TECHNISCHE UNIVERSITÄT DRESDEN

Department of Computer Science Institute of System Architecture, Operating Systems Group

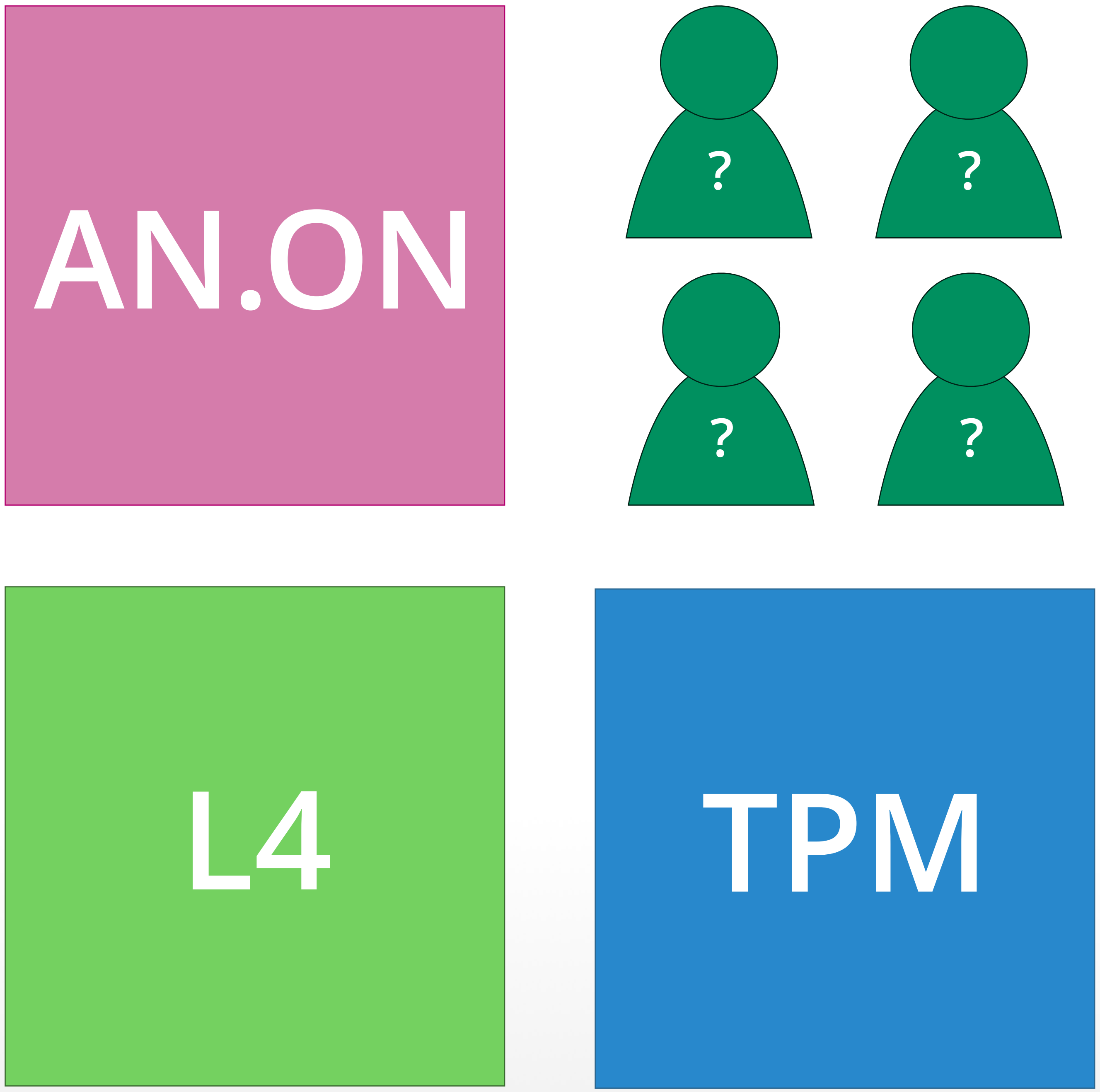
TRUSTED COMPUTING

CARSTEN WEINHOLD

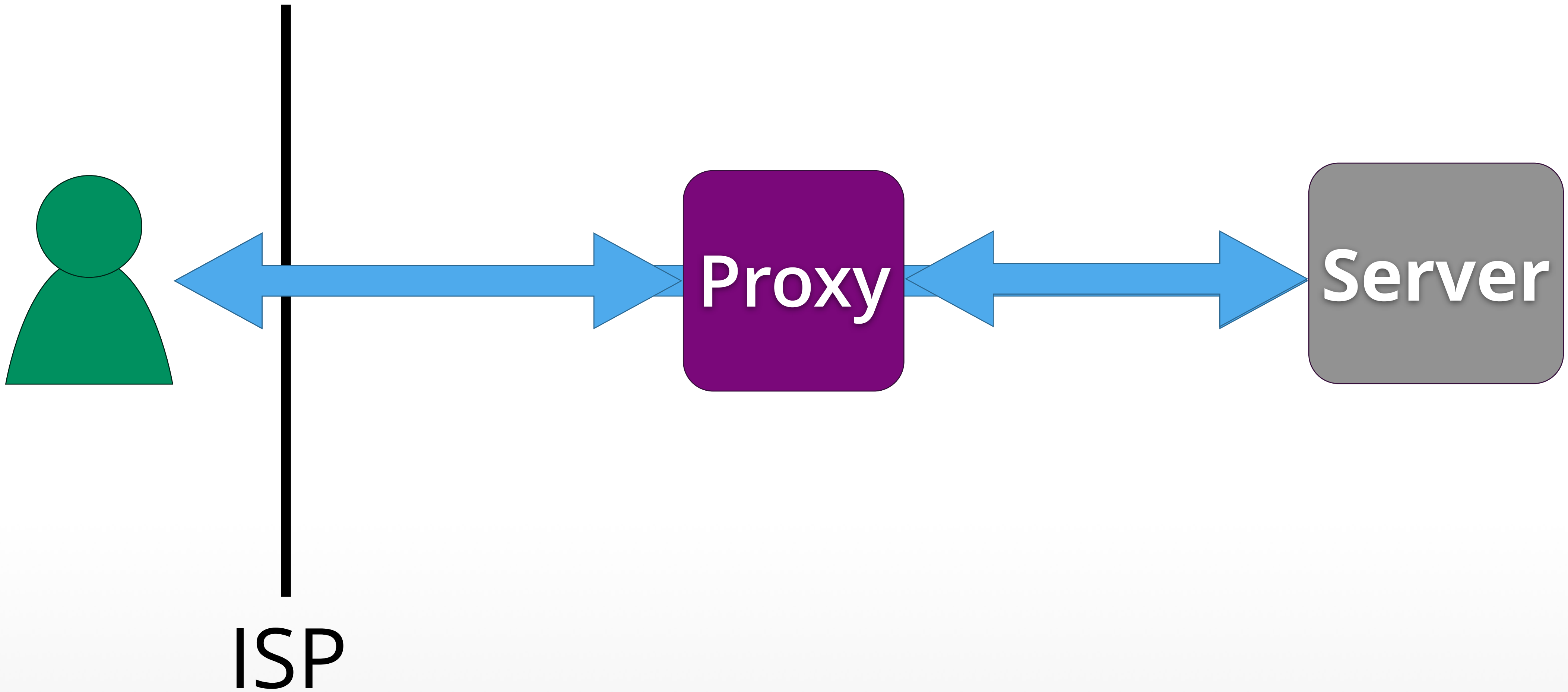
THIS LECTURE ...

- **Today: Trusted Computing Technology**
  - Lecture discusses basics in context of TPMs
  - 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

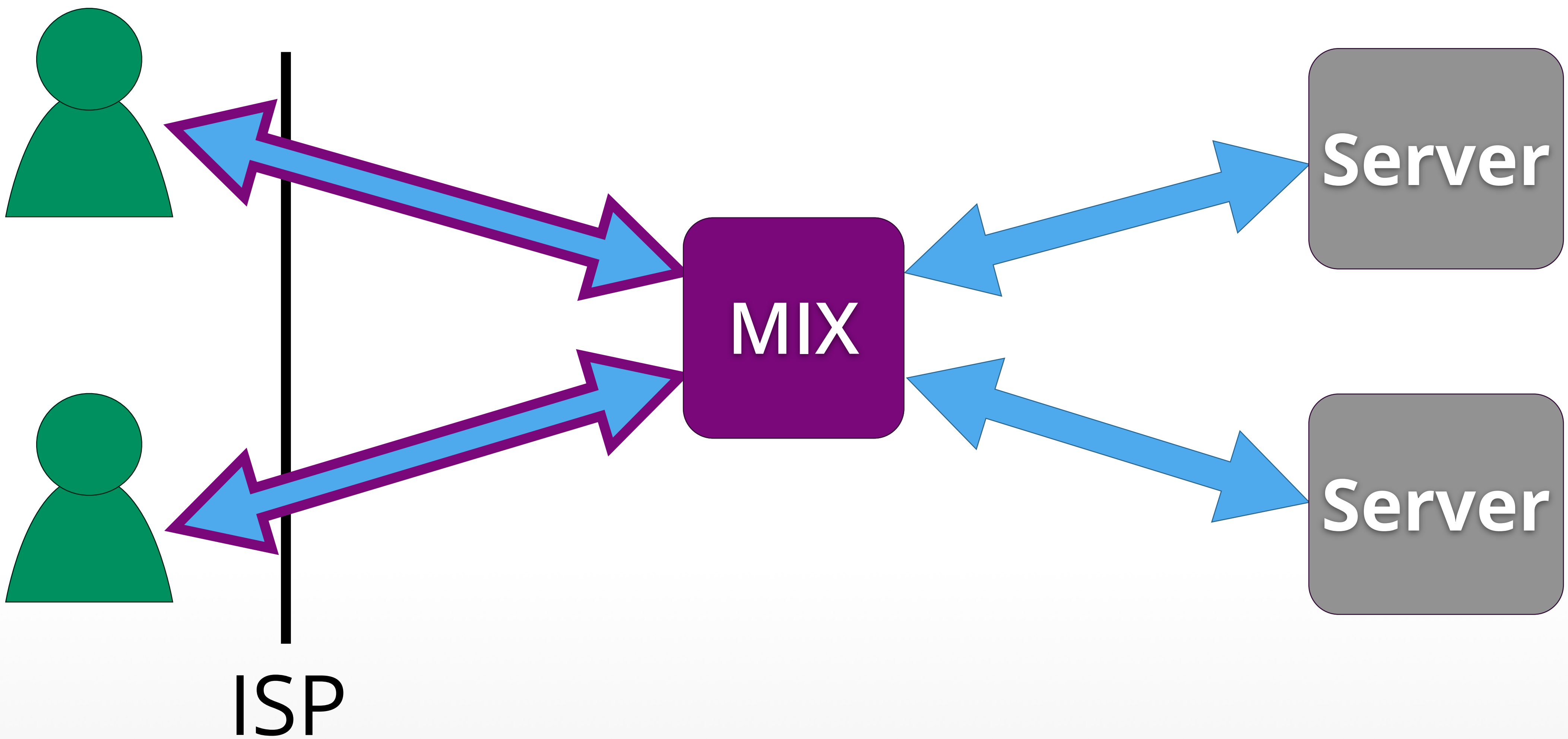
INTRODUCTION



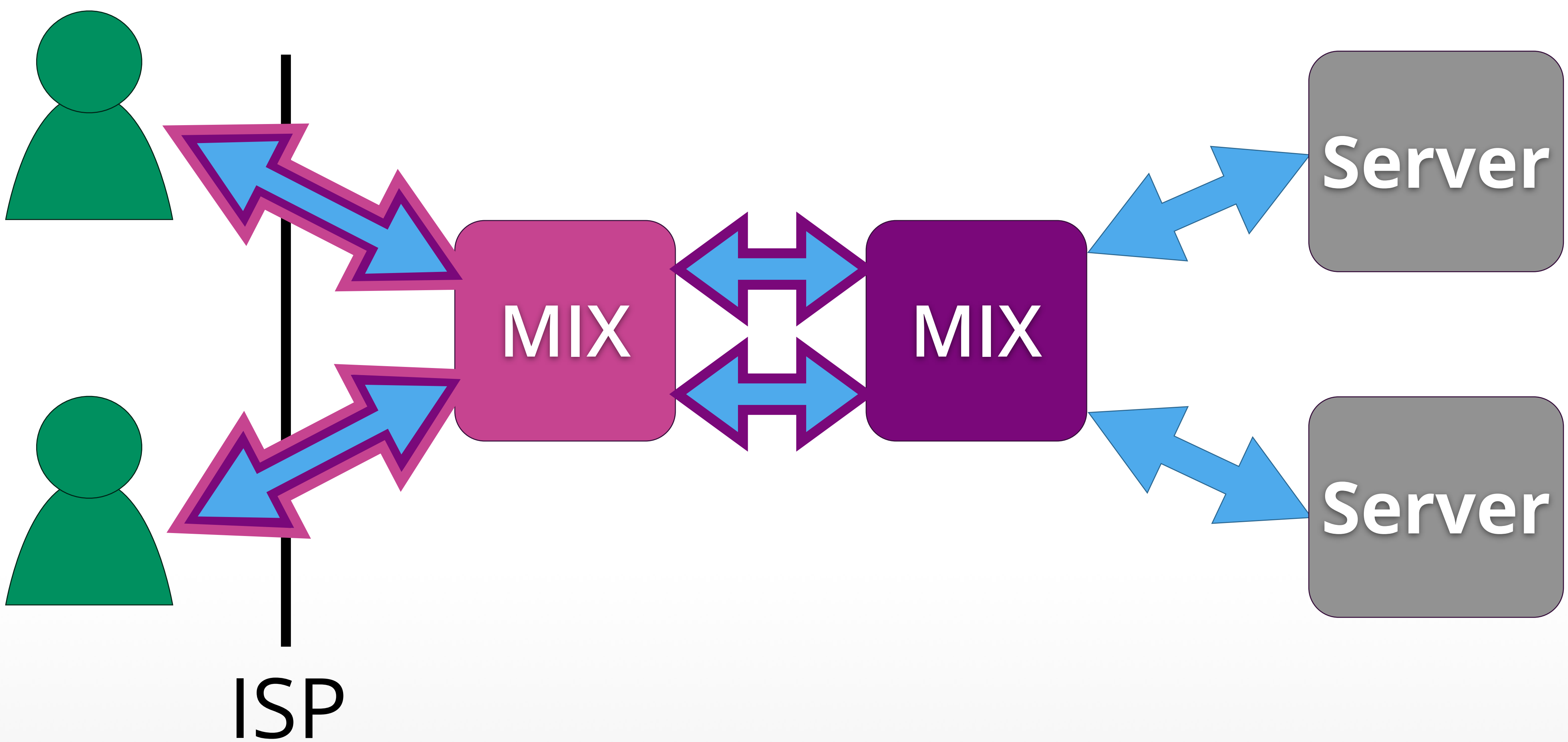
ANONYMITY



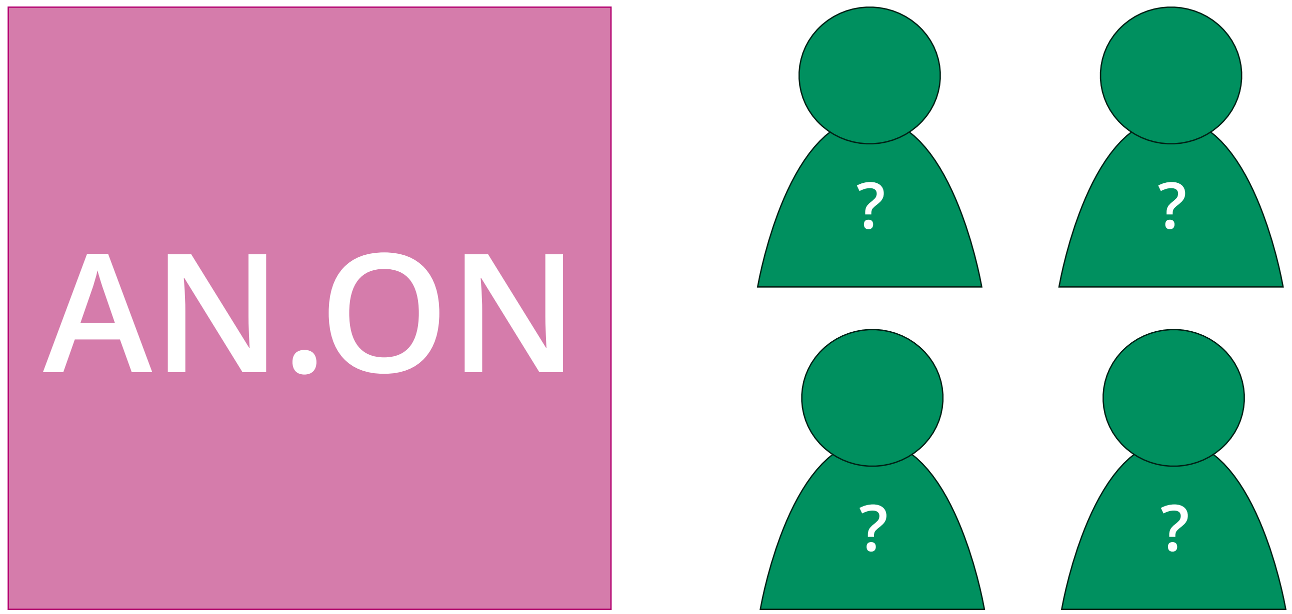
ANONYMITY

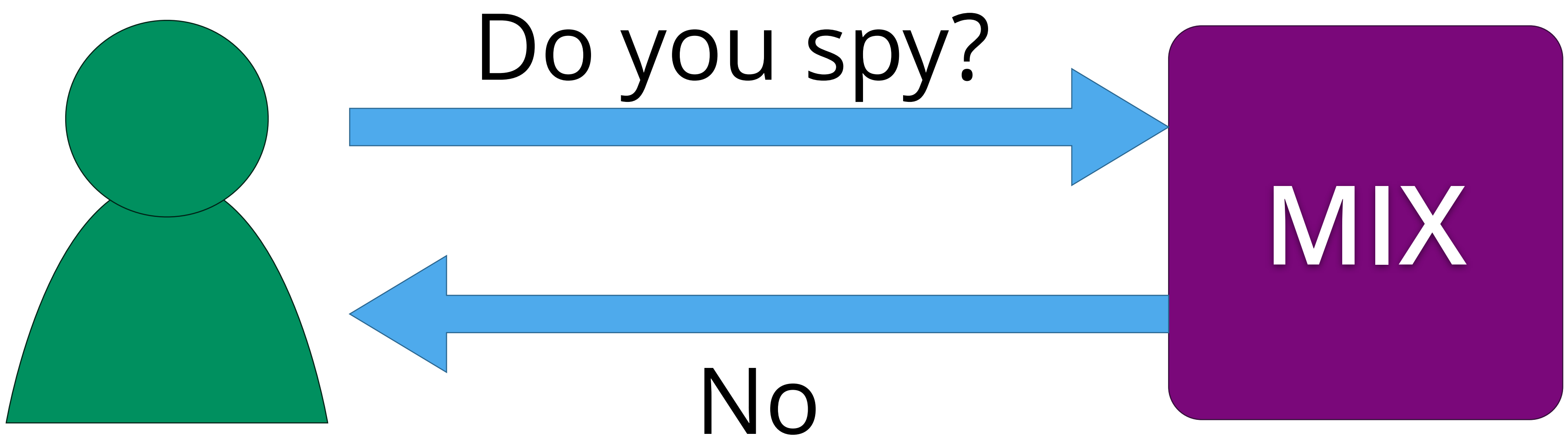


ANONYMITY

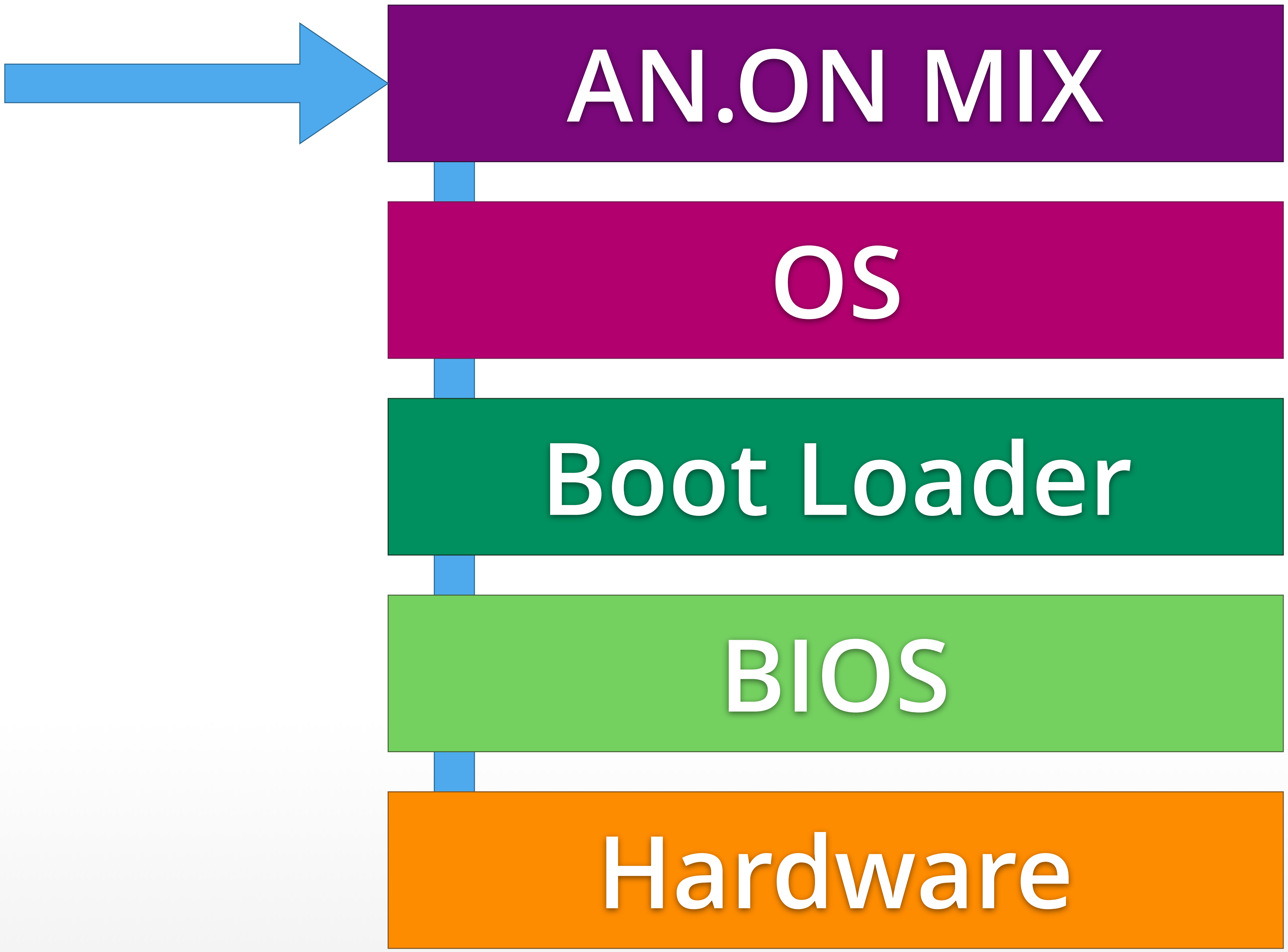


ANONYMITY




Do you spy?
MIX
No

SYSTEM LAYERS

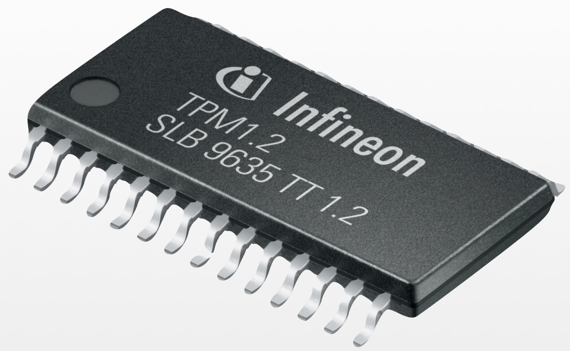


TPM

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

Platform Configuration Register

$$\mathrm{PCR} := \text{SHA-1}(\ \mathrm{PCR}\ |\ \mathbf{X}\ )$$



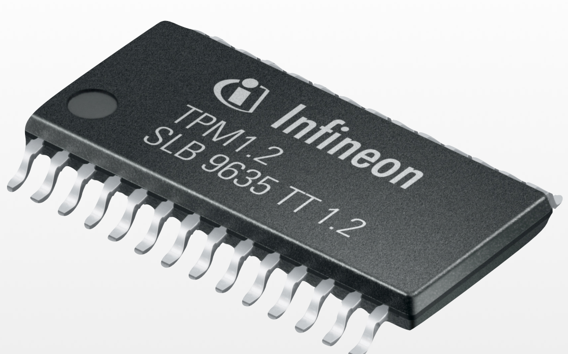
BOOTING + TPM

AN.ON MIX

OS

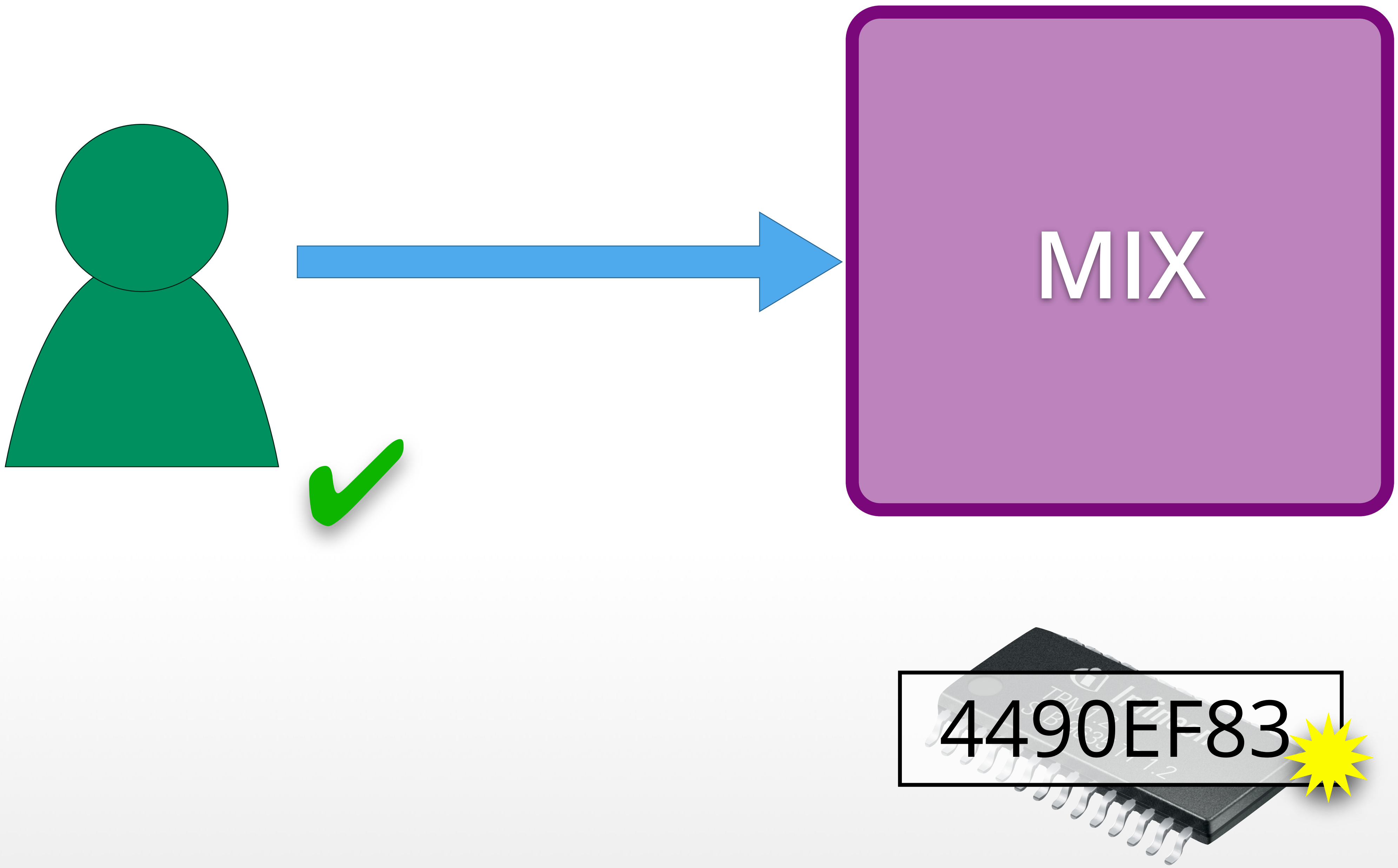
Boot Loader

BIOS

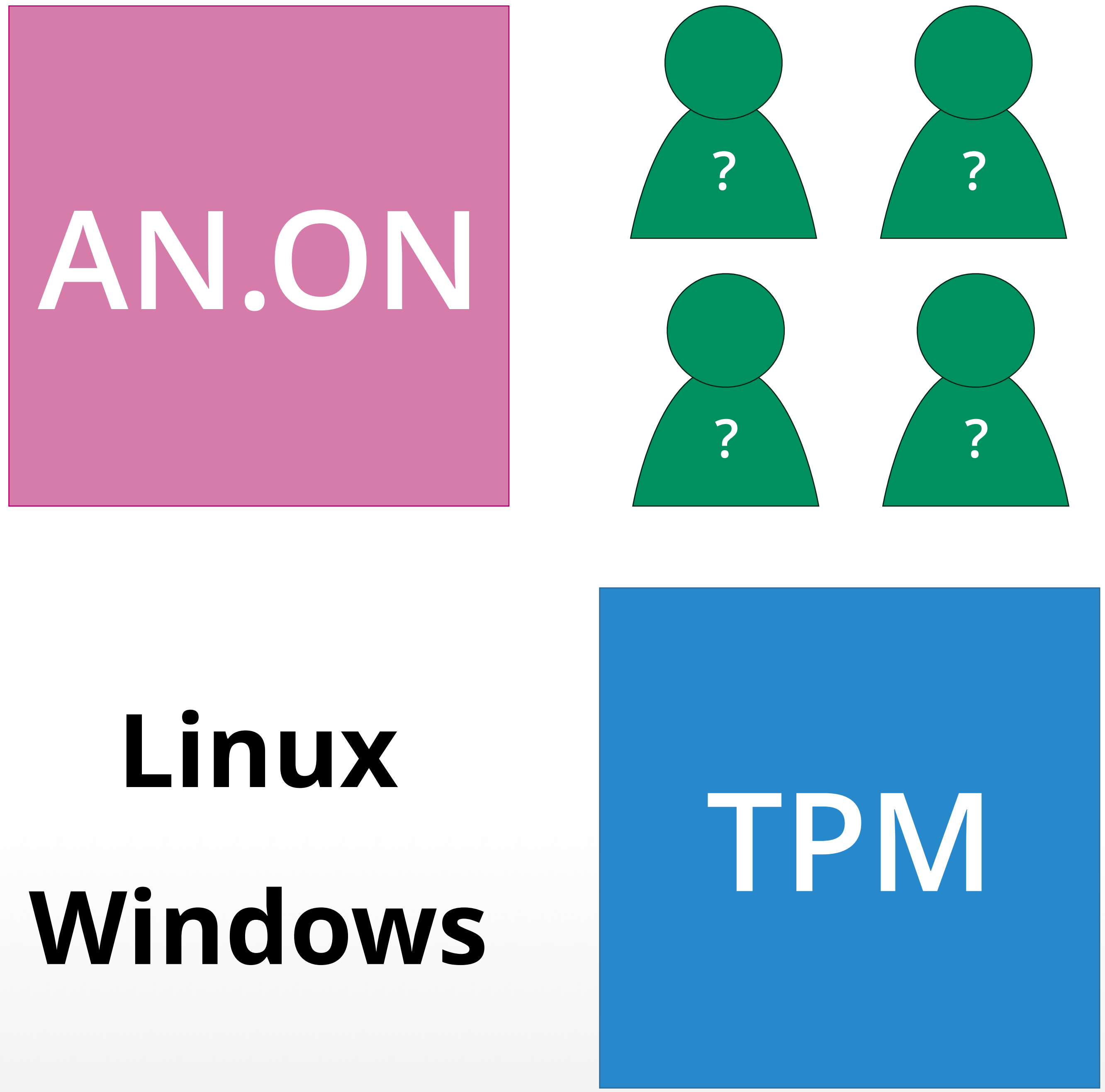


PCR 4490EF83

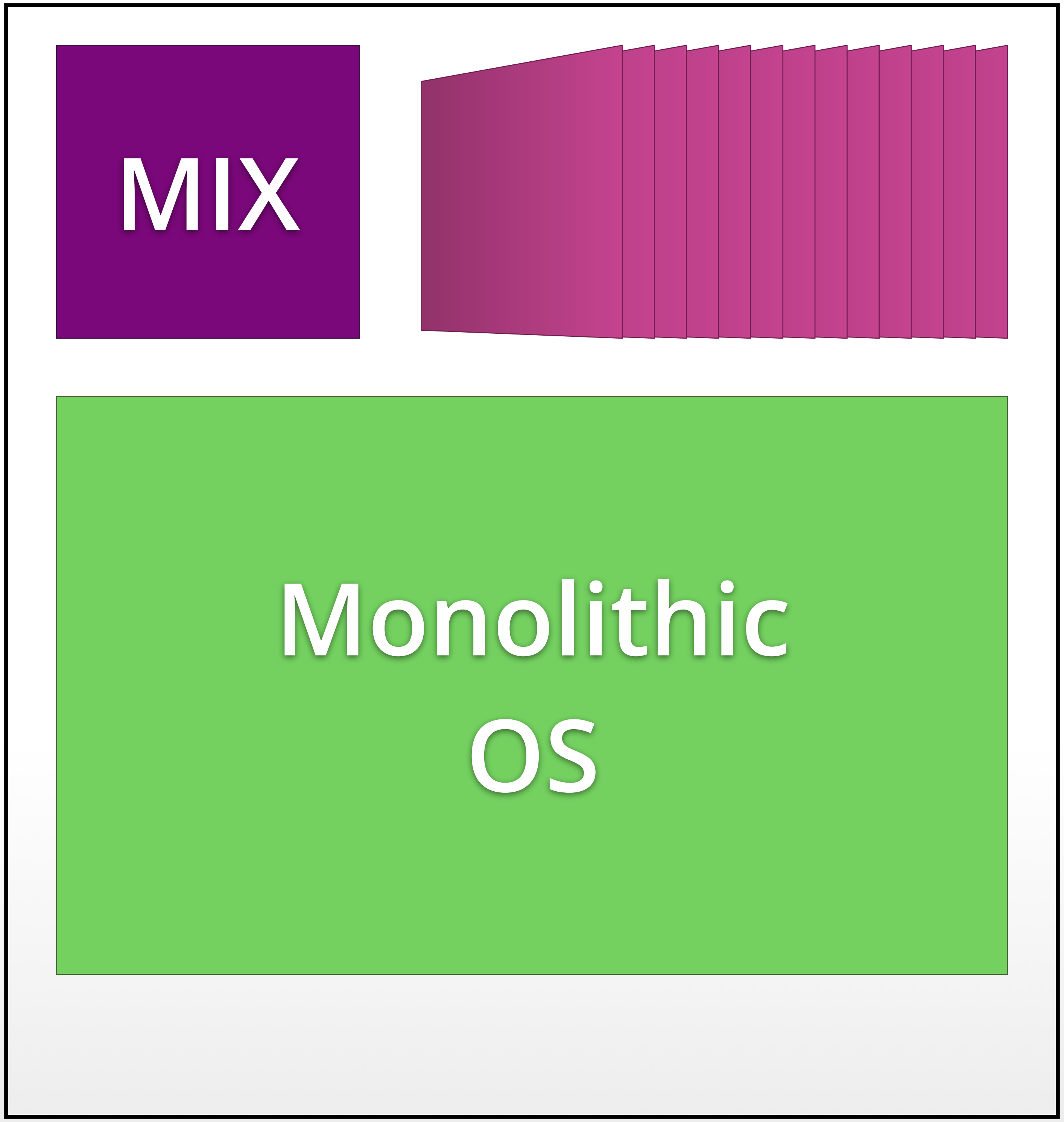
Remote Attestation



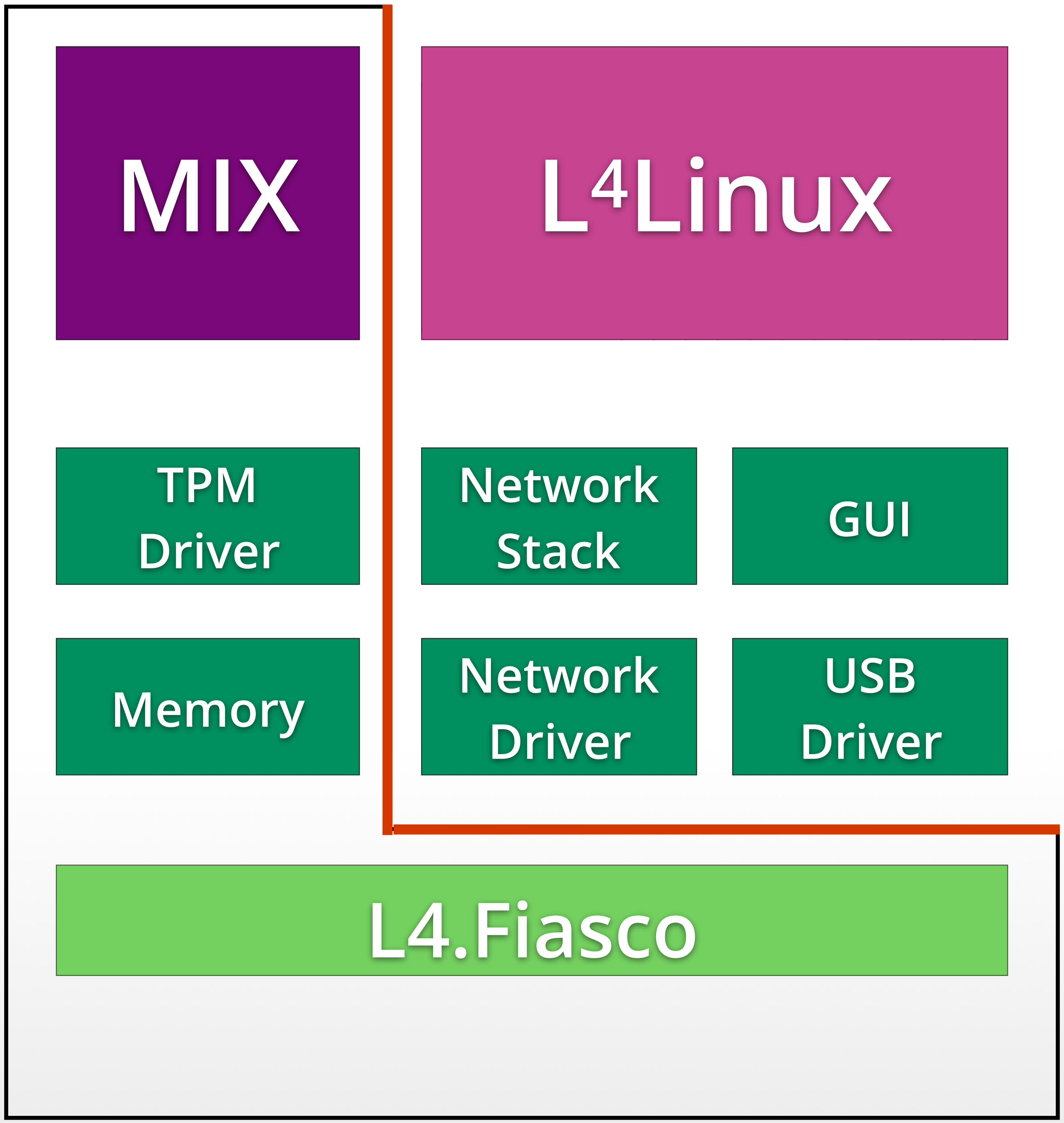
ARCHITECTURE

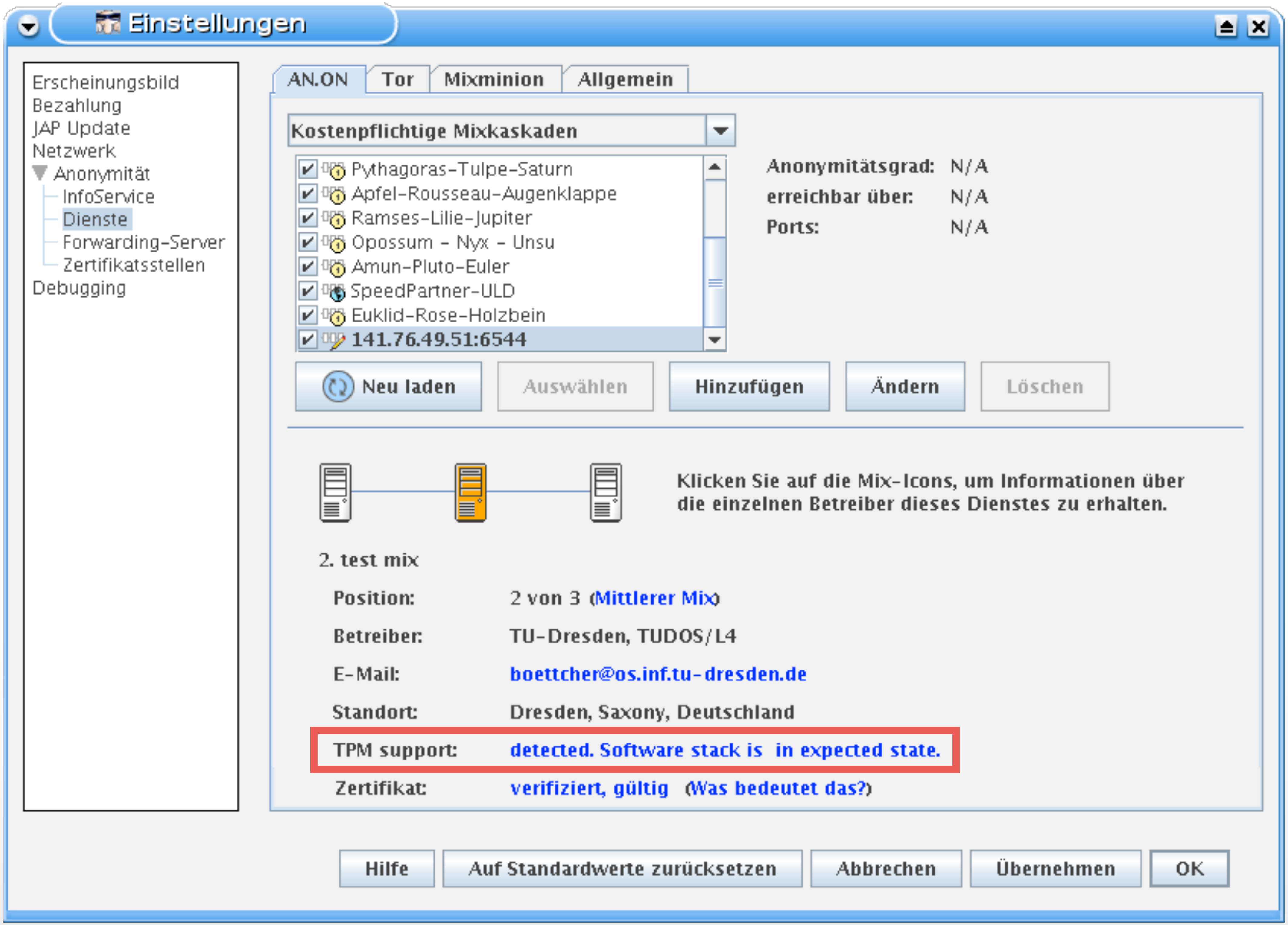


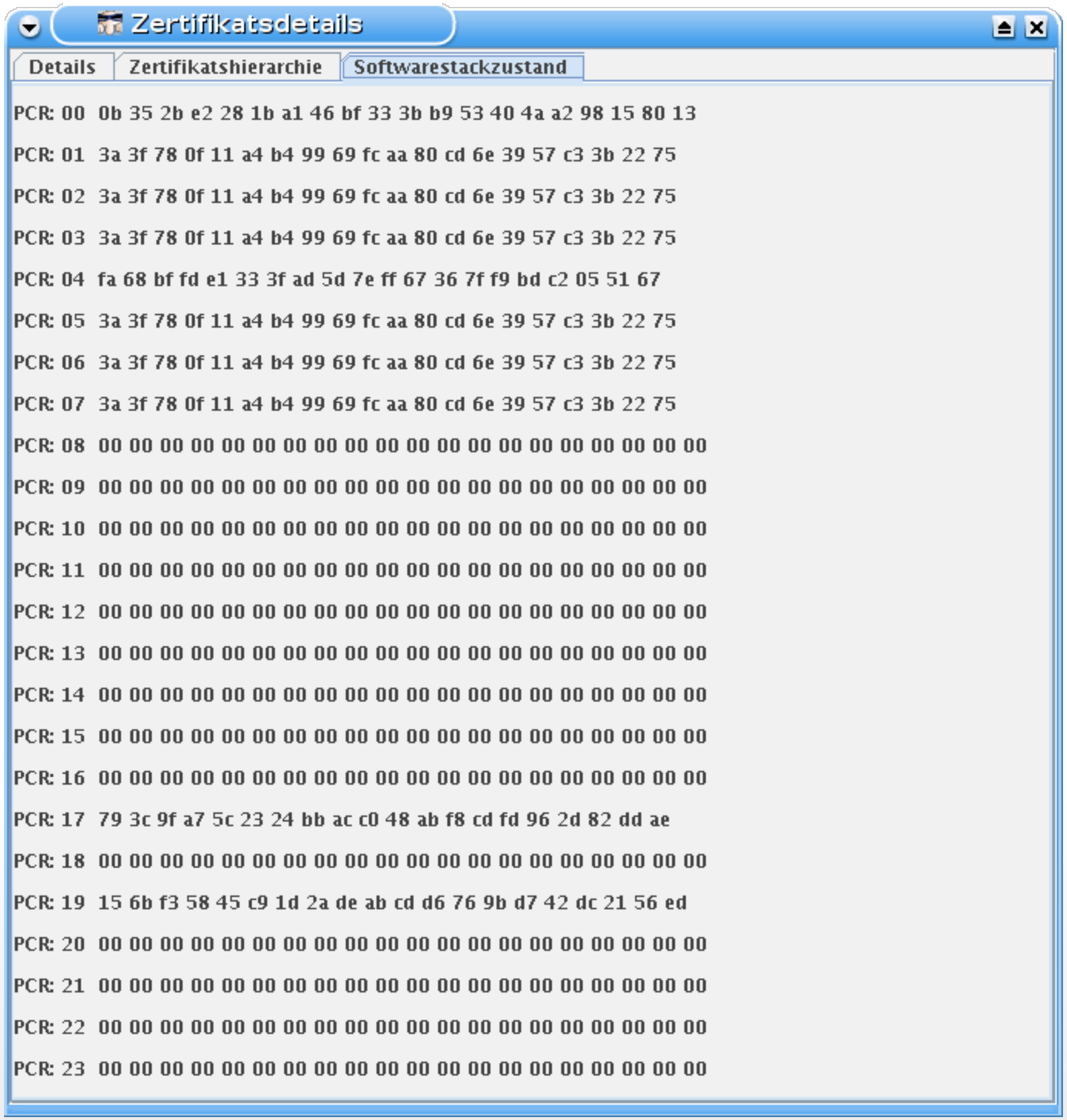
MONOLITHIC



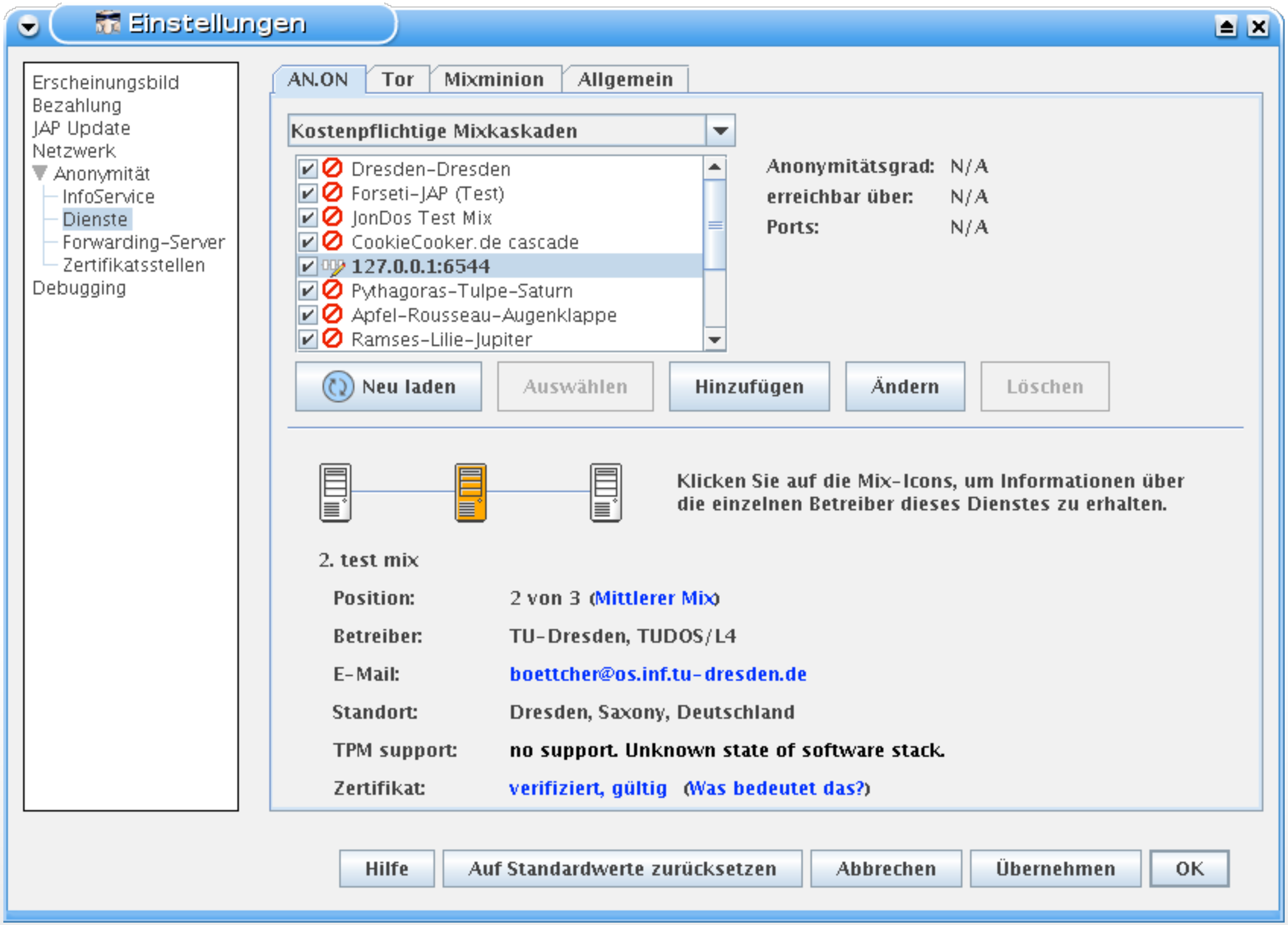
L4/AN.ON


MIX
L⁴Linux
TPM Driver
Network Stack
GUI
Memory
Network Driver
USB Driver
L4.Fiasco


Einstellungen
Erscheinungsbild
Bezahlung
JAP Update
Netzwerk
Anonymität
InfoService
Dienste
Forwarding-Server
Zertifikatsstellen
Debugging
AN.ON
Tor
Mixminion
Allgemein
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
Neu laden
Auswählen
Hinzufügen
Ändern
Löschen
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?)
Hilfe
Auf Standardwerte zurücksetzen
Abbrechen
Übernehmen
OK


Zertifikatsdetails
Details
Zertifikatshierarchie
Softwarestackzustand
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
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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
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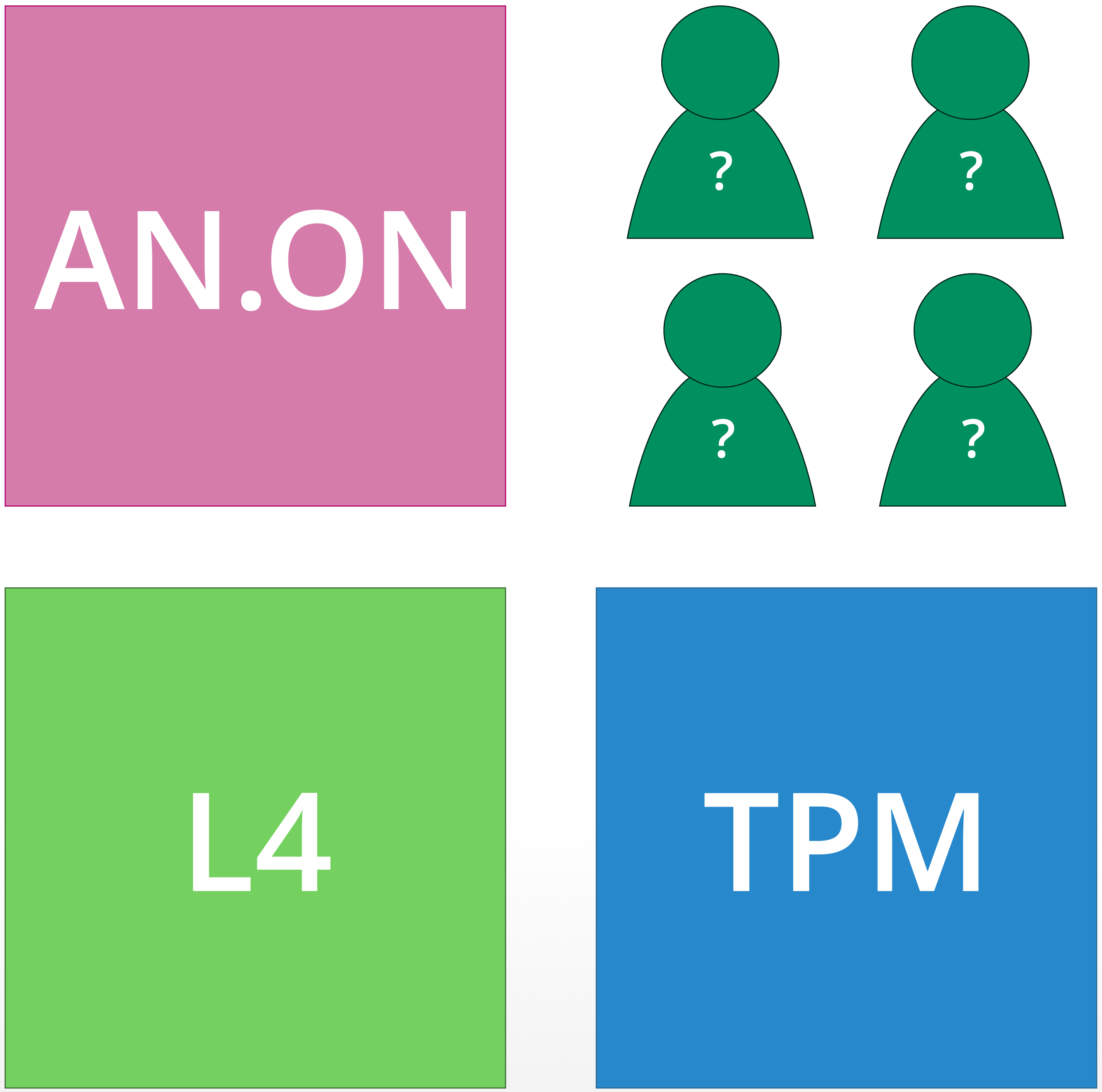

AN.ON
?
?
?
?
L4
TPM

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 8/10/RT tablets

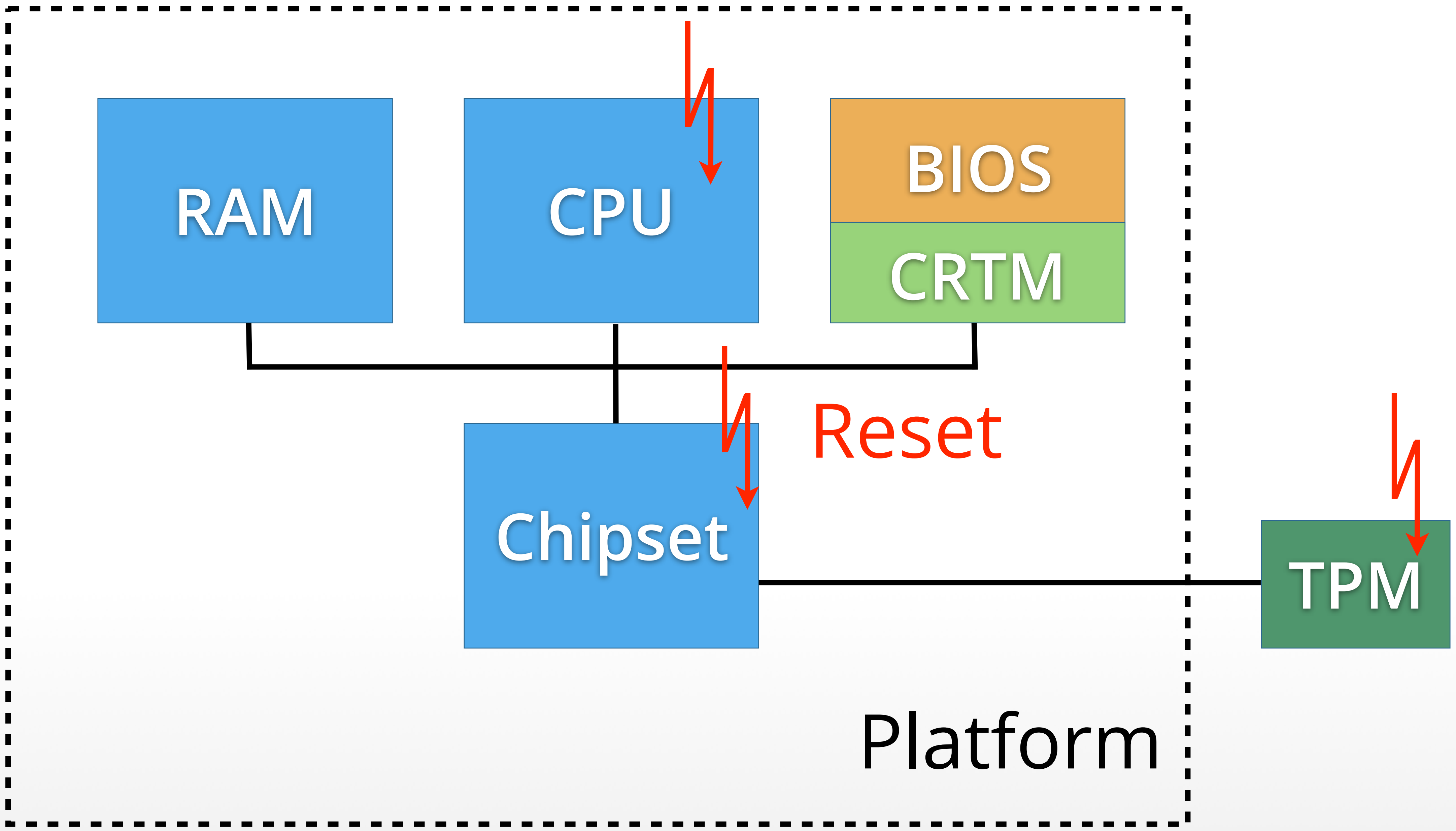
TPM OVERVIEW

- TPM is cryptographic coprocessor:
  - **RSA** (encryption, signatures), **AES** (encryption), **SHA-1** (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



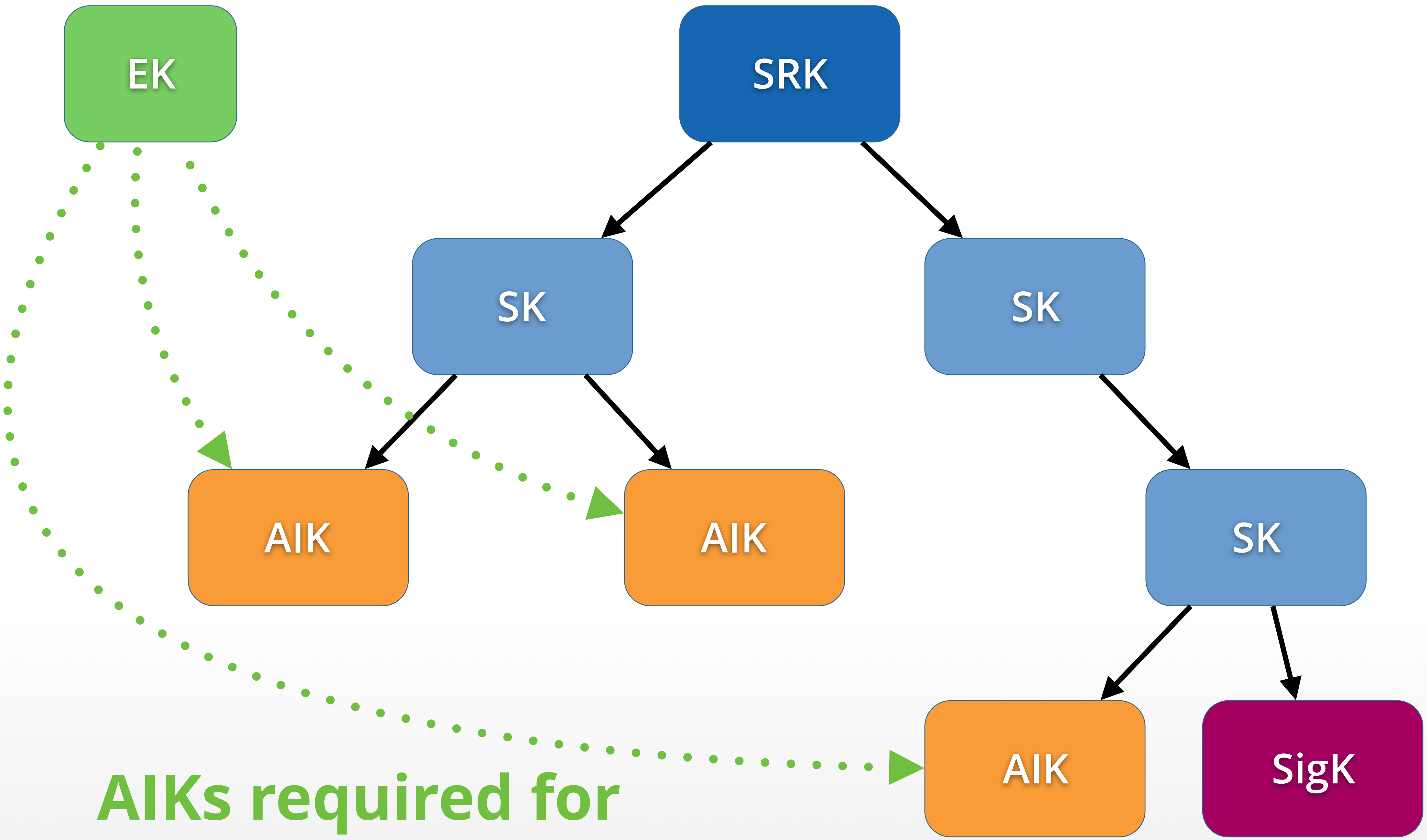
TPM IDENTITY

- 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**, 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

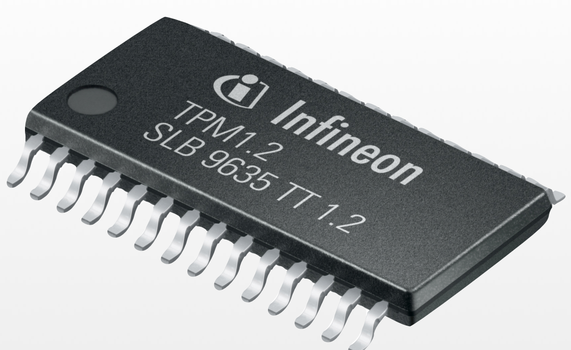
Application

OS

Boot Loader

BIOS

Authenticated Booting



PCR $\boxed{4490EF83}$

AIKS & QUOTES

TPM_Quote(AIK, Nonce, PCR)

Challenger

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 <u>only if</u> **PCR** values <u>match</u>

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

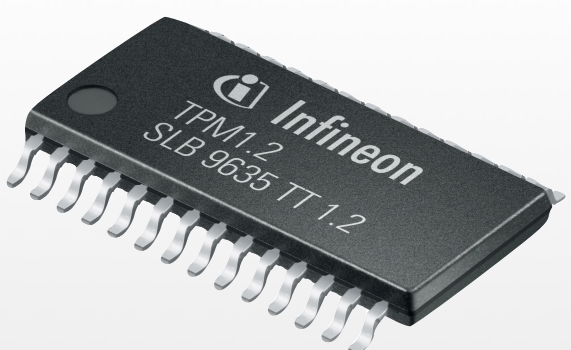
BOOTING + TPM

App A | App B

OS

Boot Loader

BIOS



PCR 83E2FF9A

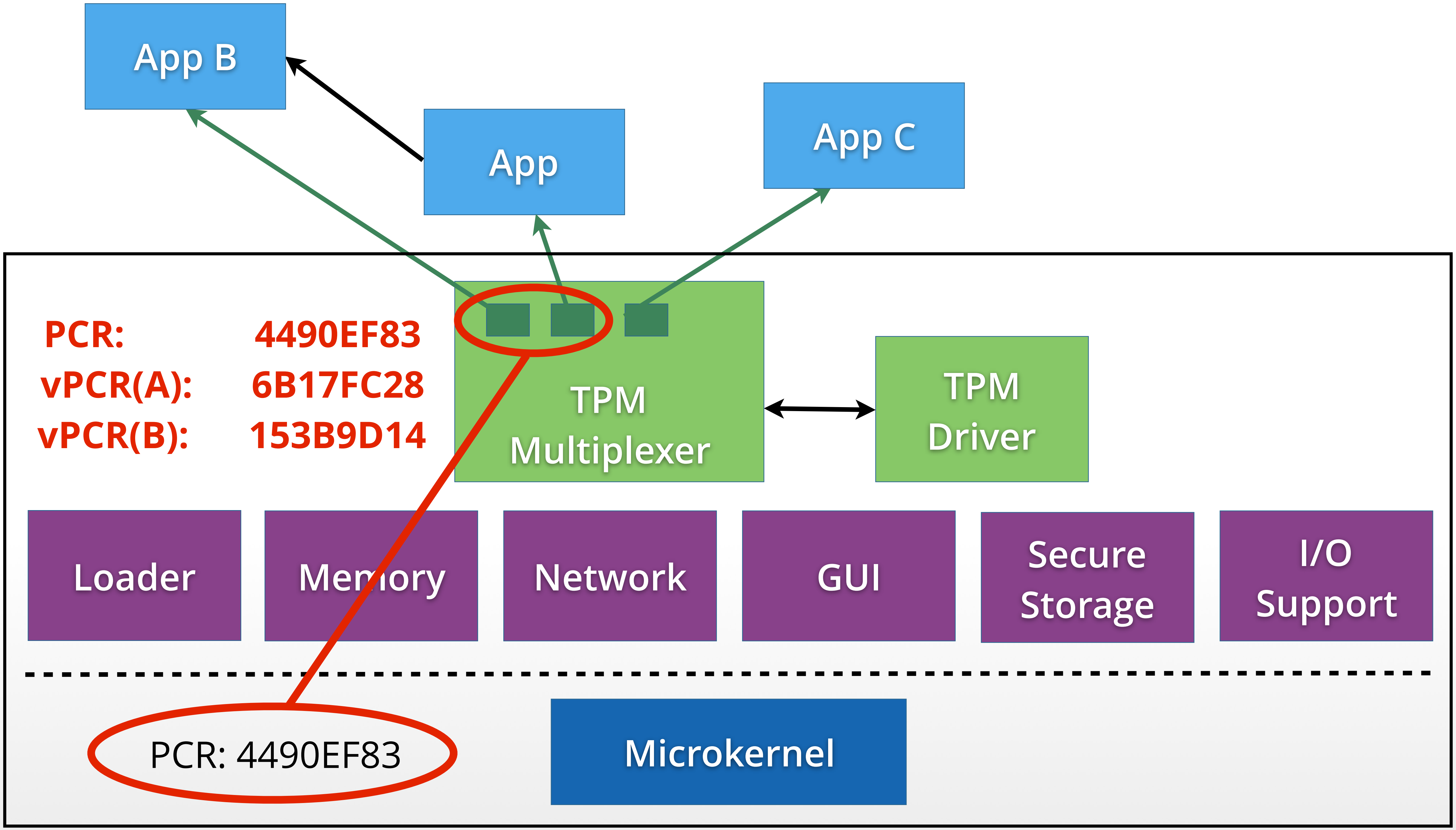
MULTIPLE APPS

- Use one PCR per application:
  - Application measurements independent
  - Number of PCRs is limited (TPM 1.2: max 24)
- 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

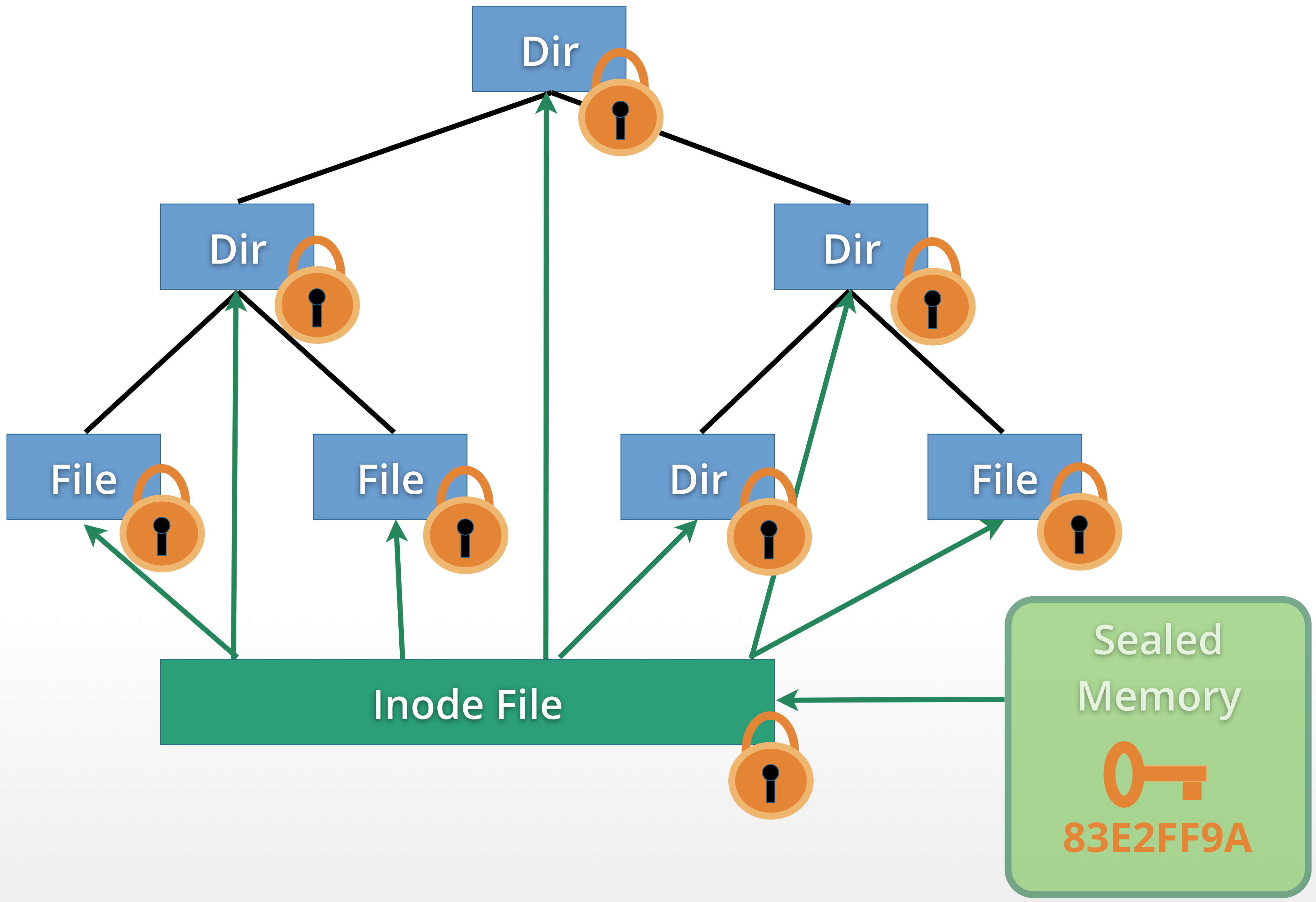


TPM MULTIPLEXED

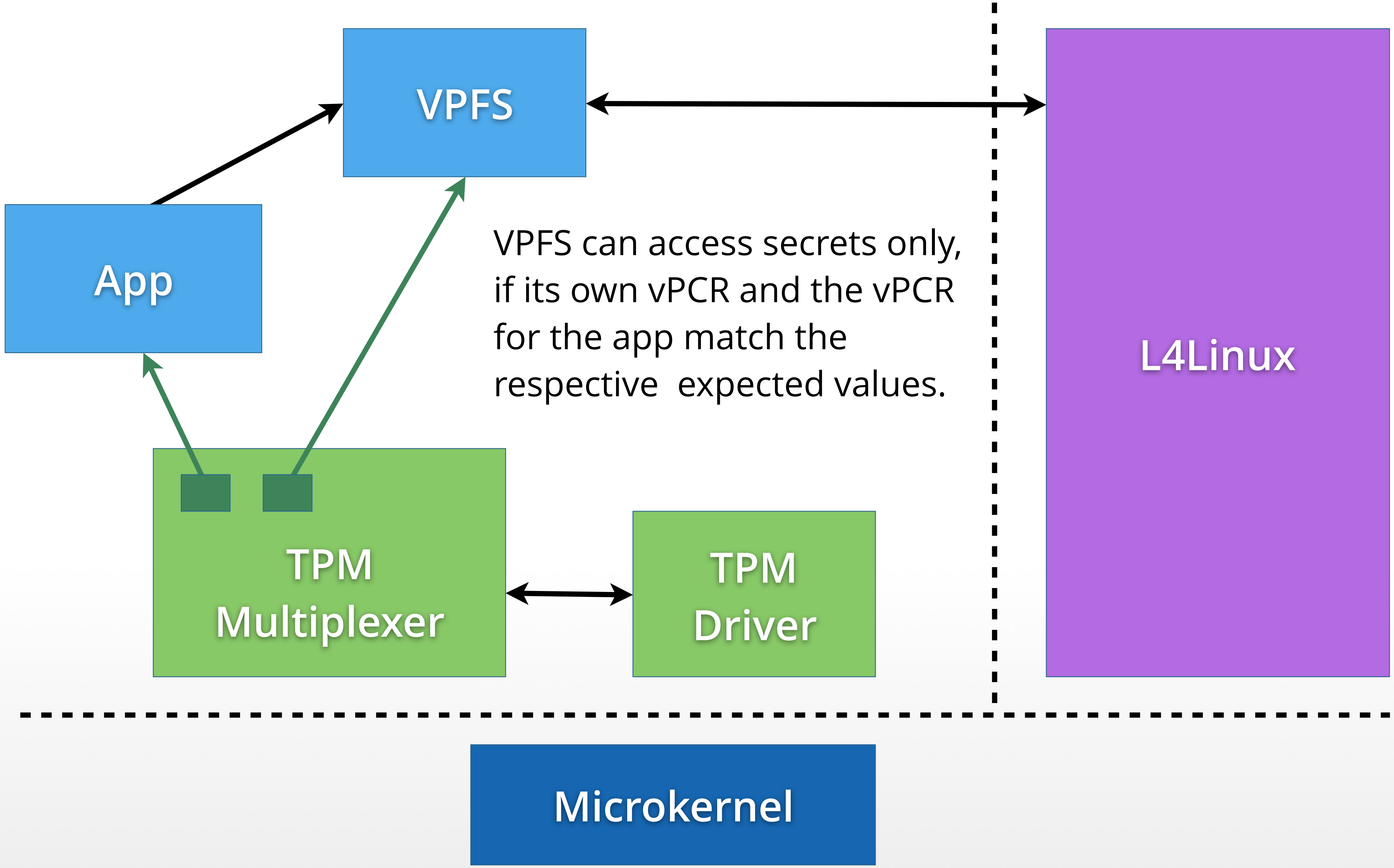
- Operations on software PCRs:
  - **Seal**, **Unseal**, **Quote**, **Extend**
  - **Add_child**, **Remove_child**
- Performed using software keys (AES, RSA)
- Software keys protected with real TPM
- Link between software **PCRs** and real **PCRs**: certificate for RSA signature key
- Implemented for L4: TPM multiplexer **Lyon**

A SECOND LOOK AT VPFS

VPFS SECURITY



VPFS TRUST



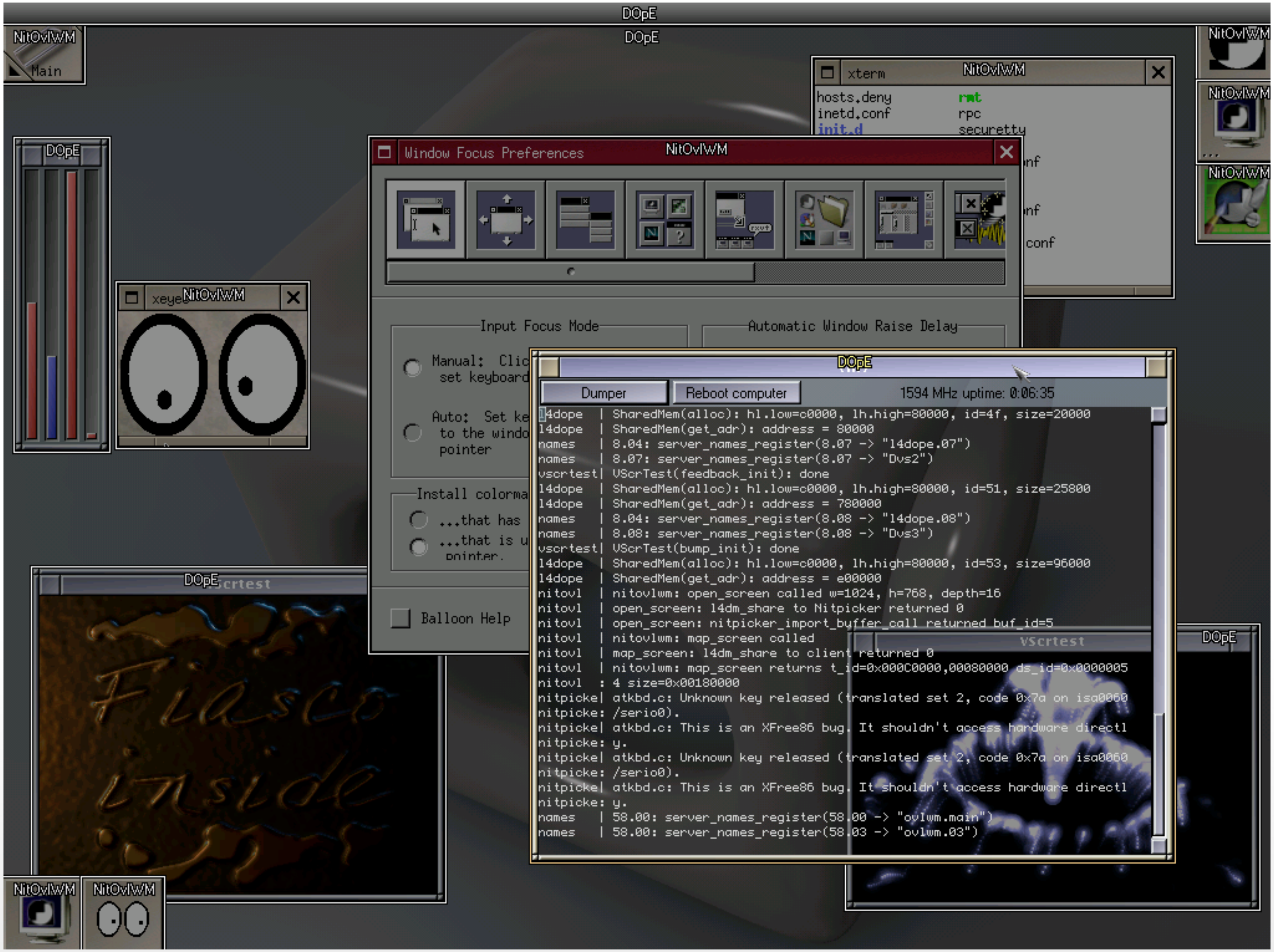
VPFS can access secrets only, if its own vPCR and the vPCR for the app match the respective expected values.

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 CLOSER LOOK AT THE WHOLE PICTURE

NITPICKER


DOpE
NitOvlWM
Main
xterm
hosts.deny
inetd.conf
init.d
rmt
rpc
securetty
Window Focus Preferences
xeyes
Input Focus Mode
Automatic Window Raise Delay
Manual: Clic
set keyboard
Auto: Set ke
to the windo
pointer
Install colorma
...that has
...that is u
Balloon Help
Dumper
Reboot computer
1594 MHz uptime: 0:06:35
l4dope | SharedMem(alloc): hl.low=c0000, lh.high=80000, id=4f, size=20000
l4dope | SharedMem(get_adr): address = 80000
names | 8.04: server_names_register(8.07 -> "l4dope.07")
names | 8.07: server_names_register(8.07 -> "Dvs2")
vscrtest| VScrTest(feedback_init): done
l4dope | SharedMem(alloc): hl.low=c0000, lh.high=80000, id=51, size=25800
l4dope | SharedMem(get_adr): address = 780000
names | 8.04: server_names_register(8.08 -> "l4dope.08")
names | 8.08: server_names_register(8.08 -> "Dvs3")
vscrtest| VScrTest(bump_init): done
l4dope | SharedMem(alloc): hl.low=c0000, lh.high=80000, id=53, size=96000
l4dope | SharedMem(get_adr): address = e00000
nitovl | nitovlwm: open_screen called w=1024, h=768, depth=16
nitovl | open_screen: l4dm_share to Nitpicker returned 0
nitovl | open_screen: nitpicker_import_buffer_call returned buf_id=5
nitovl | nitovlwm: map_screen called
nitovl | map_screen: l4dm_share to client returned 0
nitovl | nitovlwm: map_screen returns t_id=0x000C0000,00080000 ds_id=0x0000005
nitovl : 4 size=0x00180000
nitpicke| atkbd.c: Unknown key released (translated set 2, code 0x7a on isa0060
nitpicke: /serio0).
nitpicke| atkbd.c: This is an XFree86 bug. It shouldn't access hardware directl
nitpicke: y.
nitpicke| atkbd.c: Unknown key released (translated set 2, code 0x7a on isa0060
nitpicke: /serio0).
nitpicke| atkbd.c: This is an XFree86 bug. It shouldn't access hardware directl
nitpicke: y.
names | 58.00: server_names_register(58.00 -> "ovlwm.main")
names | 58.00: server_names_register(58.03 -> "ovlwm.03")
vscrtest
Fiasco inside

TRUST NITPICKER

- *User cannot just trust what he / she sees on the screen!*
- Solution:
  - Remote attestation
  - For example with trusted device:
    - User's smartphone sends **nonce** to PC
    - PC replies with quote of **nonce** + **PCR** values
    - User can decide whether to trust or not

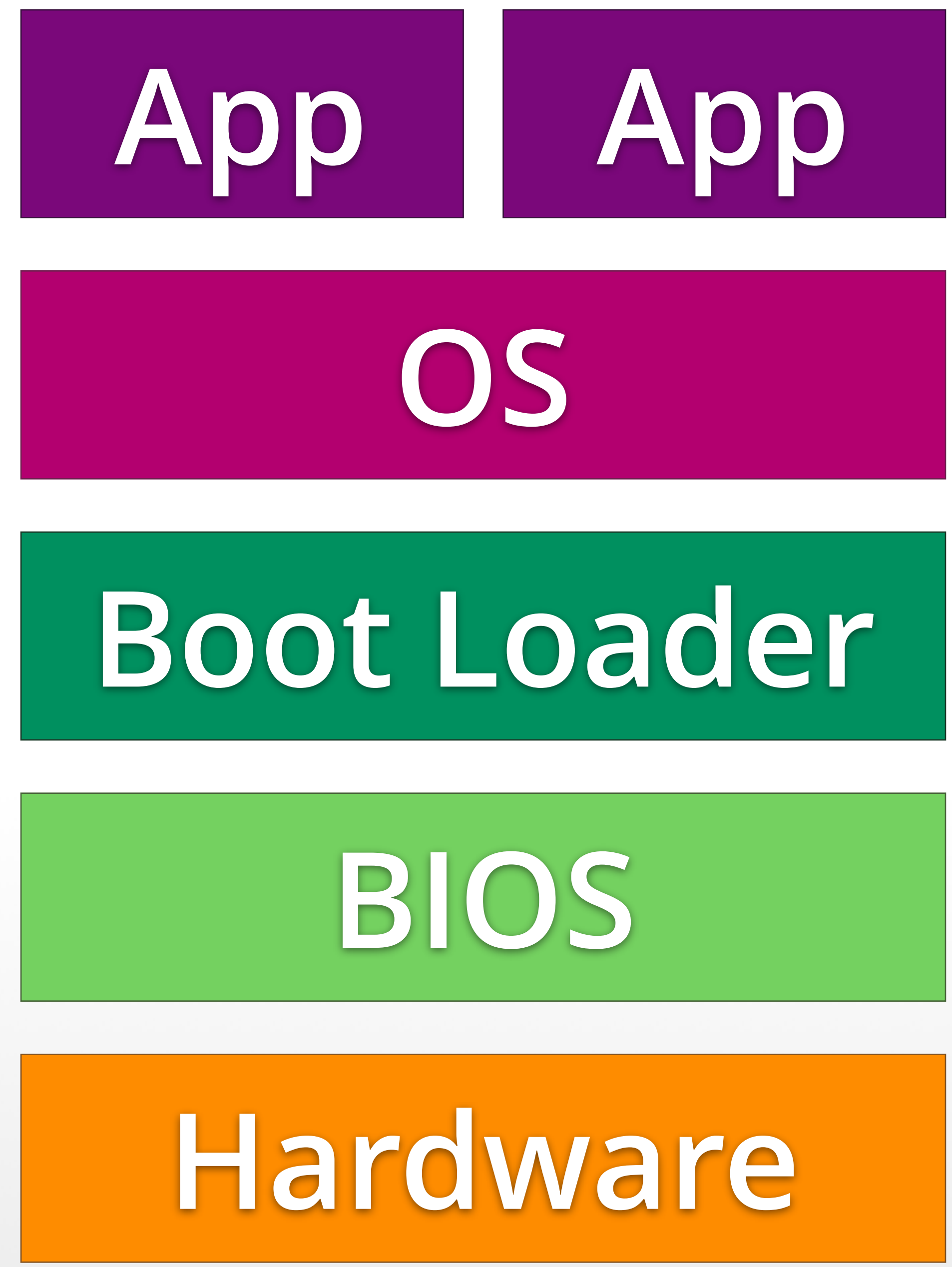
A SECOND LOOK AT THE CHAIN OF TRUST

CRTM

- When you press the power button ...
  - First code to be run: BIOS boot block
  - Stored in small ROM
  - Starts chain of trust:
    - Initialize TPM
    - Hash BIOS into TPM
    - Pass control to BIOS
- BIOS boot block is **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?

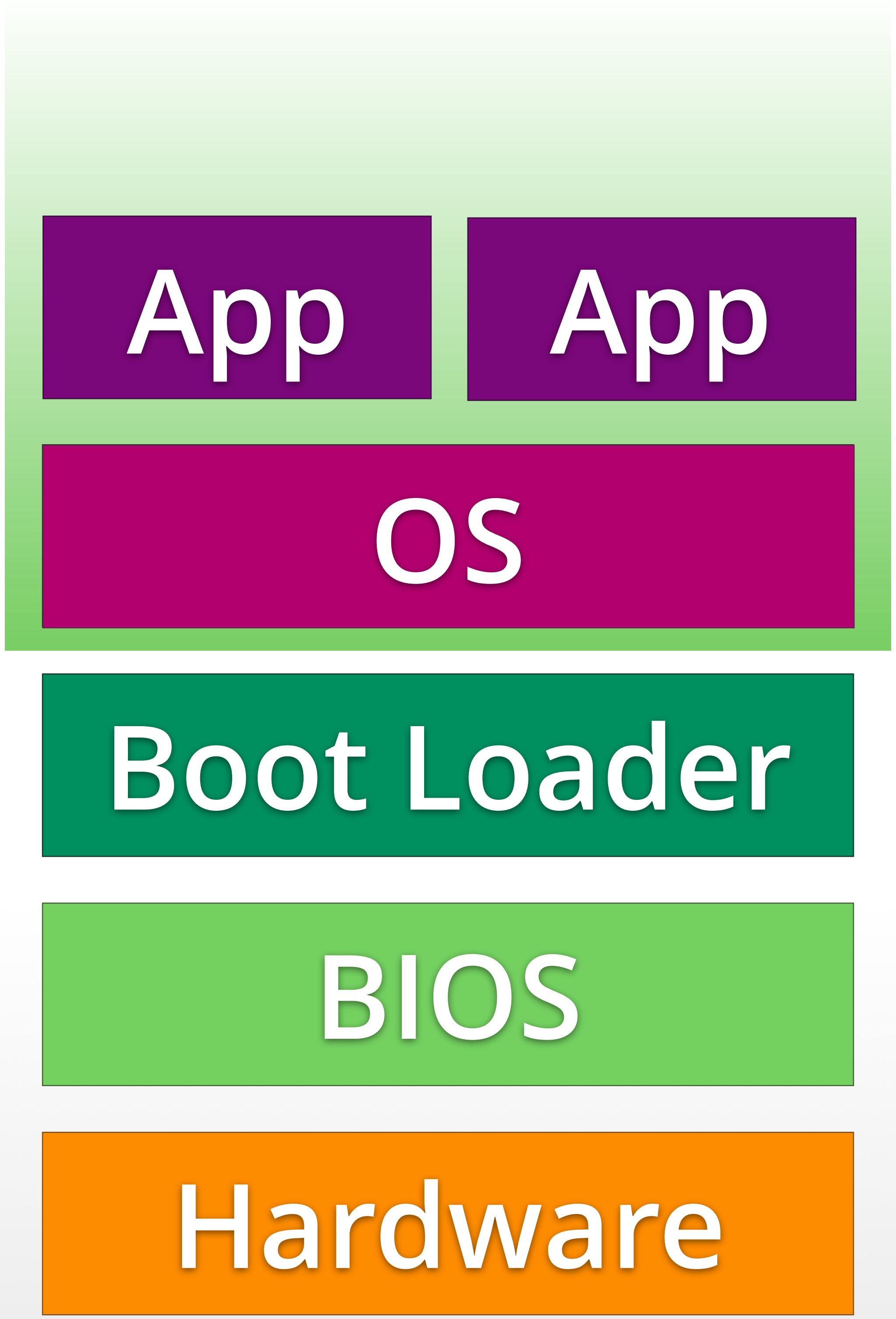


DRTM

- **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: OSLO

- First idea: **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]

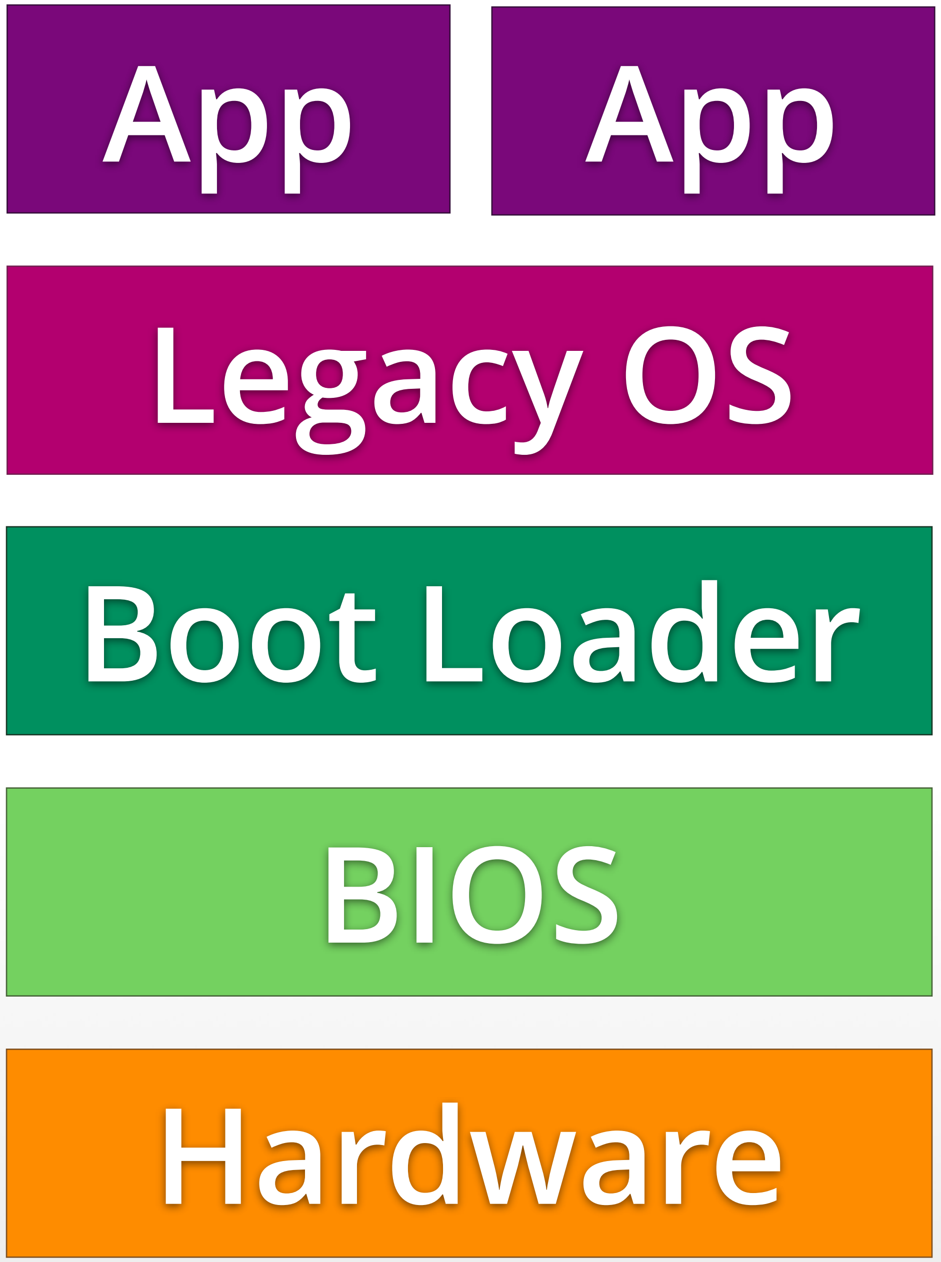


DRTM CHALLENGE

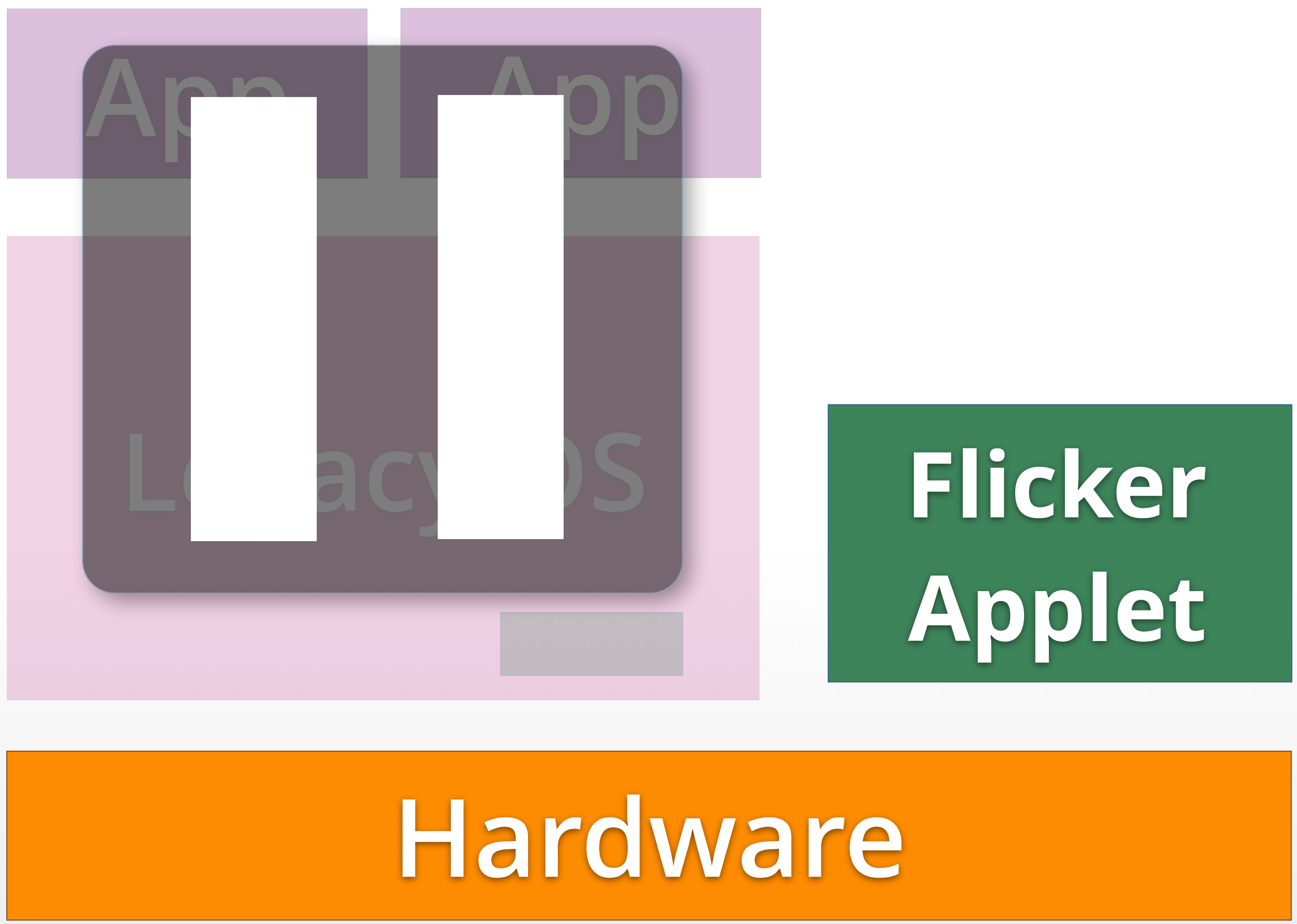
- DRTM remove boot software from TCB
- Key challenges:
  - „Secure loader“ must not be compromised
  - Requires careful checking of platform state
  - Secure loader must actually run in locked RAM, not in insecure device memory
- DRTM can also run <u>after</u> booting OS

DRTM: FLICKER

- New **DRTM** can be established anytime
- Flicker [7] approach:
  - Pause legacy OS
  - Execute critical code as **DRTM** using skinit
  - Restore CPU state
  - Resume legacy OS



DRTM: FLICKER



FLICKER DETAILS

- Pause untrusted legacy OS, stop all CPUs
- Execute skinit:
  - Start Flicker code as „secure loader“
  - Unseal input / sign data / seal output
- Restore state on all CPUs
- Resume untrusted legacy OS
- If needed: create quote with new PCRs
- *TCB in order of only few thousand SLOC!*

FLICKER LIMITS

- Problems with Flicker approach:
  - Untrusted OS must cooperate
  - Only 1 CPU active, all other CPUs stopped
  - Secure input and output only via slow TPM functionality (seal, unseal, sign)
  - Works for some server scenarios (e.g., handling credentials)
  - Client scenarios require more functionality (e.g., trusted GUI for using applications)

ISA EXTENSIONS

- **Intel Software Guard Extensions (SGX):** [9]
  - Secure enclaves: protected regions of address space for code, stack, heap
  - Sealed memory and remote attestation
- **ARM TrustZone:** [8]
  - New processor mode for critical software
  - Private memory partition (accessible only in secure processor mode)
  - Can be used to implement software TPM

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 key
- Not open: **closed** or **secure boot** instead of **authenticated booting**

WHAT'S NEXT?

- January 21, 2020:
  - Lecture „*Resilience*“
  - Paper Reading Exercise

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