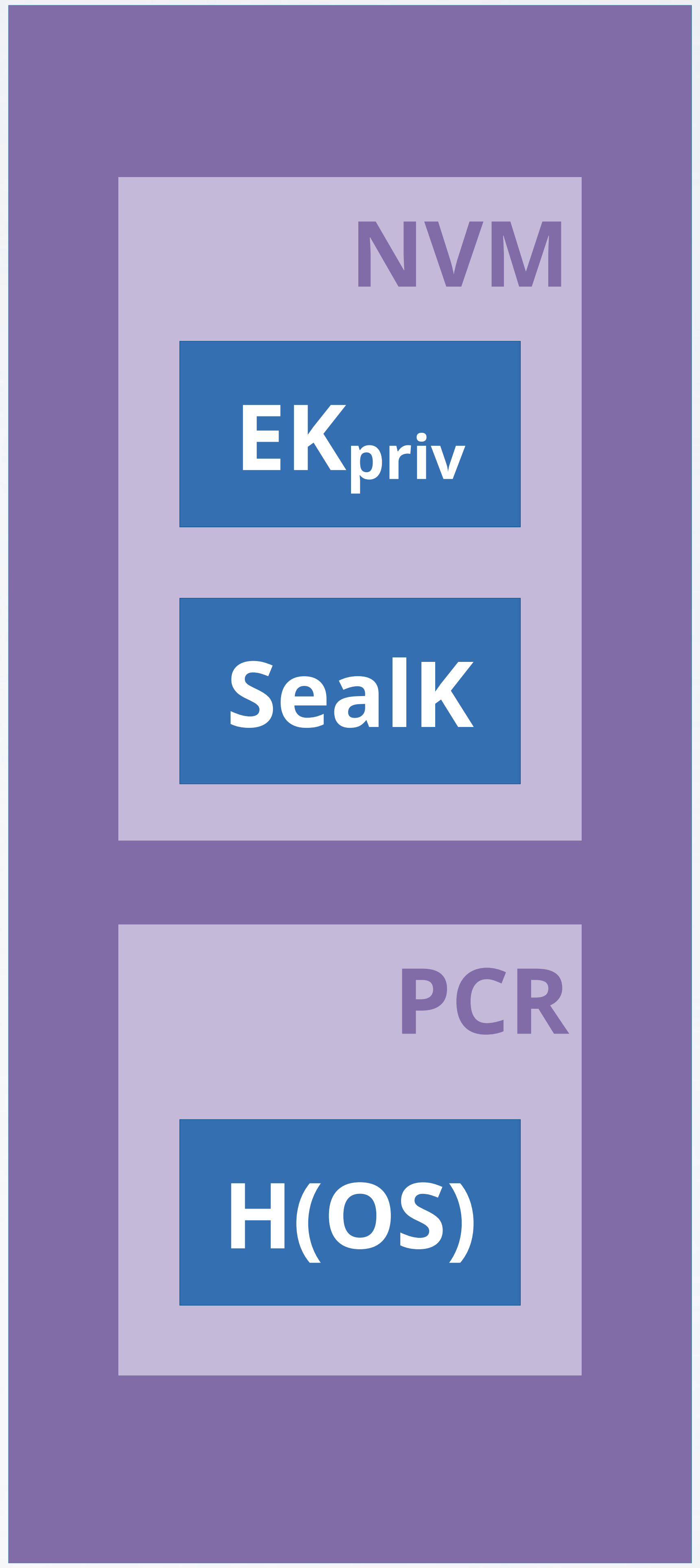
Add/remove/read/write "Sealed Memory" slots

Other slots inaccessible due to PCR mismatch

Can be accessed by currently active OS

Sealed Memory Implementation

- TRB creates secret symmetric key **SealK**
- TRB encrypts (**Seal**) and decrypts (**Unseal**) data using **SealK**
- **Seal(ExpectPCR, data)**
  → {ExpectPCR, data}SealK
- **Unseal({ExpectPCR, data}SealK) → data**
  iff current **PCR** == **ExpectPCR**
  else abort without releasing data



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Sealed Memory Flexibility

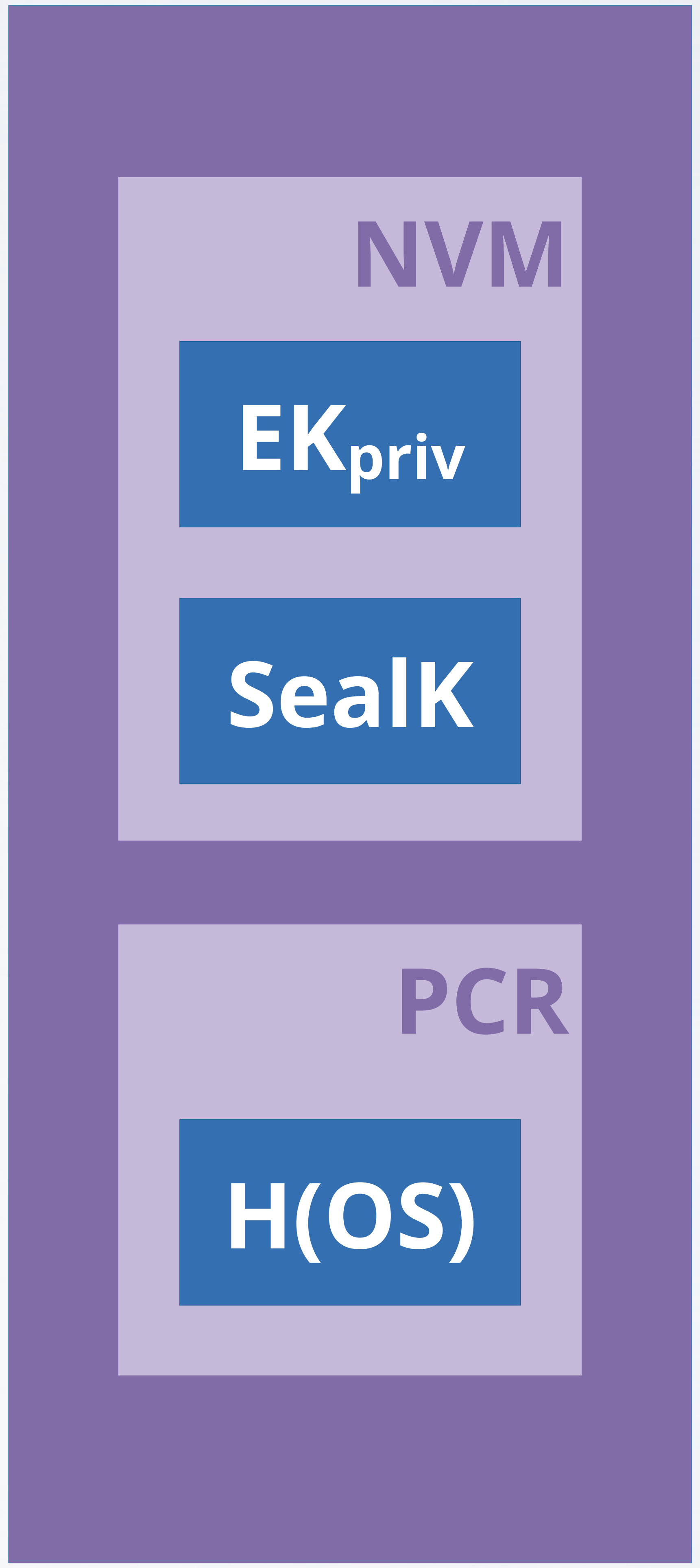
- Sealed (encrypted) data can be stored outside of TRB, allows to keep NVM small
- When sealing, arbitrary "expected PCR" values can be specified (e.g., future version of OS, or entirely different OS)

{H(Linux), Linux }SealK

{H(Windows), Windows }SealK

{H(PlayOS), PlayOS }SealK

{H(L4), L4 }SealK



Example

- **Windows:** **Seal (H(PlayOS), PlayOS_Secret)**
  → **sealed_message** (store it on disk)
- **L4:** **Unseal (sealed_message)**
  → PlayOS, PlayOS_Secret
  → ExpectPCR != PlayOS
  → **abort**
- **PlayOS:** **Unseal(sealed_message)**
  → PlayOS, PlayOS_Secret
  → ExpectPCR == PlayOS
  → **emit PlayOS_Secret**

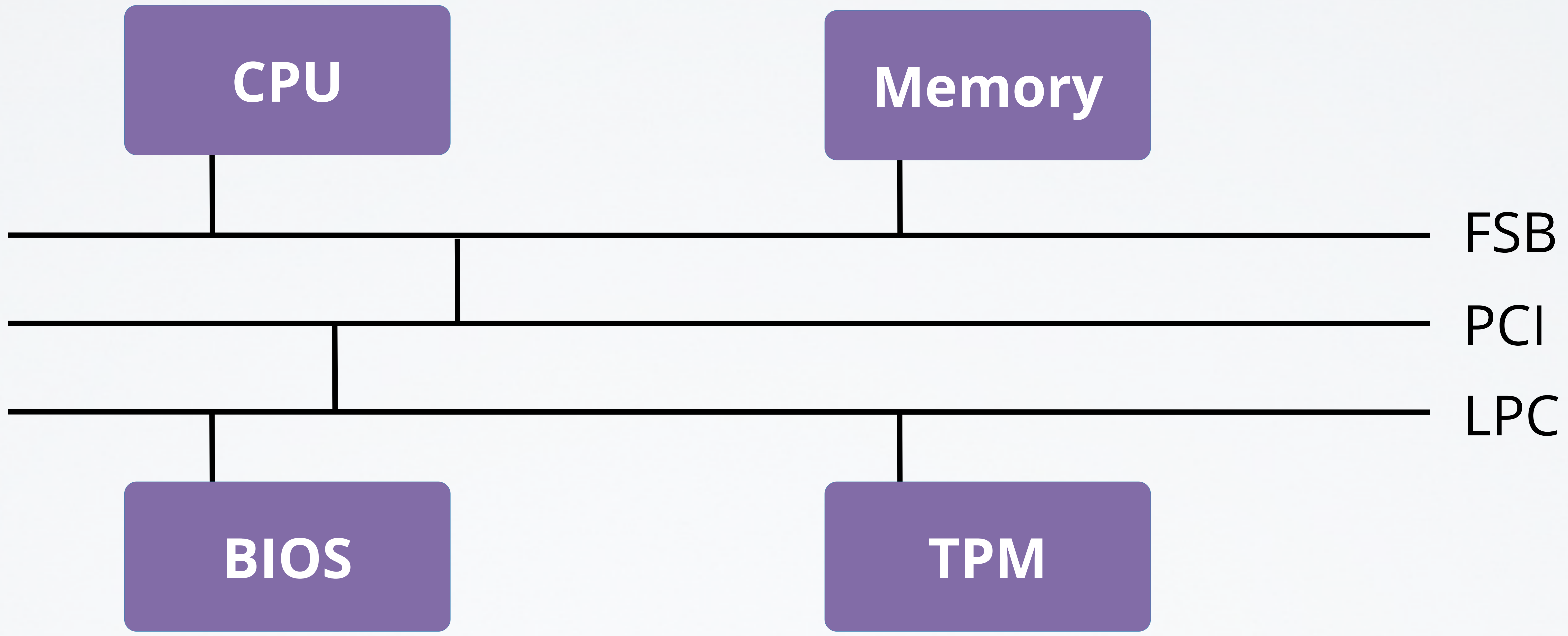
Tamper Resistant Black Box?

Ideally: includes CPU, Memory, …

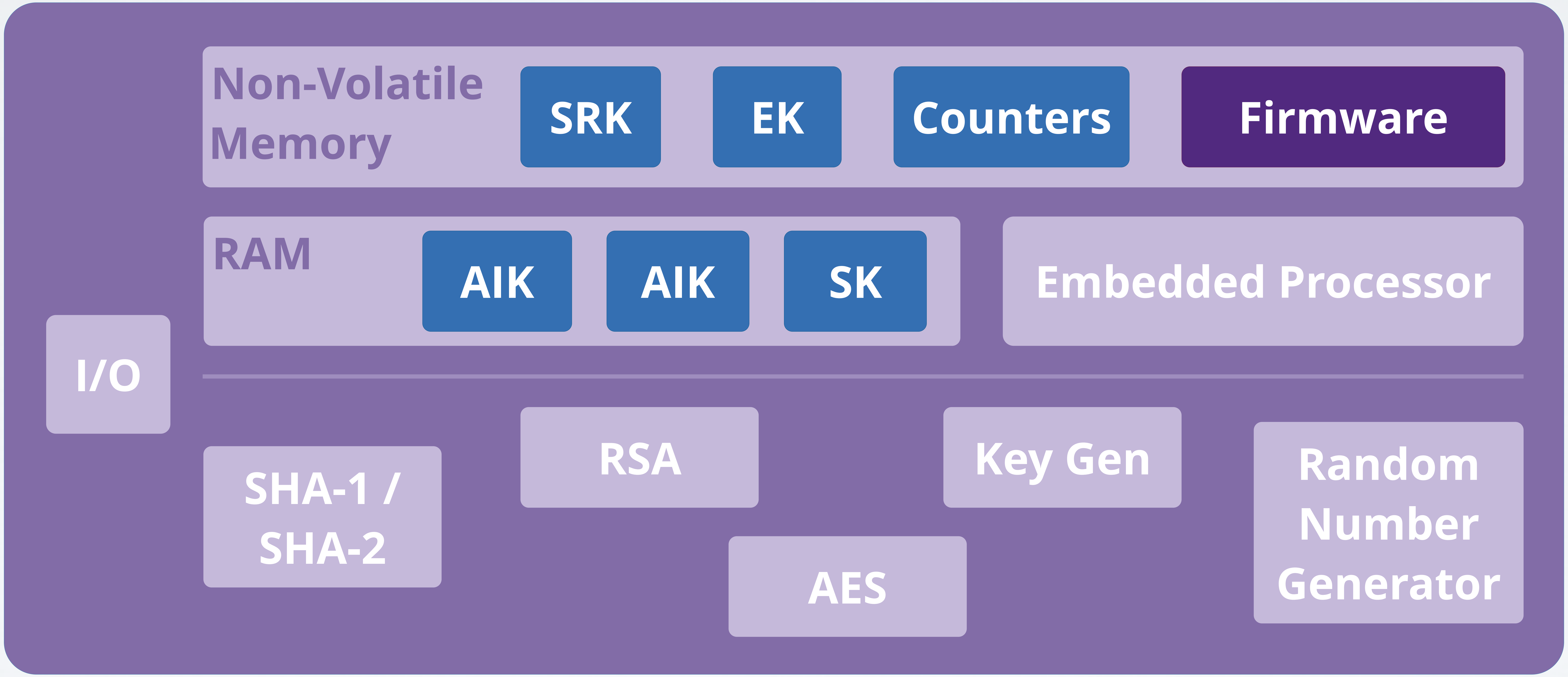
In practice:

- Additional physical protection (e.g., IBM 4758, → Wikipedia)
- Hardware support:
  - Separate “Trusted Platform Module (TPM)”: often insufficiently integrated, TRB functionality breaks when replacing BIOS, etc.
  - Add a new privilege mode: ARM TrustZone
  - Shielded more for user processes: Intel SGX

TCG PC Platform: Trusted Platform Module (TPM)



Trusted Platform Module



Protection of Application

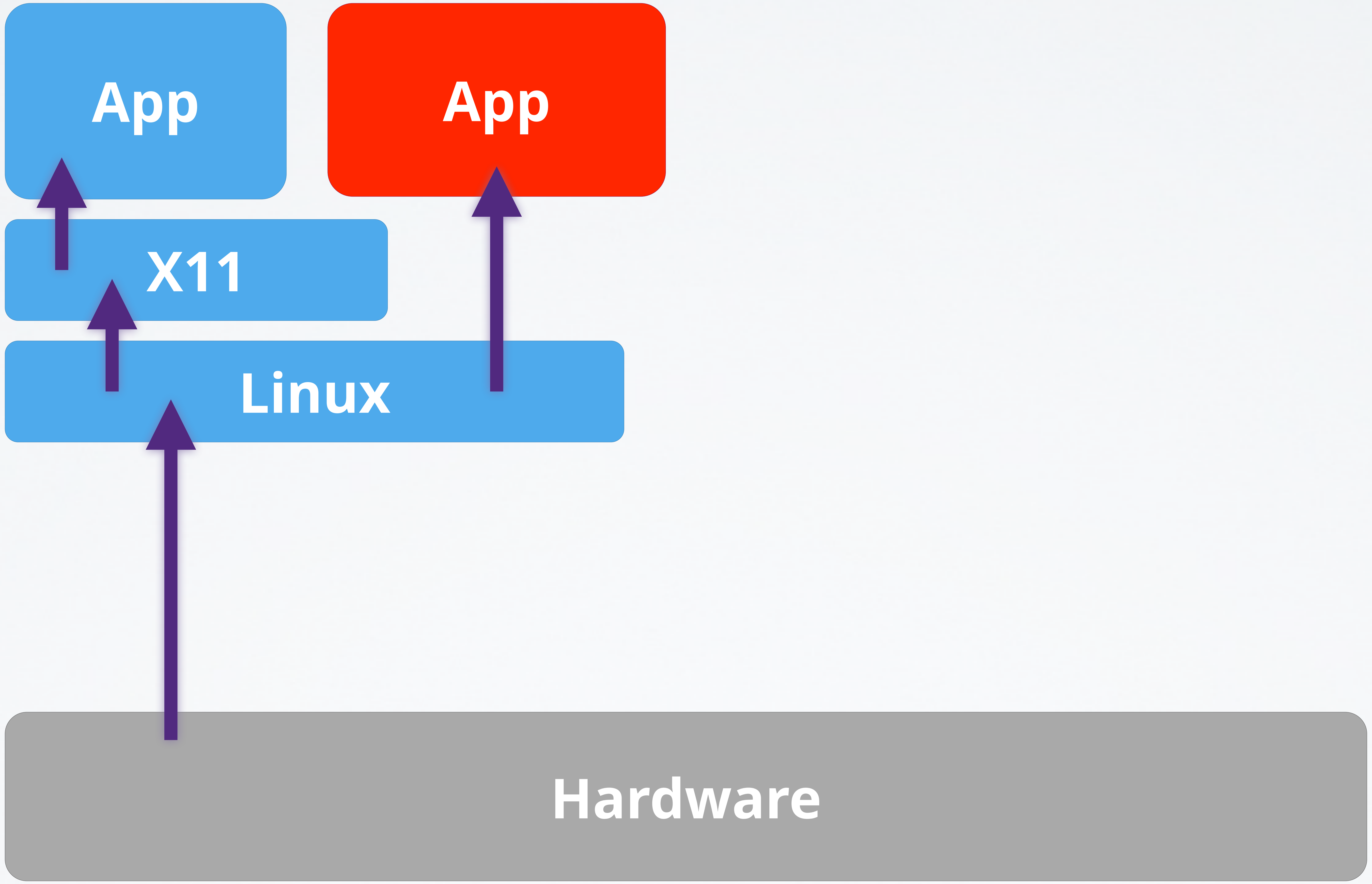
Principle Method:

- Isolate critical software
- Rely on small Trusted Computing Base (TCB)

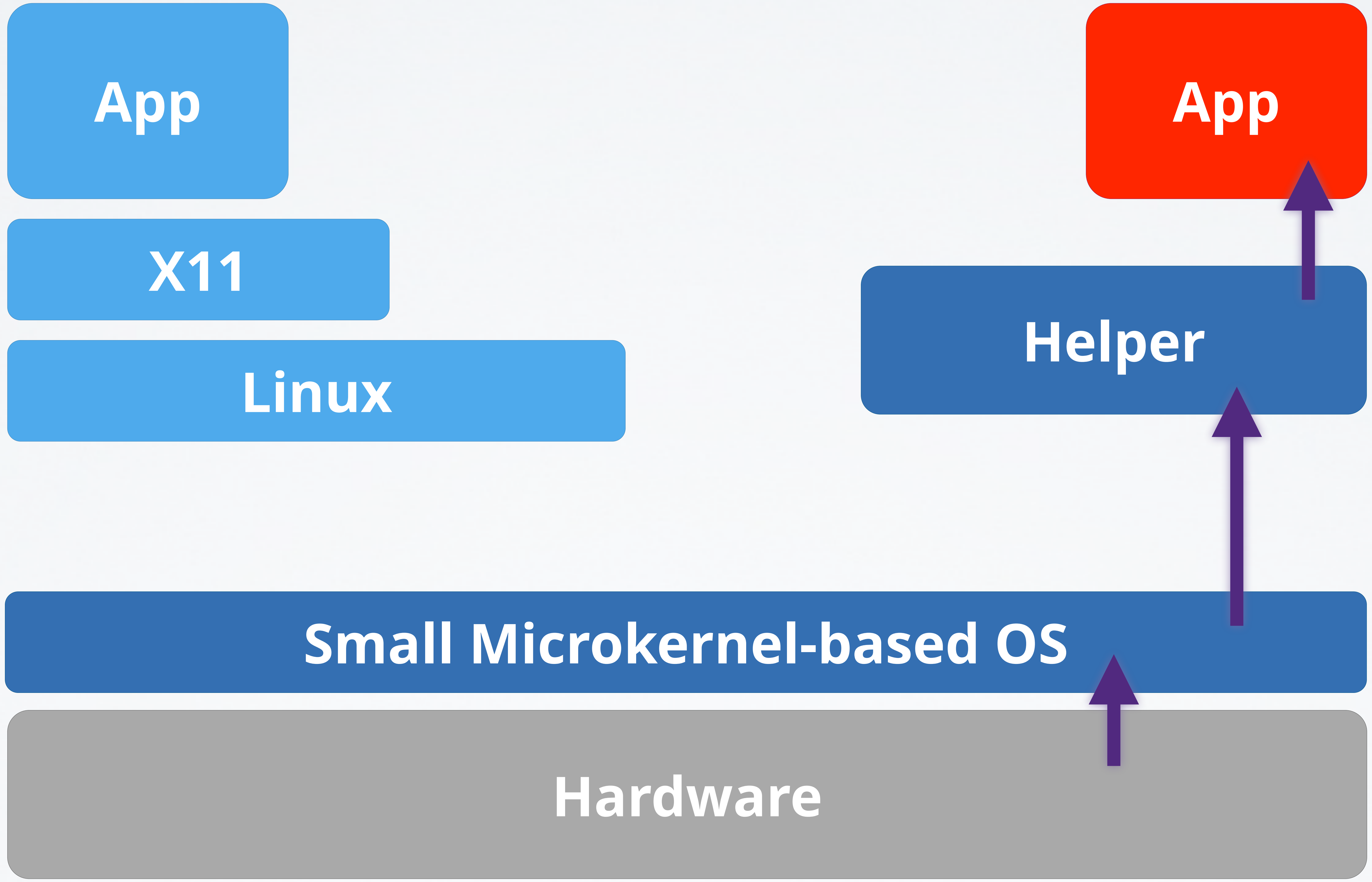
Ways to implement the method:

- Small OS kernels:
  microkernels, separation kernels, ...
- Hardware / microcode support

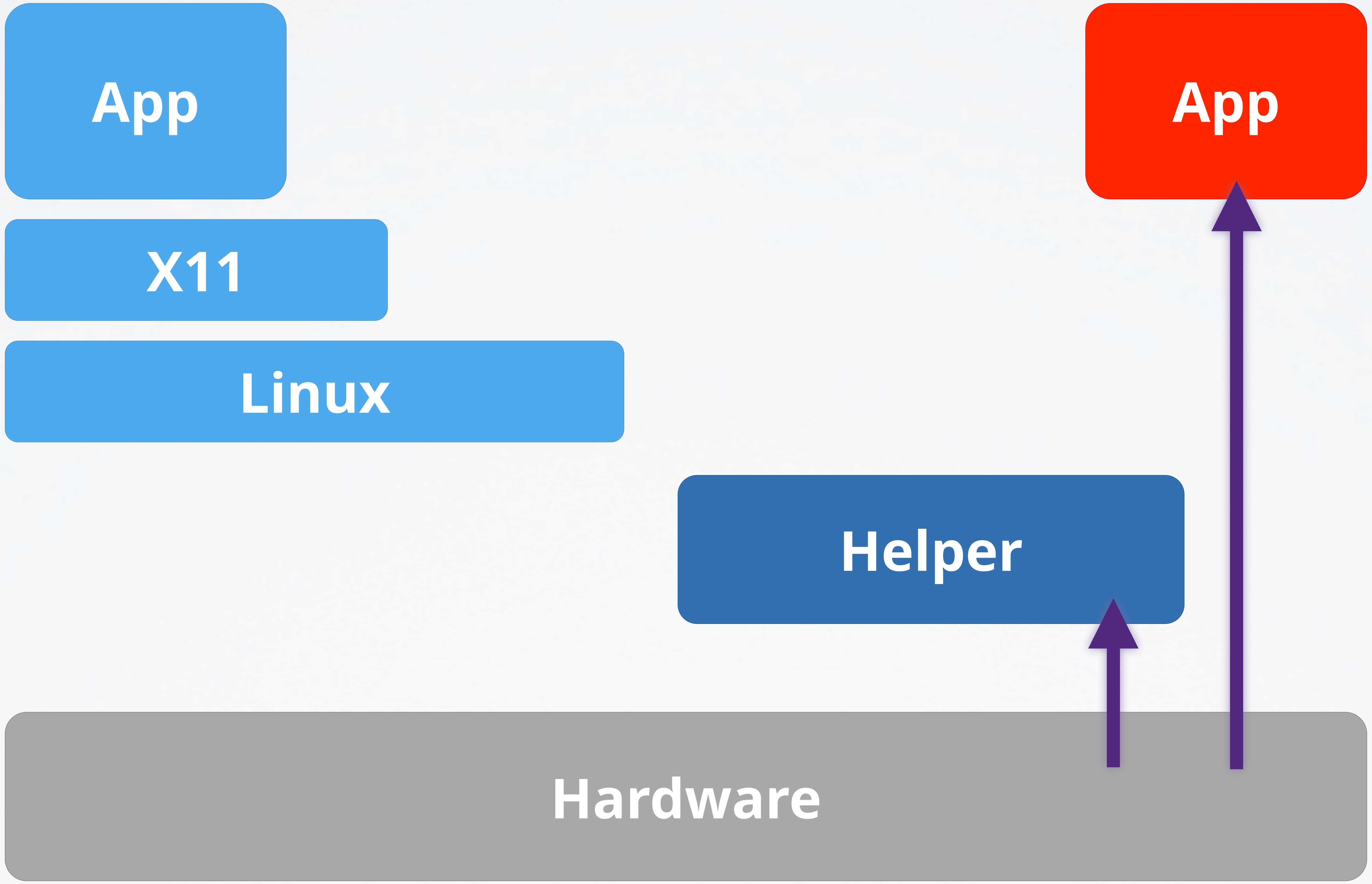
Trusted Computing Base: Big OS



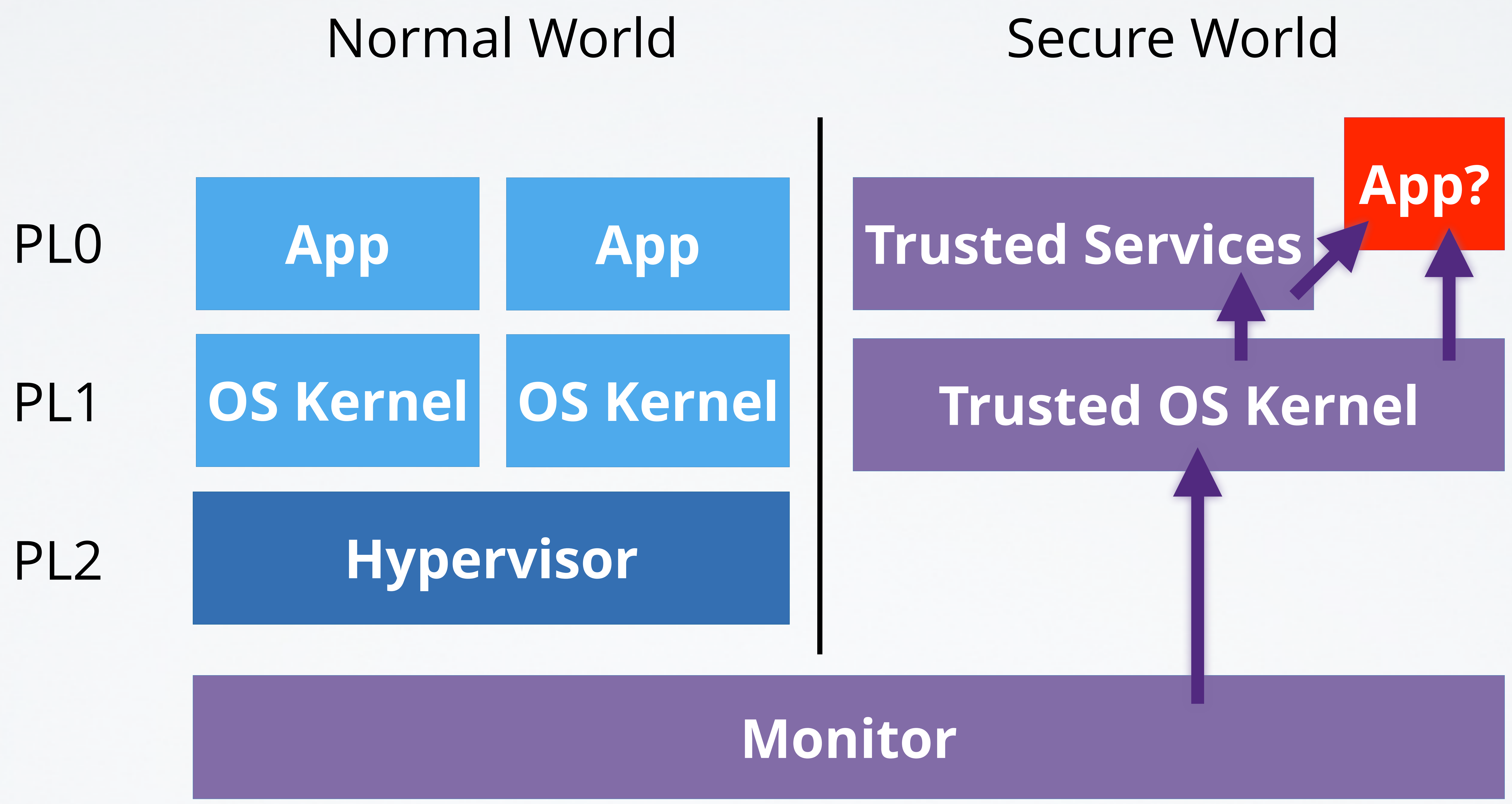
Trusted Computing Base: Small OS



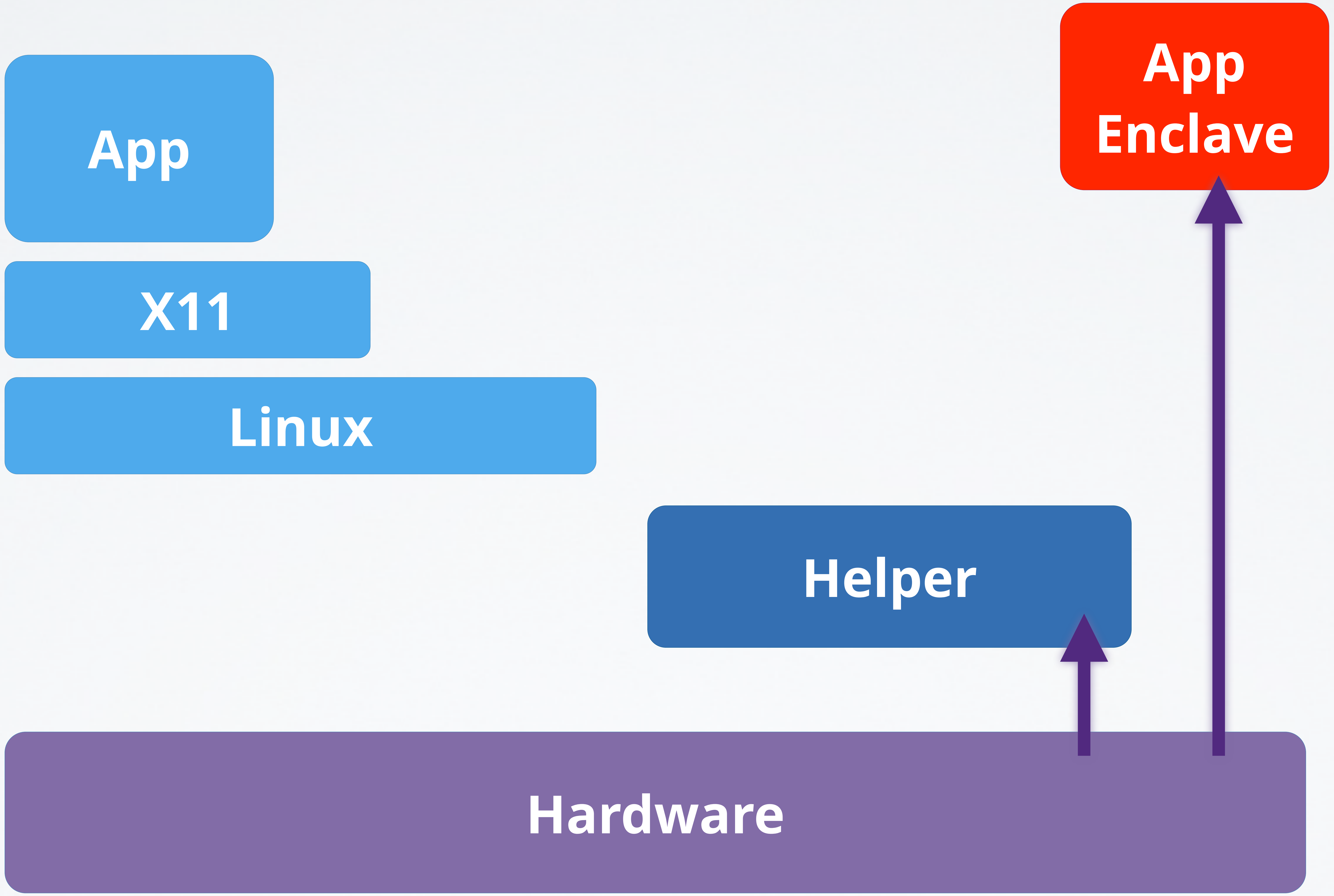
Trusted Computing Base: Only Hardware?



ARM TrustZone



Intel SGX

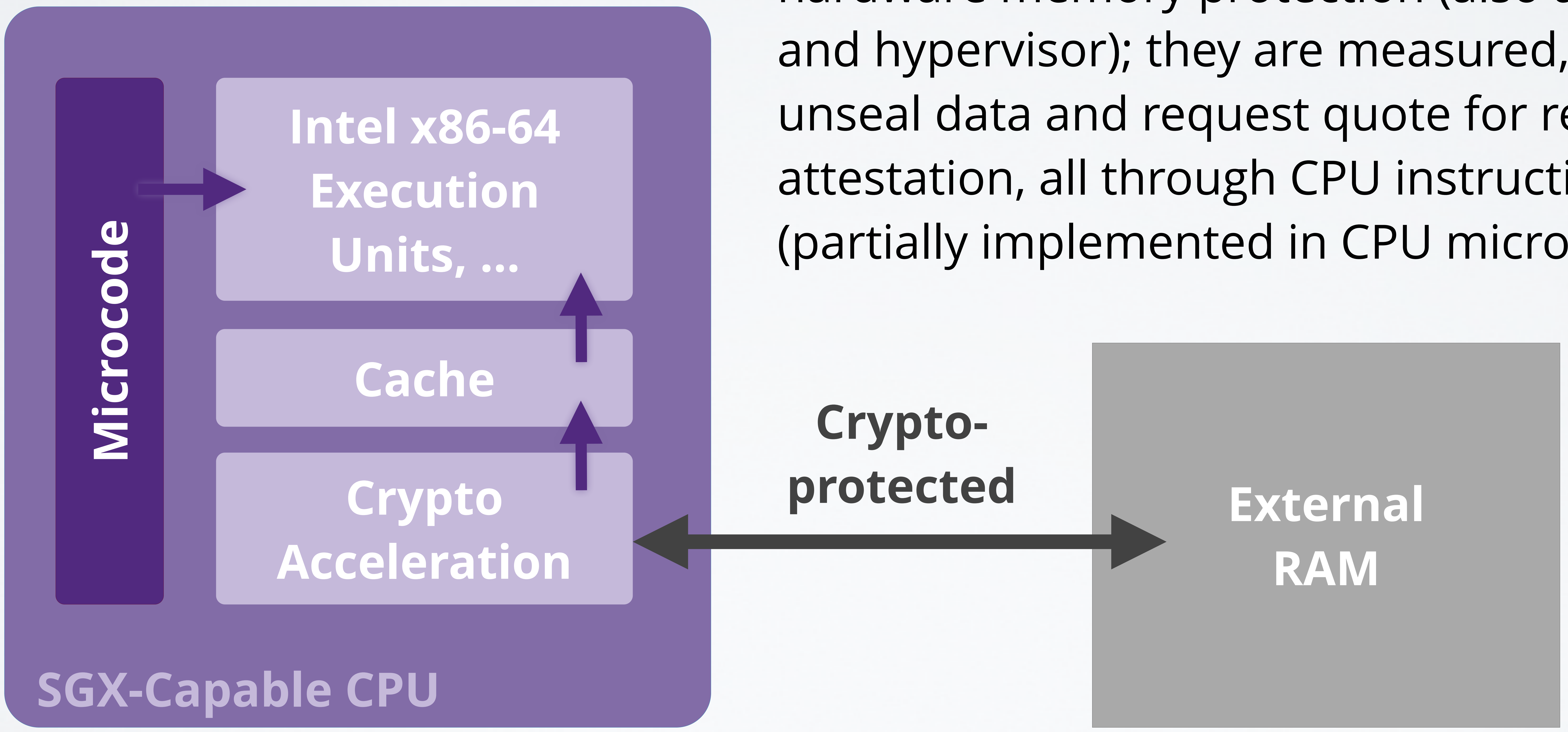


Intel SGX

“Enclaves” for applications:

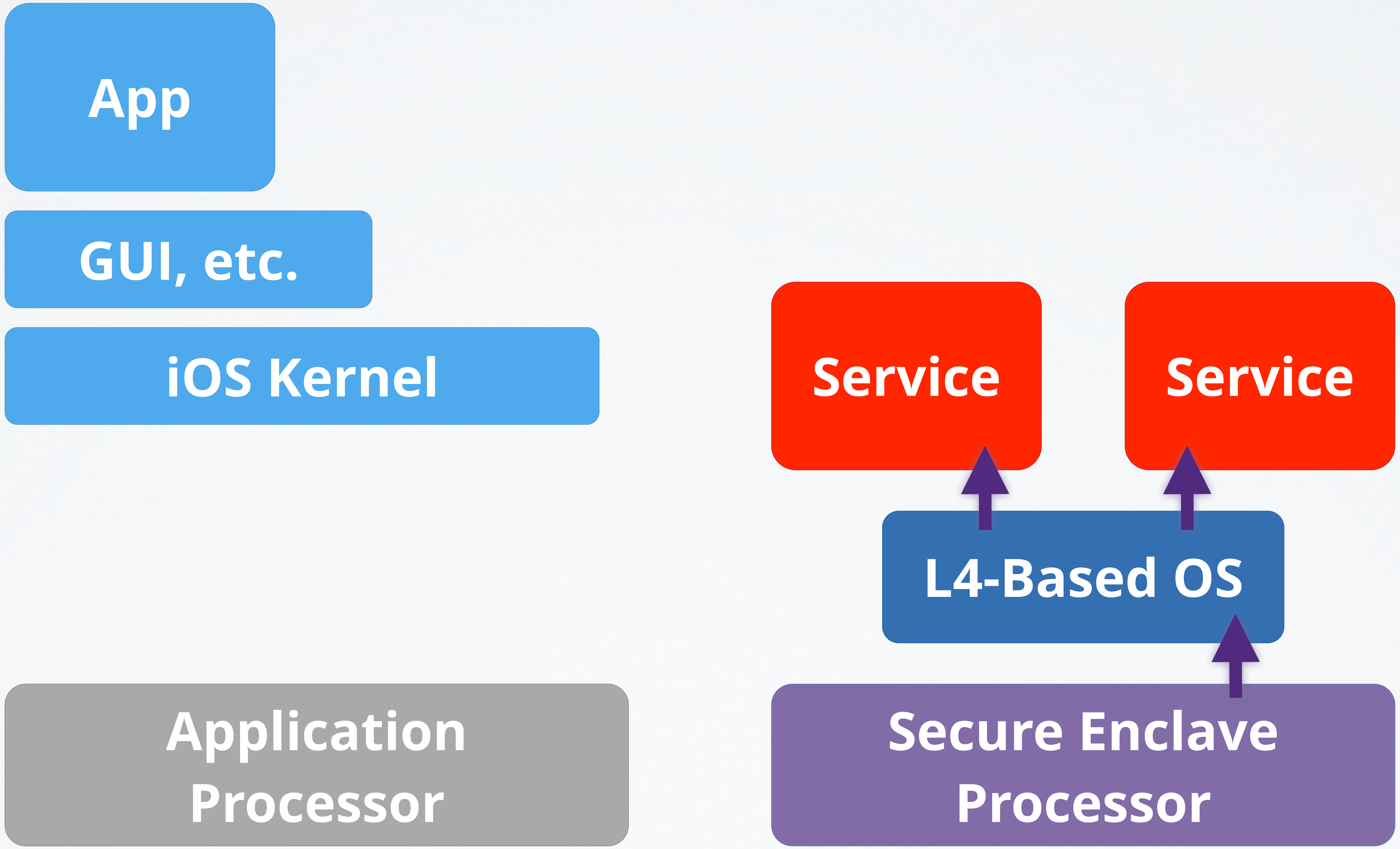
- Established per special SGX instructions
- Measured by CPU
- Provide controlled entry points
- Resource management via untrusted OS

Intel SGX



Applications executing in enclaves benefit from hardware memory protection (also against OS and hypervisor); they are measured, seal and unseal data and request quote for remote attestation, all through CPU instructions (partially implemented in CPU microcode).

iPhone


App
GUI, etc.
iOS Kernel
Service
Service
L4-Based OS
Application Processor
Secure Enclave Processor

References

Important Foundational Paper:

"Authentication in Distributed Systems: Theory and Practice", Butler Lampson, Martin Abadi, Michael Burrows, Edward Wobber, ACM Transactions on Computer Systems (TOCS)

Technical documentation:

- Trusted Computing Group's specifications https://www.trustedcomputinggroup.org
- ARM Trustzone, Intel SGX vendor documentation