TECHNISCHE UNIVERSITÄT DRESDEN

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

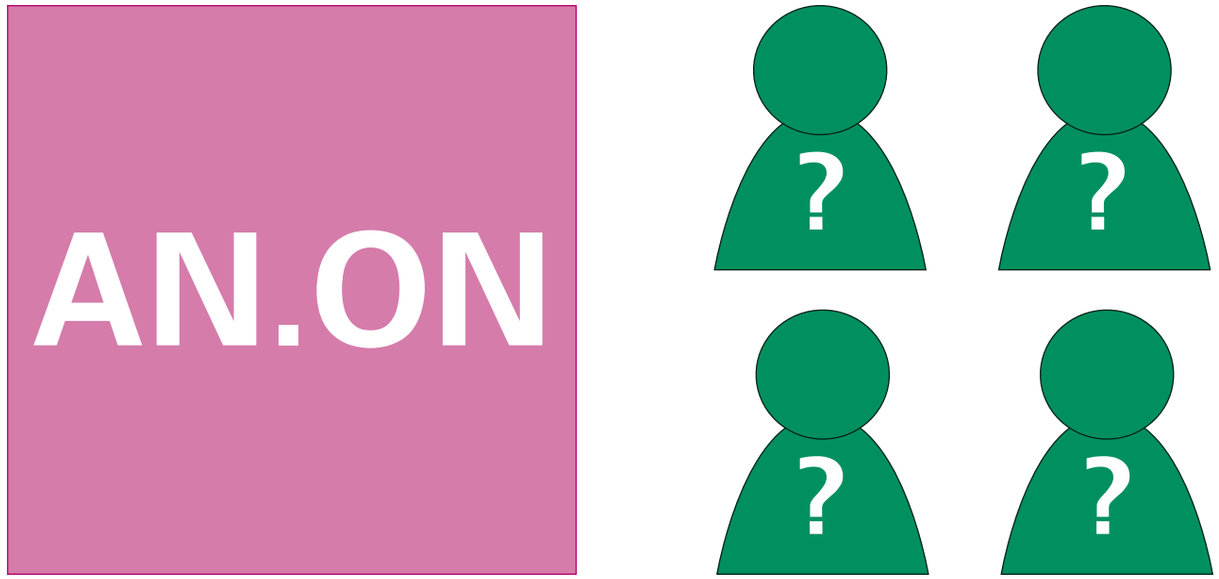
TRUSTED COMPUTING

CARSTEN WEINHOLD

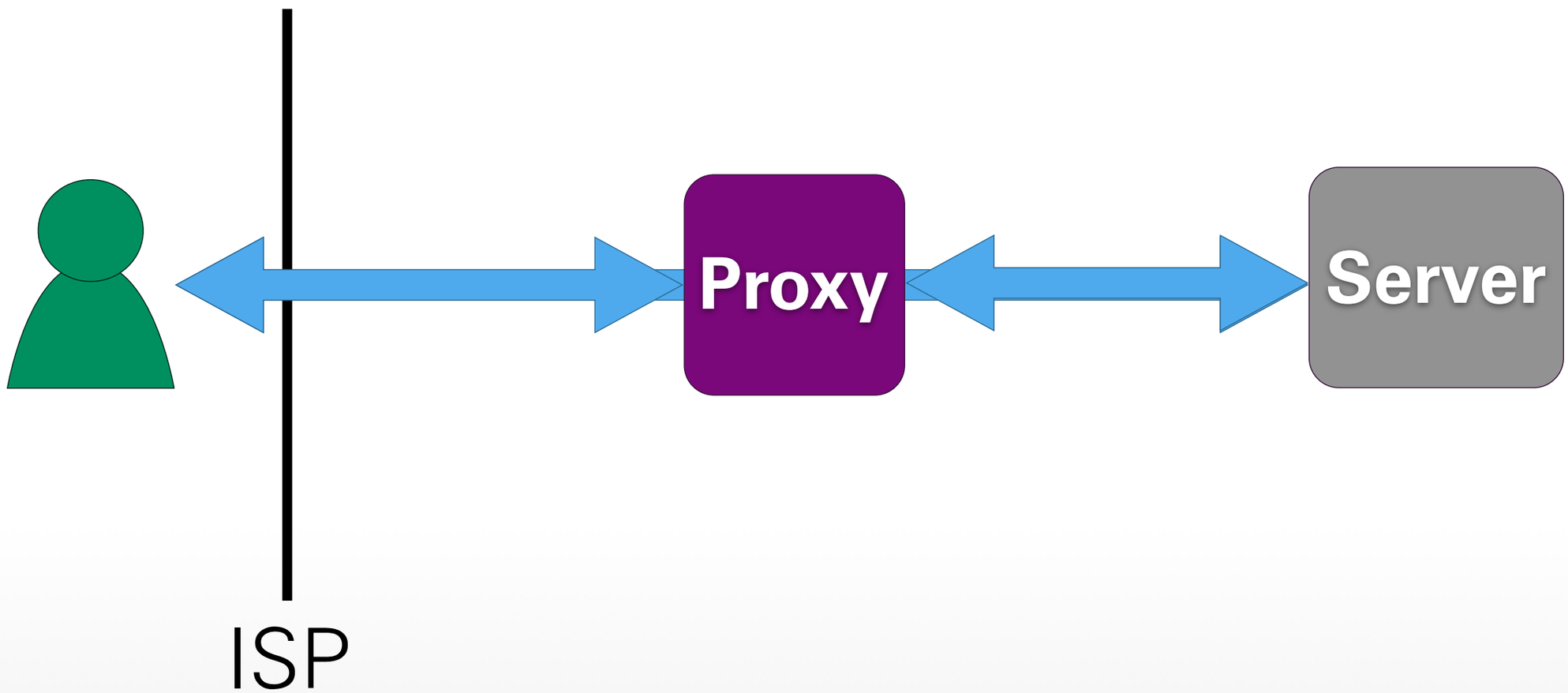
THIS LECTURE ...

- **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

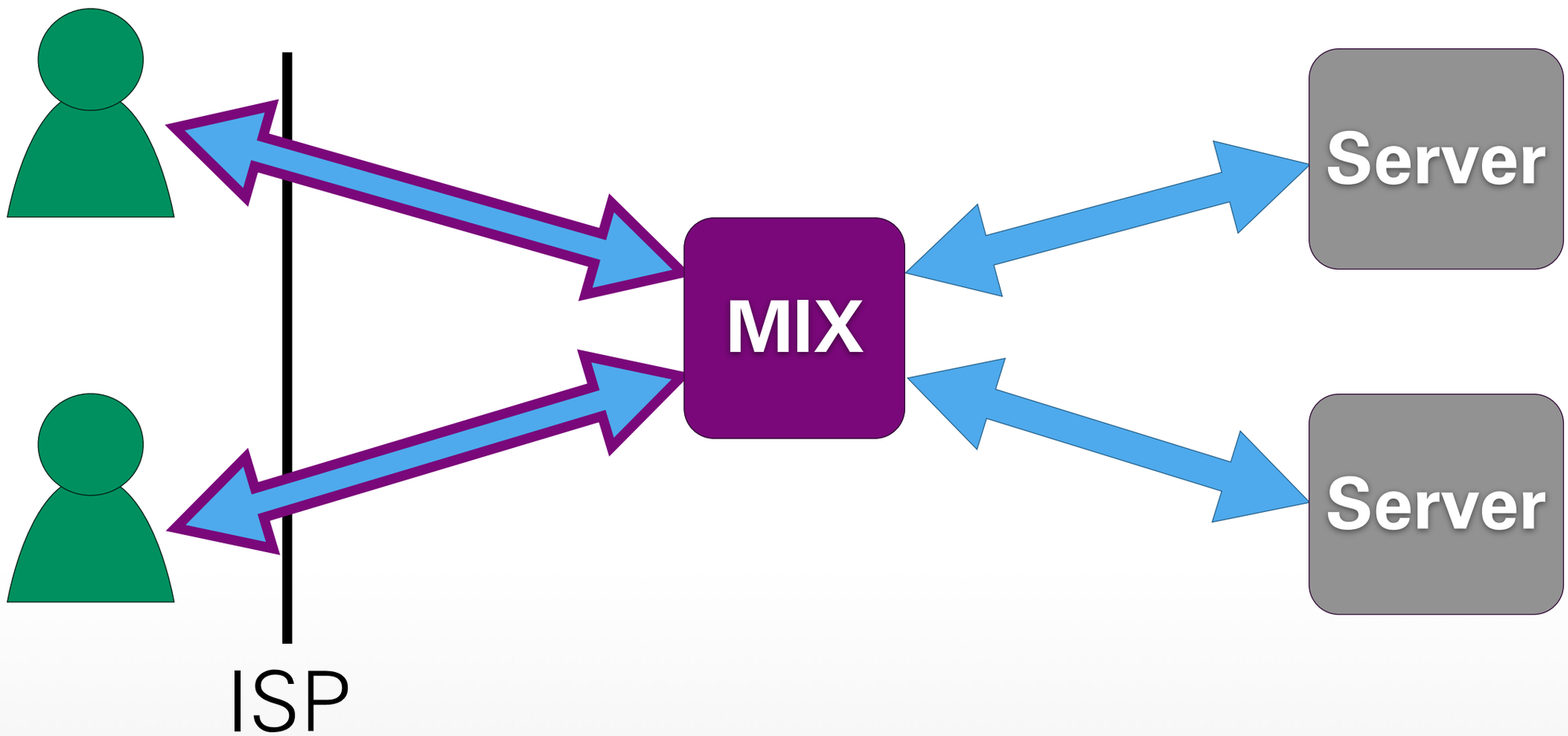
INTRODUCTION



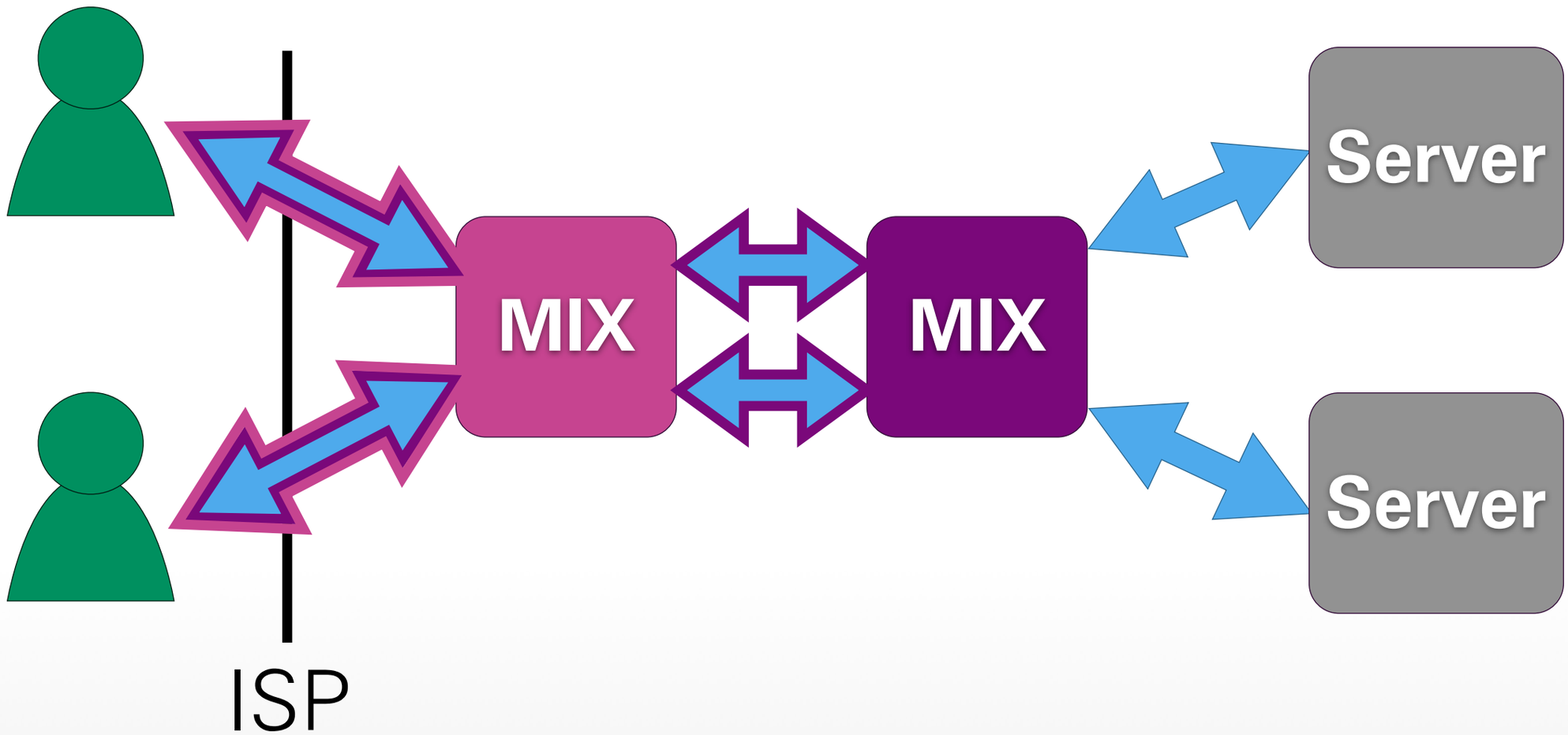
ANONYMITY



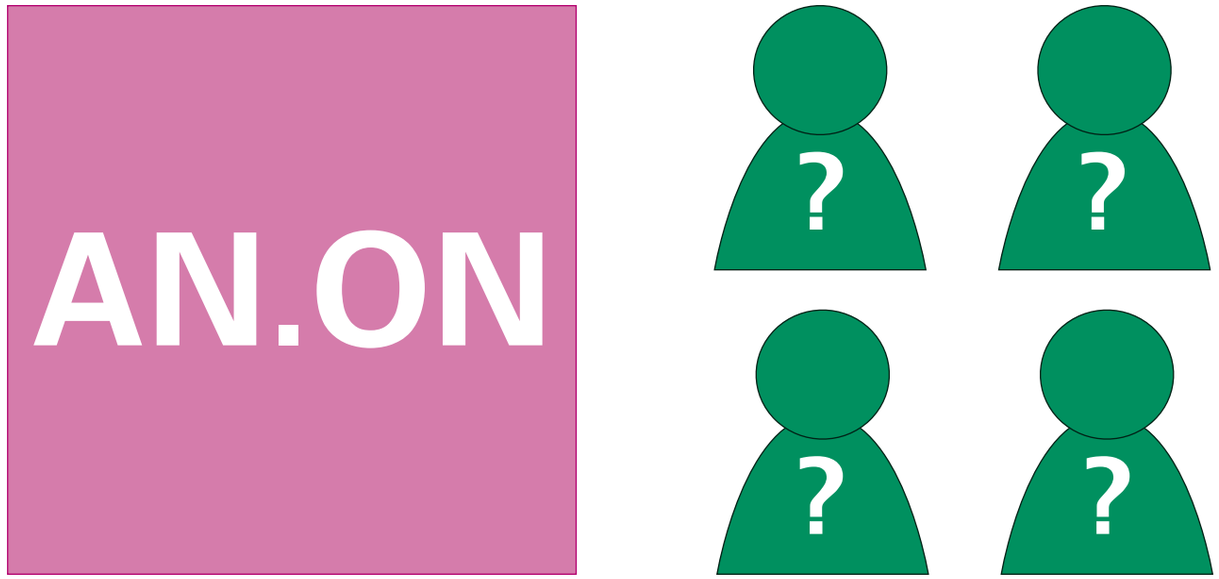
ANONYMITY



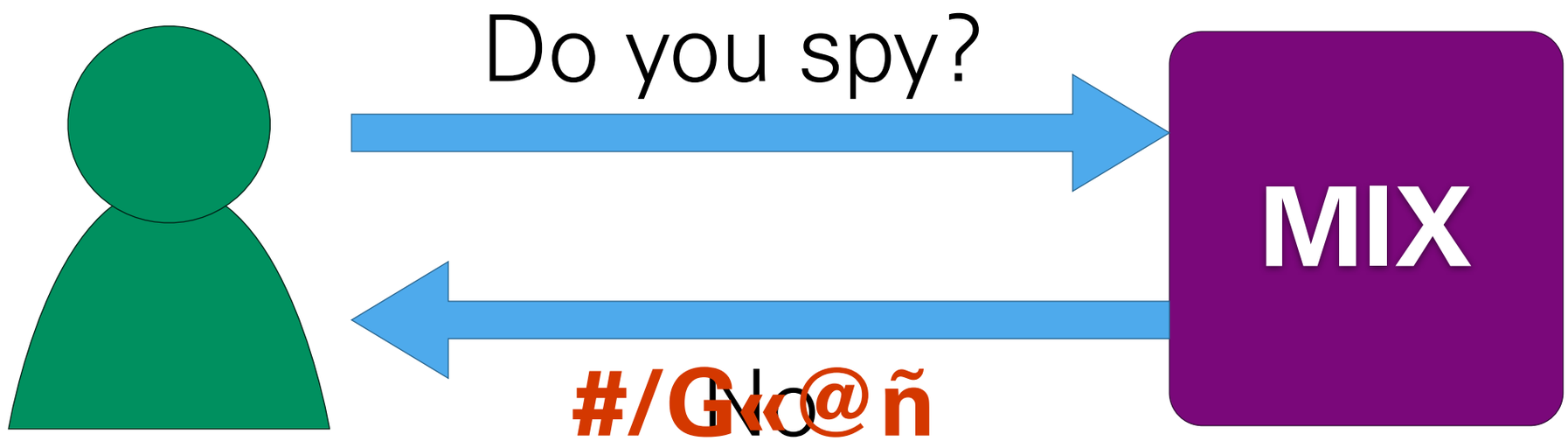
ANONYMITY



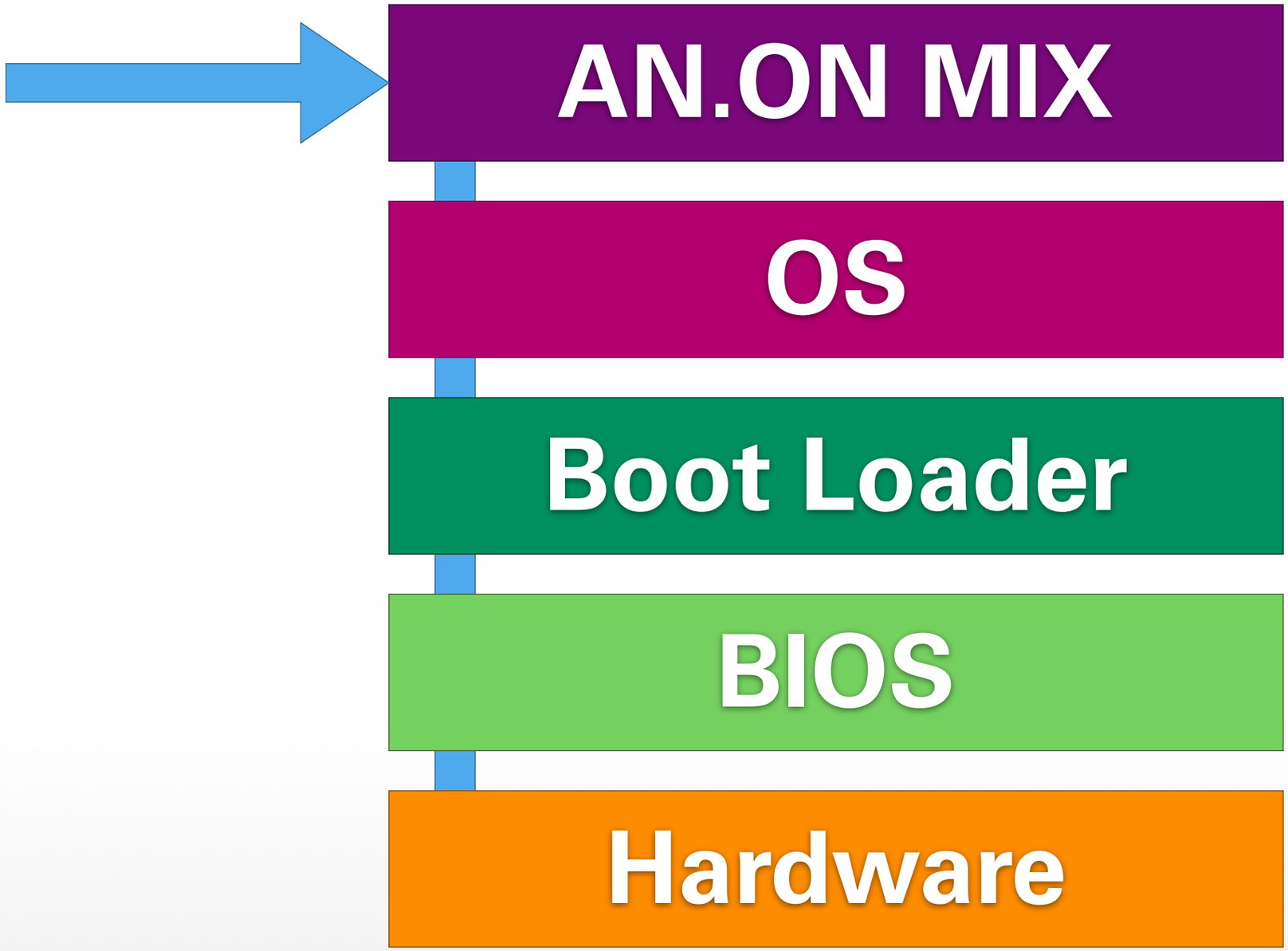
ANONYMITY



IDEA



SYSTEM LAYERS



TPM

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

Platform Configuration Register

PCR := SHA-1(PCR | **X**)

BOOTING + TPM

AN.ON MIX

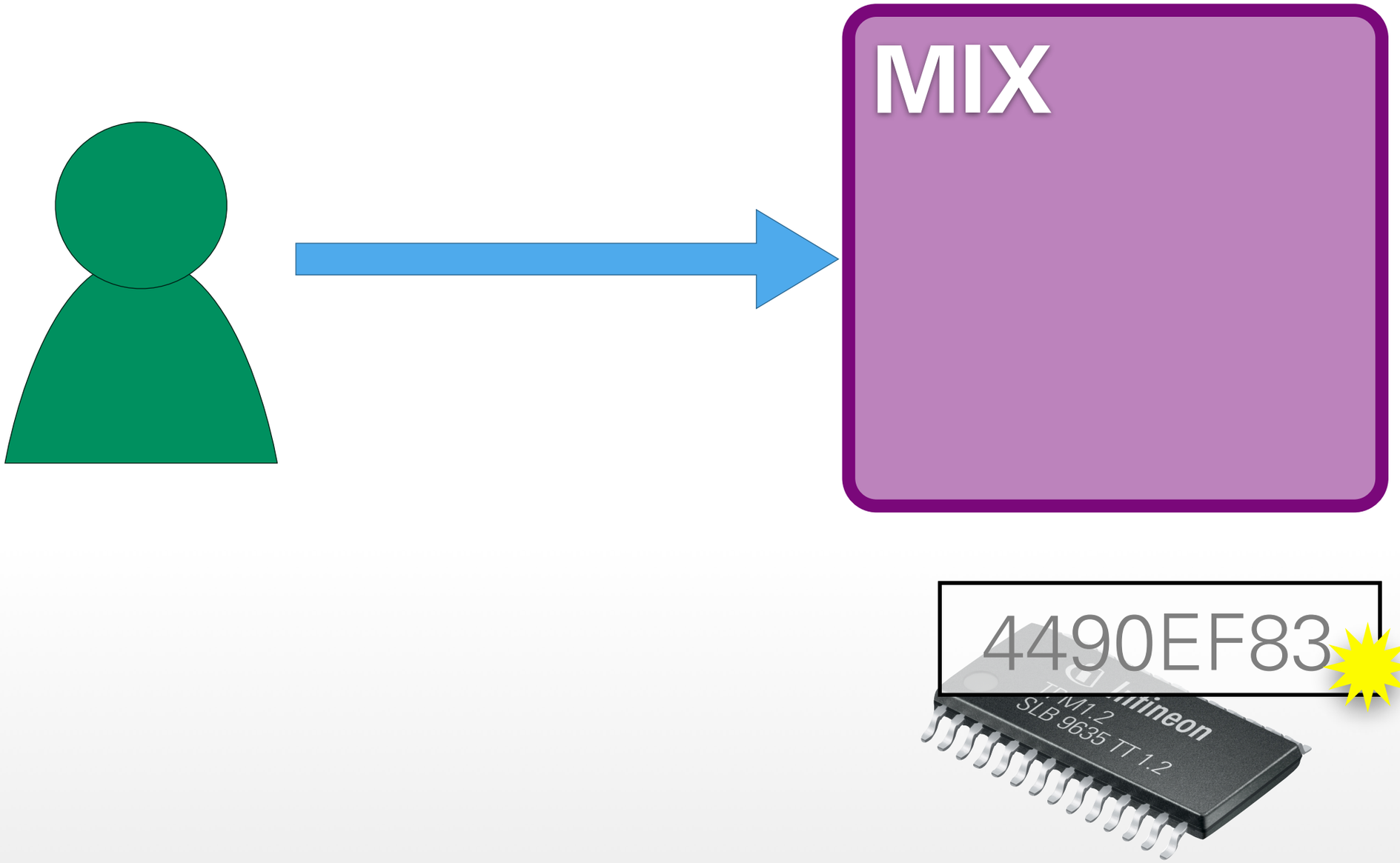
OS

Boot Loader

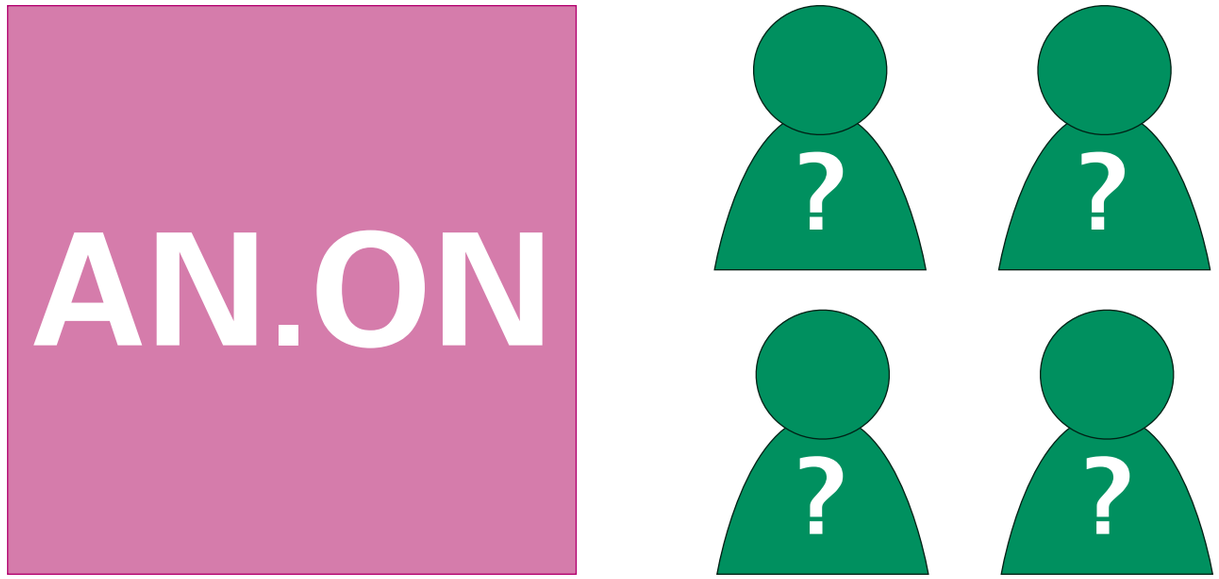
BIOS

PCR 4490EF83

Remote Attestation



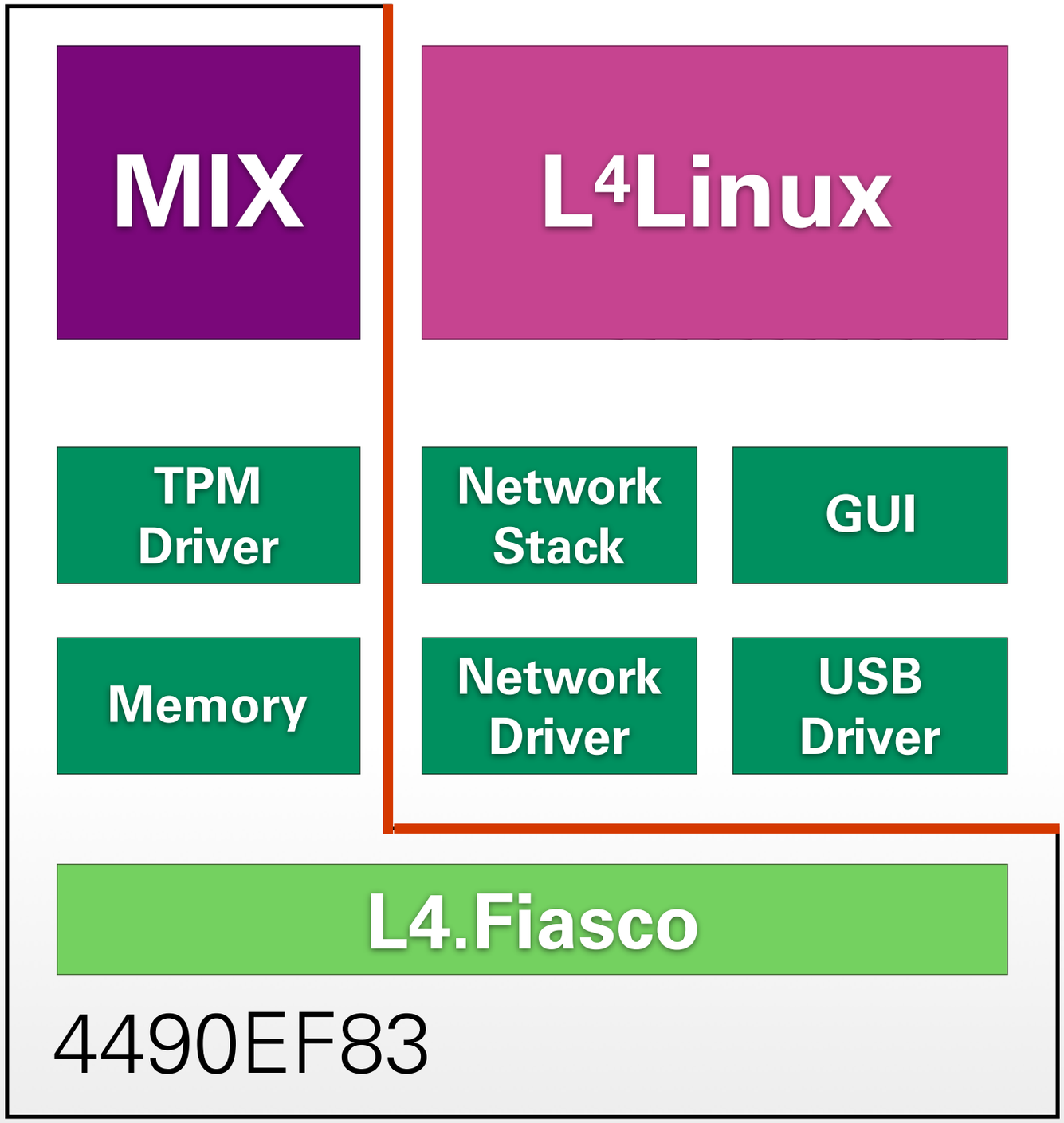
ARCHITECTURE



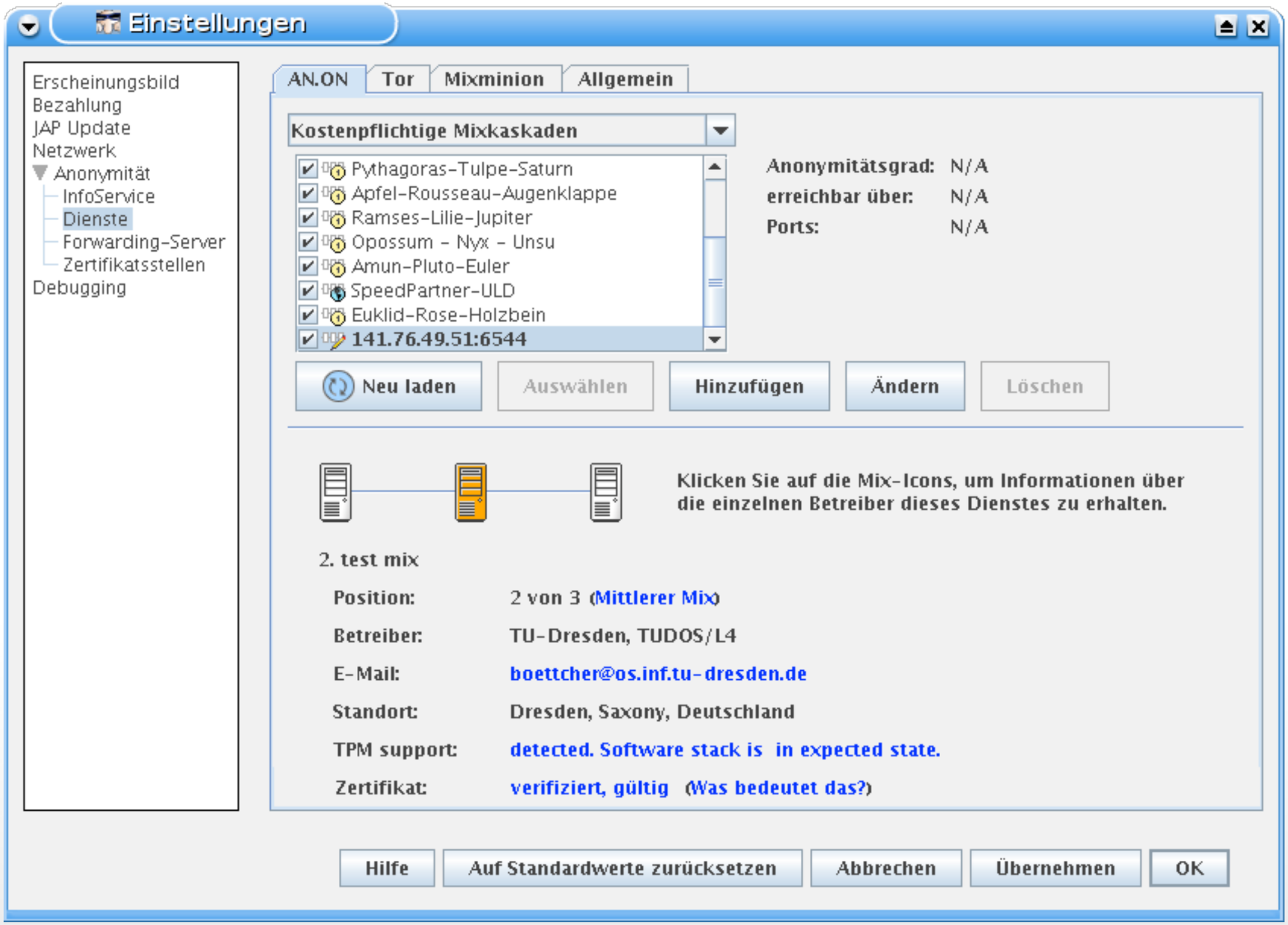
Linux

Windows

MONOLITHIC


MIX
L4Linux
TPM Driver
Network Stack
GUI
Memory
Network Driver
USB Driver
L4.Fiasco
4490EF83

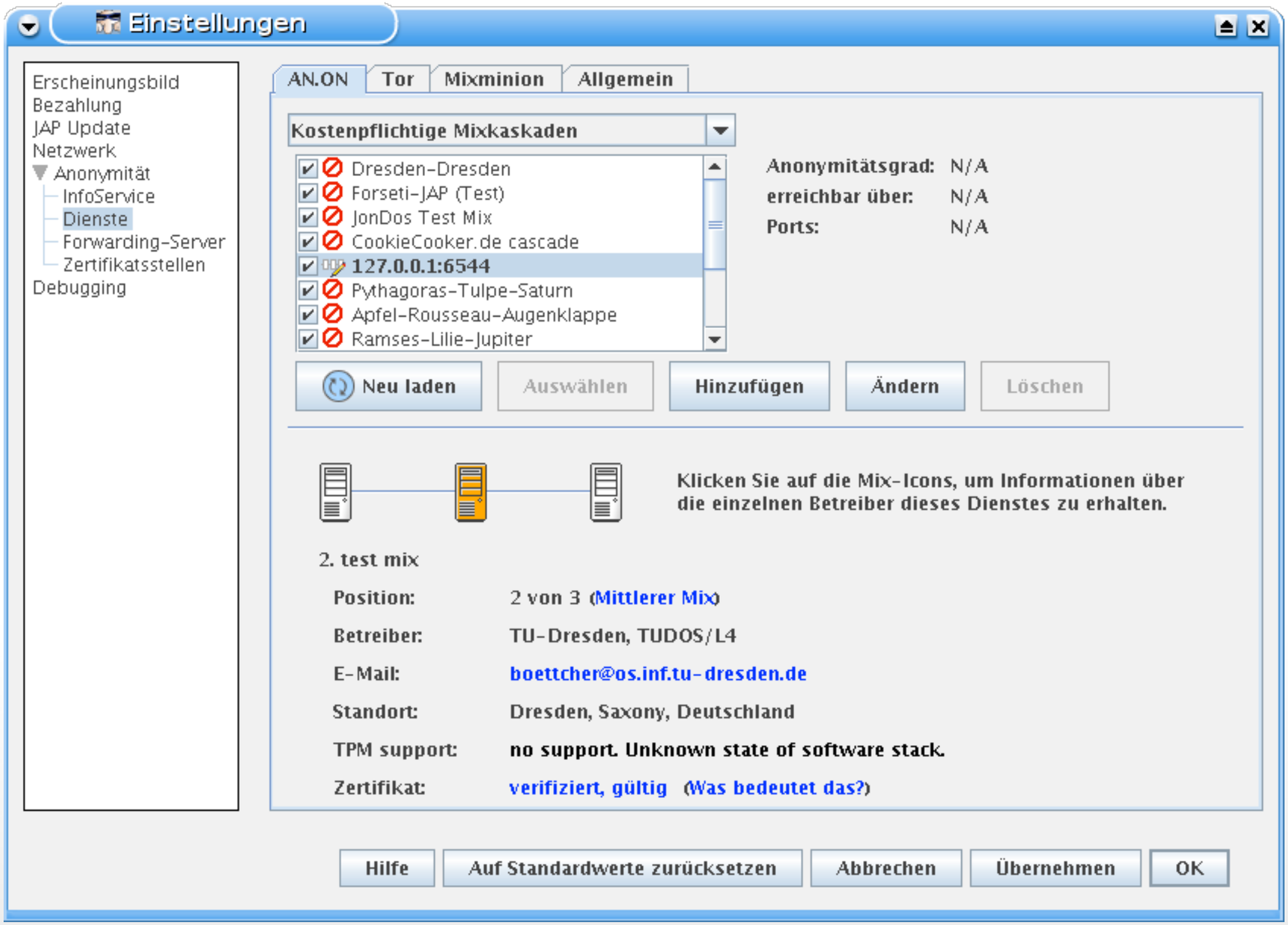
L4/AN.ON


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
```


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
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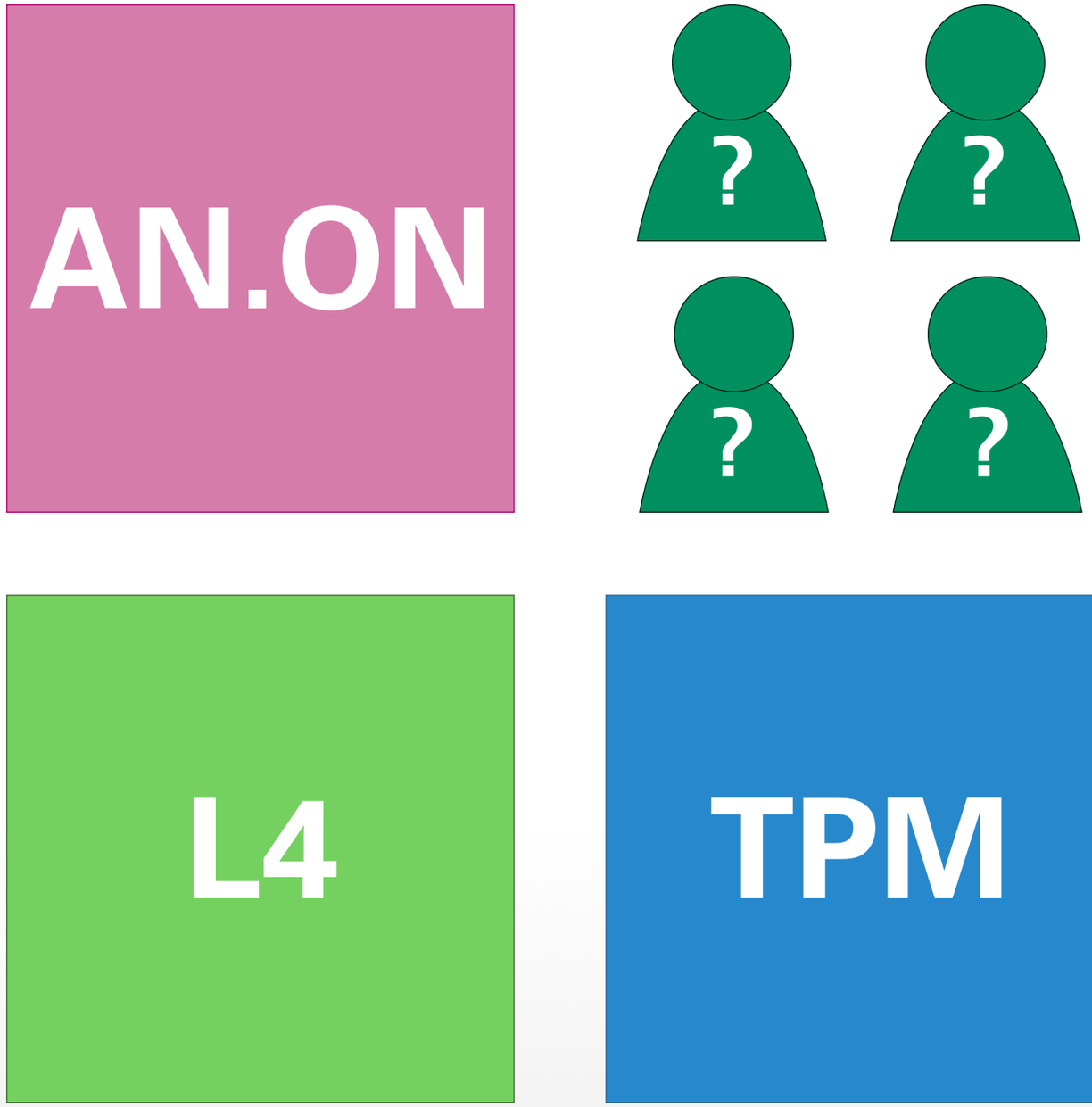
Hilfe
Auf Standardwerte zurücksetzen
Abbrechen
Übernehmen
OK

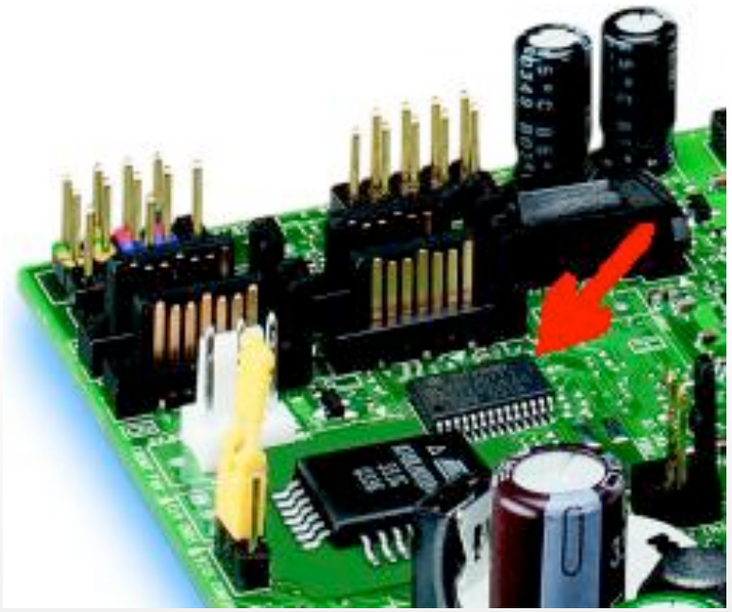
L4/AN.ON



THE TRUSTED PLATFORM MODULE

TPM HARDWARE

- TPMs are tightly integrated into platform:
  - Soldered on motherboards
  - ... or built into chipset / SoC
- Tamper resistant casing
- Widely deployed:
  - Business notebooks
  - Office desktop machines
  - Windows 8/10/RT tablets



http://www.heise.de/bilder/61155/0/0

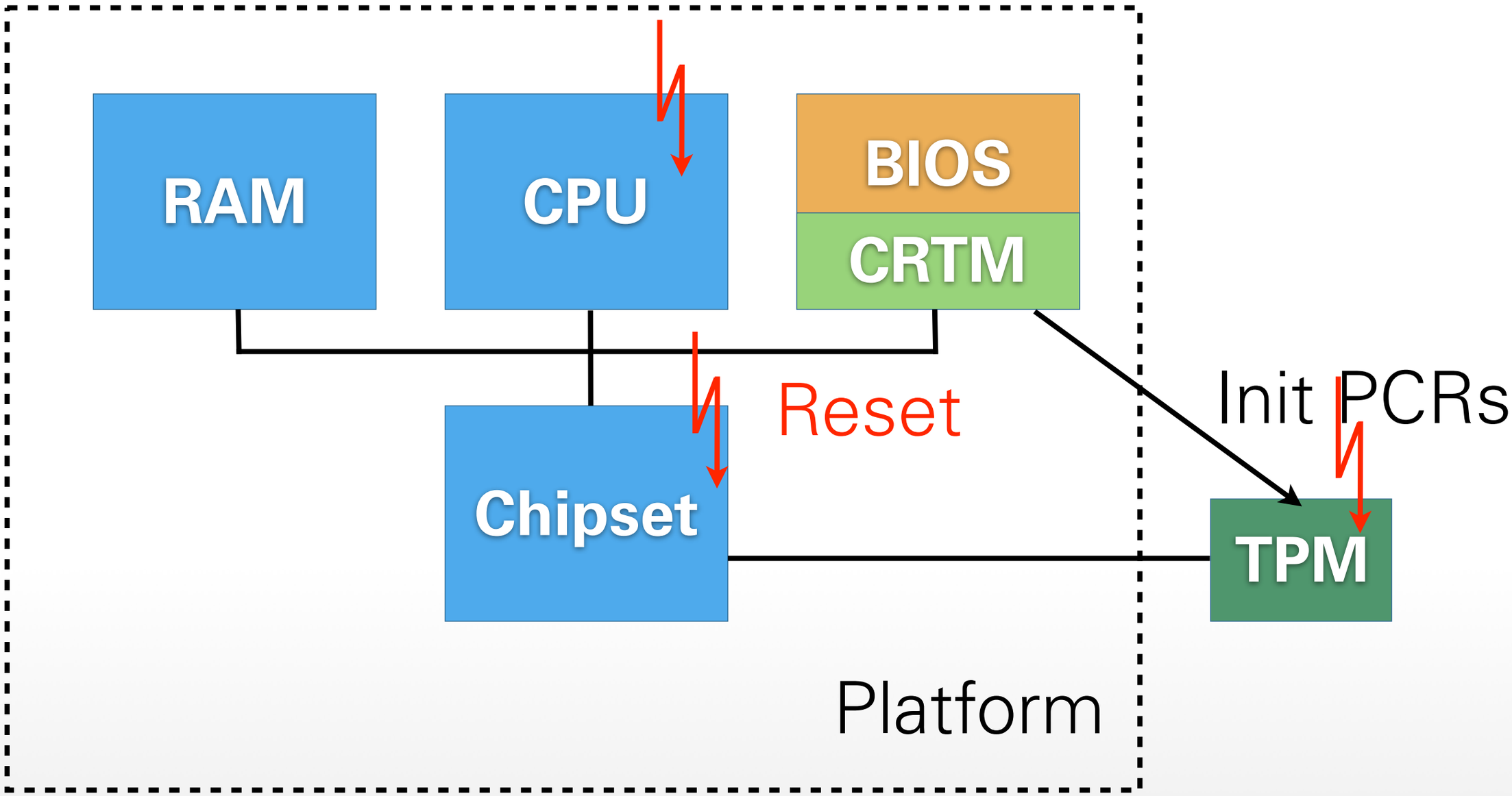
TPM OVERVIEW

- 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 hardware 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



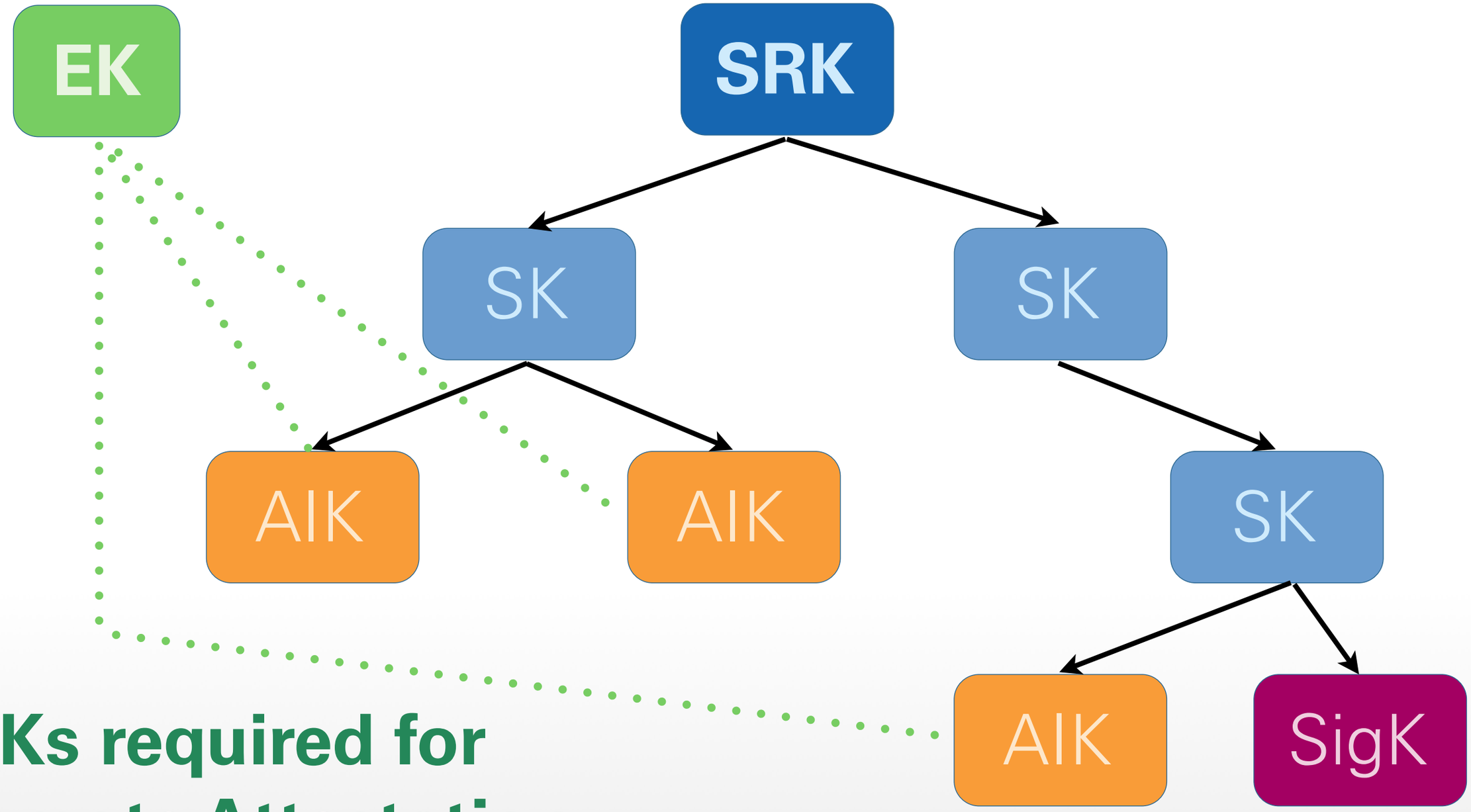
TPM IDENTITY

- 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, 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

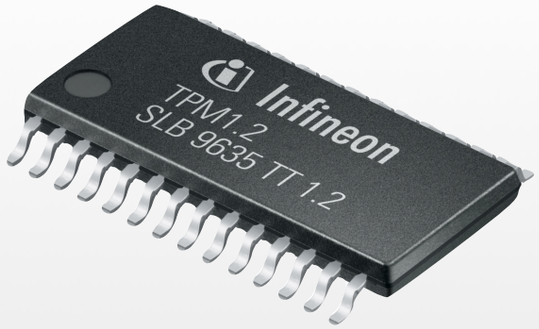
Application

OS

Boot Loader

BIOS

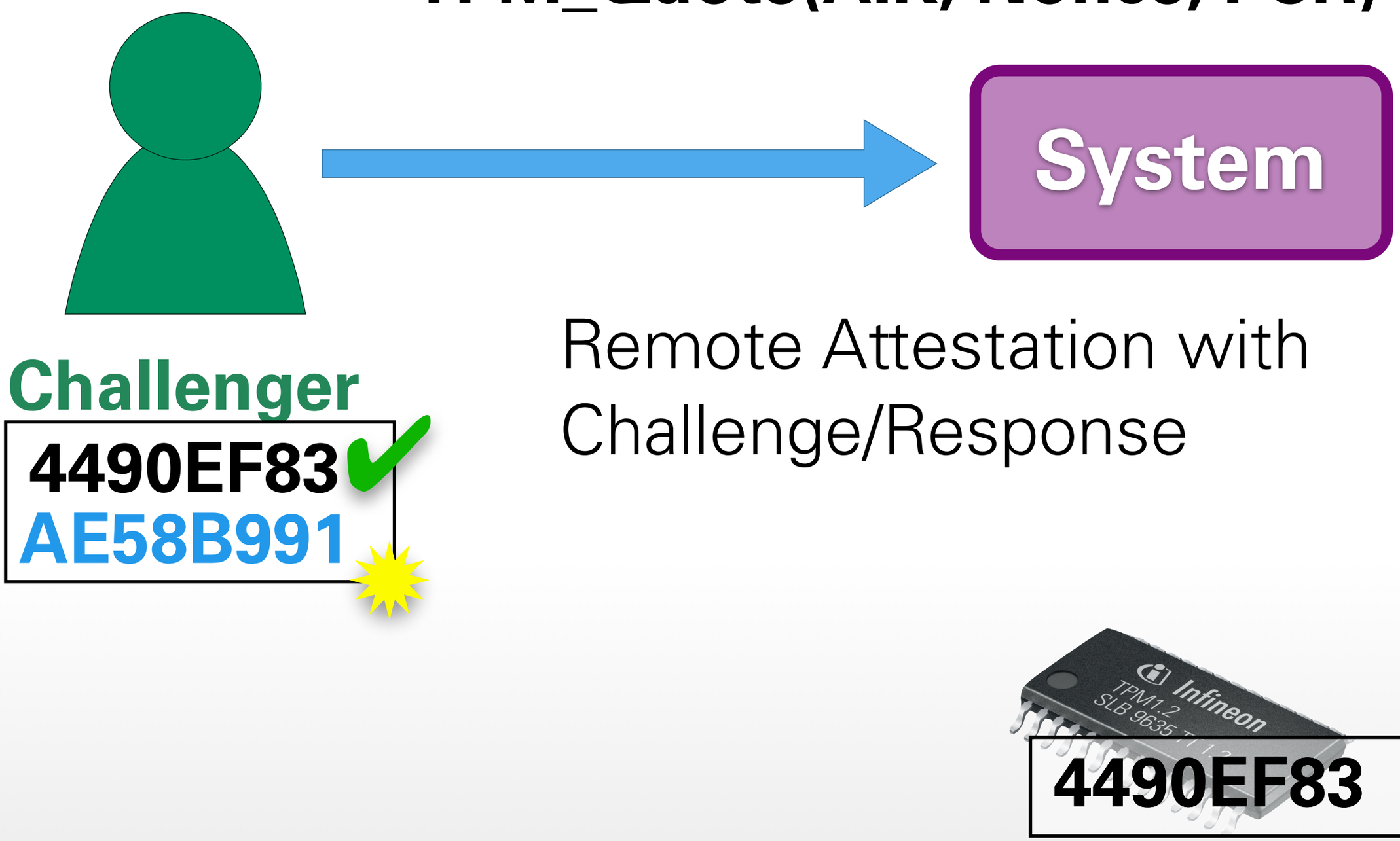
Authenticated Booting



PCR **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 <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 15FE7860 83E2FF9A

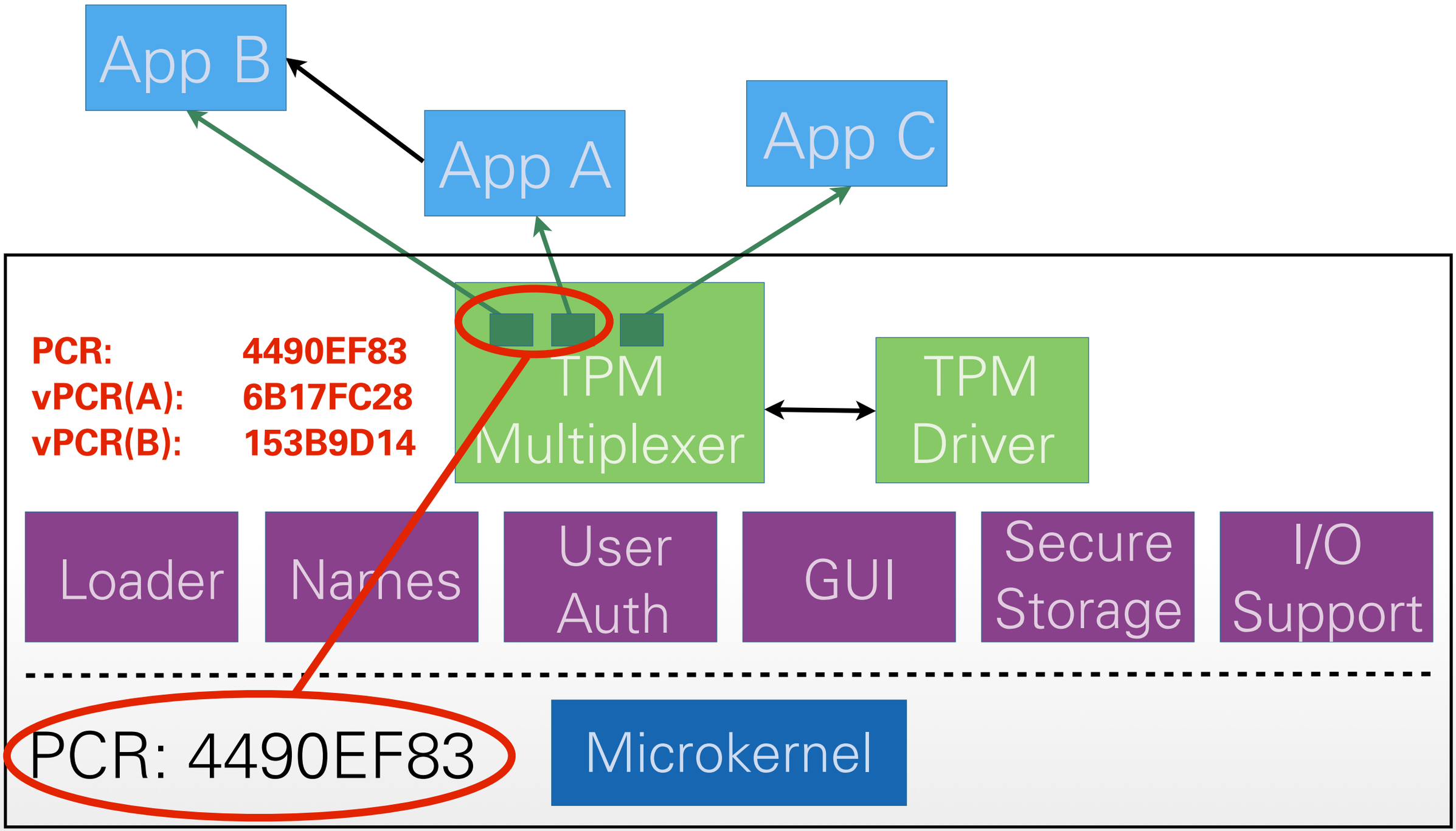
MULTIPLE APPS

- 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

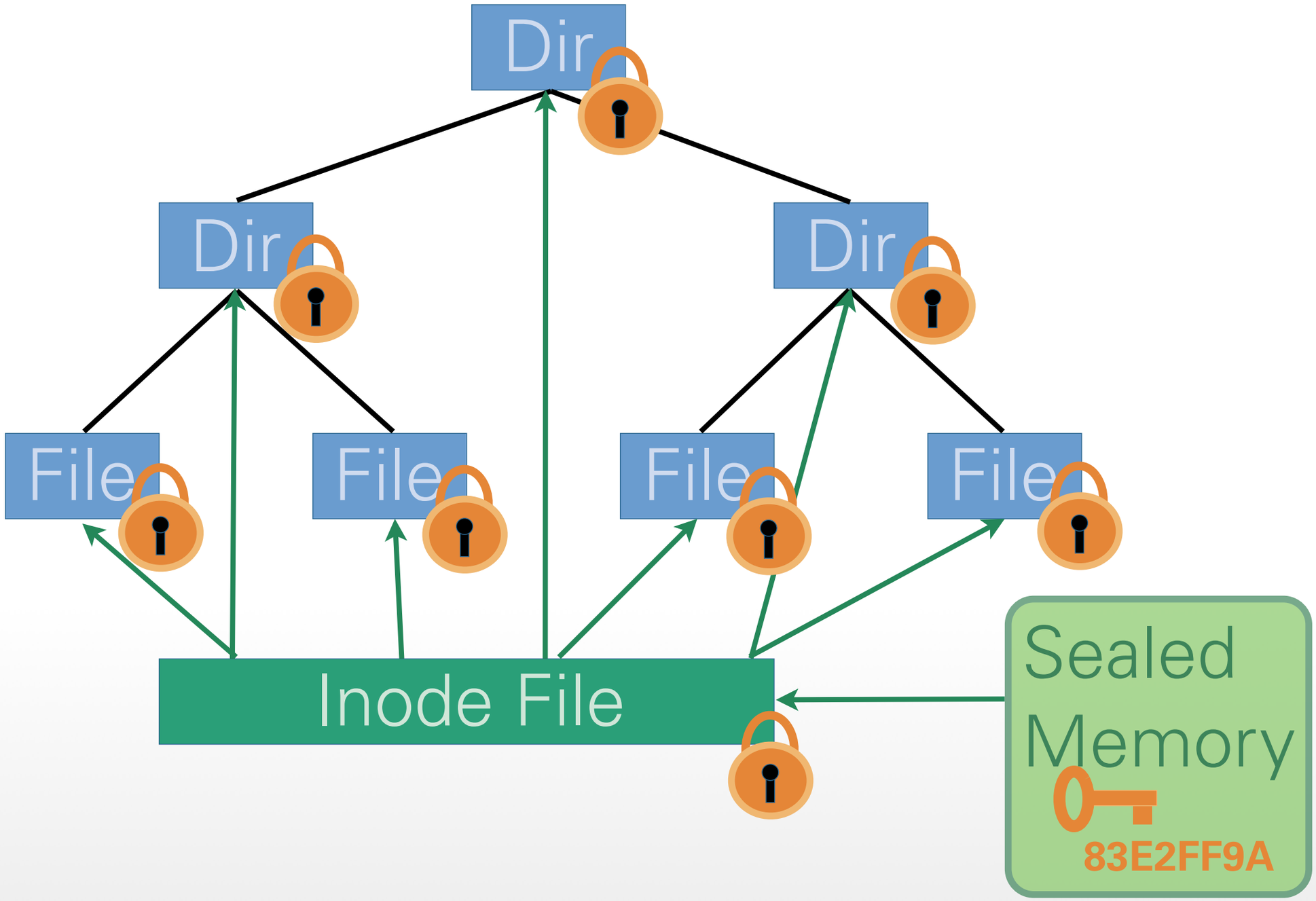


TPM MULTIPLEX'D

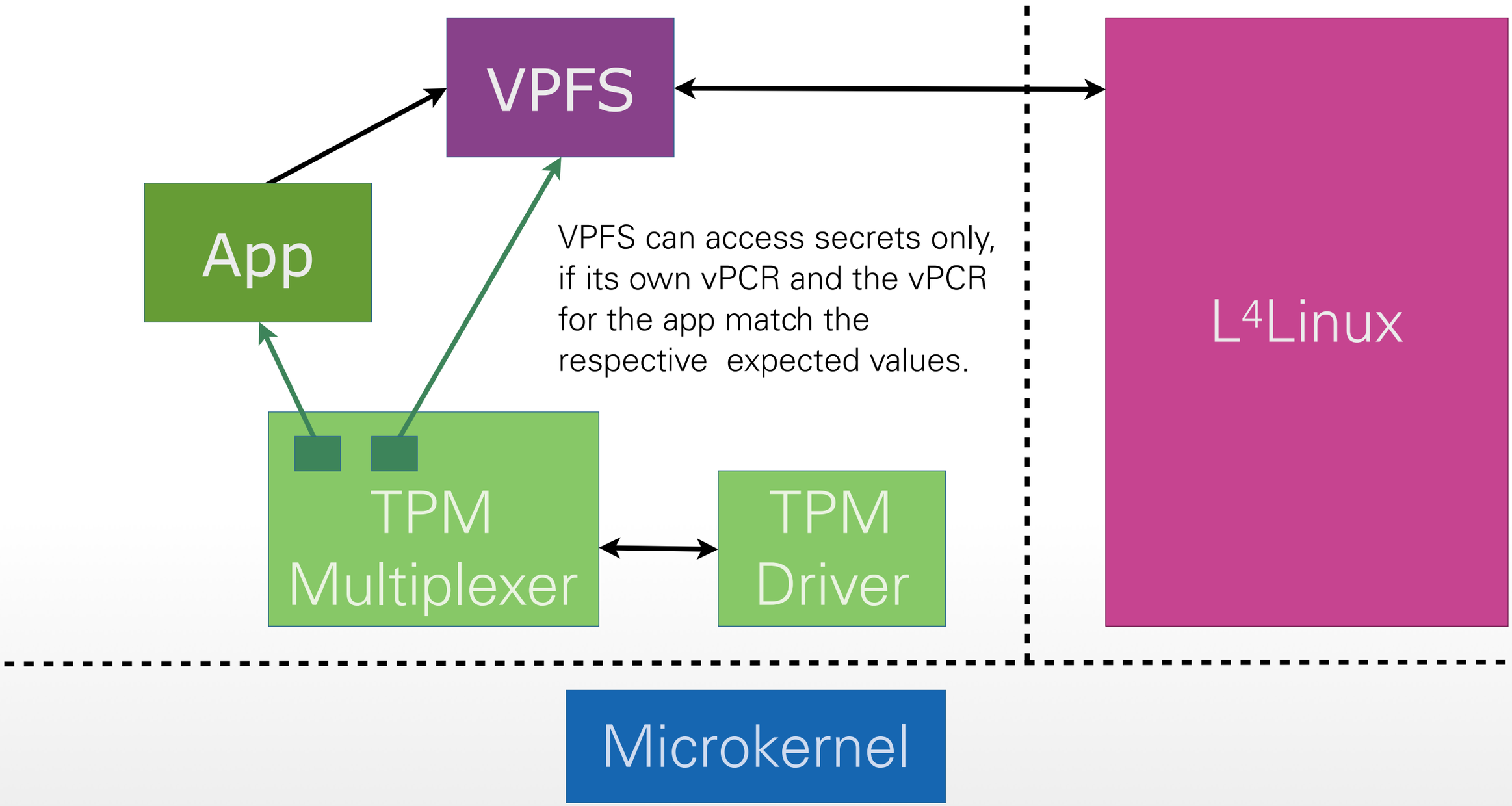
- Operations on software PCRs:
  - **Seal**, **Unseal**, **Quote**, **Extend**
  - **Add_child**, **Remove_child**
- Performed using software keys (AES, RSA)
- Software keys protected with real TPM
- Link between software **PCRs** and real **PCRs**: certificate for RSA signature key
- Implemented for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

A SECOND LOOK AT VPFS

VPFS SECURITY



VPFS TRUST

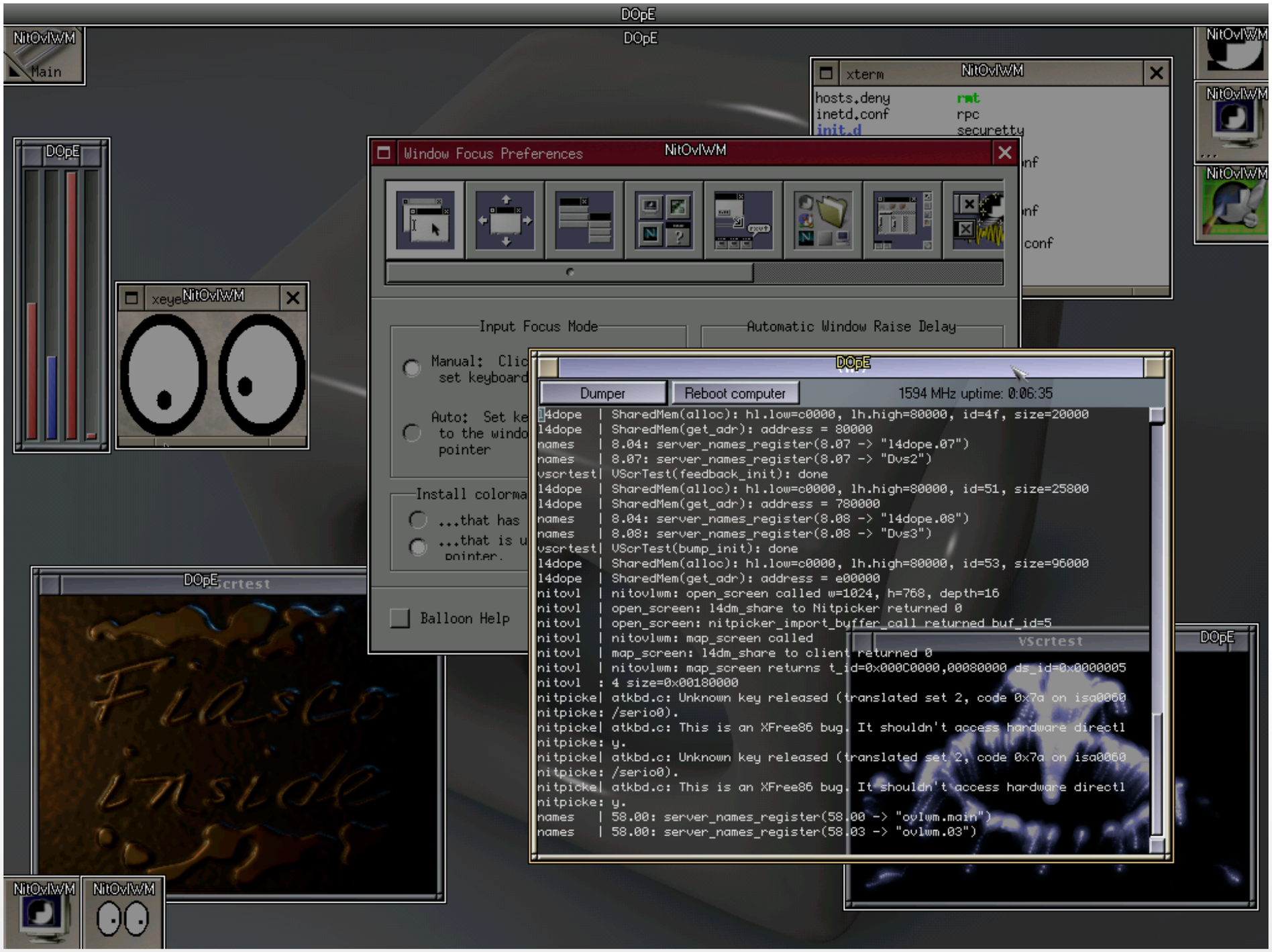

VPFS
App
VPFS can access secrets only, if its own vPCR and the vPCR for the app match the respective expected values.
L4Linux
TPM Multiplexer
TPM Driver
Microkernel

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
rpc
securetty
Window Focus Preferences
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
xeyes
Dumper
Reboot computer
1594 MHz uptime: 0:06:35
14dope | SharedMem(alloc): hl.low=c0000, lh.high=80000, id=4f, size=20000
14dope | SharedMem(get_adr): address = 80000
names | 8.04: server_names_register(8.07 -> "14dope.07")
names | 8.07: server_names_register(8.07 -> "Dvs2")
vscrtest| VScrTest(feedback_init): done
14dope | SharedMem(alloc): hl.low=c0000, lh.high=80000, id=51, size=25800
14dope | SharedMem(get_adr): address = 780000
names | 8.04: server_names_register(8.08 -> "14dope.08")
names | 8.08: server_names_register(8.08 -> "Dvs3")
vscrtest| VScrTest(bump_init): done
14dope | SharedMem(alloc): hl.low=c0000, lh.high=80000, id=53, size=96000
14dope | SharedMem(get_adr): address = e00000
nitovl | nitovlwm: open_screen called w=1024, h=768, depth=16
nitovl | open_screen: 14dm_share to Nitpicker returned 0
nitovl | open_screen: nitpicker_import_buffer_call returned buf_id=5
nitovl | nitovlwm: map_screen called
nitovl | map_screen: 14dm_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")
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

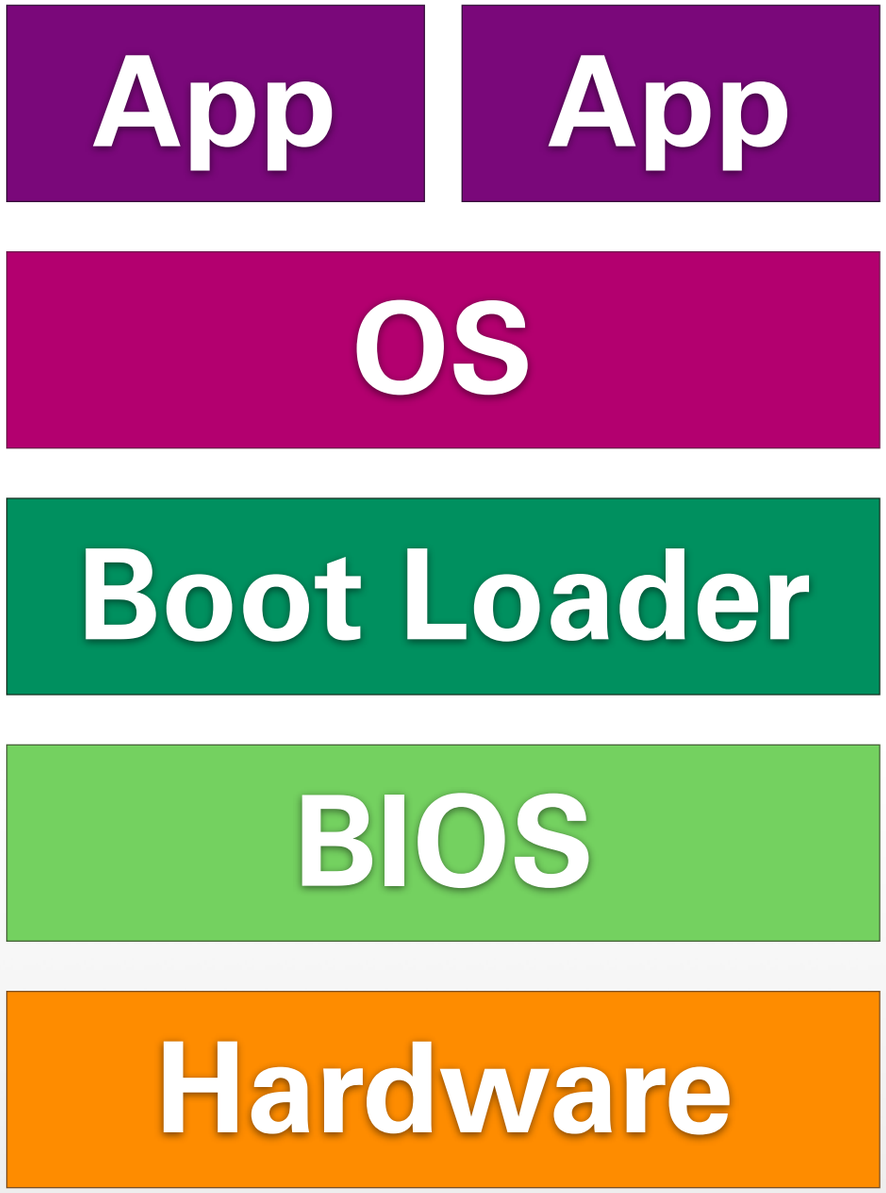
A SECOND LOOK AT THE CHAIN OF TRUST

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?

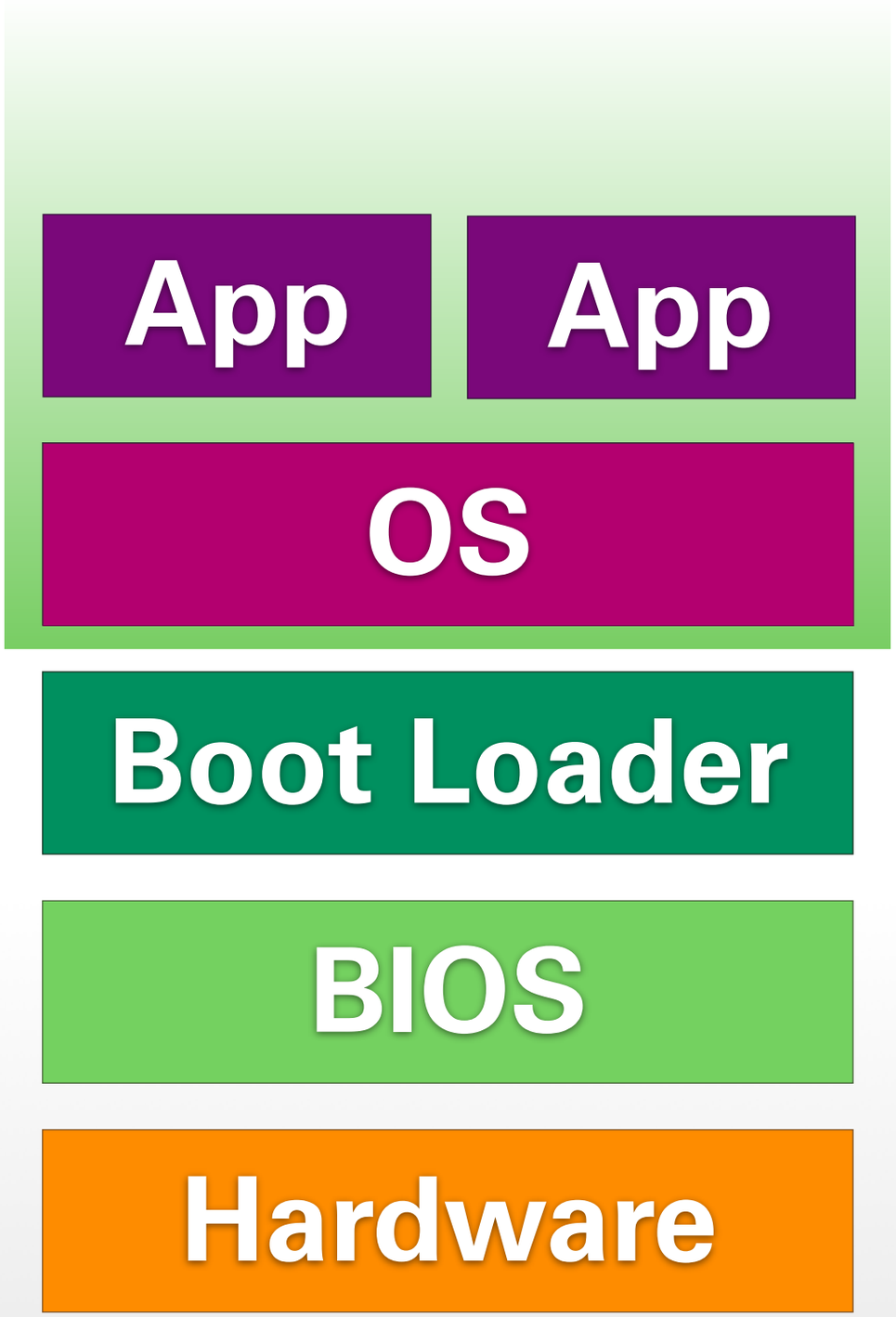


DRTM

- **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]



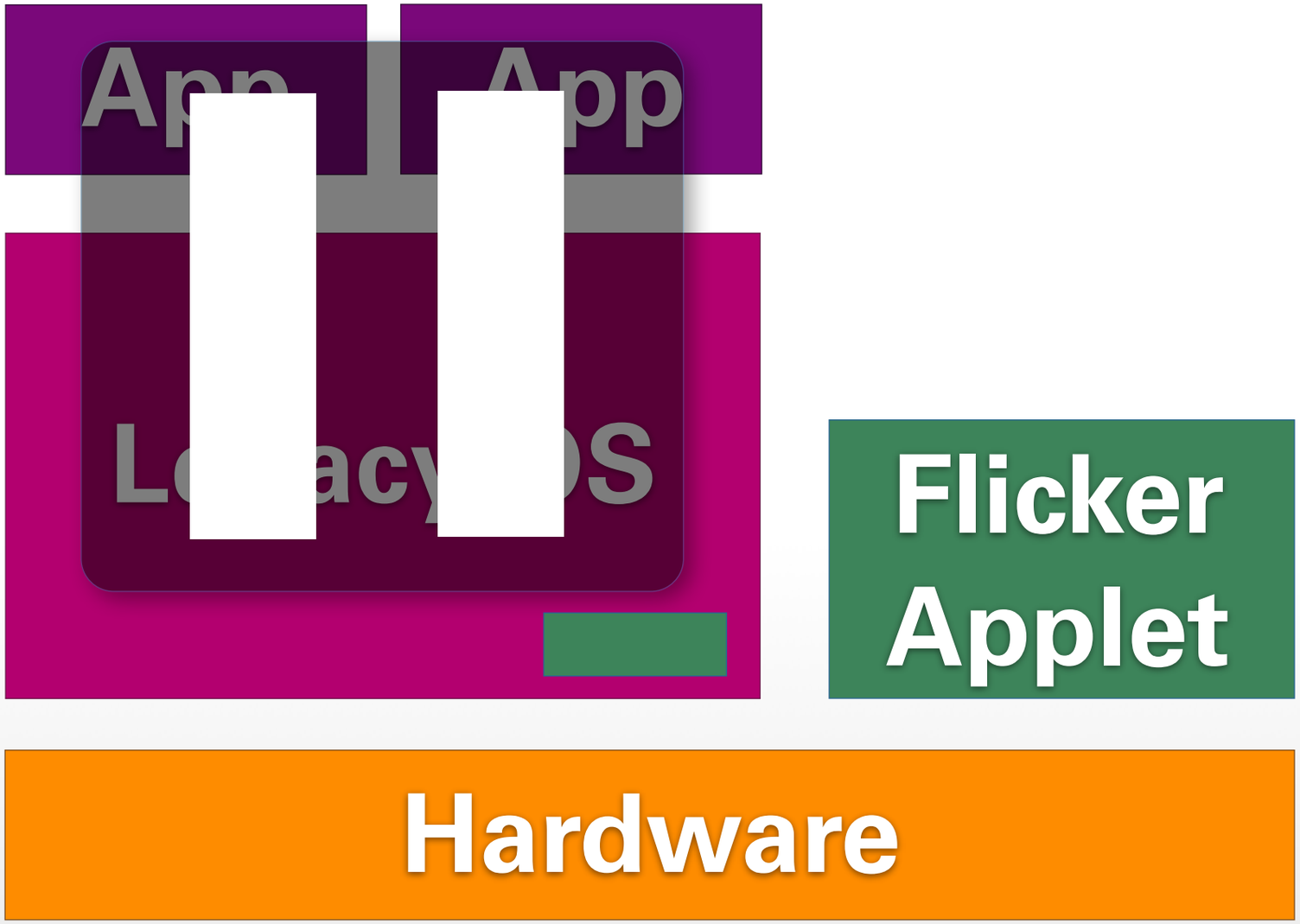
DRTM CHALLENGE

- 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
  - 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 22, 2019:
  - Lecture *„Resilience“*

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- [9] http://software.intel.com/en-us/intel-isa-extensions#pid-19539-1495