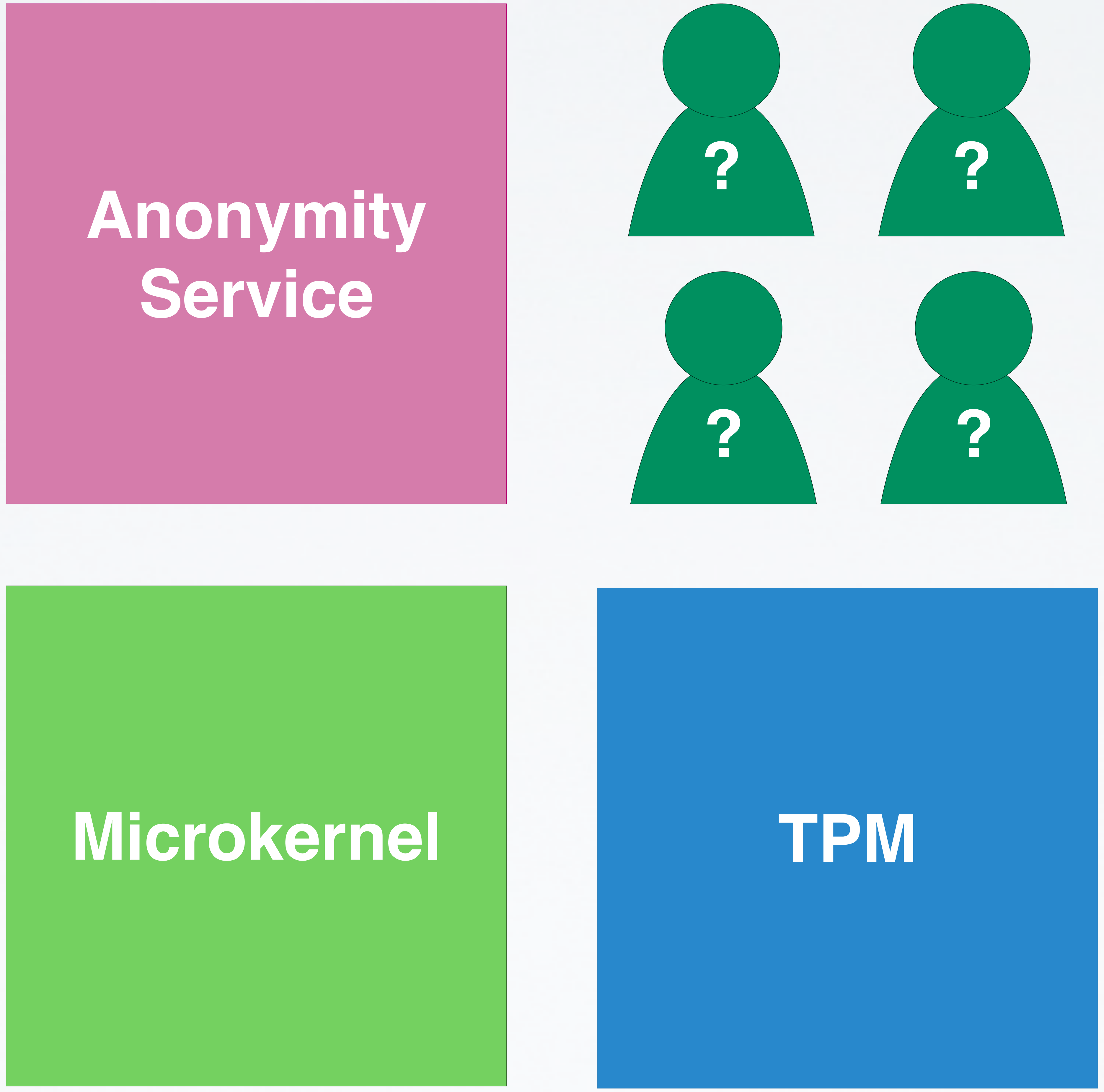
TRUSTED COMPUTING

CARSTEN WEINHOLD

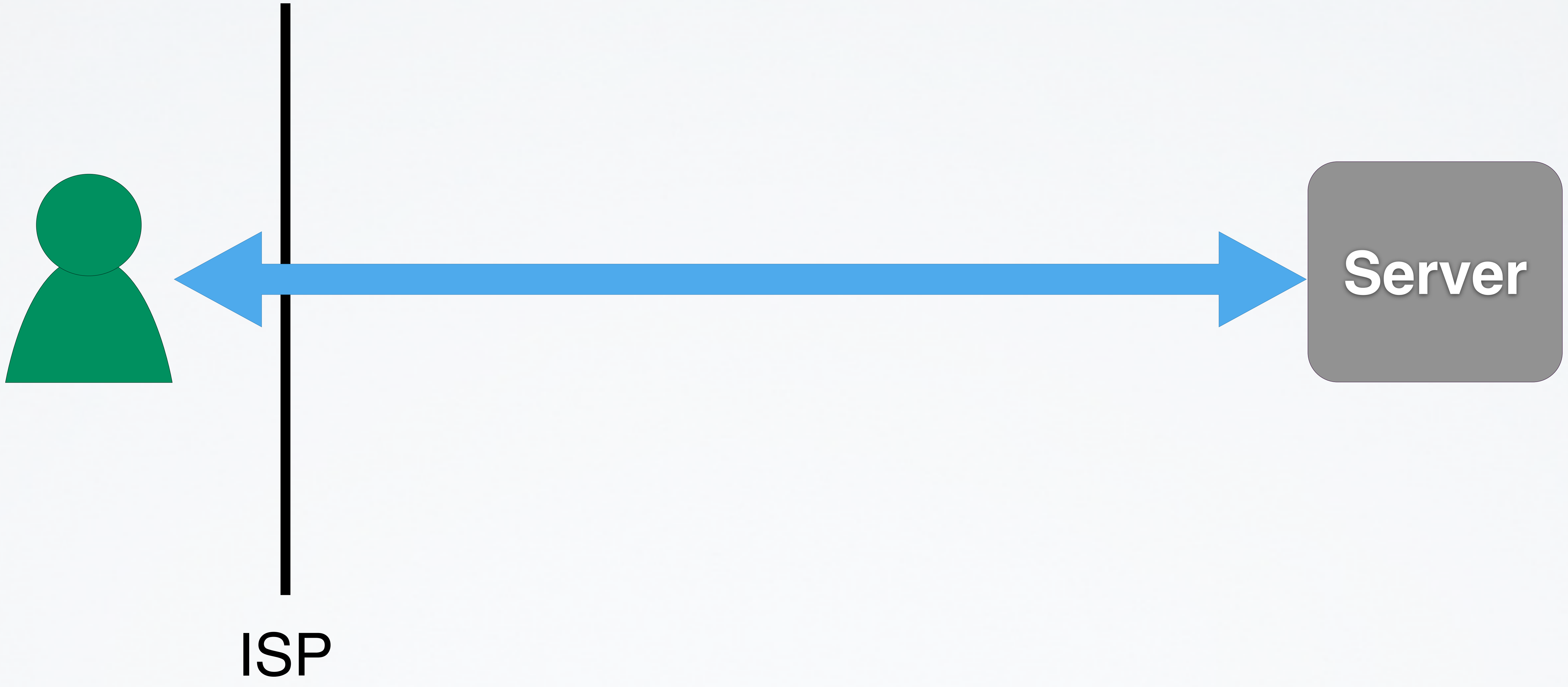
THIS LECTURE ...

- **Today: Trusted Computing Technology**
  - Lecture discusses basics in context of TPMs + outlook
  - More theoretical concepts also covered in lecture „Distributed Operating Systems“
- **Things you should have heard about:**
  - How to use asymmetric encryption
  - Concept of digital signatures
  - Collision-resistant hash functions

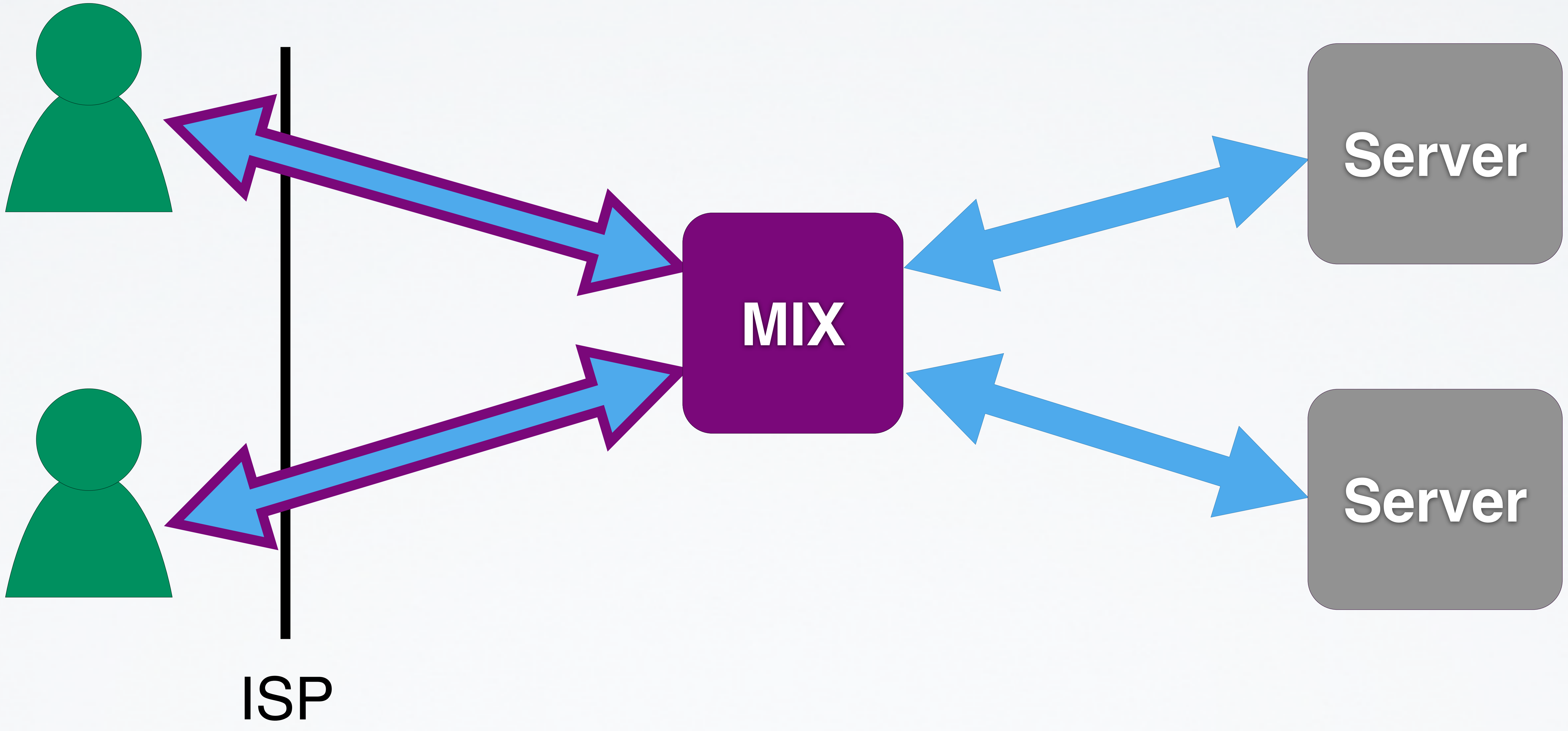
EXAMPLE USE CASE



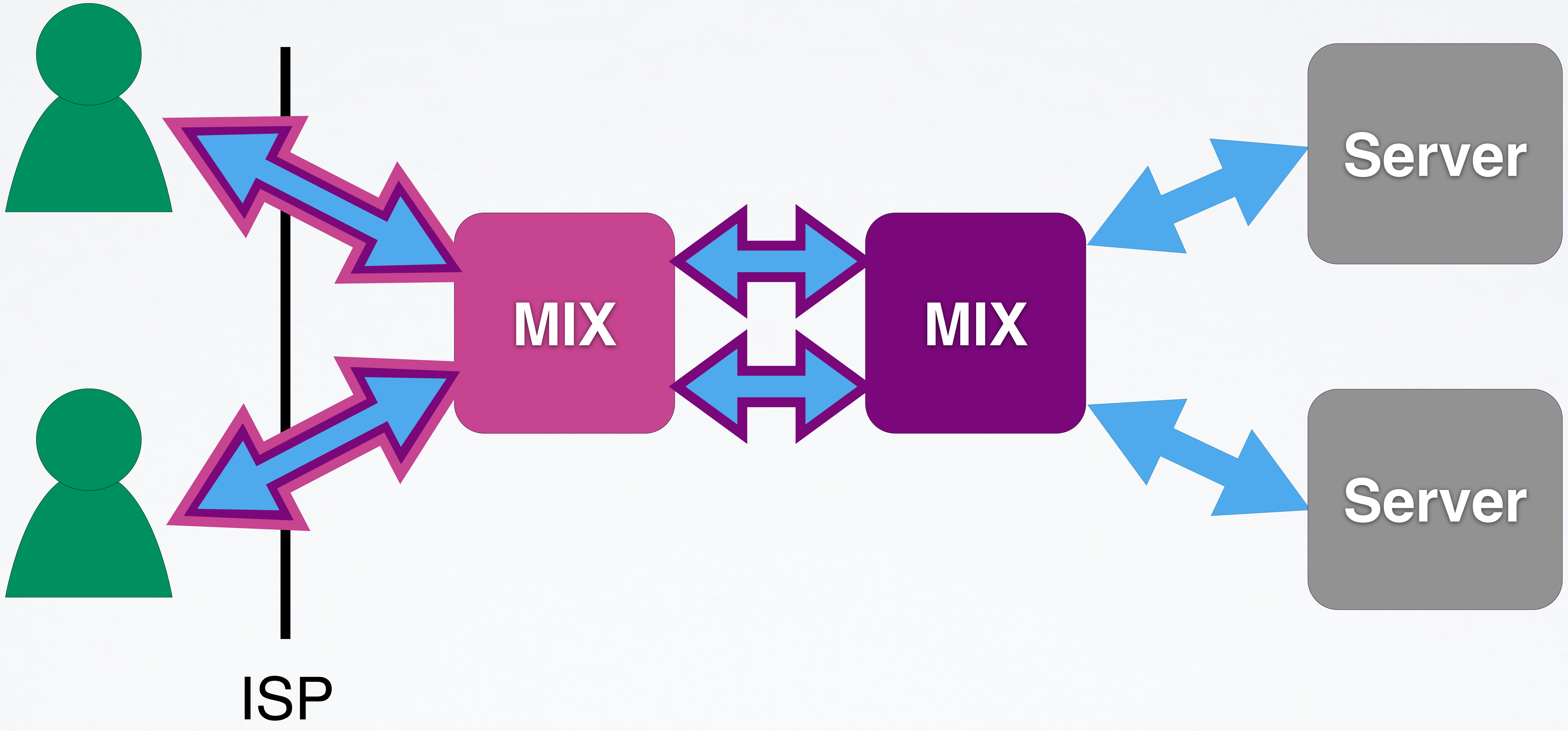
ANONYMITY



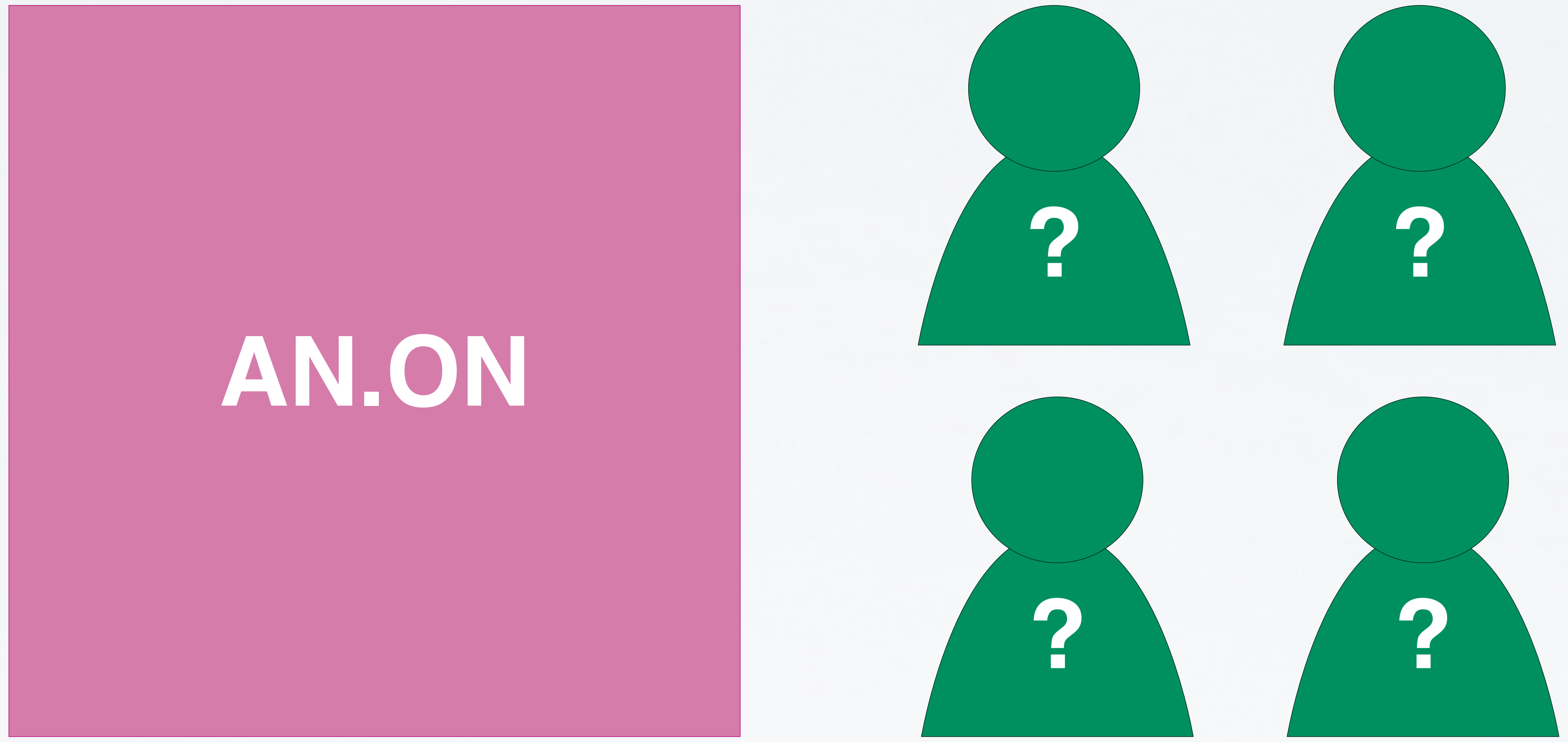
ANONYMITY



ANONYMITY

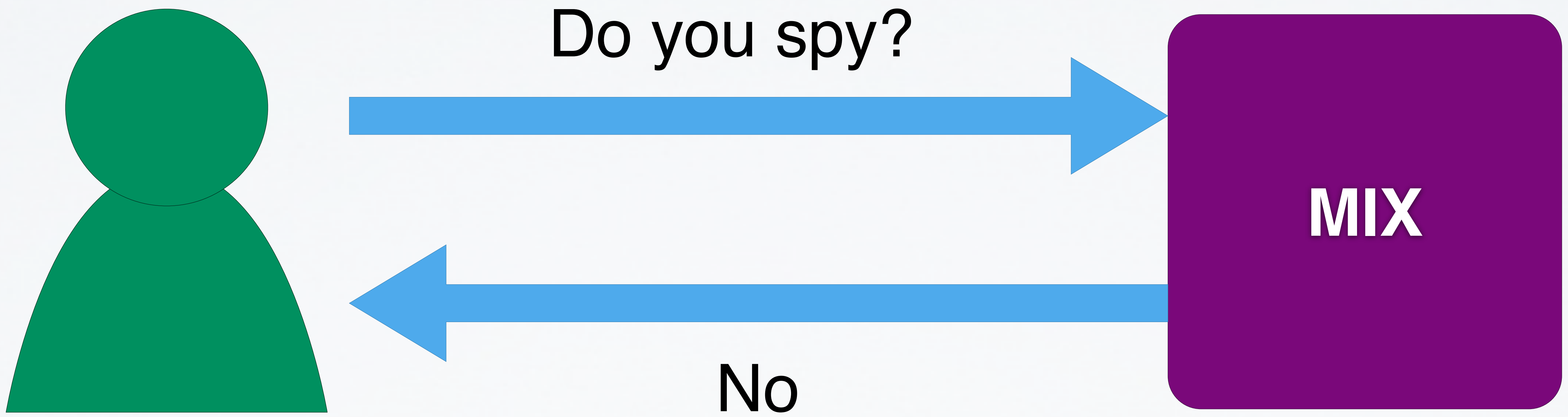


ANONYMITY



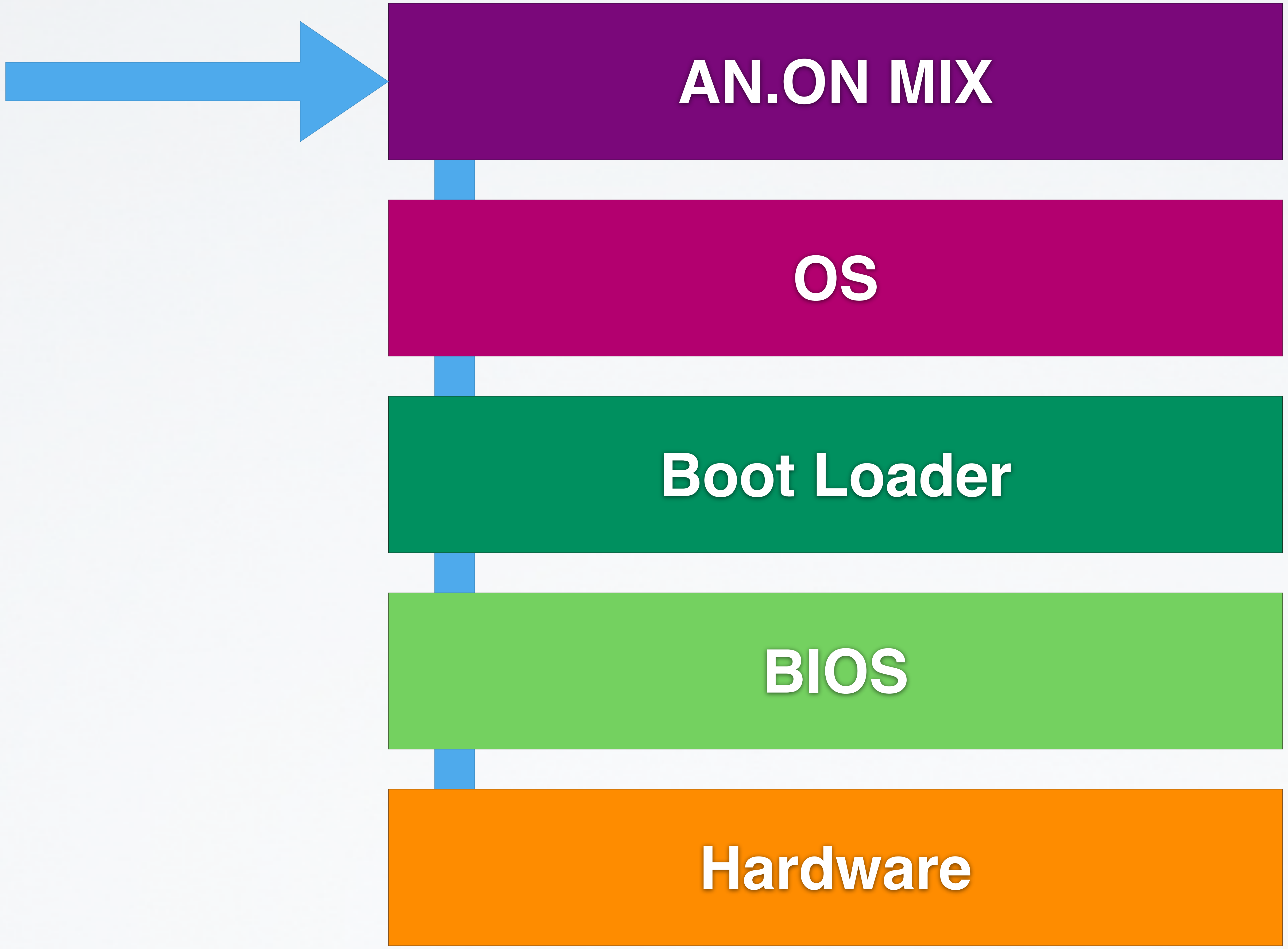
AN.ON

IDEA

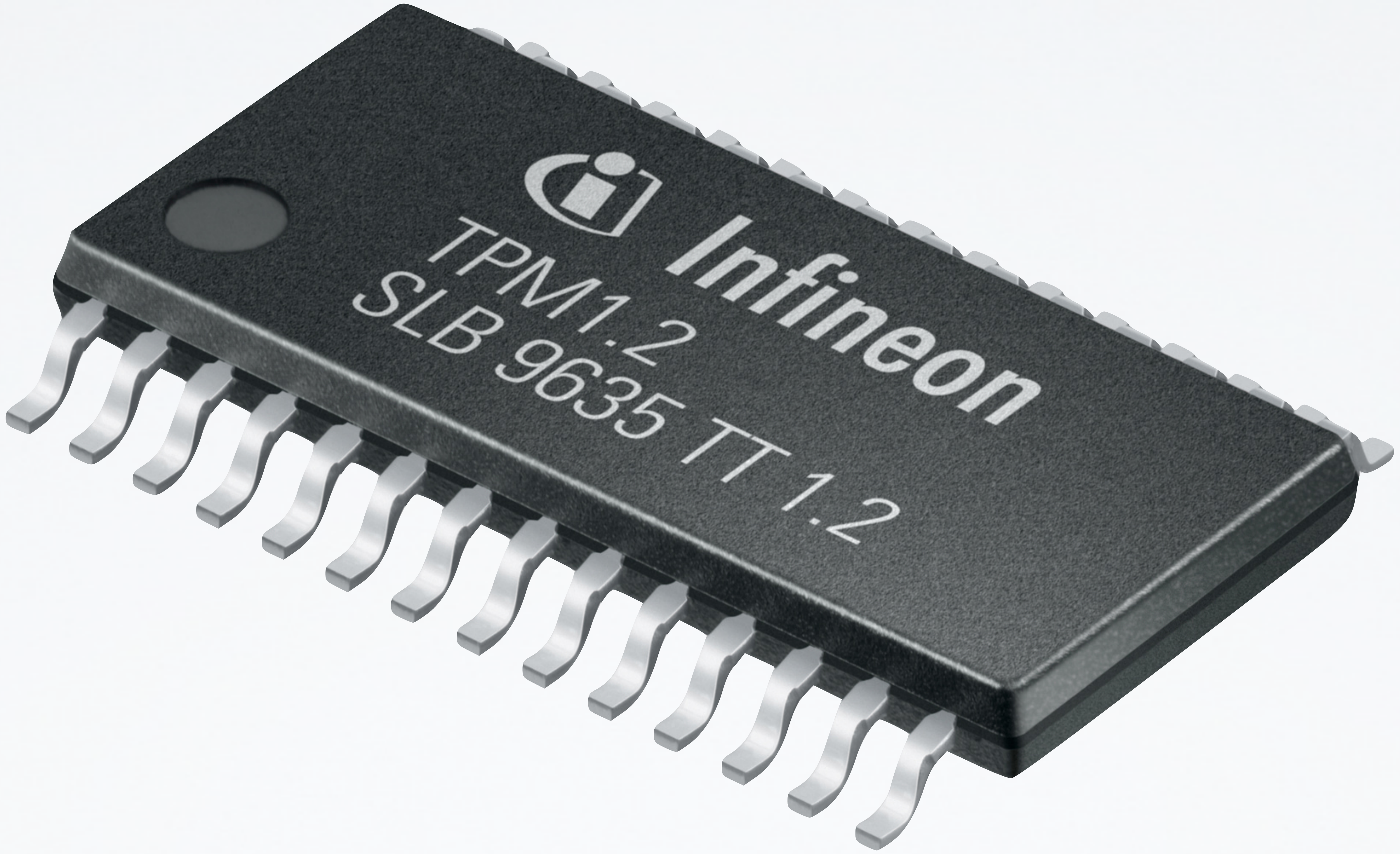


TECHNISCHE UNIVERSITÄT DRESDEN

SYSTEM LAYERS



TPM



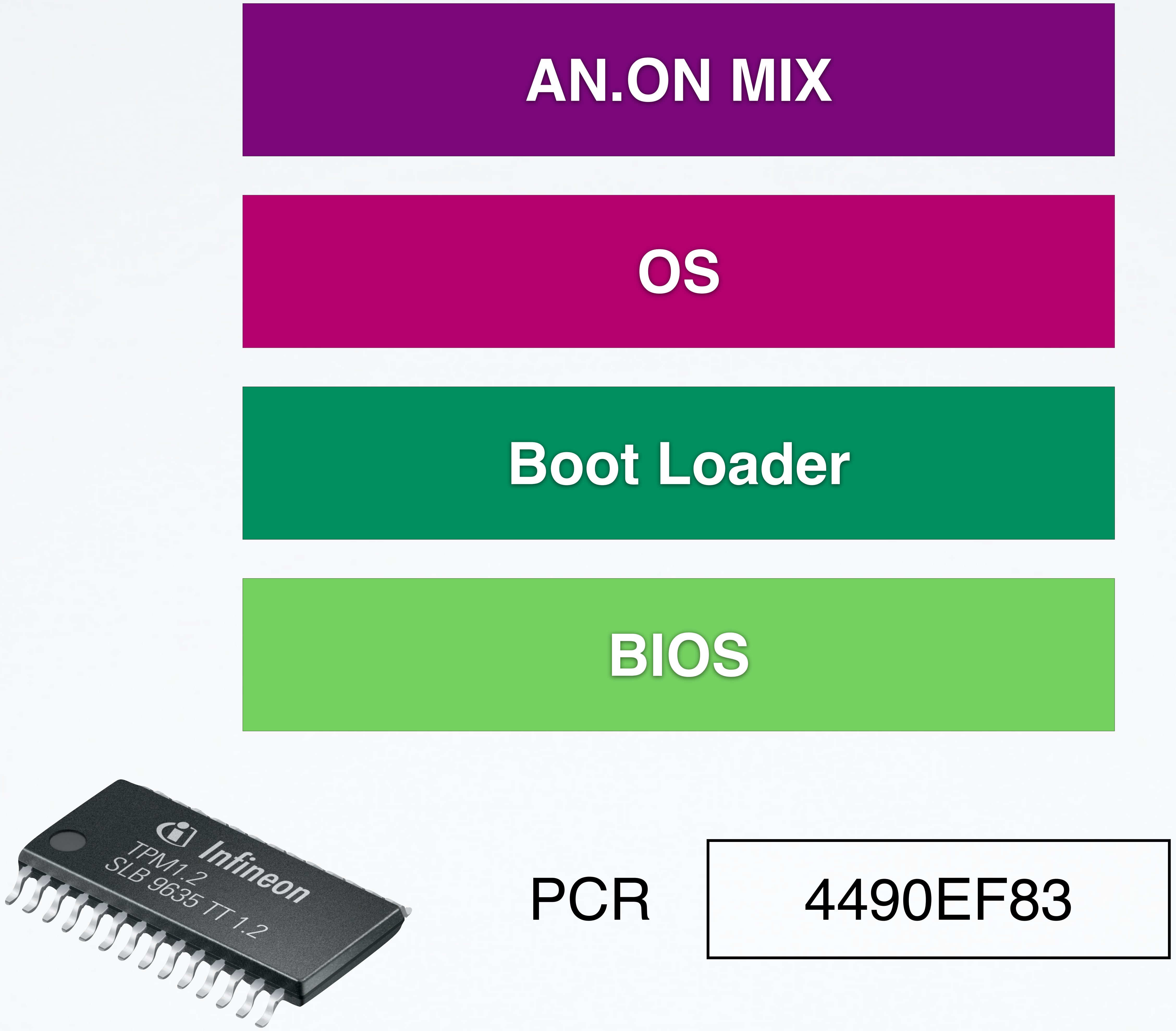
http://www.infineon.com/export/sites/default/media/press/Image/press_photo/TPM_SLB9635.jpg

Platform Configuration Register

PCR := SHA256(PCR | **X**)

Picture for illustration purposes only. SHA256 requires TPM 2.0.

BOOTING + TPM



AN.ON MIX

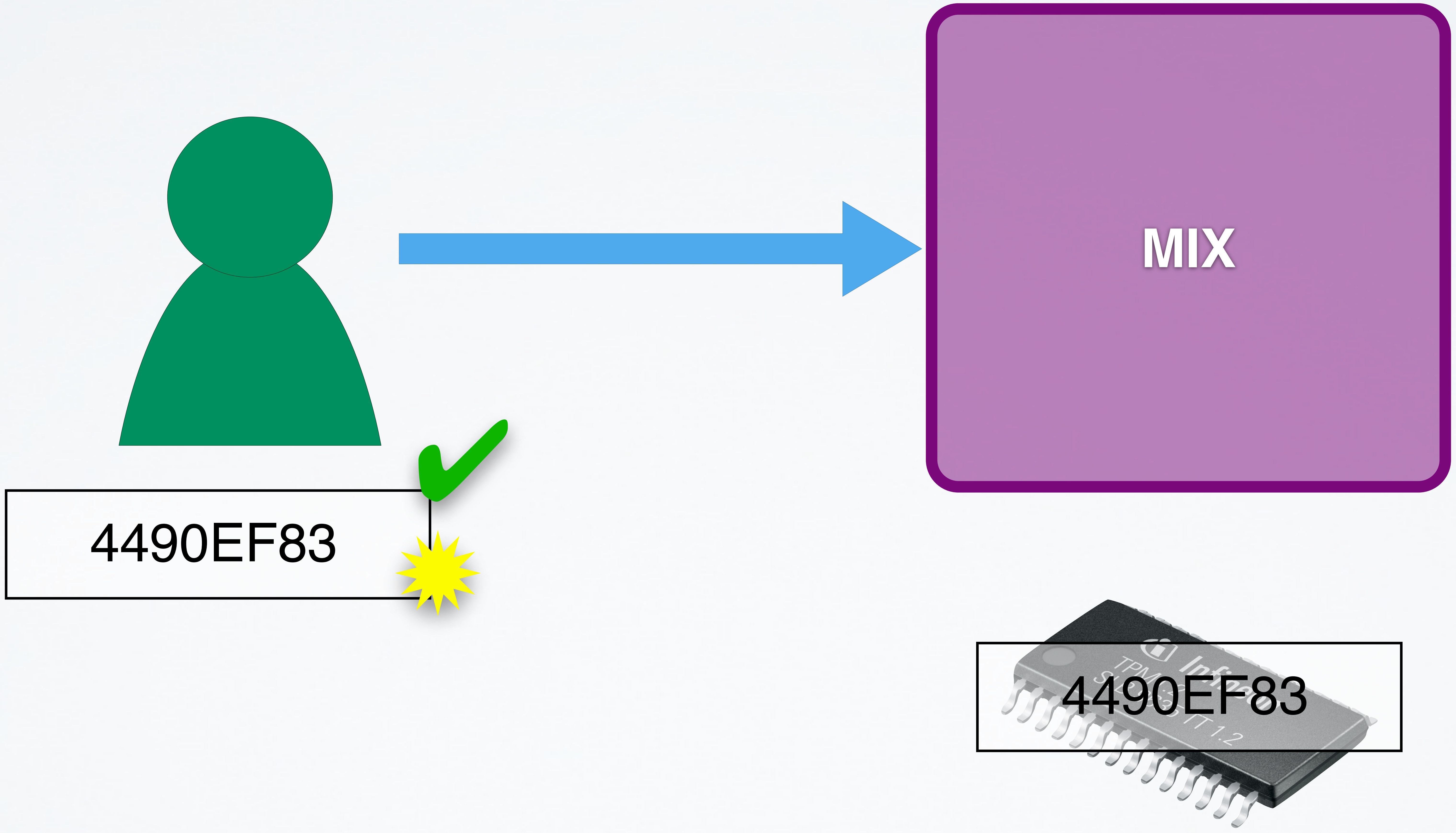
OS

Boot Loader

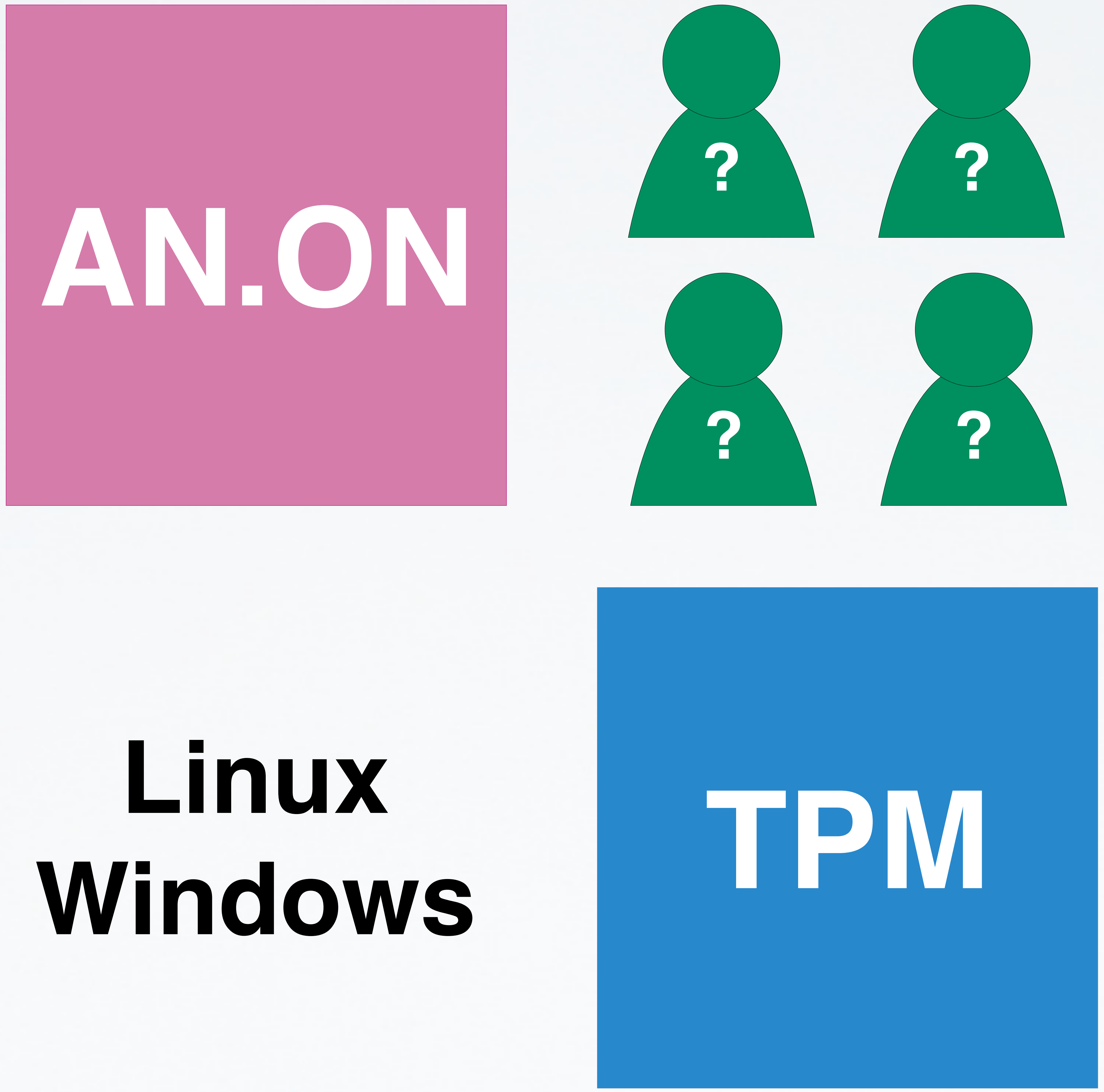
BIOS

PCR 4490EF83

Remote Attestation



ARCHITECTURE

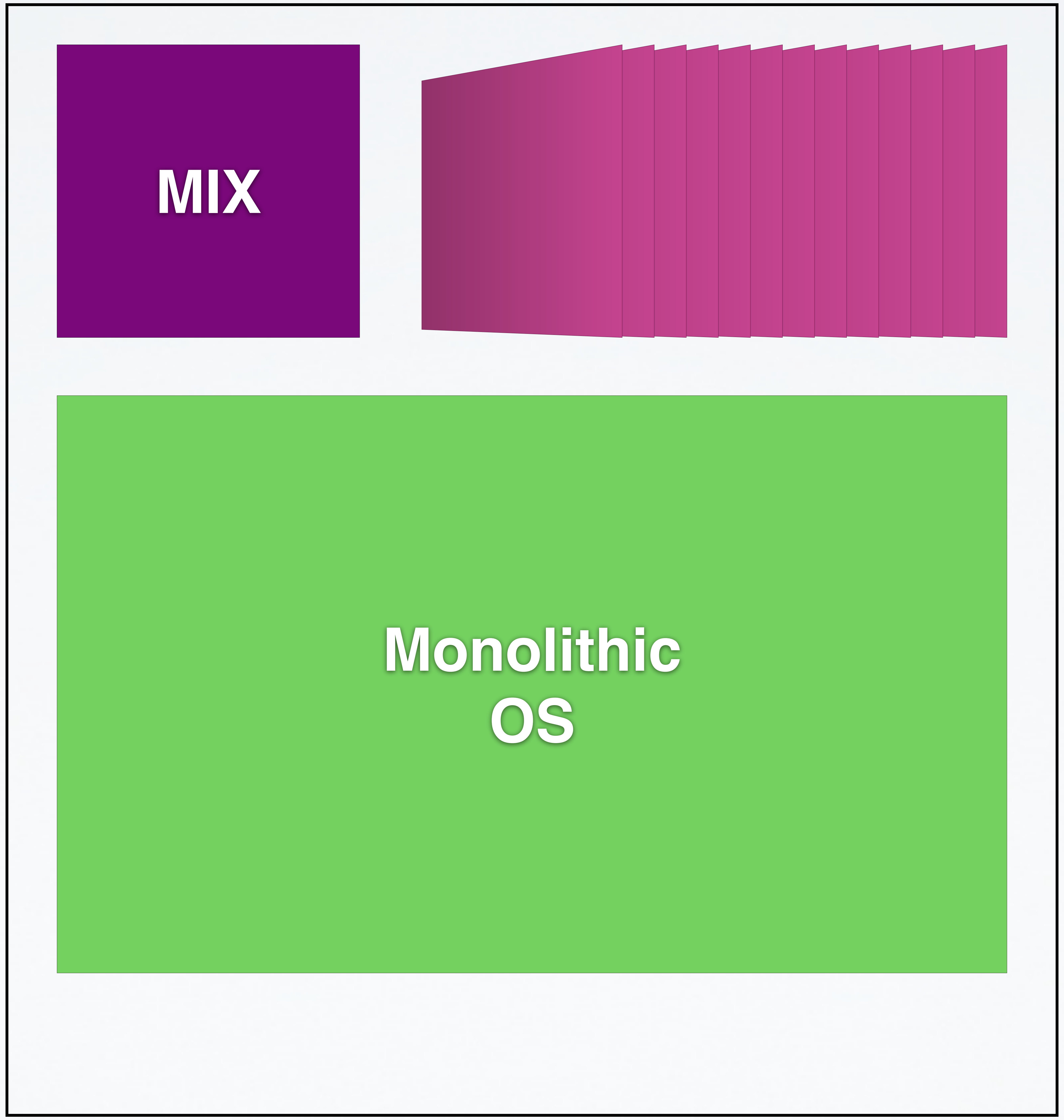


AN.ON

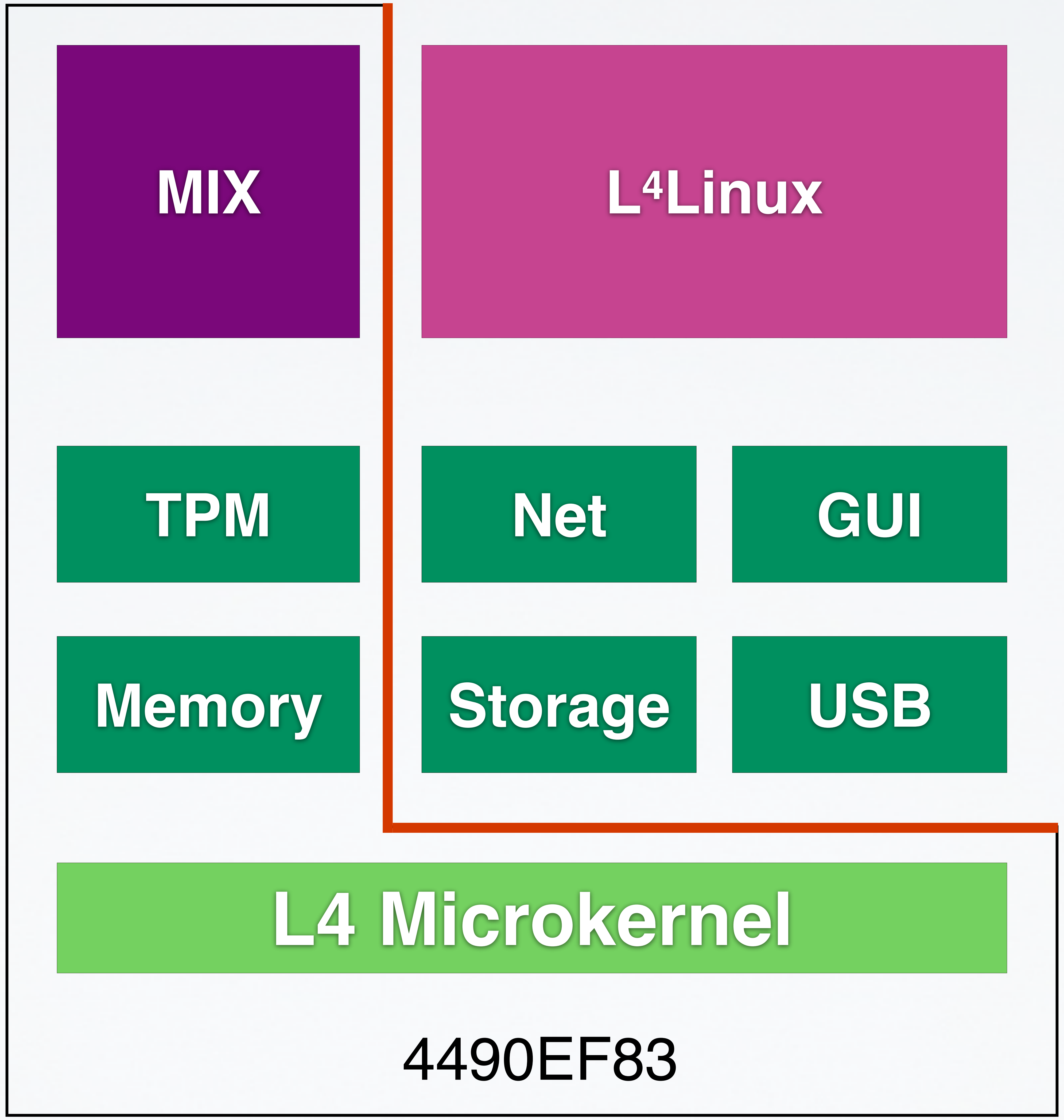
Linux
Windows

TPM

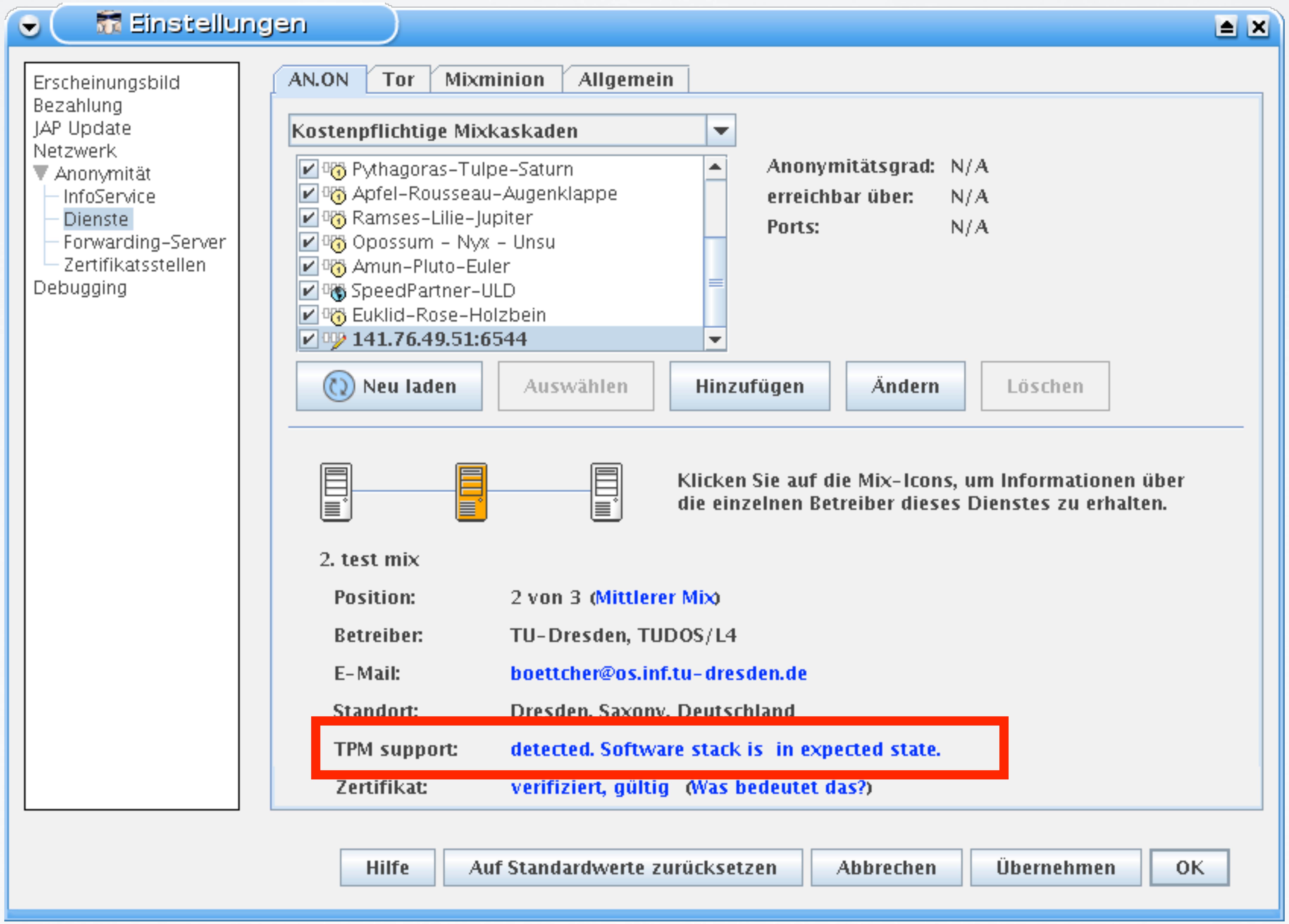
MONOLITHIC



L4/AN.ON


MIX
L⁴Linux
TPM
Net
GUI
Memory
Storage
USB
L4 Microkernel
4490EF83

L4/AN.ON



Kostenpflichtige Mixkaskaden

- ☑ Pythagoras-Tulpe-Saturn
- ☑ Apfel-Rousseau-Augenklappe
- ☑ Ramses-Lilie-Jupiter
- ☑ Opossum - Nyx - Unsu
- ☑ Amun-Pluto-Euler
- ☑ SpeedPartner-ULD
- ☑ Euklid-Rose-Holzbein
- ☑ 141.76.49.51:6544

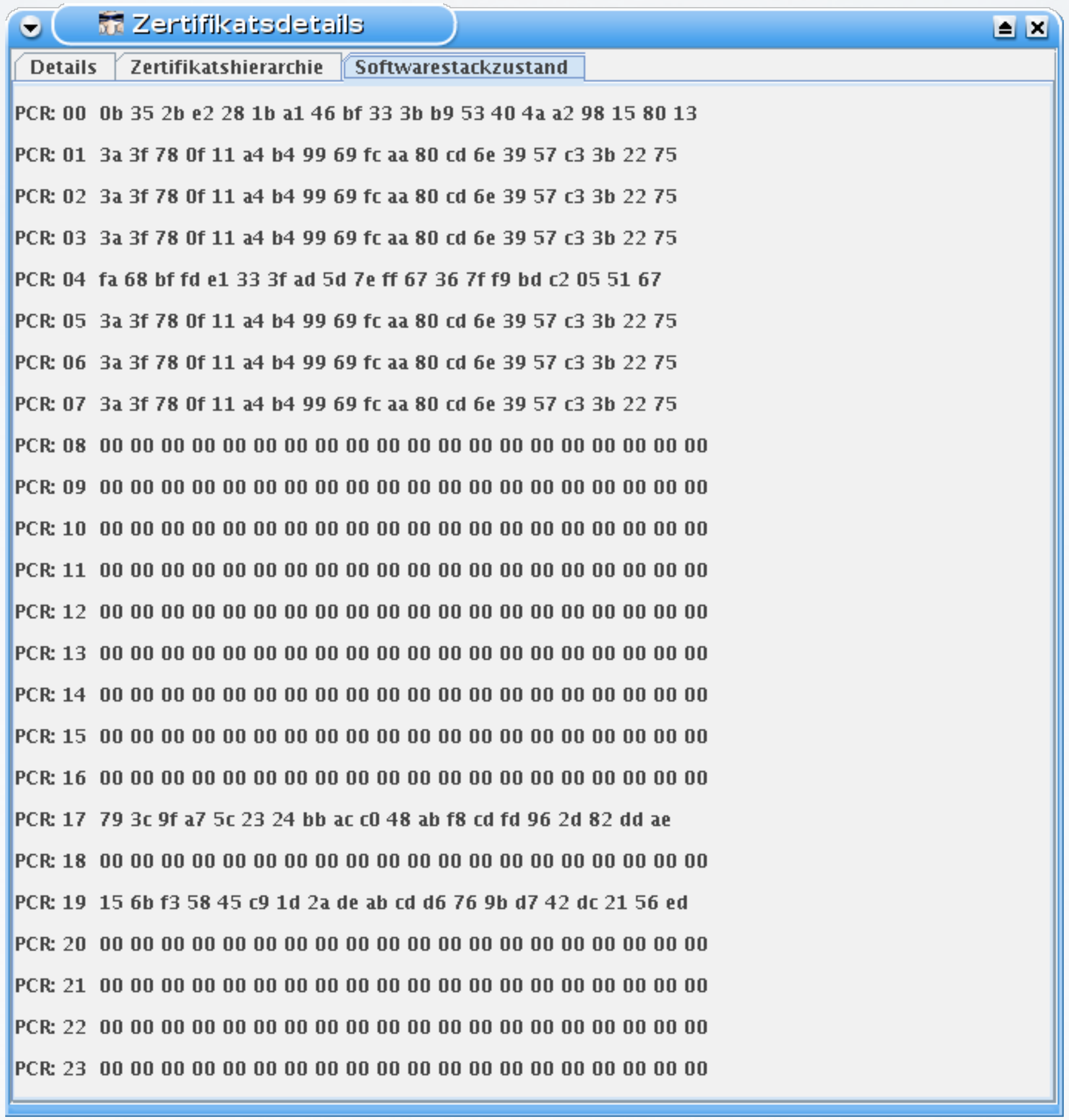
Anonymitätsgrad: N/A
erreichbar über: N/A
Ports: N/A

Klicken Sie auf die Mix-Icons, um Informationen über die einzelnen Betreiber dieses Dienstes zu erhalten.

2. test mix

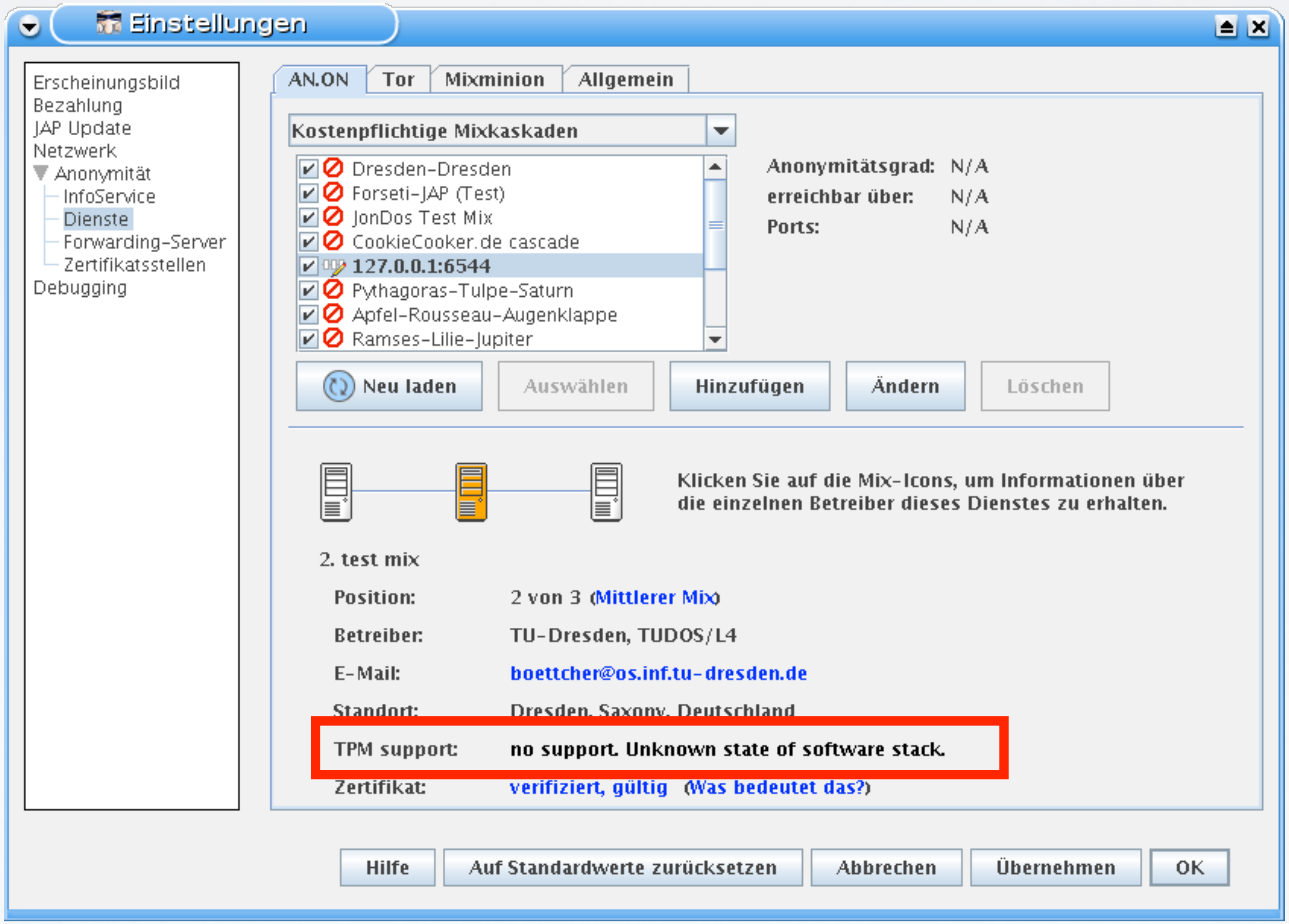
Position:	2 von 3 (Mittlerer Mix)
Betreiber:	TU-Dresden, TUDOS/L4
E-Mail:	boettcher@os.inf.tu-dresden.de
Standort:	Dresden, Saxony, Deutschland
TPM support:	detected. Software stack is in expected state.
Zertifikat:	verifiziert, gültig (Was bedeutet das?)

L4/AN.ON



```
PCR: 00  0b 35 2b e2 28 1b a1 46 bf 33 3b b9 53 40 4a a2 98 15 80 13
PCR: 01  3a 3f 78 0f 11 a4 b4 99 69 fc aa 80 cd 6e 39 57 c3 3b 22 75
PCR: 02  3a 3f 78 0f 11 a4 b4 99 69 fc aa 80 cd 6e 39 57 c3 3b 22 75
PCR: 03  3a 3f 78 0f 11 a4 b4 99 69 fc aa 80 cd 6e 39 57 c3 3b 22 75
PCR: 04  fa 68 bf fd e1 33 3f ad 5d 7e ff 67 36 7f f9 bd c2 05 51 67
PCR: 05  3a 3f 78 0f 11 a4 b4 99 69 fc aa 80 cd 6e 39 57 c3 3b 22 75
PCR: 06  3a 3f 78 0f 11 a4 b4 99 69 fc aa 80 cd 6e 39 57 c3 3b 22 75
PCR: 07  3a 3f 78 0f 11 a4 b4 99 69 fc aa 80 cd 6e 39 57 c3 3b 22 75
PCR: 08  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 09  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 10  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 11  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 12  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 13  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 14  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 15  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 16  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 17  79 3c 9f a7 5c 23 24 bb ac c0 48 ab f8 cd fd 96 2d 82 dd ae
PCR: 18  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 19  15 6b f3 58 45 c9 1d 2a de ab cd d6 76 9b d7 42 dc 21 56 ed
PCR: 20  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 21  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 22  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
PCR: 23  00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

L4/AN.ON



Einstellungen

- Erscheinungsbild
- Bezahlung
- JAP Update
- Netzwerk
- Anonymität
  - InfoService
  - Dienste
  - Forwarding-Server
  - Zertifikatsstellen
- Debugging

AN.ON | Tor | Mixminion | Allgemein

Kostenpflichtige Mixkaskaden

- ☑ Dresden-Dresden
- ☑ Forseti-JAP (Test)
- ☑ JonDos Test Mix
- ☑ CookieCooker.de cascade
- ☑ 127.0.0.1:6544
- ☑ Pythagoras-Tulpe-Saturn
- ☑ Apfel-Rousseau-Augenklappe
- ☑ Ramses-Lilie-Jupiter

Anonymitätsgrad:	N/A
erreichbar über:	N/A
Ports:	N/A

Neu laden | Auswählen | Hinzufügen | Ändern | Löschen

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2. test mix

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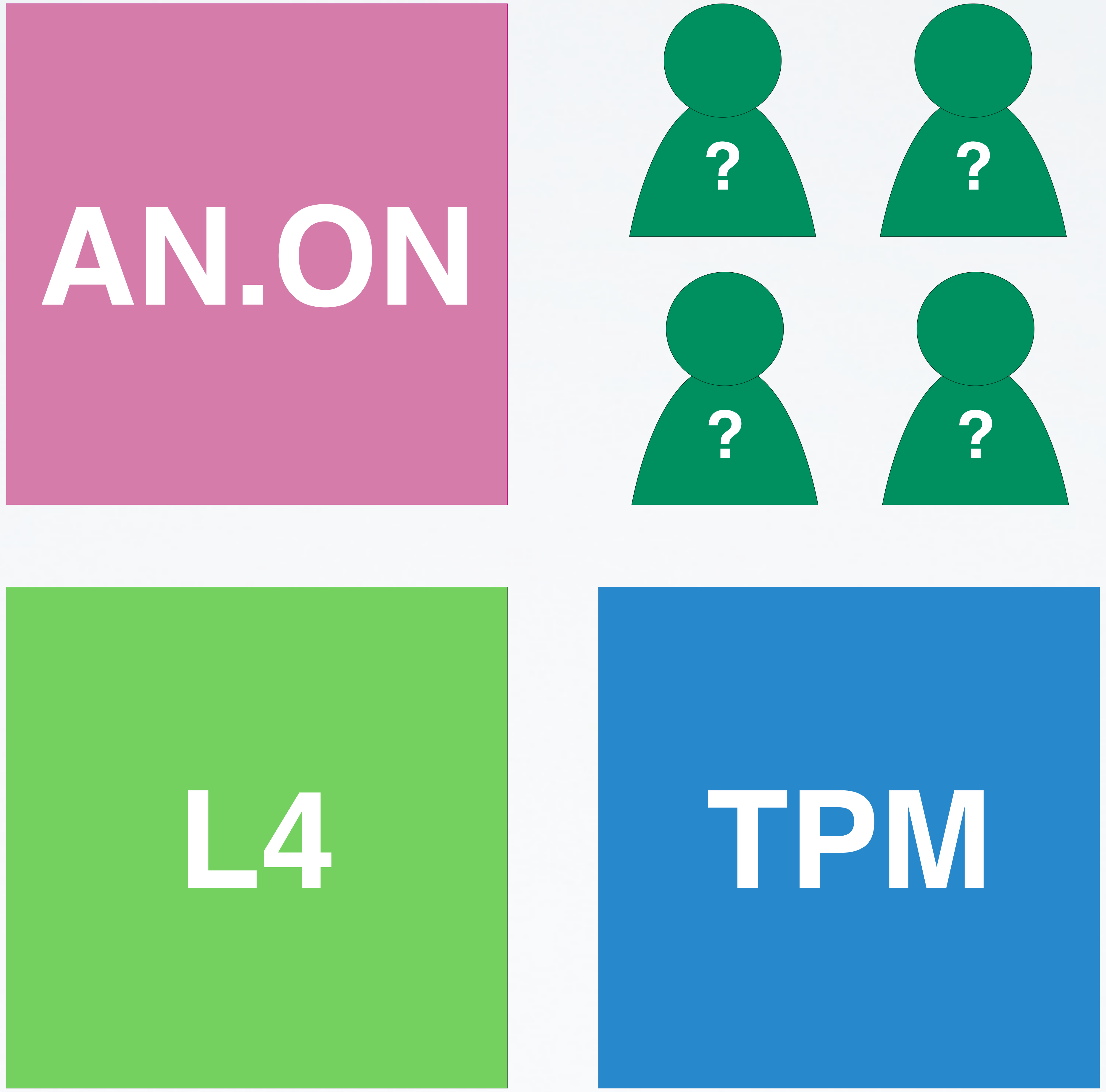
Betreiber:	TU-Dresden, TUDOS/L4
E-Mail:	boettcher@os.inf.tu-dresden.de
Standort:	Dresden, Saxony, Deutschland
TPM support:	no support. Unknown state of software stack.
Zertifikat:	verifiziert, gültig (Was bedeutet das?)

Hilfe | Auf Standardwerte zurücksetzen | Abbrechen | Übernehmen | OK

L4/AN.ON



AN.ON

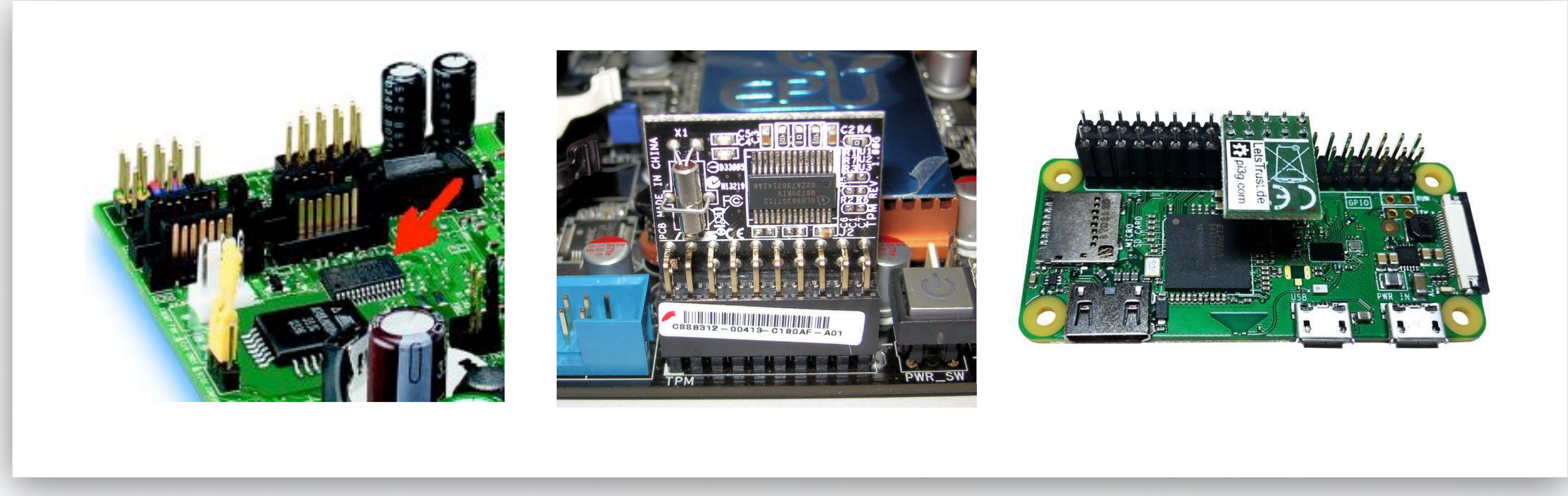
L4

TPM

THE TRUSTED PLATFORM MODULE

TPM HARDWARE

- TPMs are tightly integrated into platform:
  - Soldered on motherboard
  - Insecure / for experimentation only: Pluggable modules (PC, Raspberry Pi, ...)
  - Built into chipset / SoC
  - Implemented in Firmware
- Tamper resistant casing
- Widely deployed:
  - Business notebooks + desktops
  - Windows RT/8/10 tablets + all Windows 11 PCs



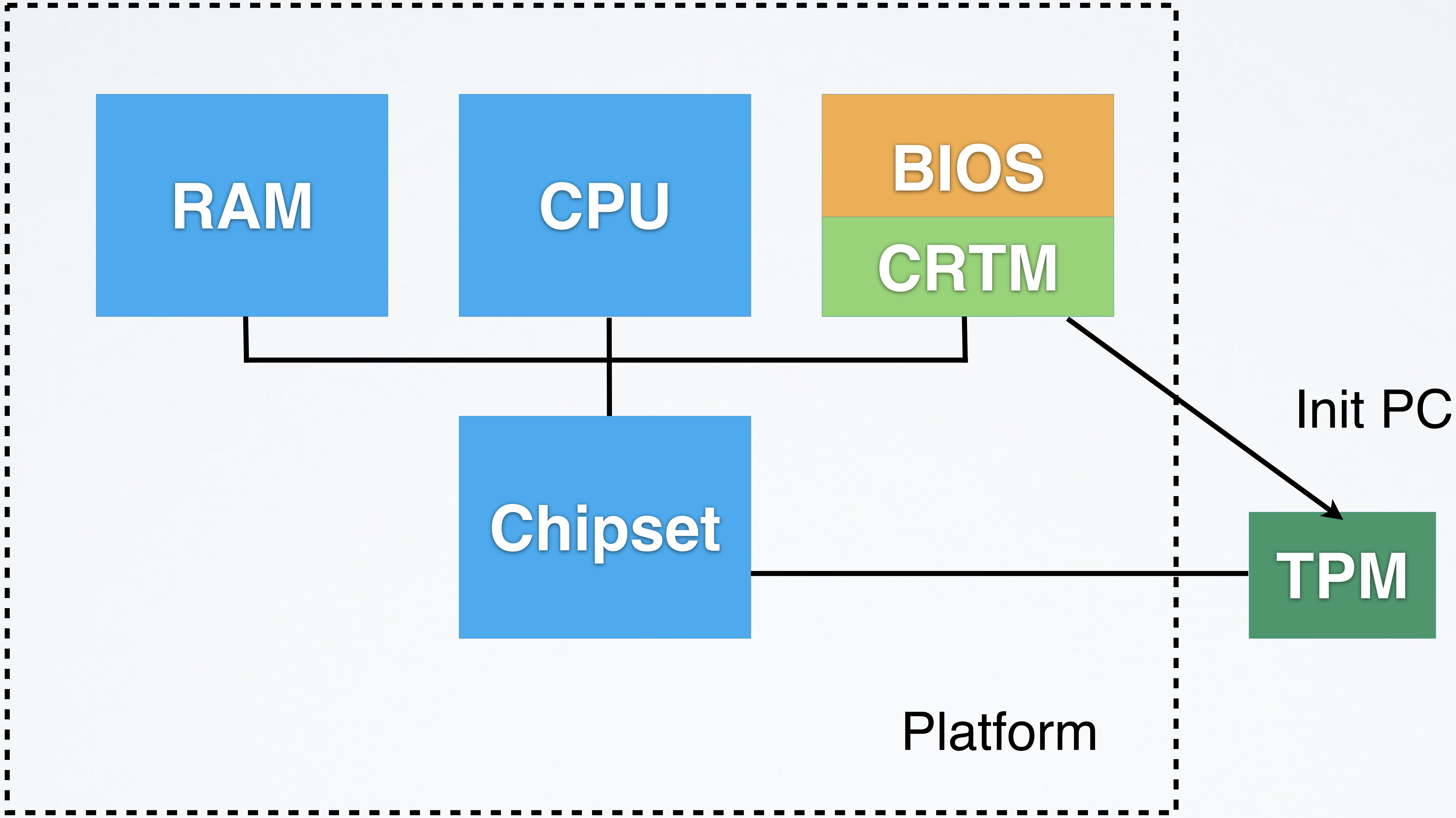
TPM OVERVIEW

- TPM is cryptographic coprocessor:
  - **RSA, Elliptic Curve** (encryption, signatures), **AES** (encryption), **SHA-256** (cryptographic hashes)
  - Other crypto schemes (e.g., **DAA**)
  - Random number generator
  - Platform Configuration Registers (**PCRs**)
  - Non-volatile memory
- TPMs are <u>passive</u> devices!

TPM SPECS

- TPMs specified by Trusted Computing Group [2]
- Multiple implementations
- TPM specifications [3,4] cover:
  - Architecture, interfaces, security properties
  - Data formats of input / output
  - Schemes for signatures, encryption, ...
  - TPM life cycle, platform requirements

TPM & PLATFORM



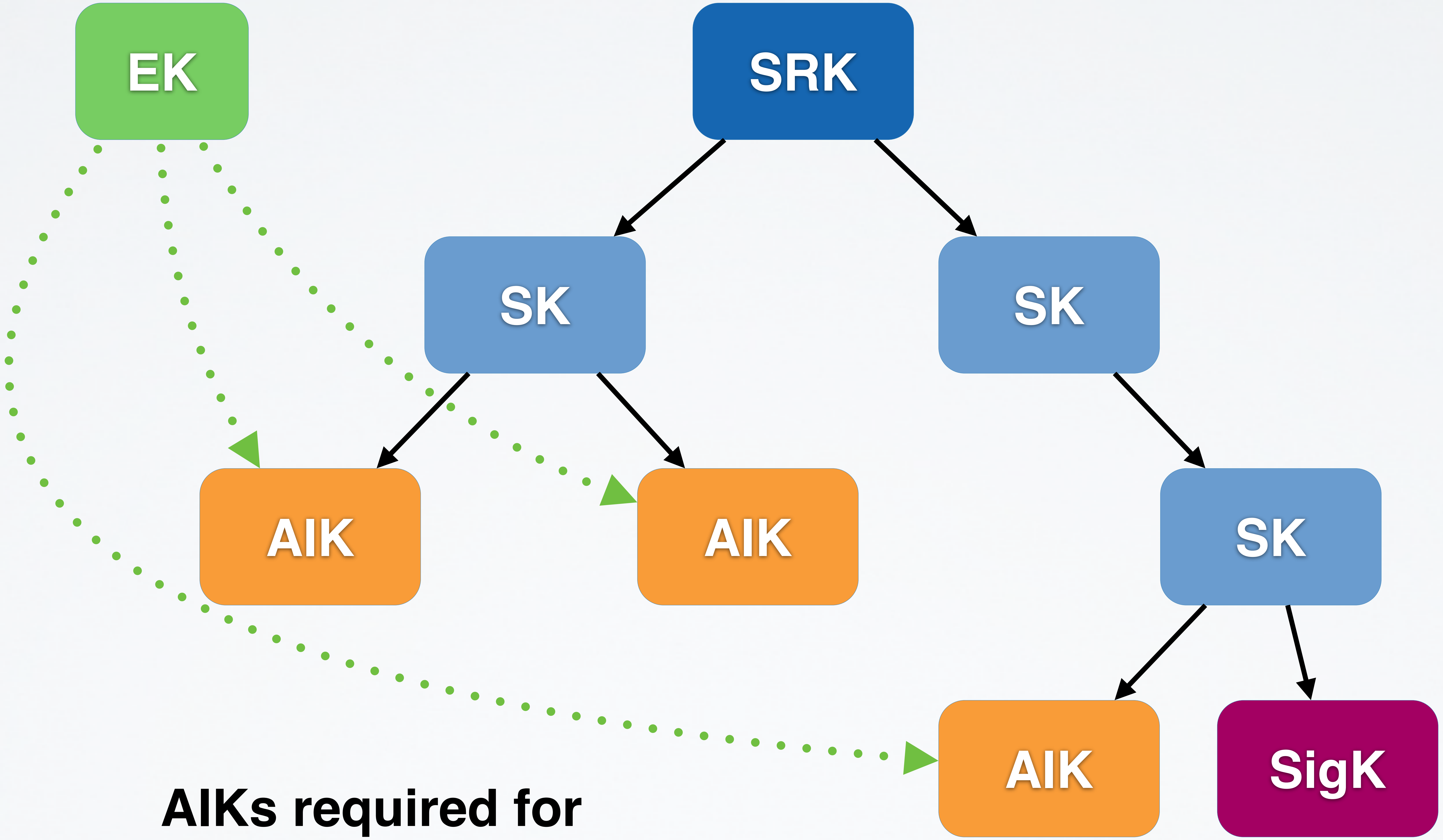
TPM IDENTITY

- TPM identified by Endorsement Key **EK**:
  - Generated in manufacturing process
  - Certified by manufacturer
  - Unique among all TPMs
  - Can only decrypt, serves as root of trust
- Creating entirely new **EK** possible (e.g., for use in corporate environments)
- Private part of **EK** <u>never</u> leaves TPM

KEY HIERARCHY

- All keys except for **EK** are part of key hierarchy below Storage Root Key **SRK**:
  - **SRK** created when user „takes ownership“
  - Key types: **storage**, **signature**, **identity**, ...
  - Storage keys are parent keys at lower levels of hierarchy (like **SRK** does at root level)
  - Keys other than **EK** / **SRK** can leave TPM:
    - Encrypted under parent key before exporting
    - Parent key required for loading and decrypting

KEY HIERARCHY

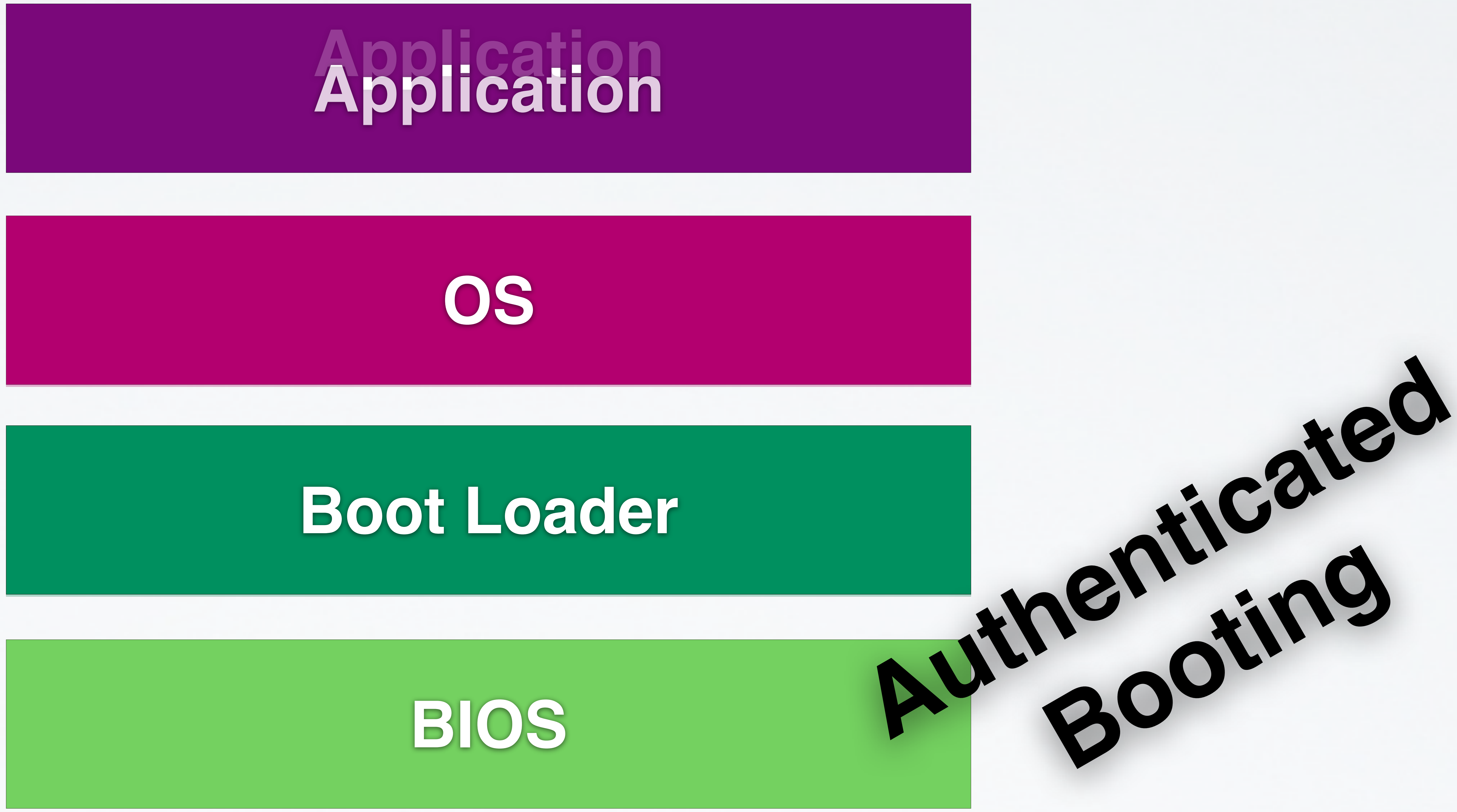


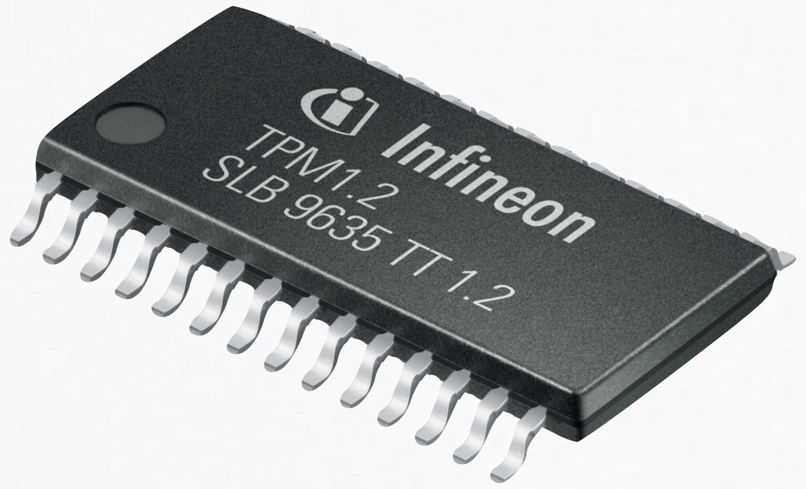
AIKs required for Remote Attestation

AIK

- Special key type for remote attestation: Attestation Identity Key (**AIKs**)
  - TPM creates AIK + certificate request
  - **Privacy CA** checks certificate request + **EK** authenticity, issues certificate and encrypts under **EK**
  - TPM can decrypt certificate using **EK**
- **AIK** certificate:
  - „This **AIK** has been created by a valid TPM“
  - TPM identity (**EK**) cannot be derived from it

BOOTING + TPM

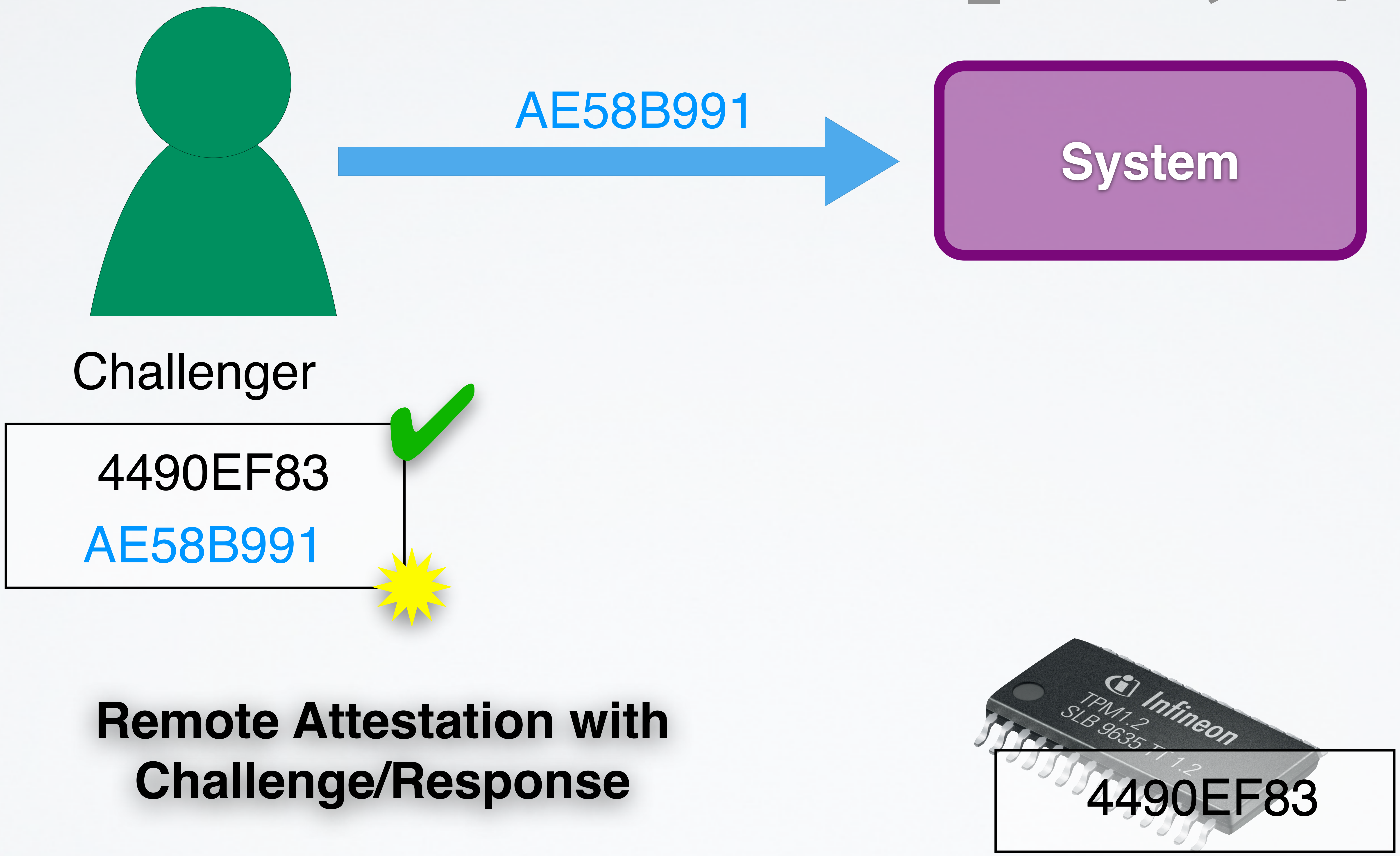




PCR 4490EF83

AIKS & QUOTES

TPM_Quote(AIK, Nonce, PCR)

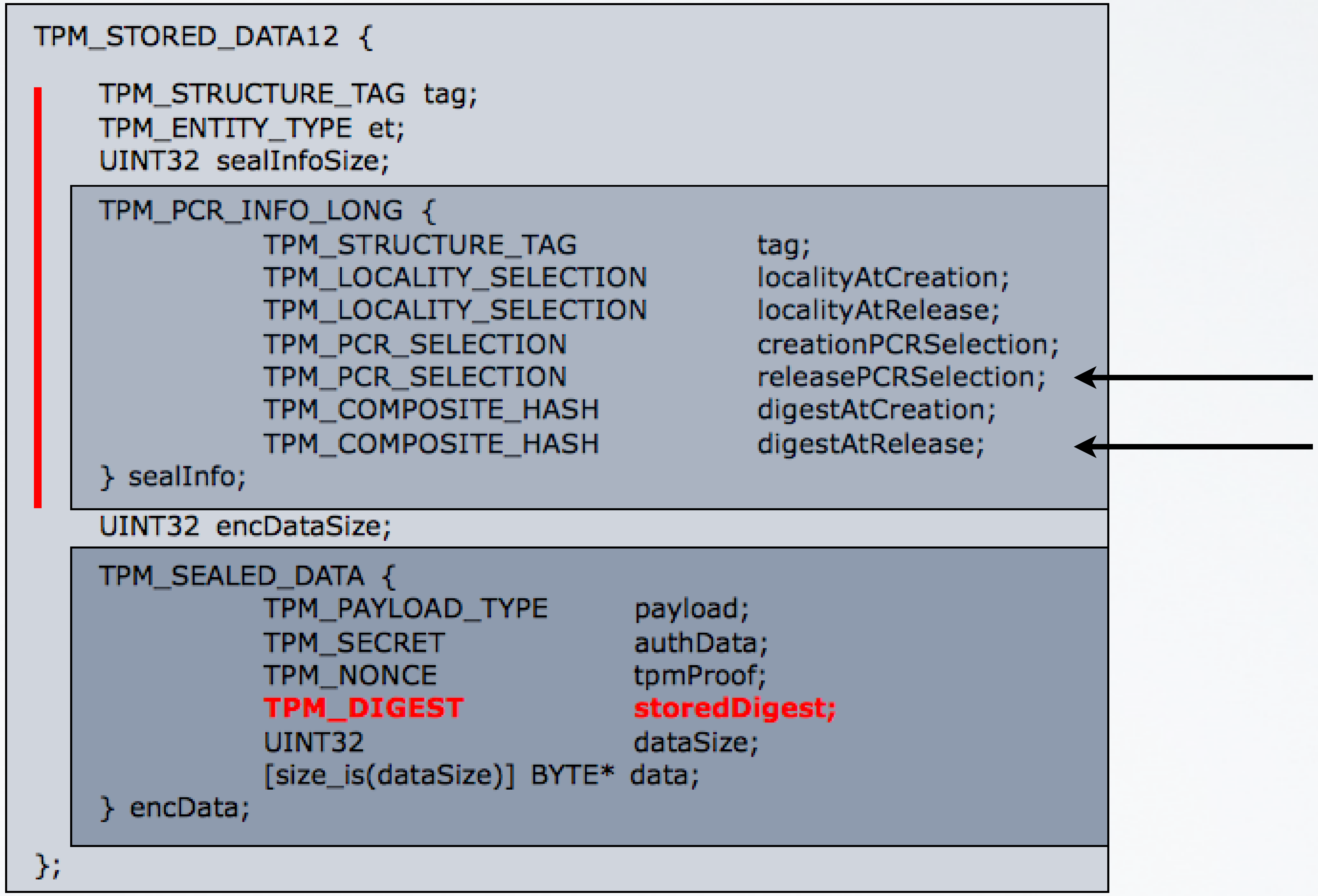


Remote Attestation with Challenge/Response

SEALED MEMORY

- Applications require secure storage
- TPMs can lock data to **PCR** values:
  - **TPM_Seal()**:
    - Encrypt user data under specified storage key
    - Encrypted blob contains **expected PCR** values
  - **TPM_Unseal()**:
    - Decrypt encrypted blob using storage key
    - Compare **current** and **expected PCR** values
    - Release user data only if **PCR** values match

SEALED BLOBS



```
TPM_STORED_DATA12 {
        TPM_STRUCTURE_TAG  tag;
        TPM_ENTITY_TYPE  et;
        UINT32  sealInfoSize;
        TPM_PCR_INFO_LONG  {
                    TPM_STRUCTURE_TAG               tag;
                    TPM_LOCALITY_SELECTION          localityAtCreation;
                    TPM_LOCALITY_SELECTION          localityAtRelease;
                    TPM_PCR_SELECTION               creationPCRSelection;
                    TPM_PCR_SELECTION               releasePCRSelection;
                    TPM_COMPOSITE_HASH              digestAtCreation;
                    TPM_COMPOSITE_HASH              digestAtRelease;
        } sealInfo;
        UINT32  encDataSize;
        TPM_SEALED_DATA  {
                    TPM_PAYLOAD_TYPE        payload;
                    TPM_SECRET              authData;
                    TPM_NONCE               tpmProof;
                    TPM_DIGEST              storedDigest;
                    UINT32                  dataSize;
                    [size_is(dataSize)] BYTE*  data;
        } encData;
};
```

Only the TPM_SEALED_DATA structure is encrypted

FRESHNESS

- Sealed data is stored outside the TPM
- Vulnerable to replay attacks:
  - Multiple versions of sealed blob may exist
  - Any version can be passed to TPM
  - TPM happily decrypts, if crypto checks out
- Problem:
  - What if sealed data must be current?
  - How to prevent use of older versions?

COUNTERS

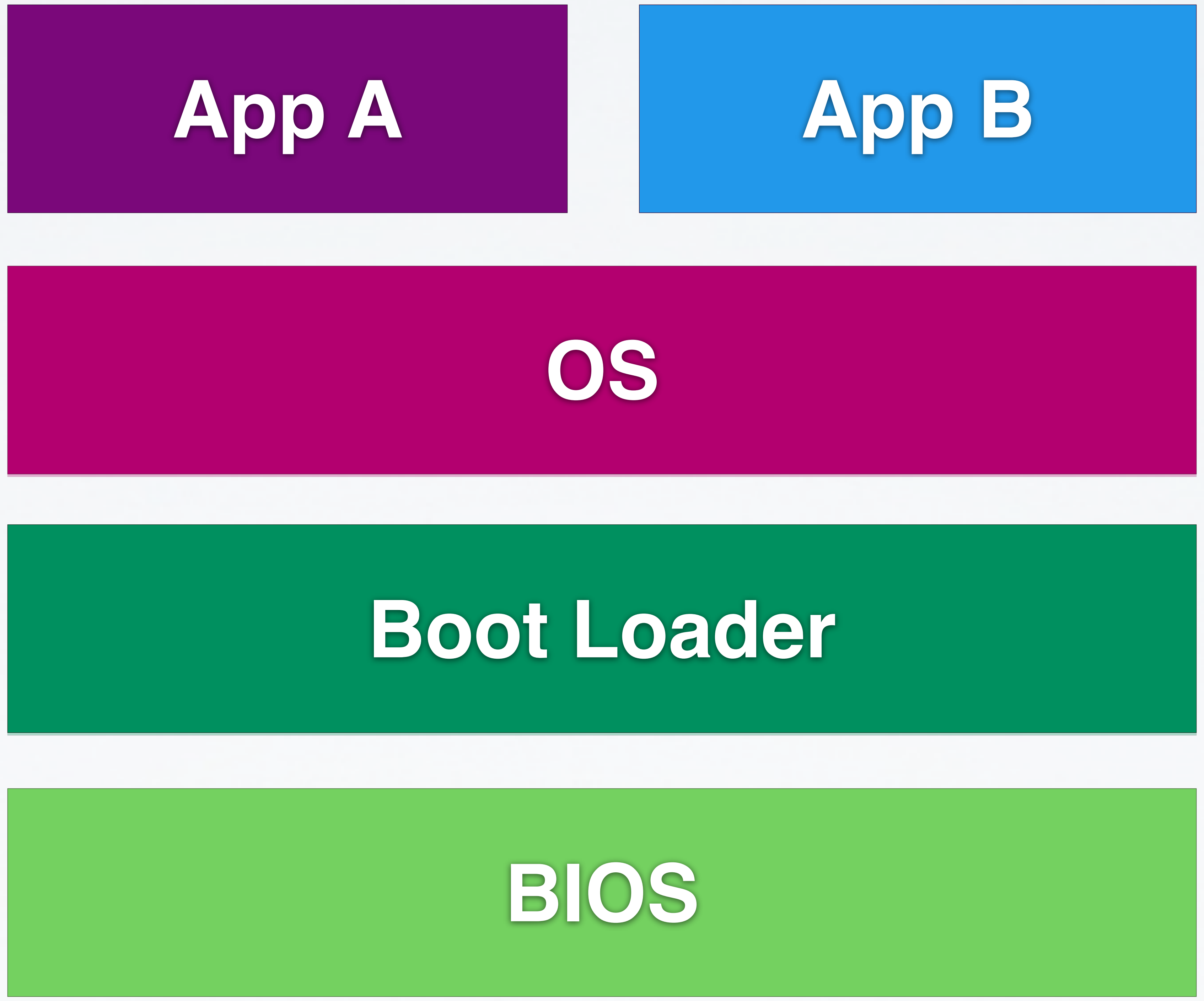
- TPMs provide **monotonic counters**
- Only two operations: **increment**, **read**
- Password protected
- Prevent replay attacks:
  - Seal expected value of counter with data
  - After unseal, compare unsealed value with current counter
  - Increment counter to invalidate old versions

TPM SUMMARY

- Key functionality of TPMs:
  - Authenticated booting
  - Remote attestation
  - Sealed memory
- Problems with current TPMs:
  - No (sensible) support for virtualization
  - Can be slow (hundreds of ms / operation)
  - Linear chain of trust

TPMS IN NIZZA ARCHITECTURE

BOOTING + TPM



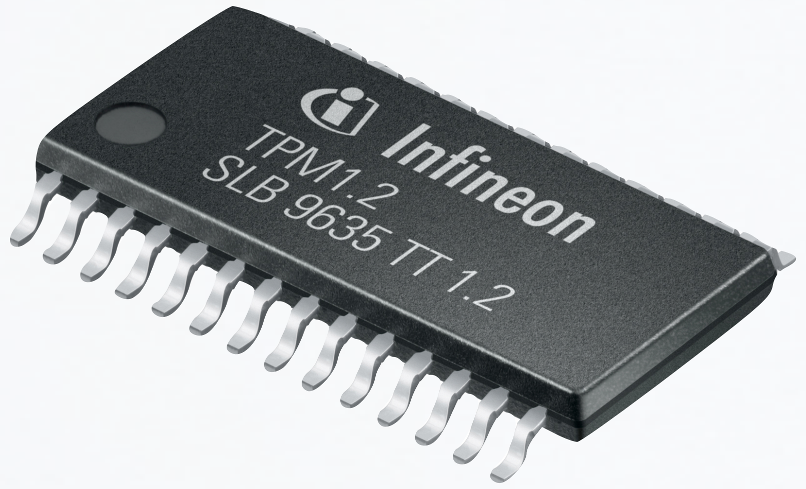
App A

App B

OS

Boot Loader

BIOS



PCR

83E2FF9A
~~4490EF83~~

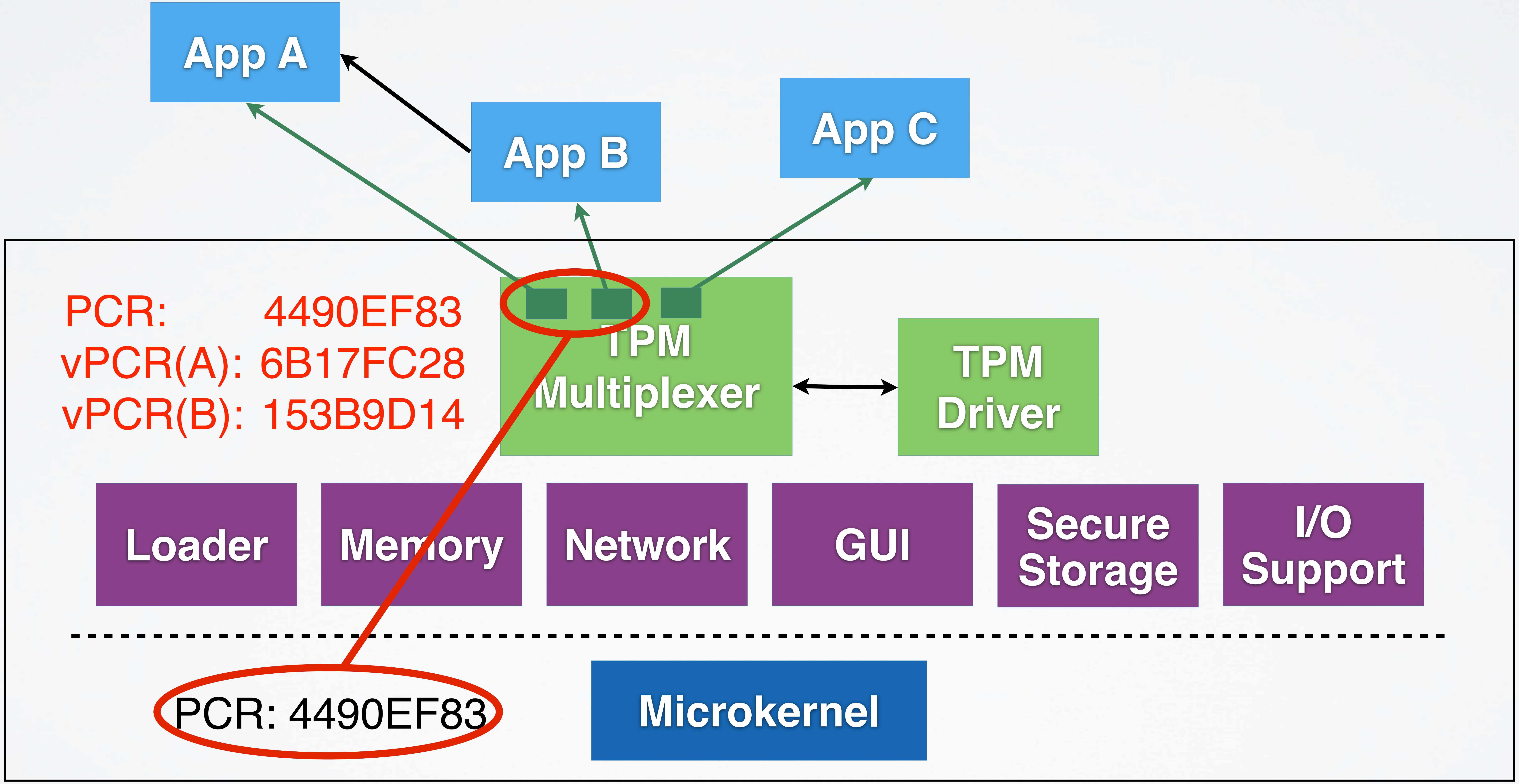
MULTIPLE APPS

- Use one PCR per application:
  - Application measurements independent
  - Number of PCRs is limited (usually 24 PCRs)
- Use one PCR for all applications:
  - Chain of trust / application log grows
  - All applications reported in remote attestation (raises privacy concerns)
  - All applications checked when unsealing

EXTENDING TPMS

- Idea: per-application PCRs in software:
  - Measure only base system into TPM PCRs (microkernel, basic services, TPM driver, ...)
  - „Software TPM“ provides „software PCRs“ for each application
  - More flexibility with „software **PCRs**“:
    - Chain of trust common up to base system
    - Extension of chains of trust for applications fork above base system
    - Branches in **Tree of Trust** are independent

SOFTWARE PCRS

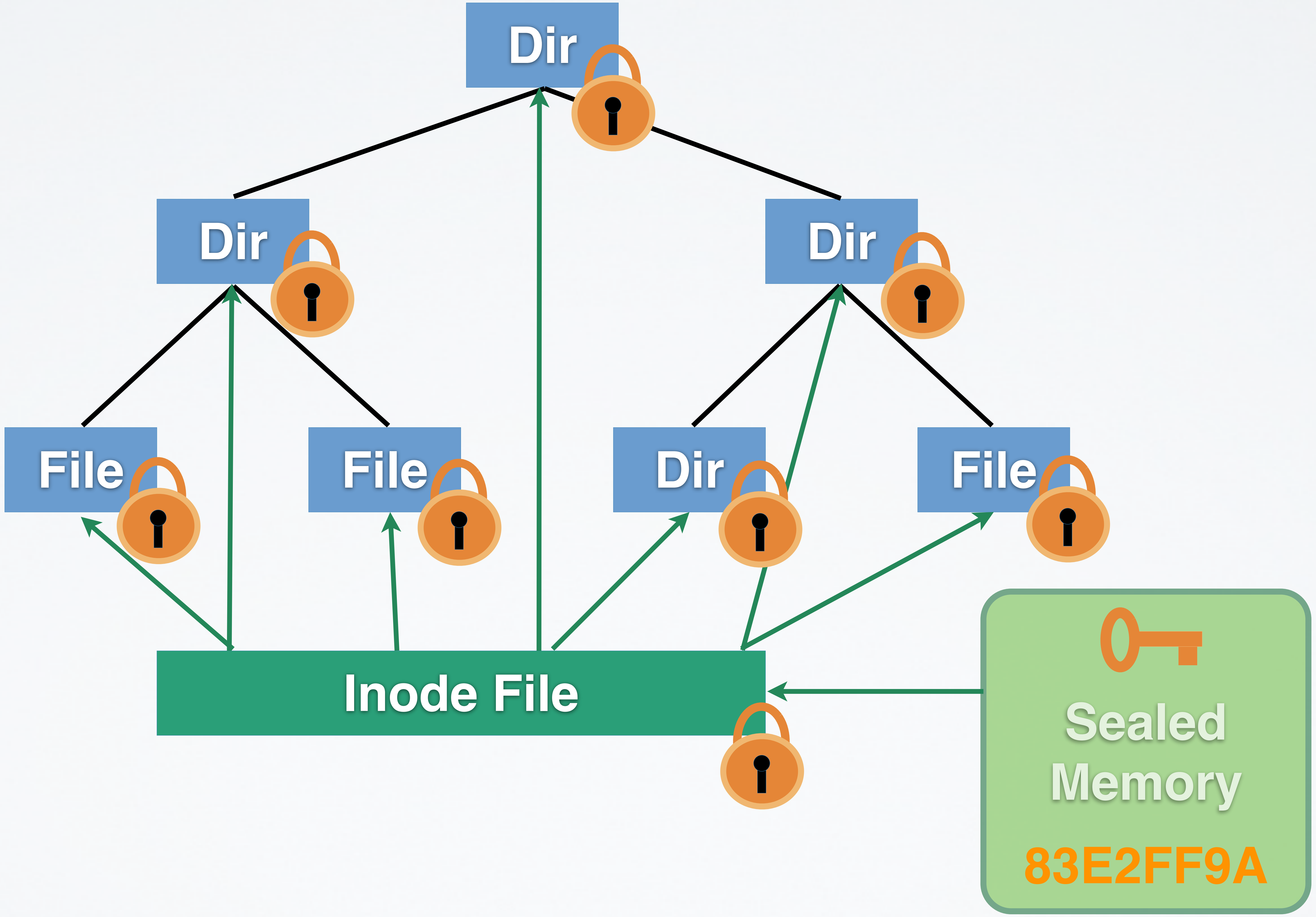


TPM MULTIPLEXED

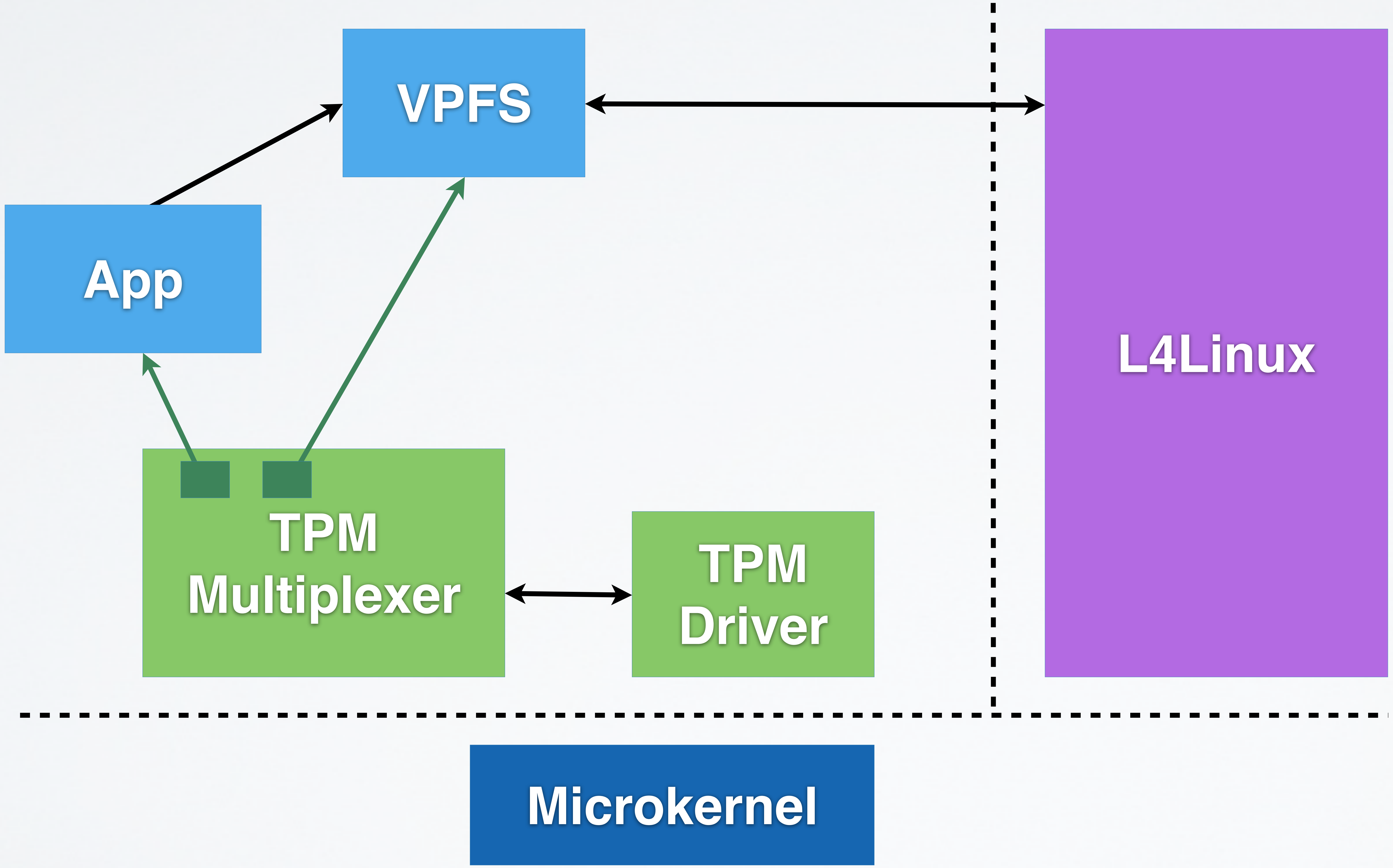
- Operations on software PCRs:
  - **Seal**, **Unseal**, **Quote**, **Extend**
  - **Add_child**, **Remove_child**
- Performed using software keys (AES, RSA, EC)
- Software keys protected with real TPM
- Link between software **PCRs** and real **PCRs**: certificate for RSA/EC signature key

A SECOND LOOK AT VPFS

VPFS SECURITY



VPFS TRUST



VPFS can access secrets only, if its own vPCR and the vPCR for the app match the respective expected values.

VPFS SECURITY

- VPFS uses **sealed memory:**
  - Secret encryption key
  - Root hash of Merkle hash tree
- Second use case is **remote attestation:**
  - Trusted backup storage required, because data in untrusted storage can be lost
  - Secure access to backup server needed
  - VPFS challenges backup server: „Will you store my backups reliably?“

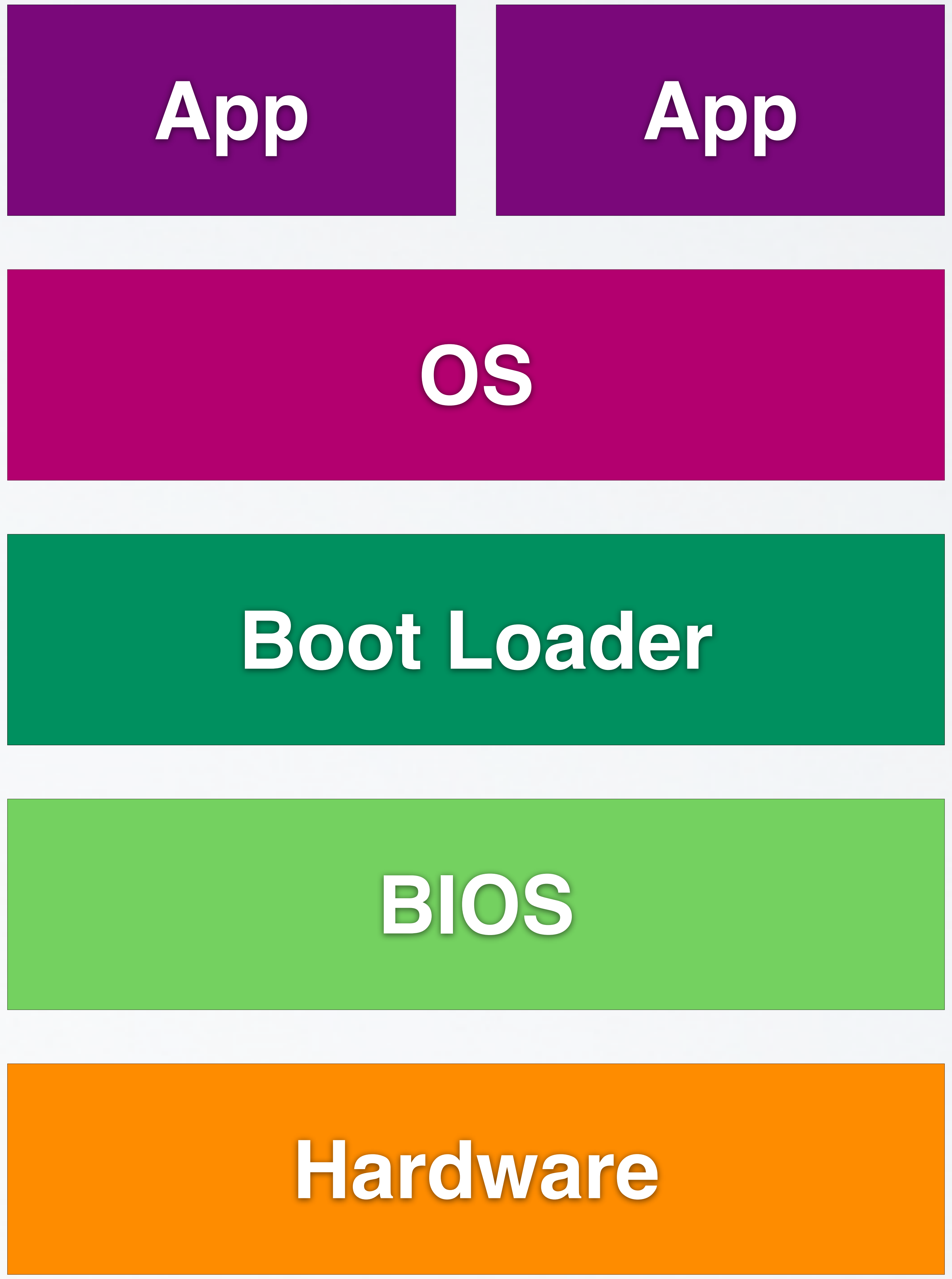
A SECOND LOOK AT THE CHAIN OF TRUST

CRTM

- When you press the power button ...
  - First code to be run: BIOS boot block (stored in ROM)
  - Starts chain of trust:
    - Initialize TPM
    - Hash BIOS into TPM
    - Pass control to BIOS
- **C**ore **R**oot of **T**rust for **M**easurement **(CRTM)**

CHAIN OF TRUST

- Discussed so far:
  - **CRTM** & chain of trust
  - How to make components in chain of trust smaller
- **Observation:** BIOS and boot loader only needed for booting
- **Question:** can chain of trust be shorter?

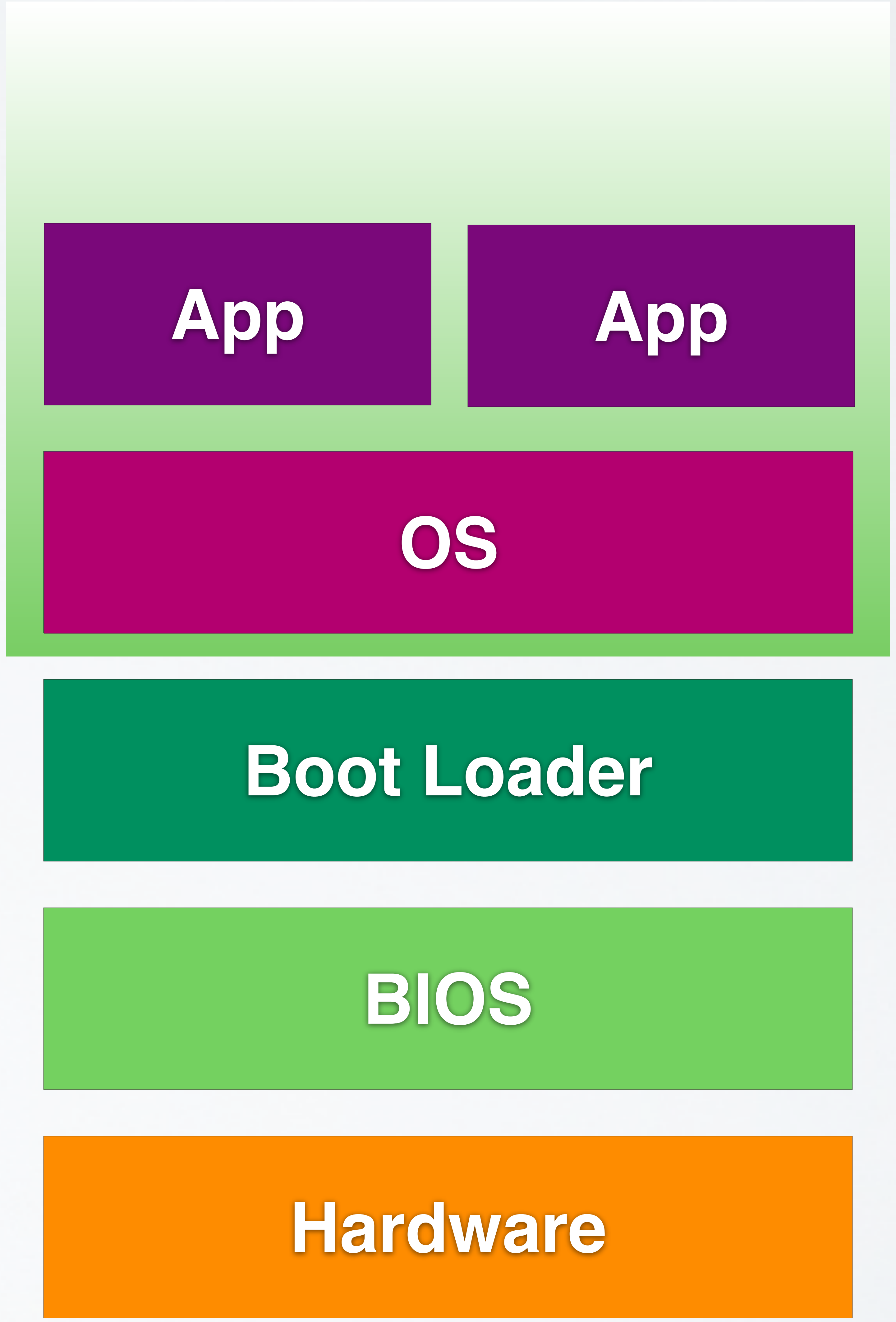


DRTM

- **CRTM** starts chain of trust early
- **D**ynamic **R**oot of **T**rust for **M**easurement (**DRTM**) starts it late:
    - Special CPU instructions (AMD: skinit, Intel: senter)
    - Put CPU in known state
    - Measure small „secure loader“ into TPM
    - Start „secure loader“
- **DRTM**: Chain of trust can start anywhere

DRTM BOOTLOADER

- Simple: **DRTM** put right below OS
- Smaller TCB:
  - Large and complex BIOS / boot loader removed
  - Small and simple **DRTM** bootstrapper added
- Open Secure Loader **OSLO**: **1,000** SLOC, **4KB** binary size [6]



DRTM CHALLENGES

- DRTM remove boot software from TCB
- Key challenges:
  - „Secure loader“ must not be compromised
  - Requires careful checking of platform state
  - Secure loader must actually run in locked RAM, not in insecure device memory
- DRTM can also run <u>after</u> booting OS

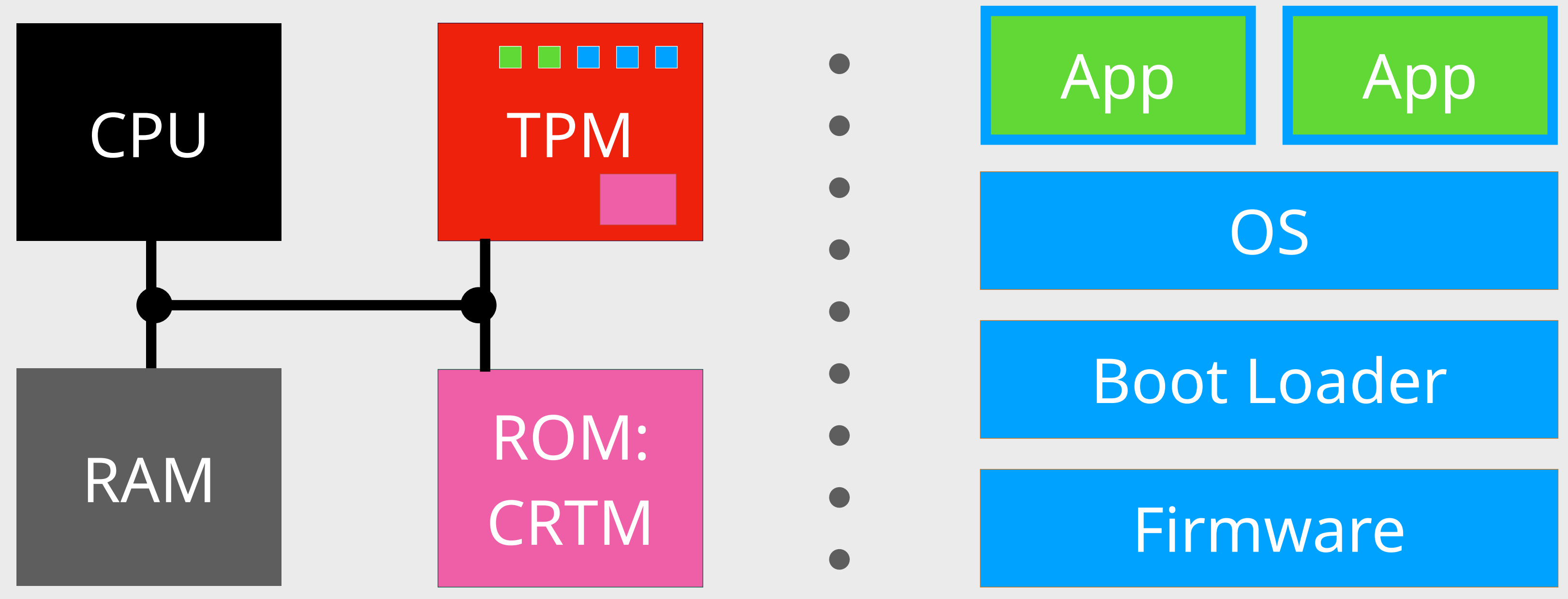
BEYOND THE TRUSTED PLATFORM MODULE

MOBILE DEVICES

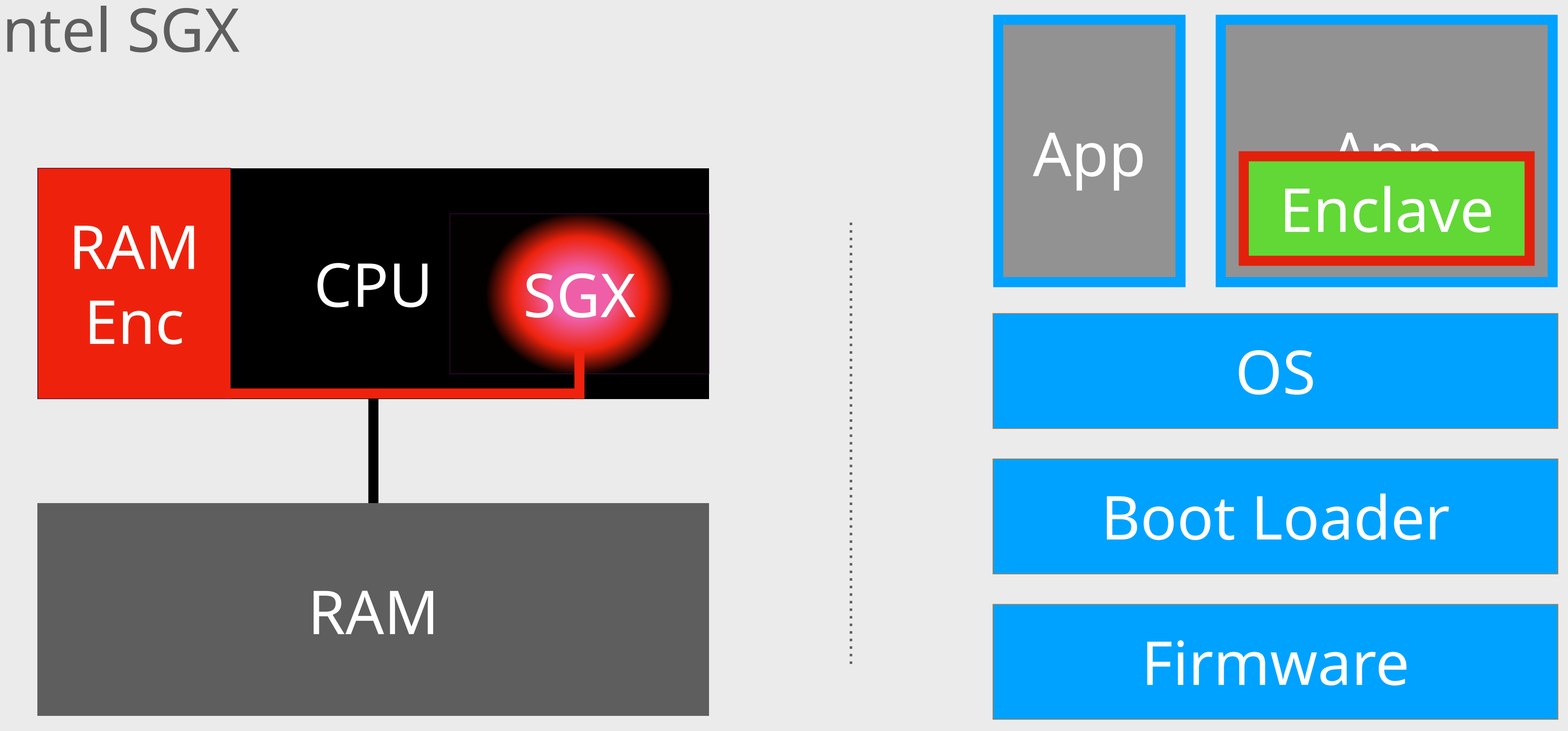
- Simple implementations in smartphones, etc.
  - Non-modifiable boot ROM loads OS
  - OS is signed with manufacturer key, checked by ROM-based boot loader
  - Small amount of flash integrated into SoC
  - Cryptographic co-processor: software can use (but not obtain) encryption and signature keys
- Not open: **closed** or **secure boot** instead of **authenticated booting**

THERE'S MORE ...

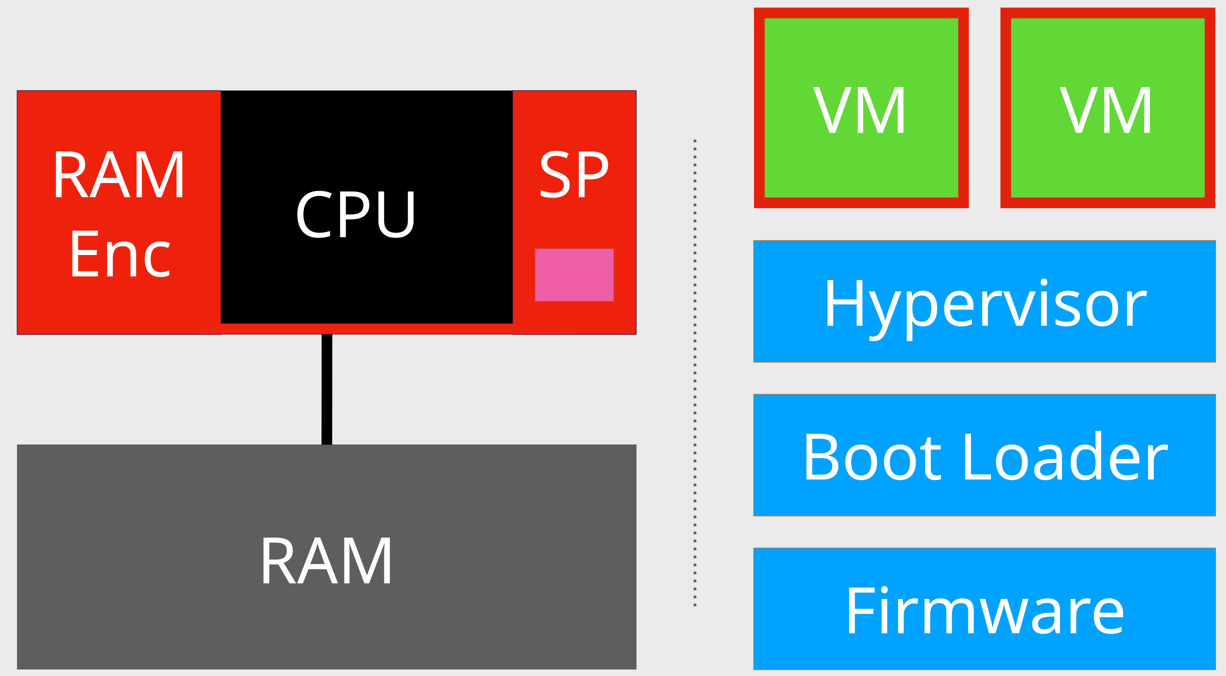
Trusted Computing Group: TPM



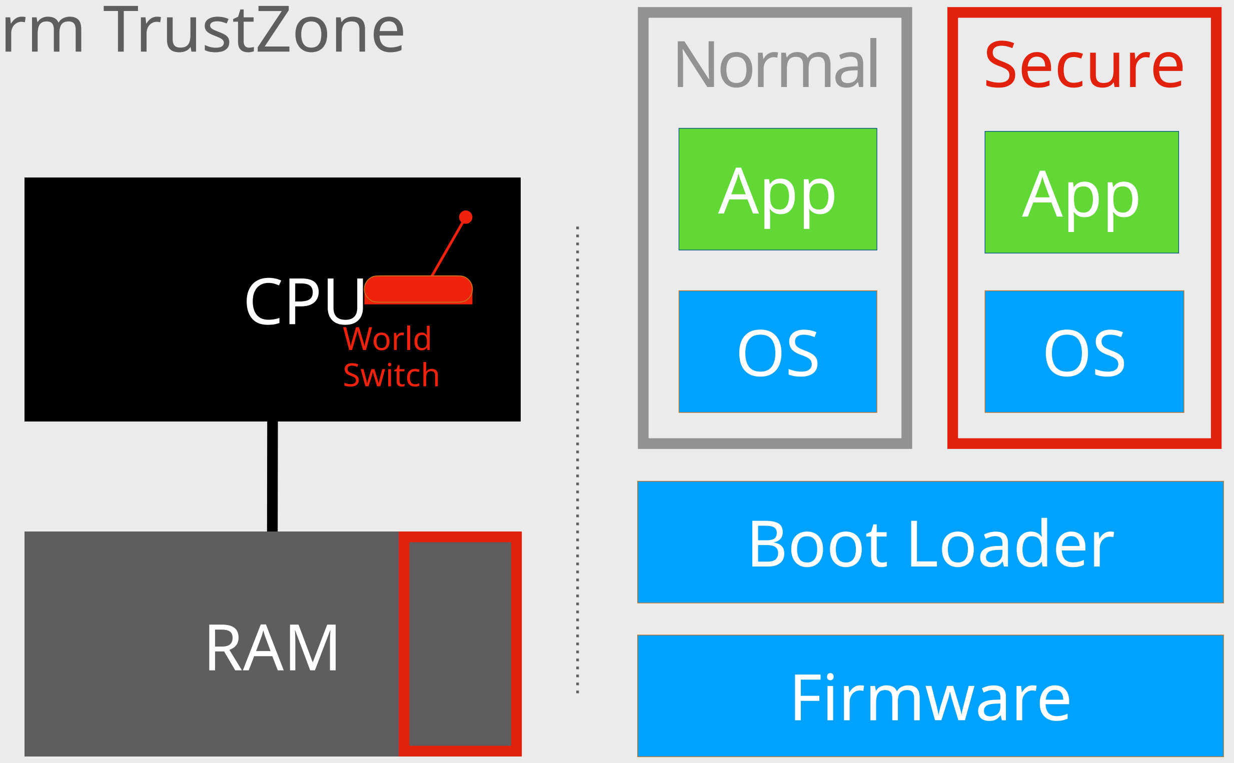
Intel SGX



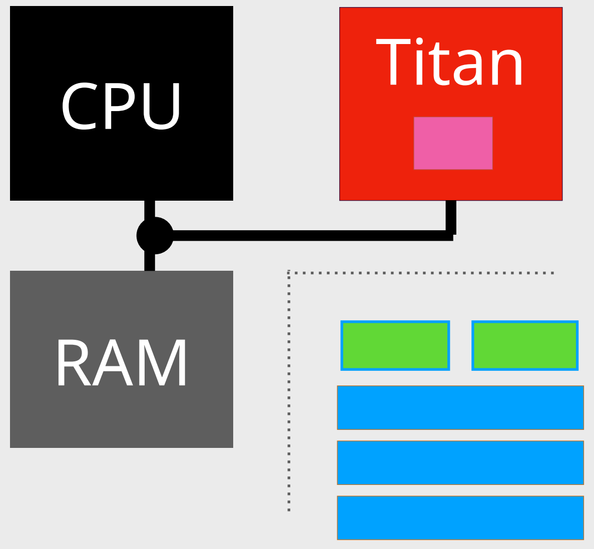
AMD SEV / SEV-ES / SEV-SNP



Arm TrustZone



Google Titan



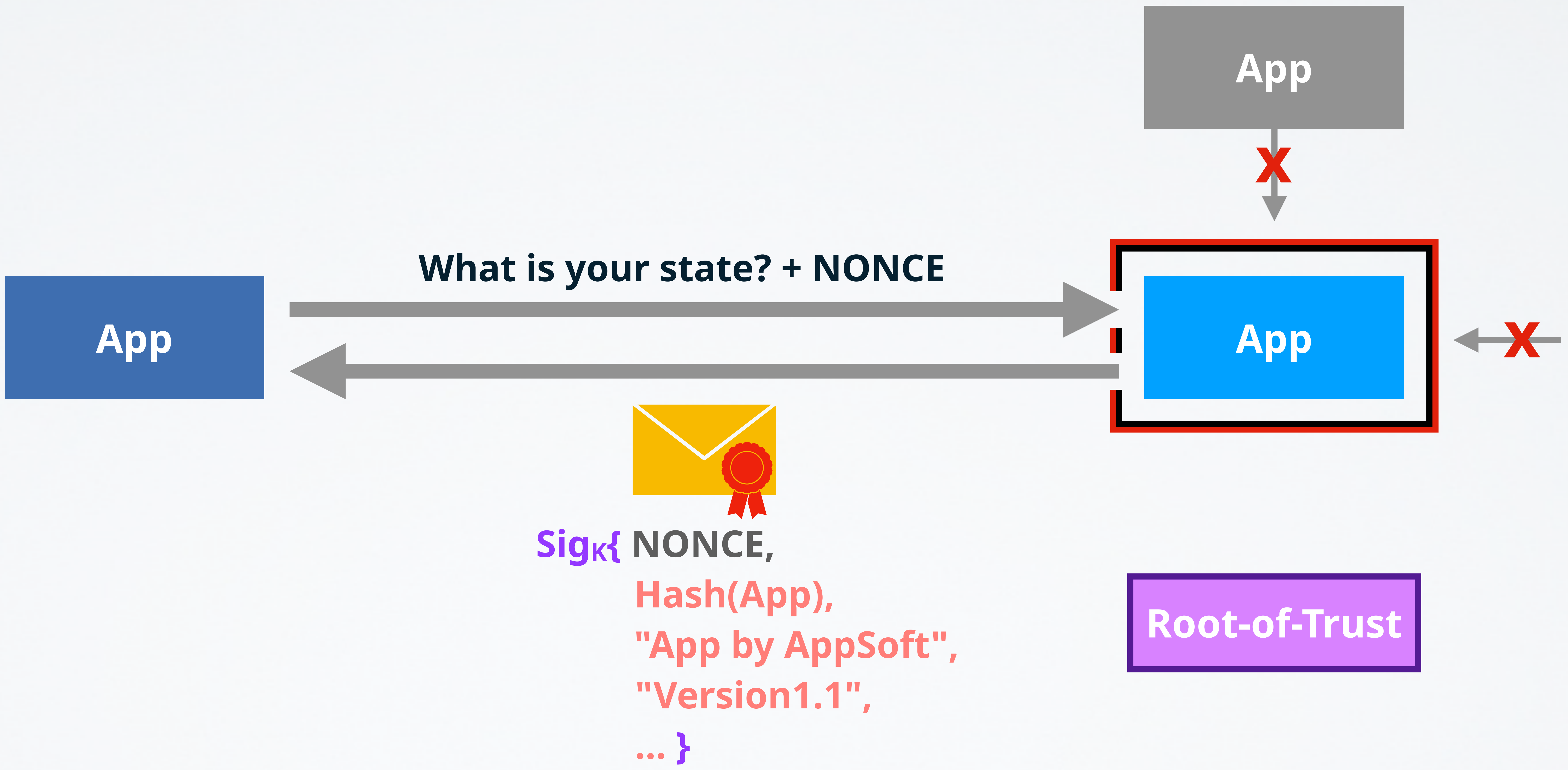
opentitan.org

… AND EVEN MORE

- Intel TDX: 4th Gen Xeon Scalable Processors
- Arm Confidential Compute Architecture (CCA) (introduced with Armv9)
- TPM support in VMs
  - Software TPM: libtpms + SWTPM
  - SWTPM runs as process outside VM
  - SWTPM identity linked to hardware TPM

WHAT IS A TRUSTED EXECUTION ENVIRONMENT?

WHAT IS A TEE?

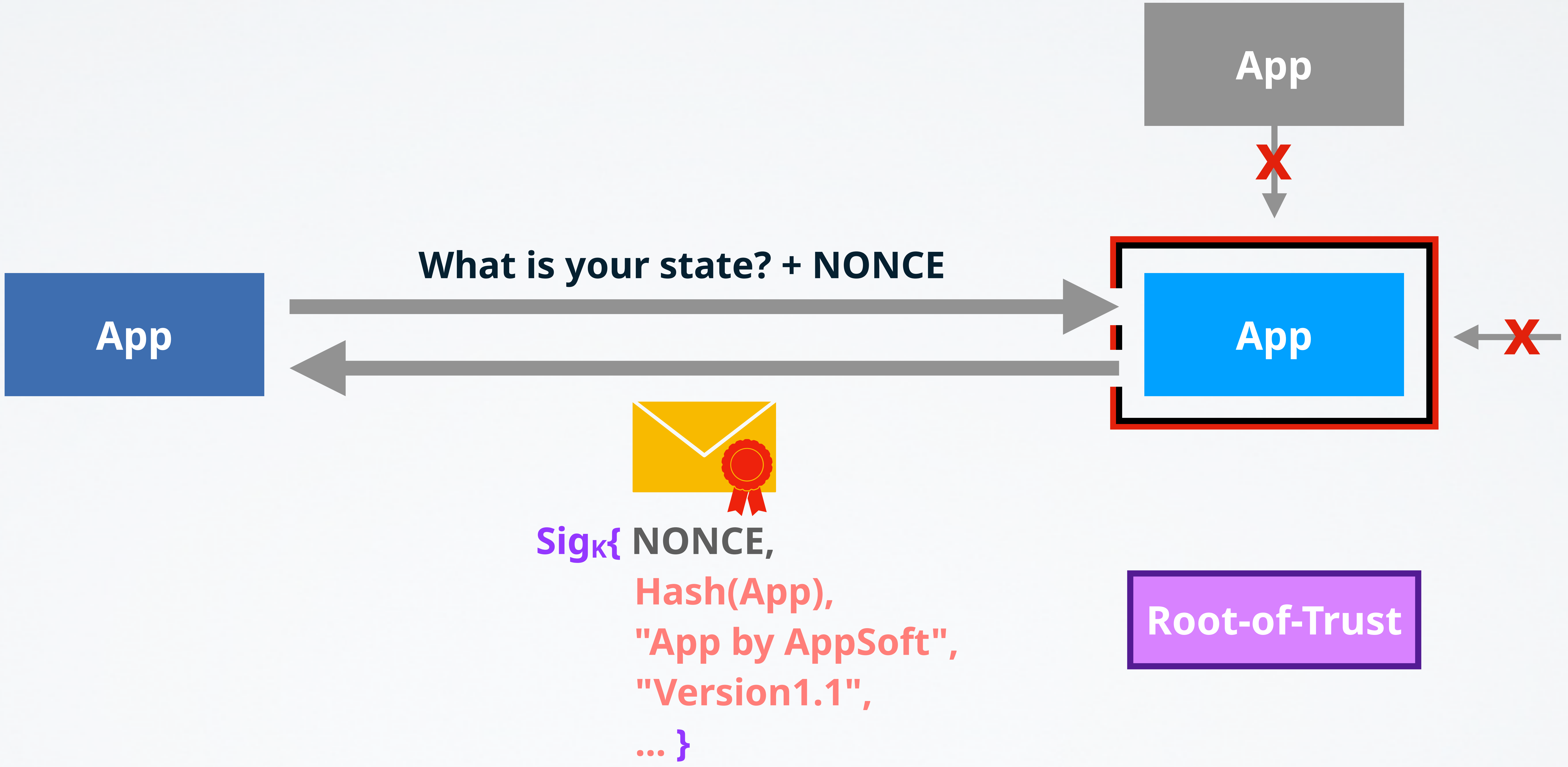

App
App
What is your state? + NONCE
App
Sig_K{ NONCE,
Hash(App),
"App by AppSoft",
"Version1.1",
... }
Root-of-Trust

WHAT YOU CAN BUY

There are many TEEs, but there is not much choice:

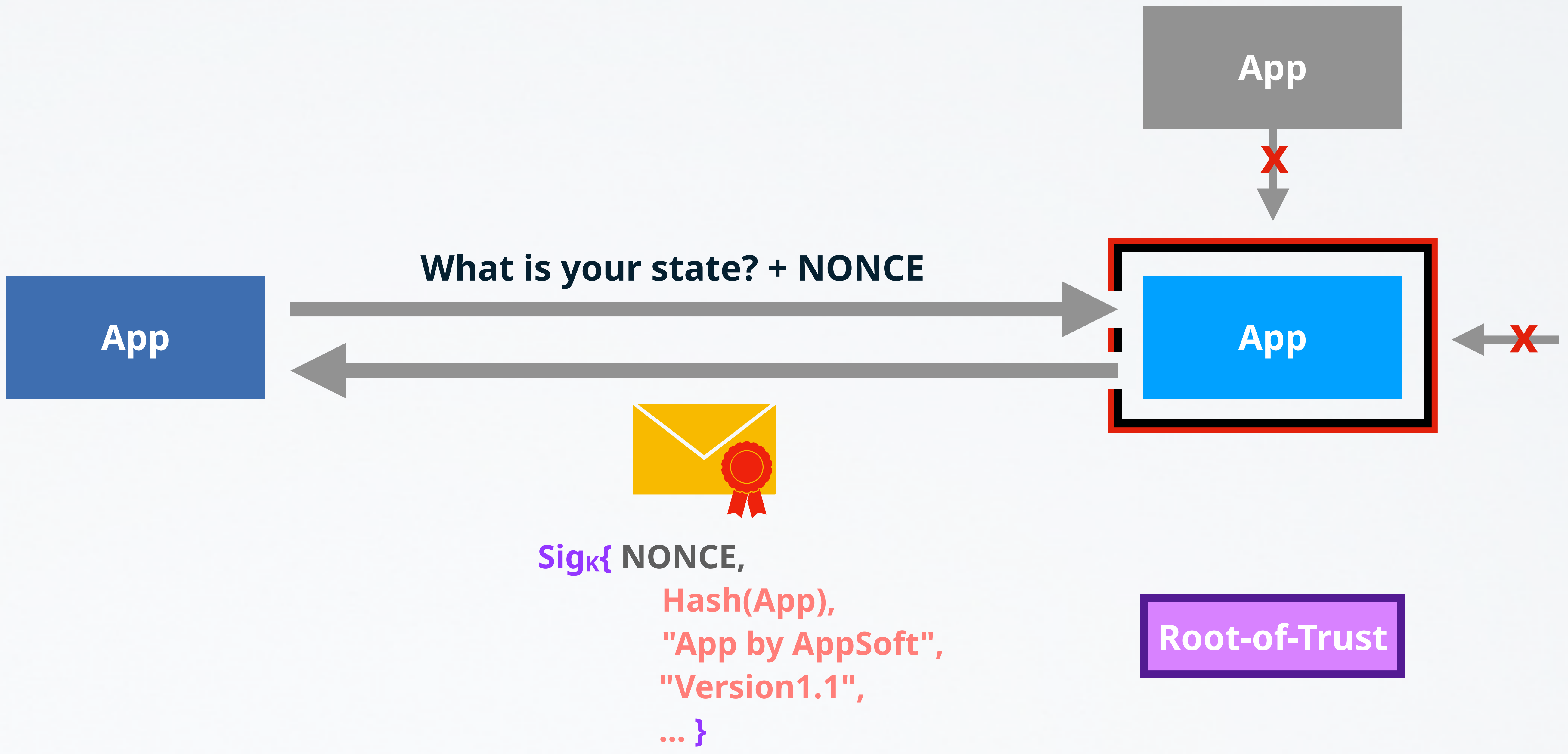
- TEE and ISA cannot be chosen independently
- TEE implementation deeply integrated with core microarchitecture
- TEEs lack "good" integration with system software

WHAT IS A TEE?


App
App
What is your state? + NONCE
App
X
X
Sig$_K${ NONCE,
Hash(App),
"App by AppSoft",
"Version1.1",
... }
Root-of-Trust

TEE CONCERNS

- Computation
- Measurement
- Root of Trust
- Isolation
- Management
- Environment



MONOLITHIC TEE

Environment

Management

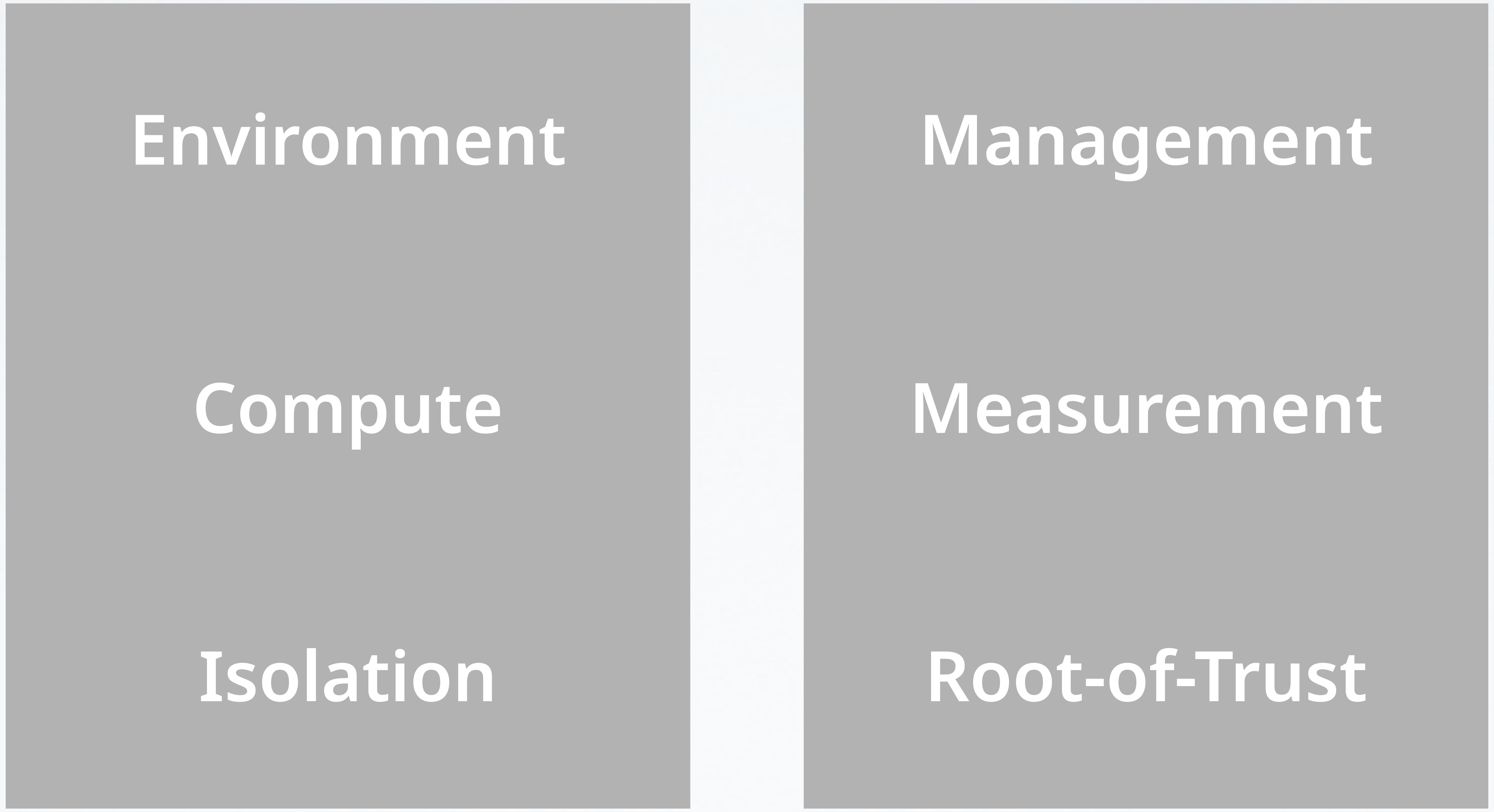
Compute

Measurement

Isolation

Root-of-Trust

SPLIT TEE?



Environment

Compute

Isolation

Management

Measurement

Root-of-Trust

SPLIT TEE?

Environment

Management

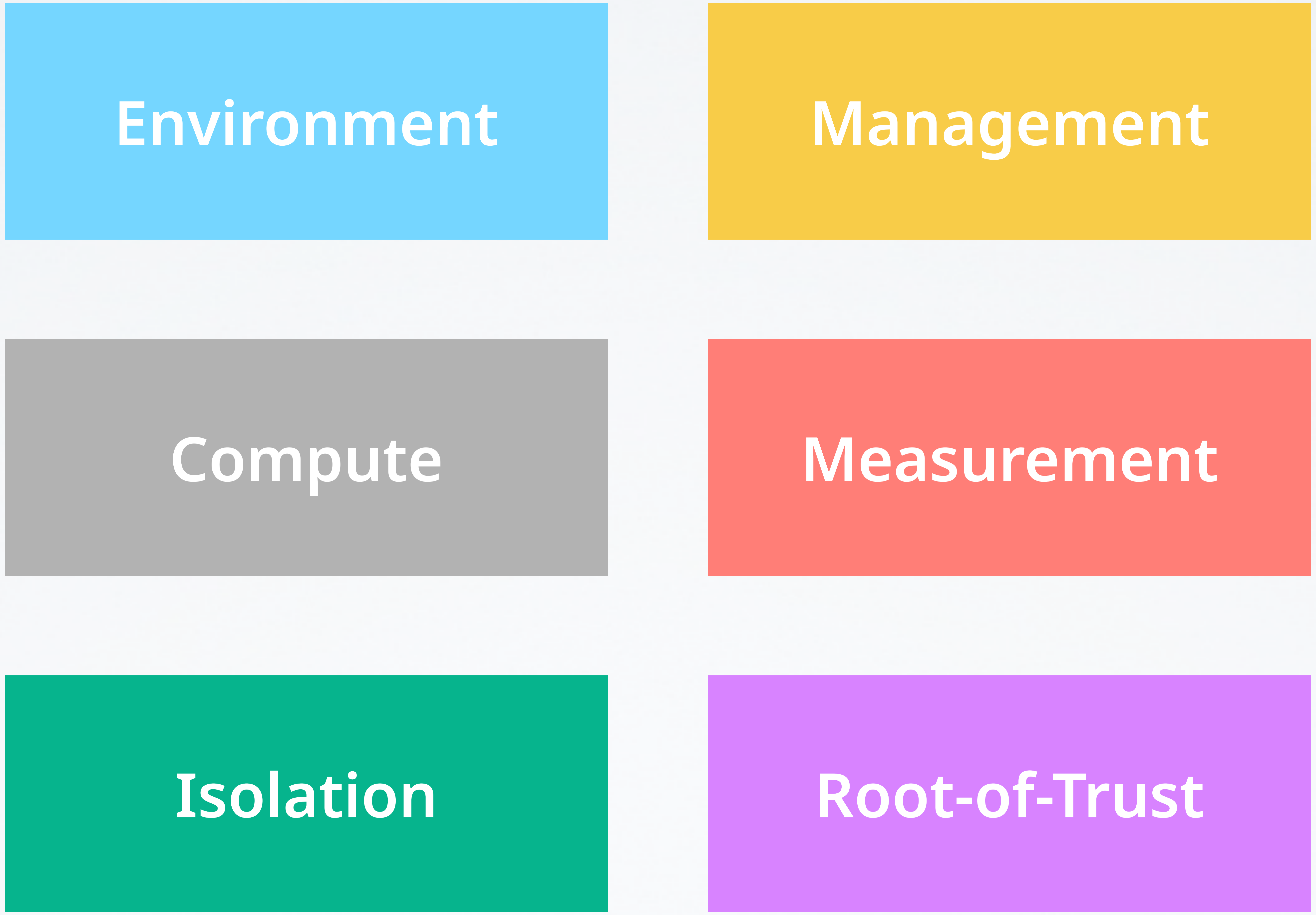
Compute

Measurement

Isolation

Root-of-Trust

MODULAR TEE?



Environment

Management

Compute

Measurement

Isolation

Root-of-Trust

[10]

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