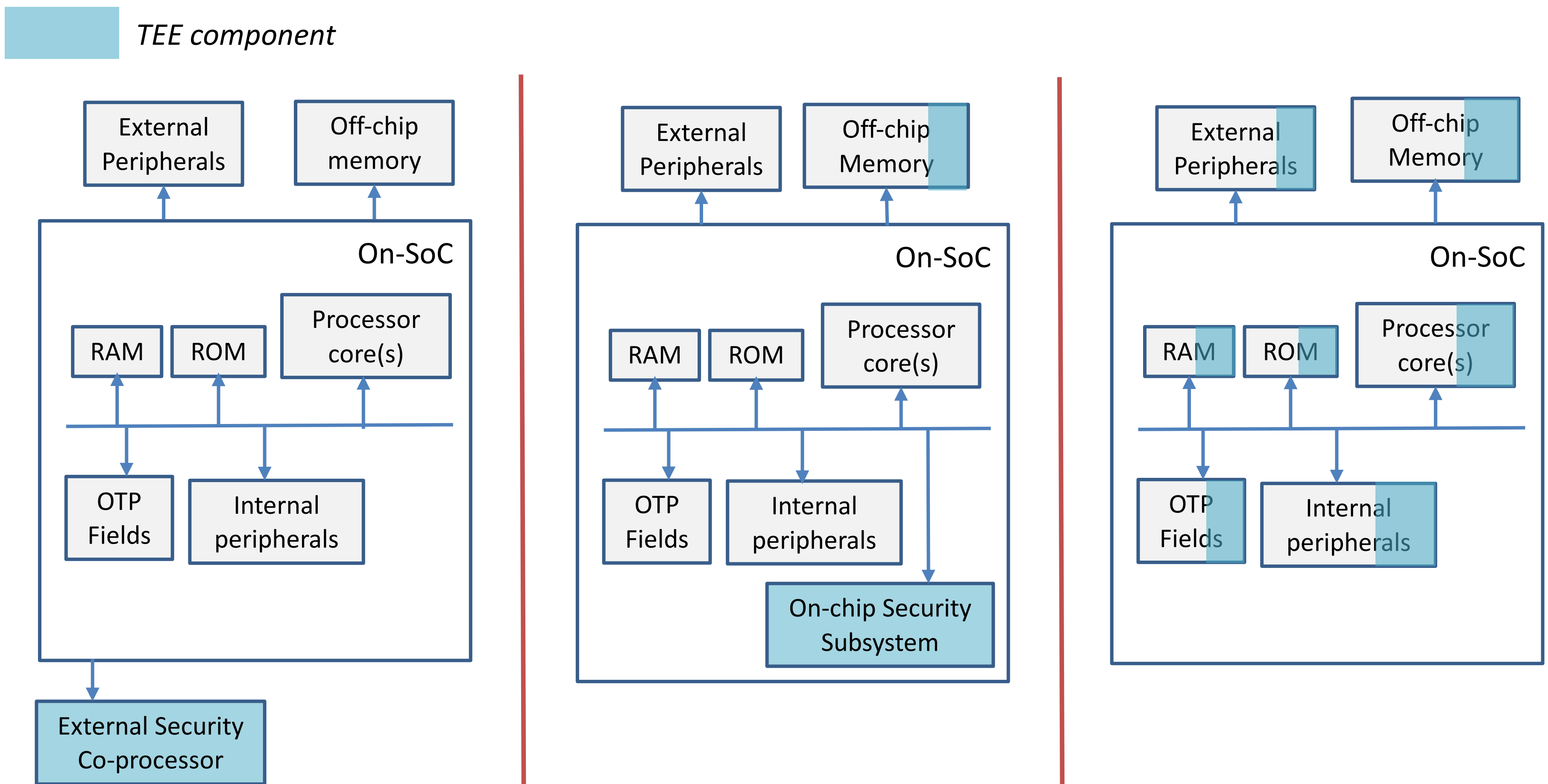
Module: Hardware Security

TRUSTED EXECUTION ENVIRONMENT (TEE)

Legend:
SoC : system-on-chip
OTP: one-time programmable

TEE hardware realization alternatives



External Secure Element (TPM, smart card)

Embedded Secure Element (smart card)

Processor Secure Environment (TrustZone, M-Shield)

Figure adapted from: Global Platform. TEE system architecture. 2011.

TEE Specifications: www.trustedcomputinggroup.org

TRUSTED COMPUTING GROUP TPM / TPM2

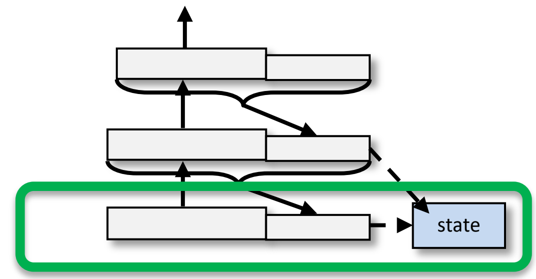
Trusted Platform Module (TPM)

- Collects state information about a system
  - separate from system on which it reports

- For remote parties
  - well-defined **remote attestation**
  - **Authorization** for functions/objects in TPM

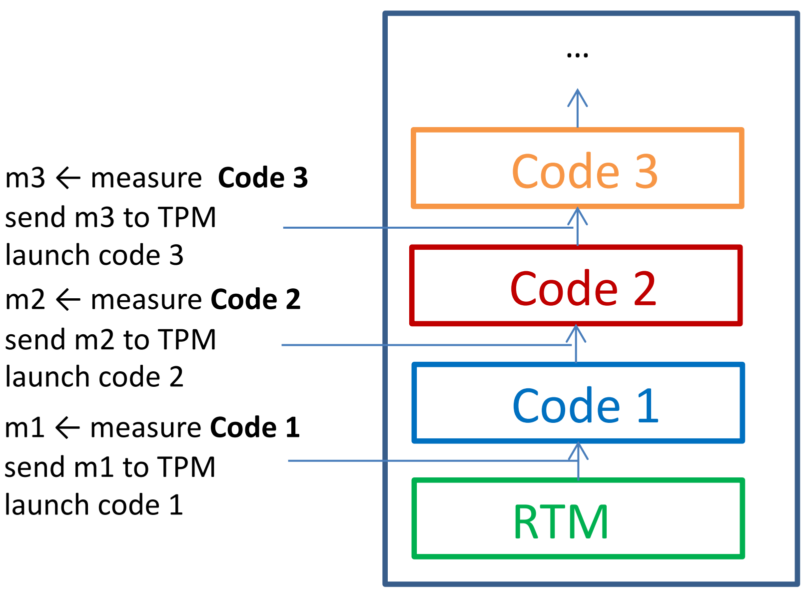
- Locally
  - **Generation/use** of TPM-resident keys
  - **Sealing:** Securing data for **non-volatile storage** (w/ binding)
    - *Binding: conditions to met when unsealing the data*
  - **Engine** for cryptographic operations

Platform Configuration Registers (PCRs)



Authenticated boot

- Integrity-protected registers
  - in volatile memory
  - represent current system configuration
- Store aggregated platform "state" measurement
  - a given state reached ONLY via the correct "extension" sequence
  - Requires a root of trust for measurement (RTM)



$H_{new} = H(H_{old} \mid new)$

$H_0 = 0$

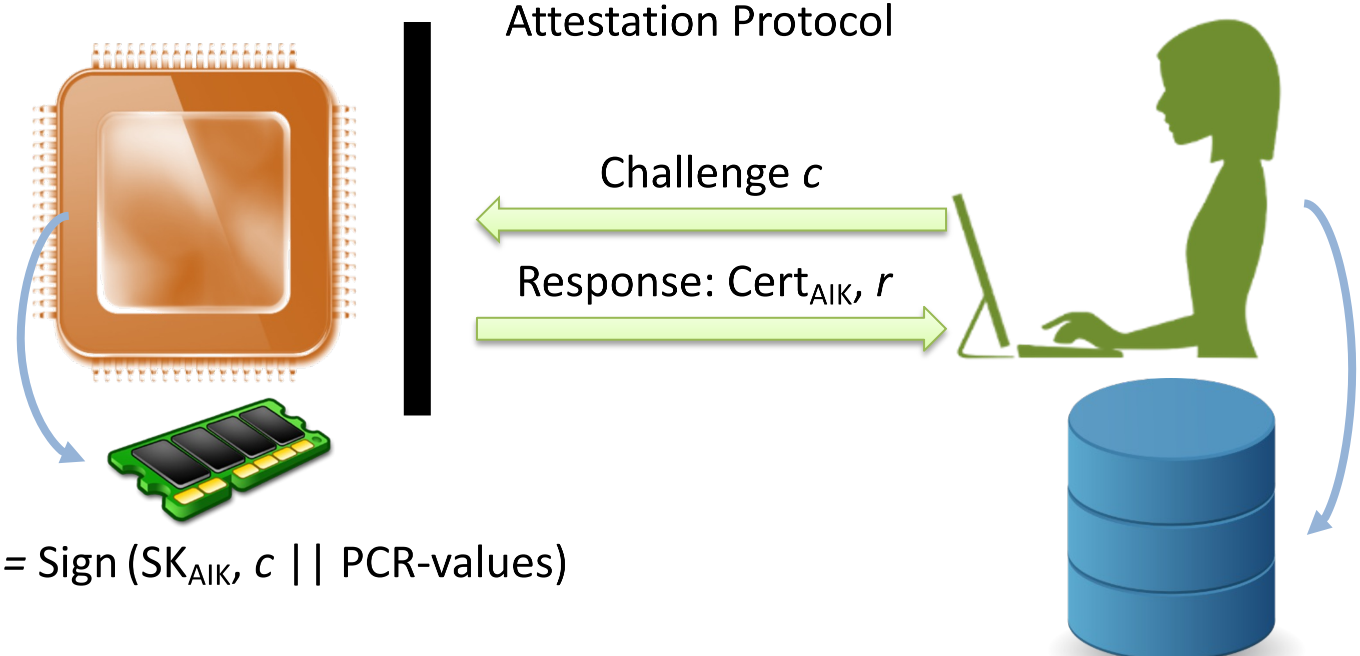
$H_1 = H(0|m1)$

$H_2 = H(H(0|m1)|m2)$

$H_3 = H(H(H(0|m1)|m2)|m3)$

TPM Remote Attestation

Goal: Check whether the prover is in a trustworthy state



"TPM Quote" r = Sign (SK_{AIK}, c || PCR-values)

Attestation Identity Key (AIK) is a unique keypair whose private key (SK_{AIK}) is *TPM-protected*
$Cert_{AIK}$ certificate for PK_{AIK} issued by, e.g., manufacturer

Sealing

Goal: Bind secret data to a specific configuration

- E.g.,
  - create RSA keypair PK/SK when PCR_X is Y
  - bind private key: $Enc_{SRK}(SK, PCR_X=Y)$
    - SRK is known only to TPM (cf. “device key” K_D)
    - “**Storage Root Key**” (created on TPM “take ownership” process)
  - TPM will “unseal” key **iff** PCR_X value is Y
    - Y is the “reference value”

Isolated Execution with TPMs

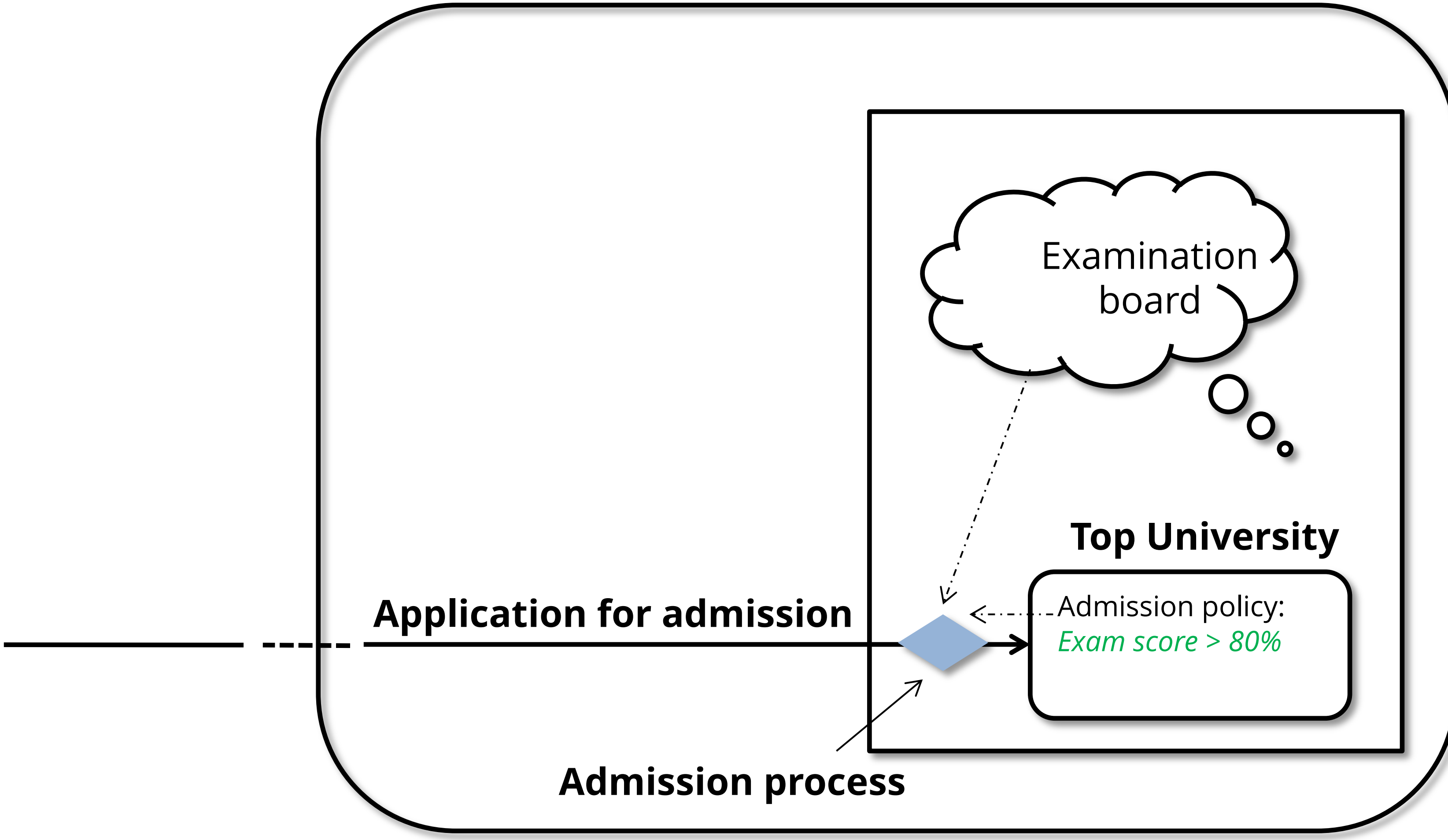
Dynamic RTM

- Dynamic PCRs (17-23) set to -1 on boot
- Special CPU instruction to
  - reset dynamic PCRs to 0
  - measure and extend a code block to PCR 17
  - launch that code
- "Late launch" of a hypervisor
- Can be used as a TEE for arbitrary code: Flicker by McCune et al: https://doi.org/10.1145/1352592.1352625

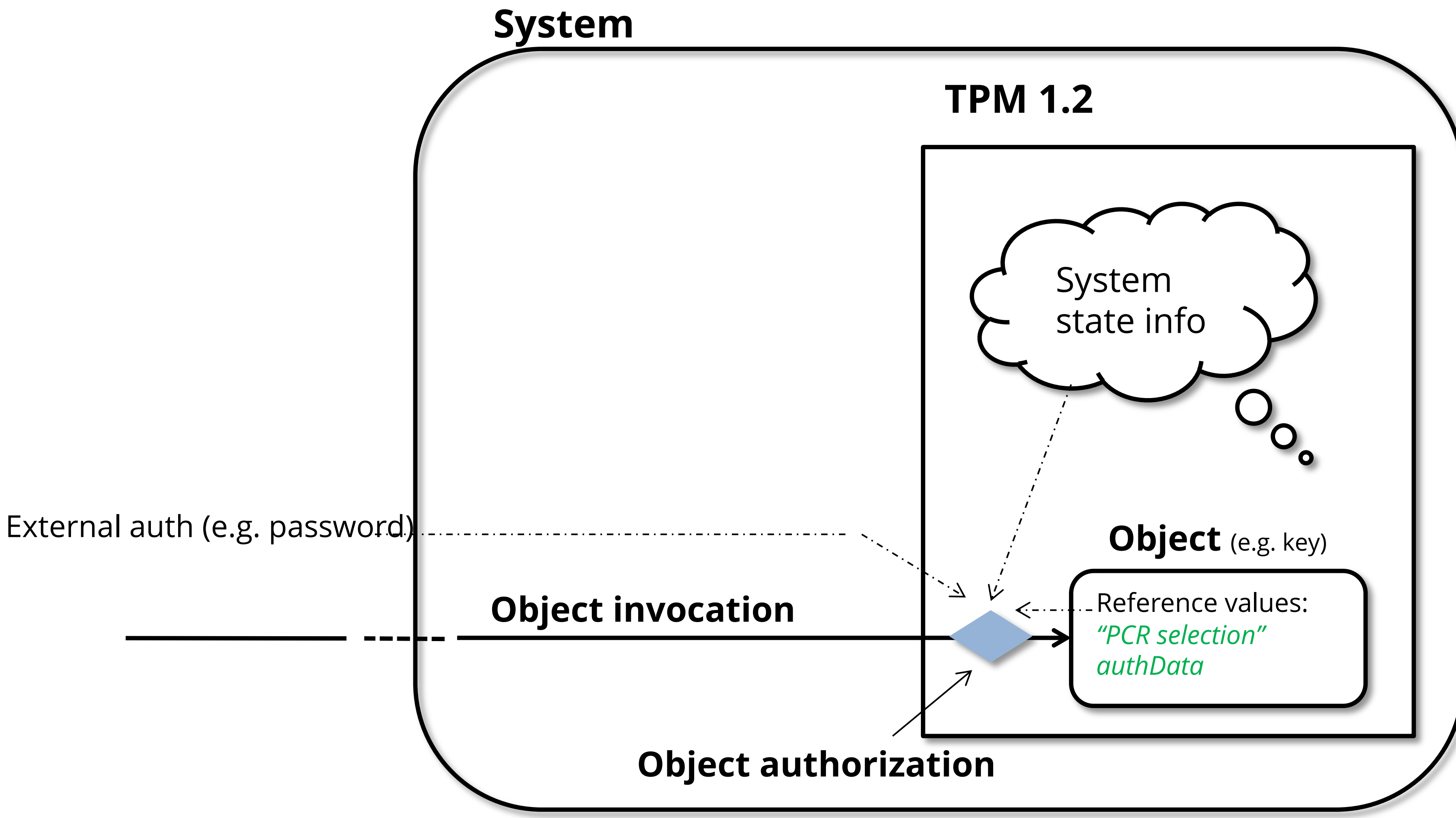
TPM authorization

- Authorization essential for access to sensitive TPM services/resources.
- TPMs have **awareness of system state** (cf., removable smartcards)

Authorization example: university admissions

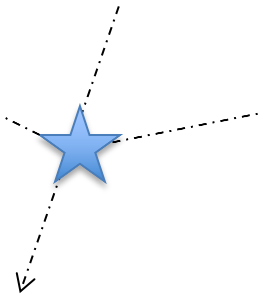


Authorization (policy) in TPM 1.2

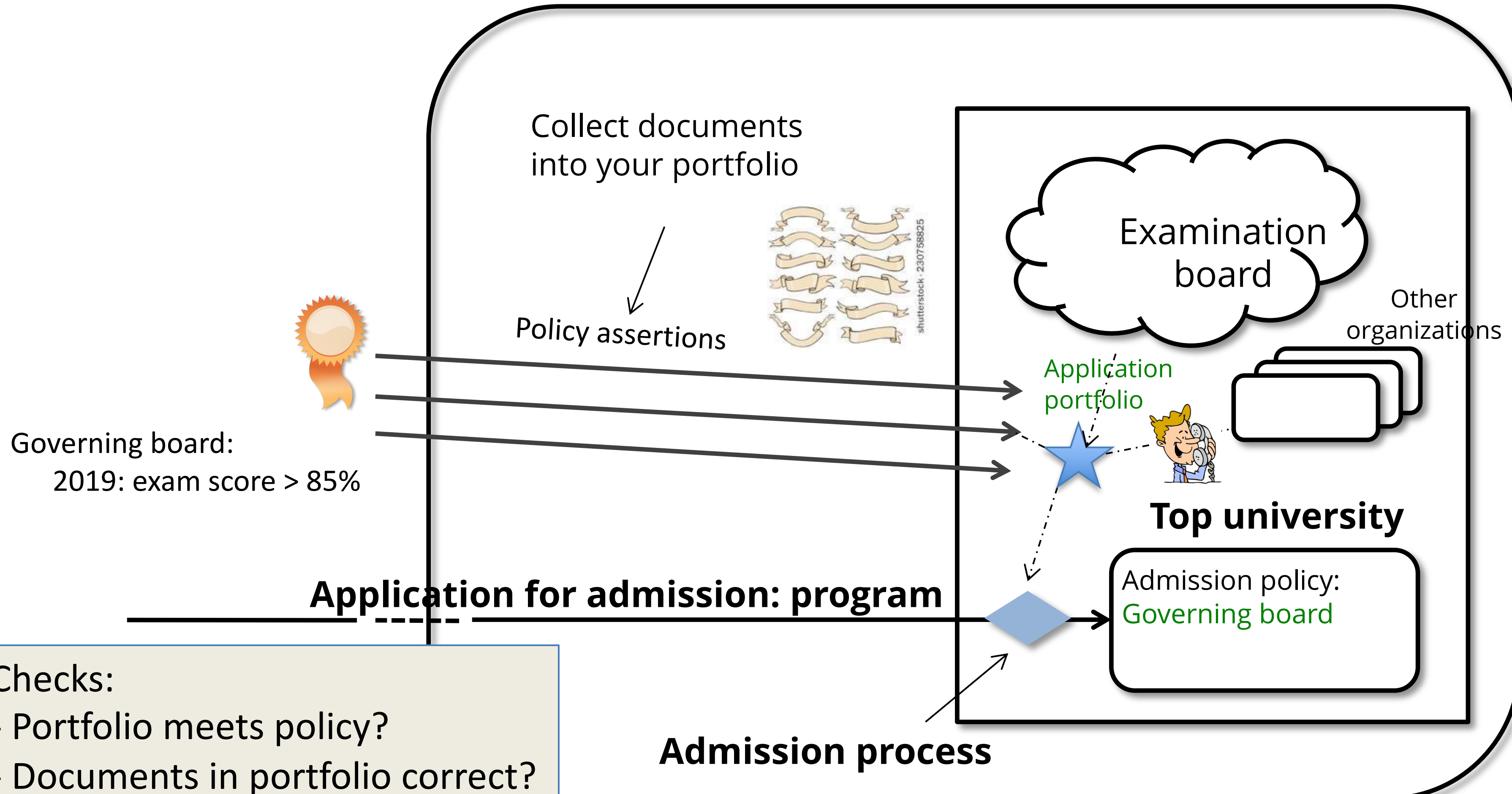


TPM 2.0

- More expressive policy definition model
- Various policy preconditions
- Logical operations (AND, OR)
- A policy session accumulates all authorization information

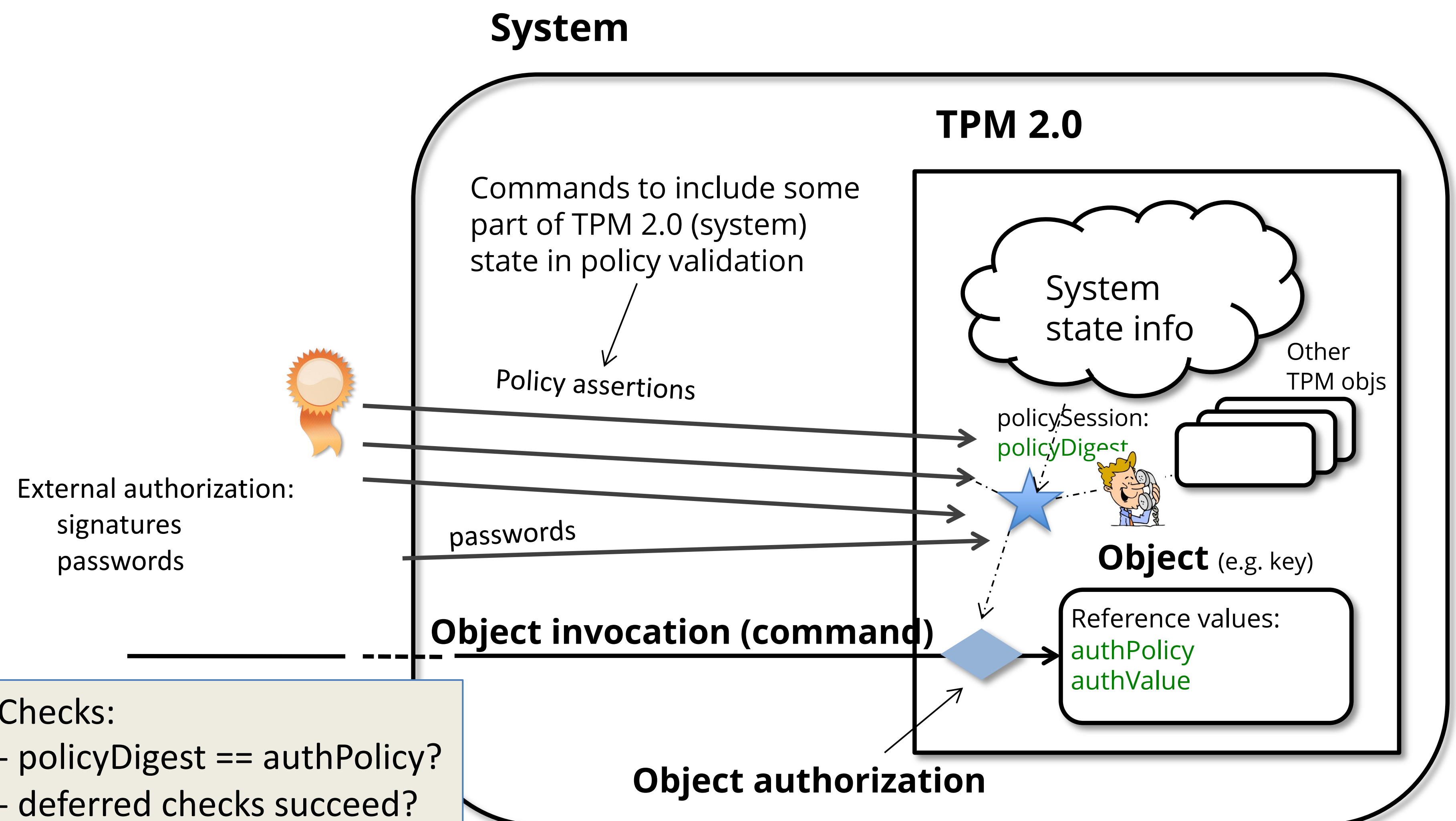


University admissions 2.0



Checks:
- Portfolio meets policy?
- Documents in portfolio correct?

Authorization (policy) in TPM 2.0

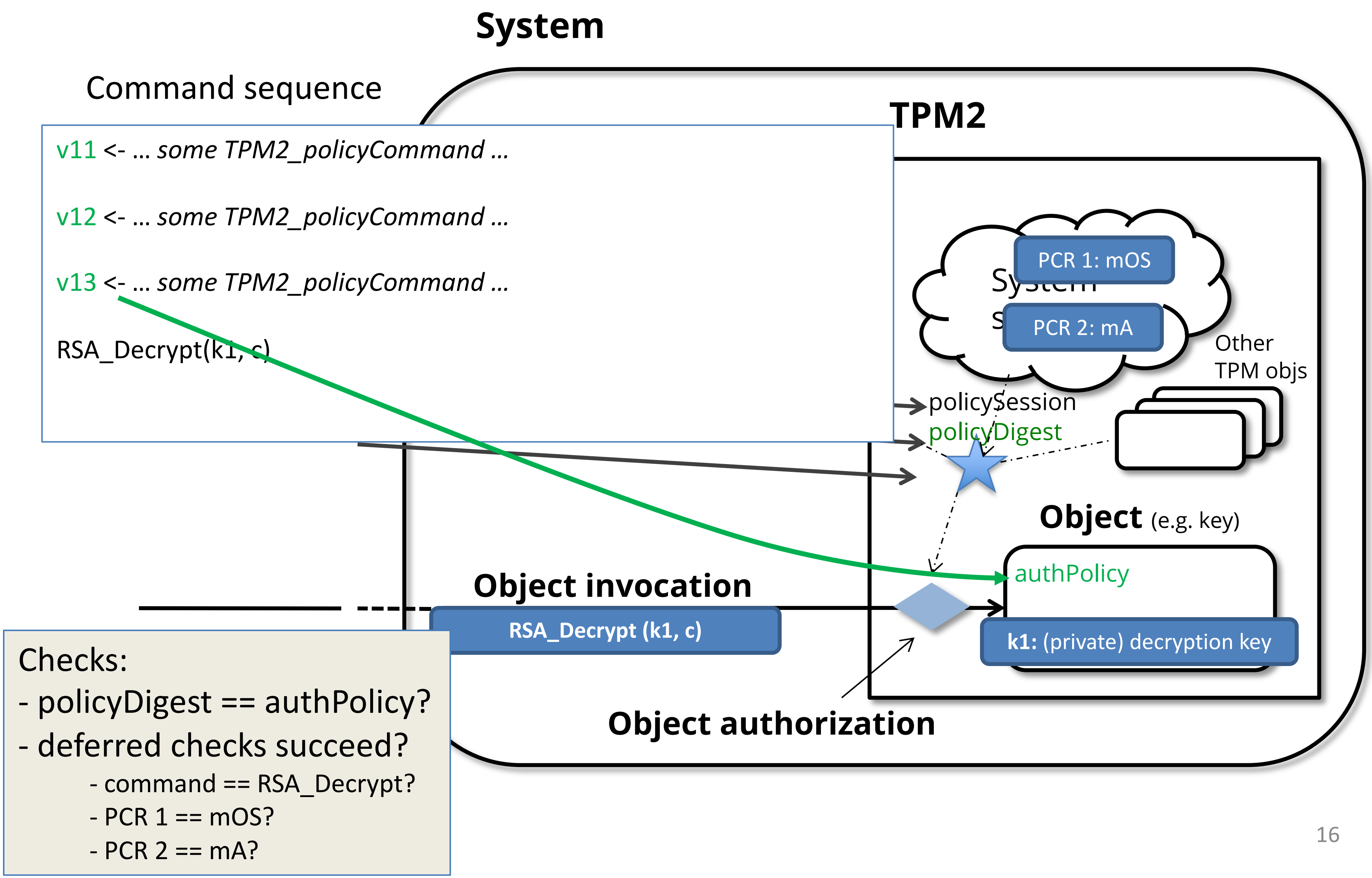


Checks:
- policyDigest == authPolicy?
- deferred checks succeed?
  - command == X?
  - PCR 1 Y == Z?

Authorization Policy Example

- Allow app A (and no other app) to use a TPM-protected RSA keypair **k1**
  - Only when a certain OS is in use
- Assume that
  - When right OS is used, **PCR 1 = mOS**
  - When app A in foreground, **PCR 2 = mA**

Enforcing the example policy



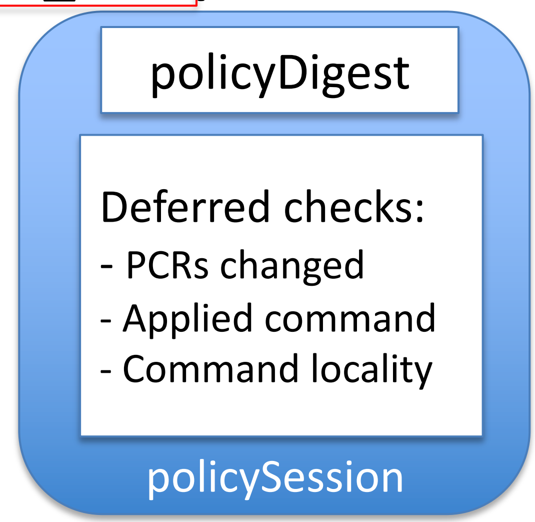
TPM2 Policy Session Contents

- accumulated session policy value: **policyDigest**

newDigestValue := H(oldDigestValue ||
commandCode || state_info)

- Some policy commands **reset** value

IF condition THEN
newDigestValue := H(0 || commandCode
|| state_info)



- **deferred policy checks** at object access time.

TPM2 Policy Command Examples

- **TPM2_PolicyPCR:** PCR values

  update *policyDigest* with *[pcr index, pcr value]*

  newDigest := H(oldDigest || TPM_CC_PolicyPCR || pcrs || digestTPM)

- **TPM2_PolicyNV:** reference value and operation (<, >, eq) for non-volatile memory area

  e.g., *if counter5 > 2 then*
  update *policyDigest* with *[ref, op, mem.area]*

  newDigest := H(oldDigest || TPM_CC_PolicyNV || args || nvIndex->Name)

TPM2 Deferred Policy Example

- **TPM2_PolicyCommandCode:** Check command during "object invocation" :

  update *policyDigest* with *[command code]*

  newDigest := H(oldDigest || TPM_CC_PolicyCommandCode || code)

  additionally save *policySession->commandCode := command code*

policySession->commandCode checked before object invocation!

Skip to example

Other policy commands

- **TPM2_PolicyOR:** Authorize one of several options:
  Input: *List* of digest values <D1, D2, D3, .. >

  IF *policyDigest* in *List* **THEN**
  newDigest := H(0 || TPM2_CC_PolicyOR || List)

- **TPM2_PolicyAuthorize:** Validate a signature on a policyDigest:
  Input: signature and pubic key
  IF signature validates **AND** signed text matches *policyDigest* **THEN**
  newDigest := H(0 || TPM2_CC_PolicyAuthorize|| **H(pub)**|| ..)

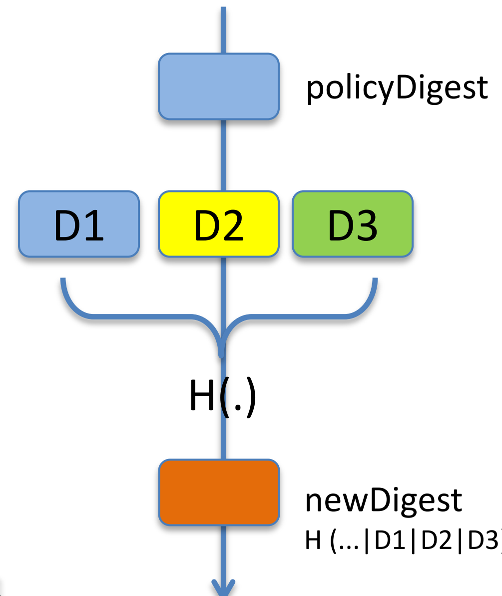
Policy disjunction

TPM2_PolicyOR: Authorize one of several options:

Input: *List* of digest values <D1, D2, D3, .. >

IF *policySession->policyDigest* in *List* **THEN**

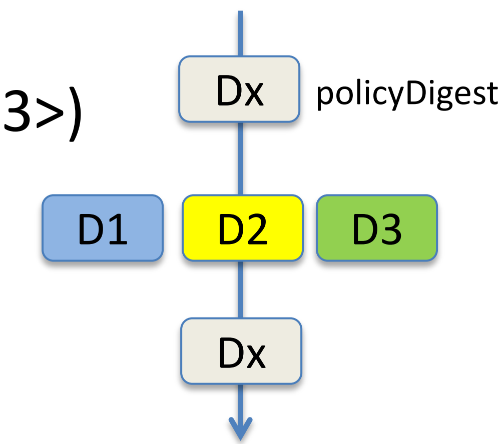
newDigest := H(0 || TPM2_CC_PolicyOR || List)



(Successful OR)

Reasoning: For a wrong digest Dx (not in <D1 D2 D3>) difficult to find *List2* = <Dx Dy, Dz, .. >

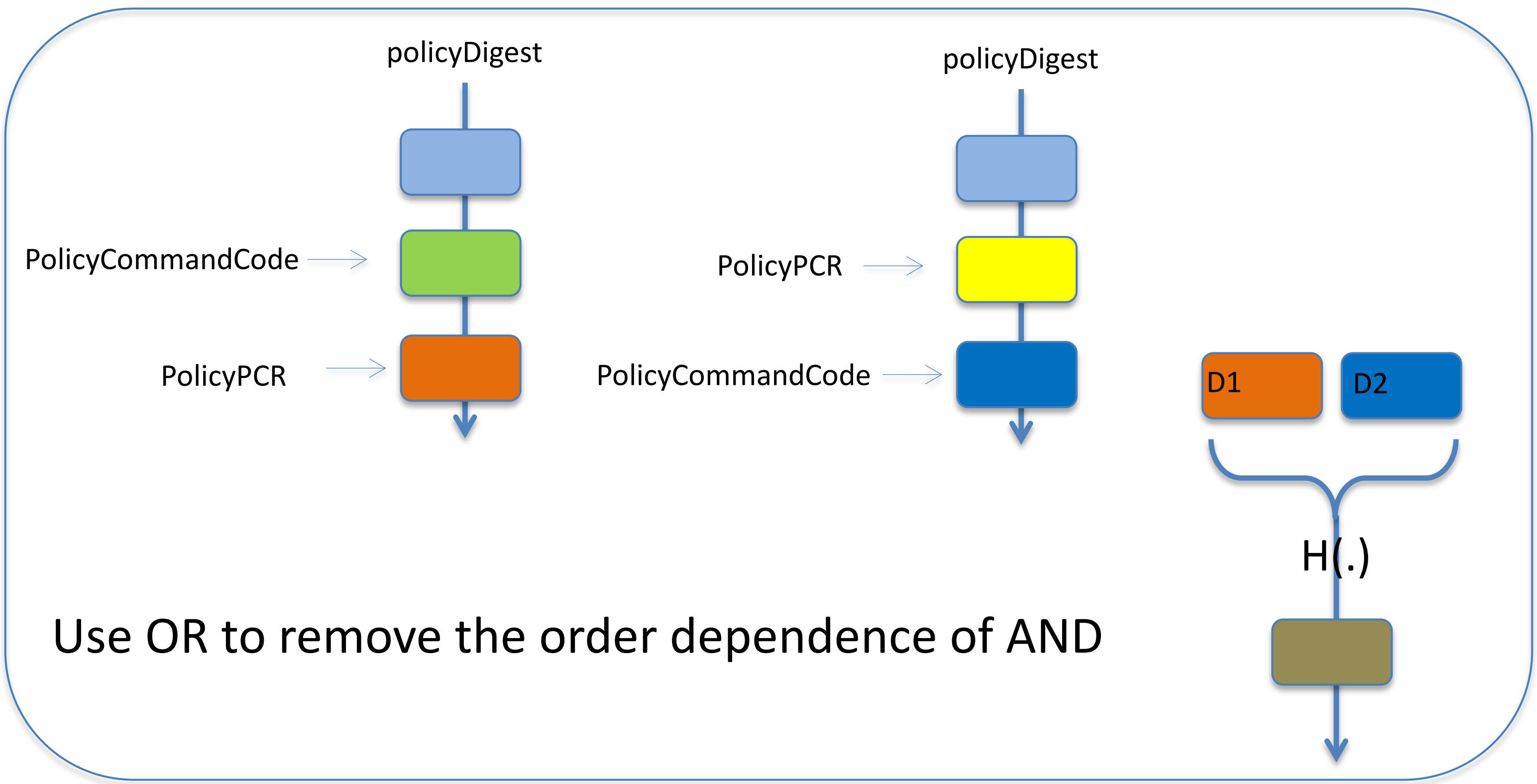
such that H(... |List) == H(... |List2)



(Failing OR)

Policy conjunction

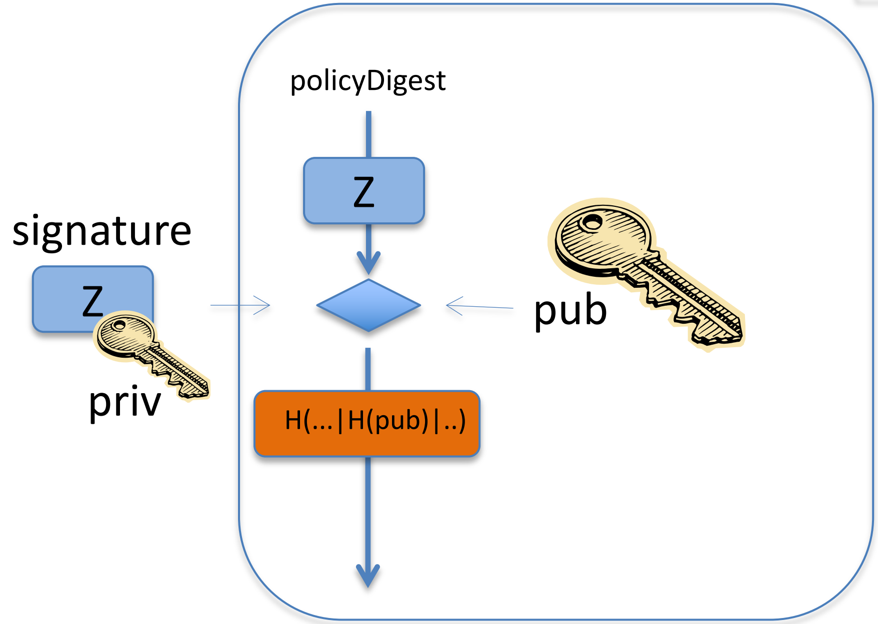
- No explicit AND command
- AND: consecutive auth. commands → order dependence

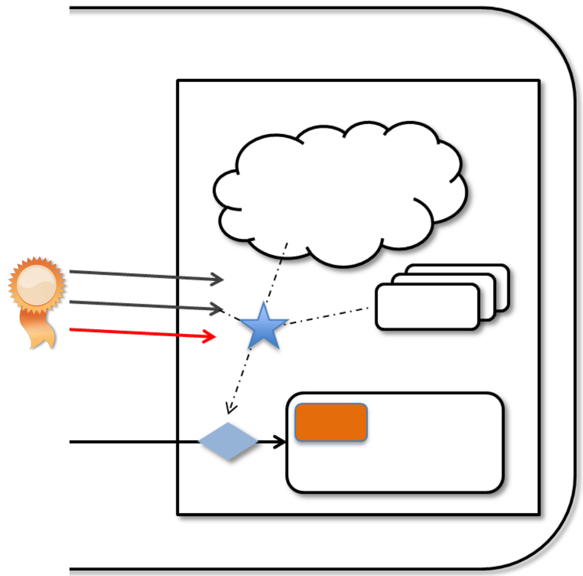


External Authorization

TPM2_PolicyAuthorize: Validate a signature on a policyDigest:

IF signature validates **AND** signed text matches *policySession->policyDigest*
THEN
newDigest := H(0 || TPM2_CC_PolicyAuthorize || **H(pub)** || ..)



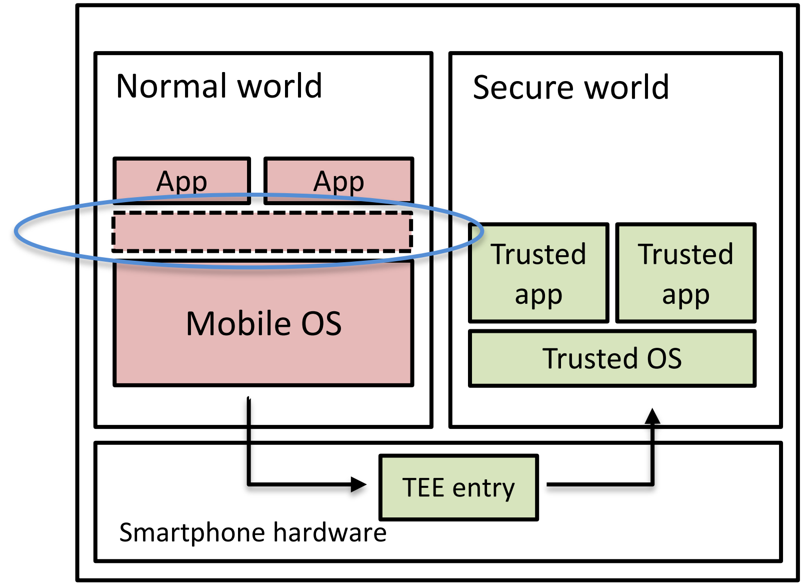


Using TEEs

ANDROID KEYSTORE

Mobile TEE deployment

- TrustZone support available in majority of current smartphones
- Mainly used for manufacturer internal purposes
  - Digital rights management, Subsidy lock…
- *APIs for developers?*



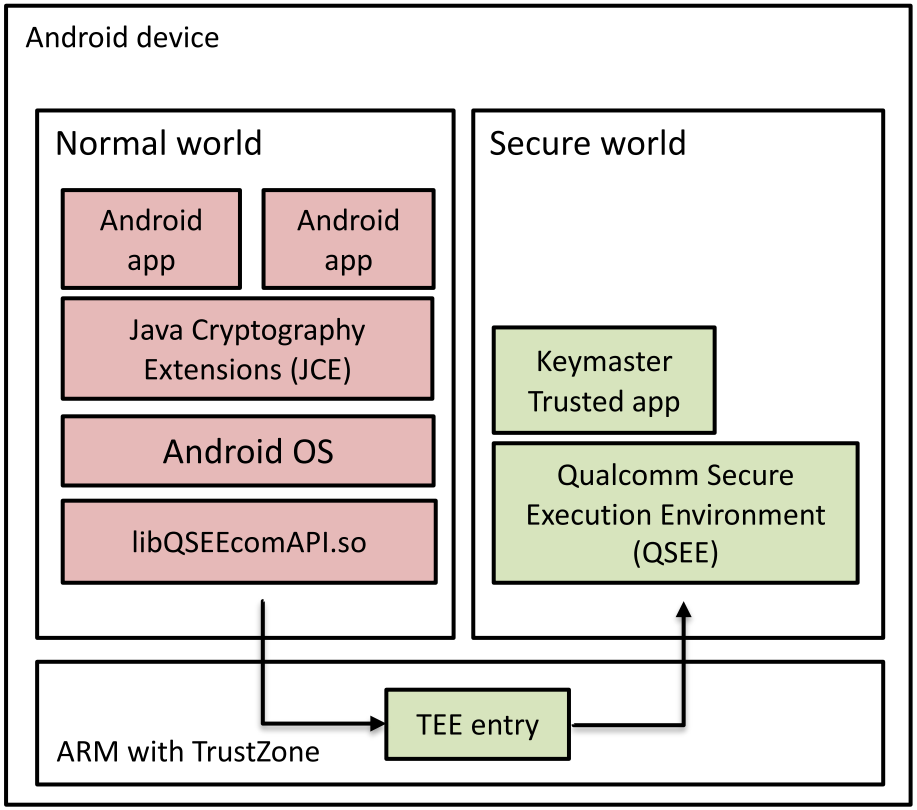
Android Key Store API

Android Key Store example

```
// create RSA key pair
Context ctx;
KeyPairGeneratorSpec spec = new
    KeyPairGeneratorSpec.Builder("key1",KeyProperties.PURPOSE_
SIGN);
…
spec.build();

KeyPairGenerator gen =
    KeyPairGenerator.getInstance(KeyProperties.KEY_ALGORITHM_R
SA,     "AndroidKeyStore");
gen.initialize(spec);
KeyPair kp = gen.generateKeyPair();

// make a signature
Signature sig = Signature.getInstance("SHA256withRSA/PSS"):
sig.initSign(kp.getPrivate()):
```

Android, Hardware-backed Keystore, 2015-2018

Key Store implementation: example



Keymaster operations

- Public key algorithms
- Symmetric key algorithms (AES, HMAC) from v1.0
- Access control, key usage restrictions
- Key attestation (from v2.0), "ID attestation" (from v3.0)
- Android Protected Confirmation (Android 9, API level 28)

Persistent storage on Normal World

Elenkov. Credential storage enhancements in Android 4.3. 2013
Android, Hardware-backed Keystore, 2015-2018
Android, Protected Confirmation, 2018

Android Key Store

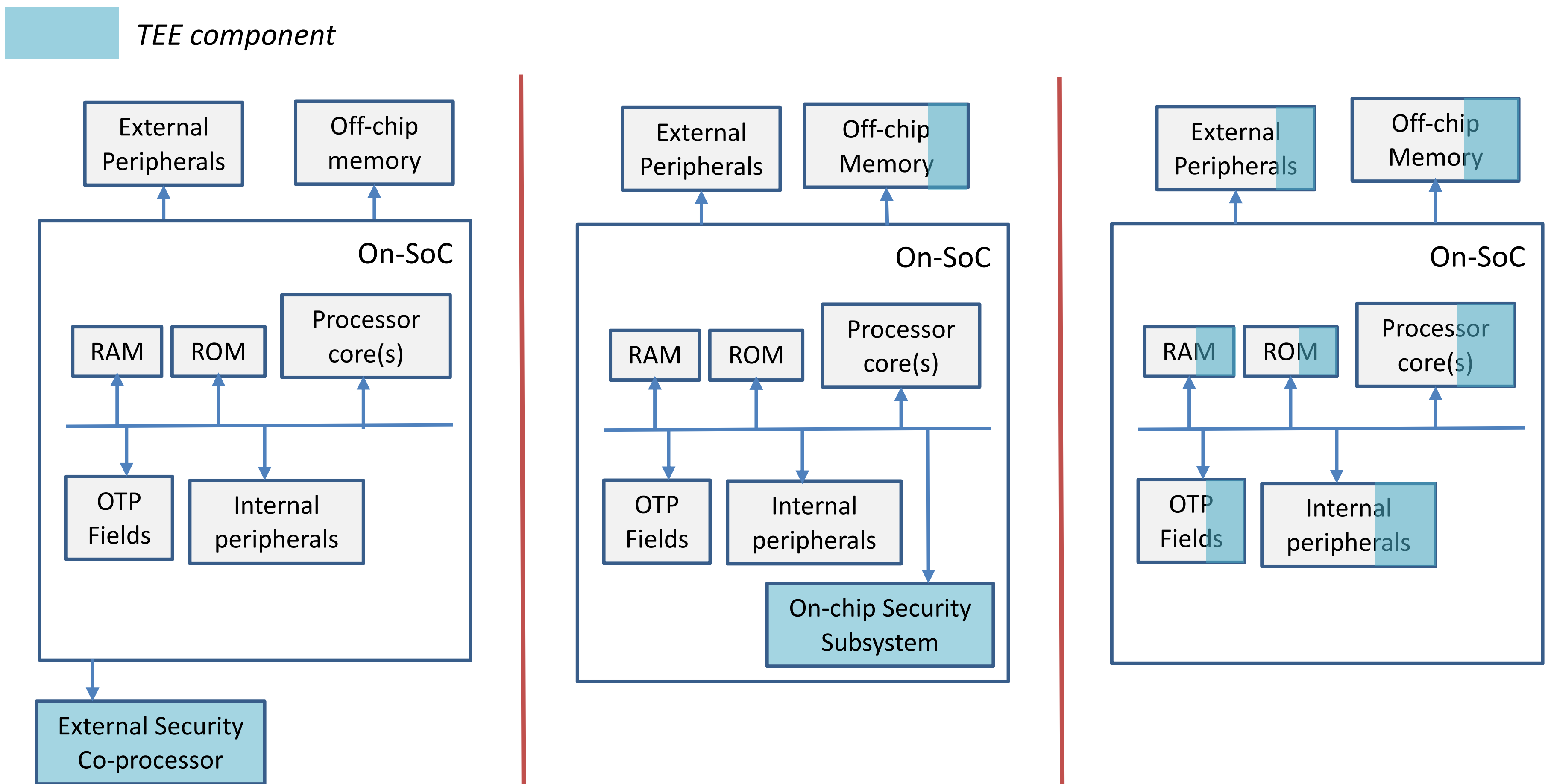
- Available operations
  - Signatures
  - Encryption/decryption
  - Attestation, confirmation

- Developers cannot utilize programmability of mobile TEEs
  - Not possible to run arbitrary trusted applications

- Different API abstraction and architecture needed
  - Example: On-board Credentials
  - GlobalPlatform device working group specifications

Legend:
SoC : system-on-chip
OTP: one-time programmable

TEE hardware realization alternatives



External Secure Element (TPM, smart card)

Embedded Secure Element (smart card)

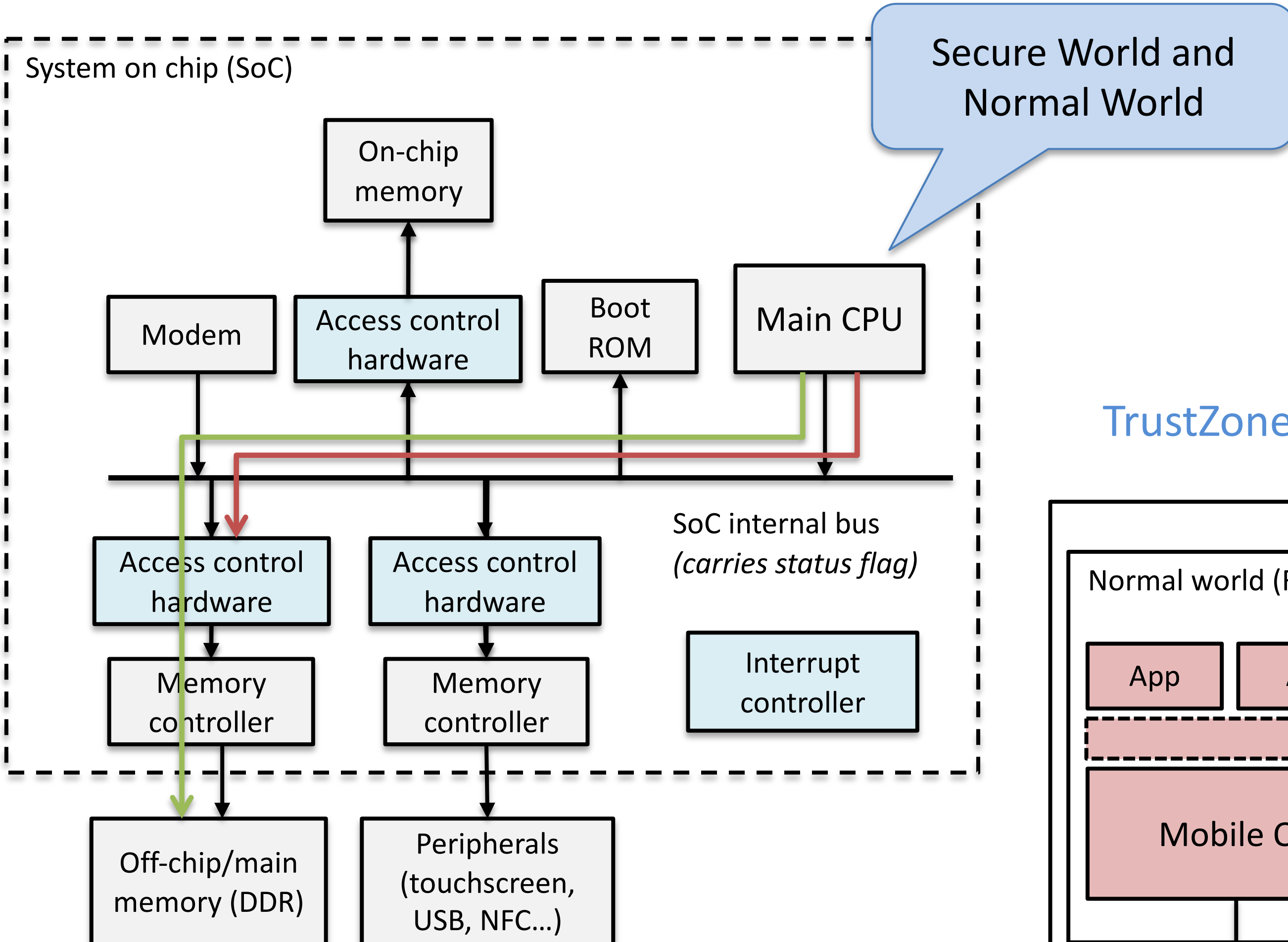
Processor Secure Environment (TrustZone, M-Shield)

Figure adapted from: Global Platform. TEE system architecture. 2011.

TEE instances

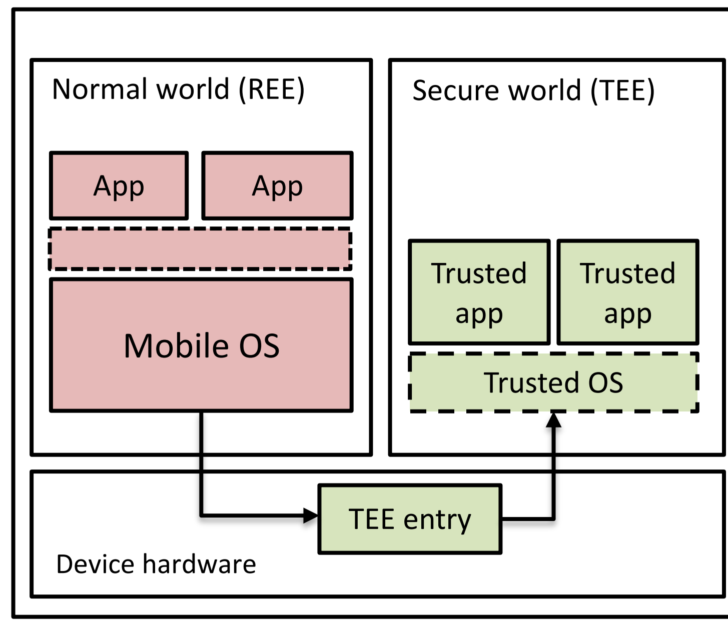
ARM TRUSTZONE

ARM TrustZone architecture



TrustZone hardware architecture

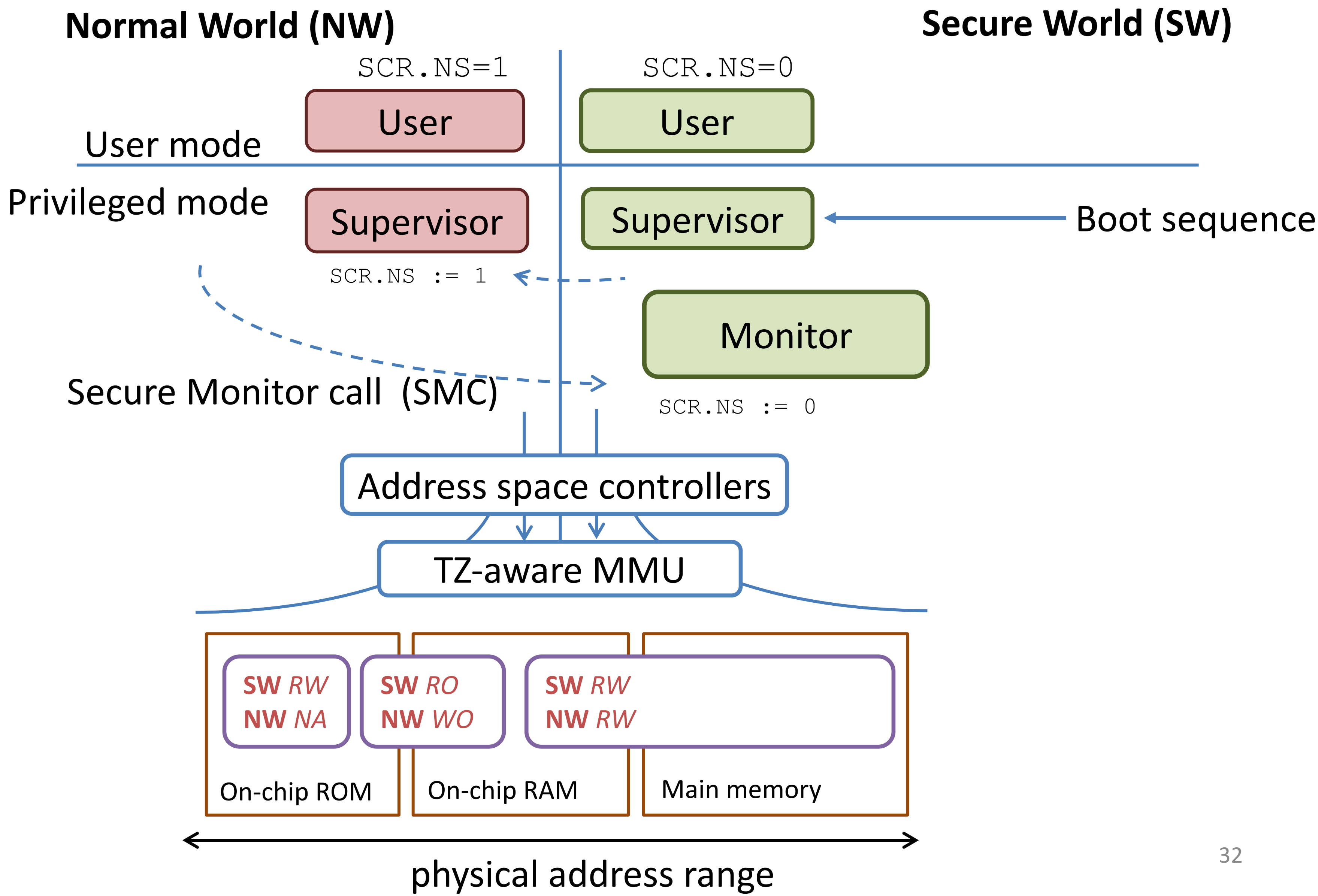
TrustZone system architecture



ARM Ltd., "[ARM Security Technology - Building a Secure System using TrustZone Technology]", Whitepaper 2009

Legend:
MMU: memory management unit

TrustZone overview



TrustZone example (1/2)

1. Boot begins in Secure World Supervisor mode (set access control)

Boot sequence → Secure World Supervisor

2. Copy code and keys from on-chip ROM to on-chip RAM

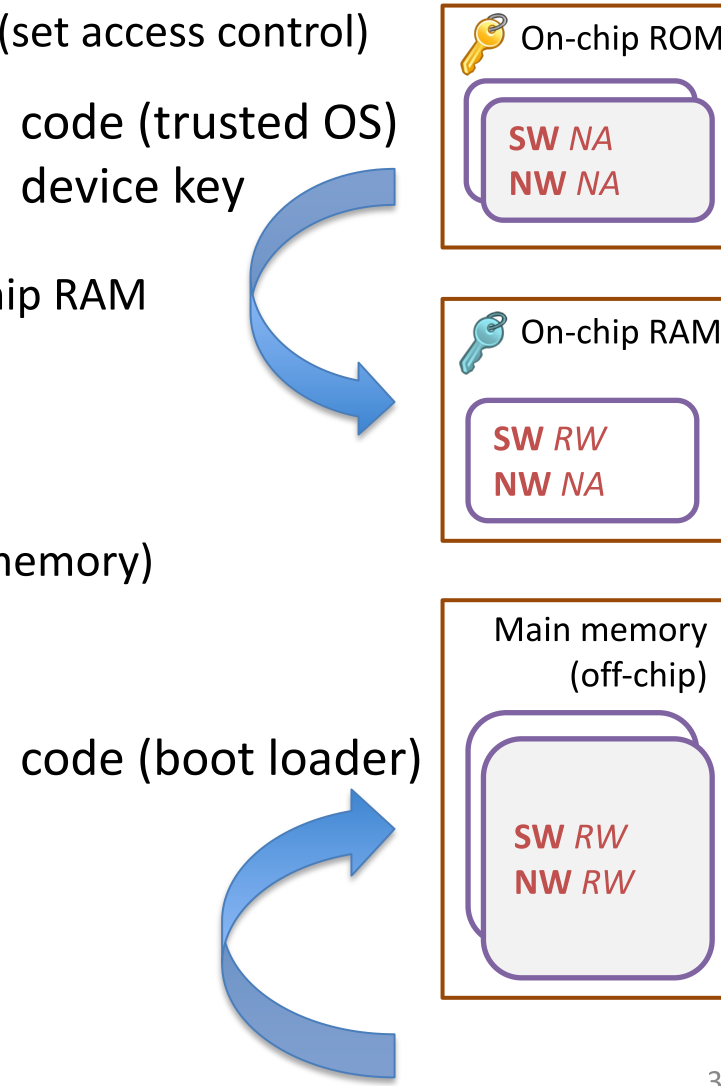
Secure World Supervisor

3. Configure address controller (protect on-chip memory)

Secure World Supervisor

4. Prepare for Normal World boot

Secure World Supervisor



TrustZone example (2/2)

5. Jump to Normal World Supervisor for traditional boot

Secure World Supervisor → Normal World Supervisor SCR.NS→1

An ordinary boot follows: Set up MMU, load OS, drivers…

6. Set up trusted application execution

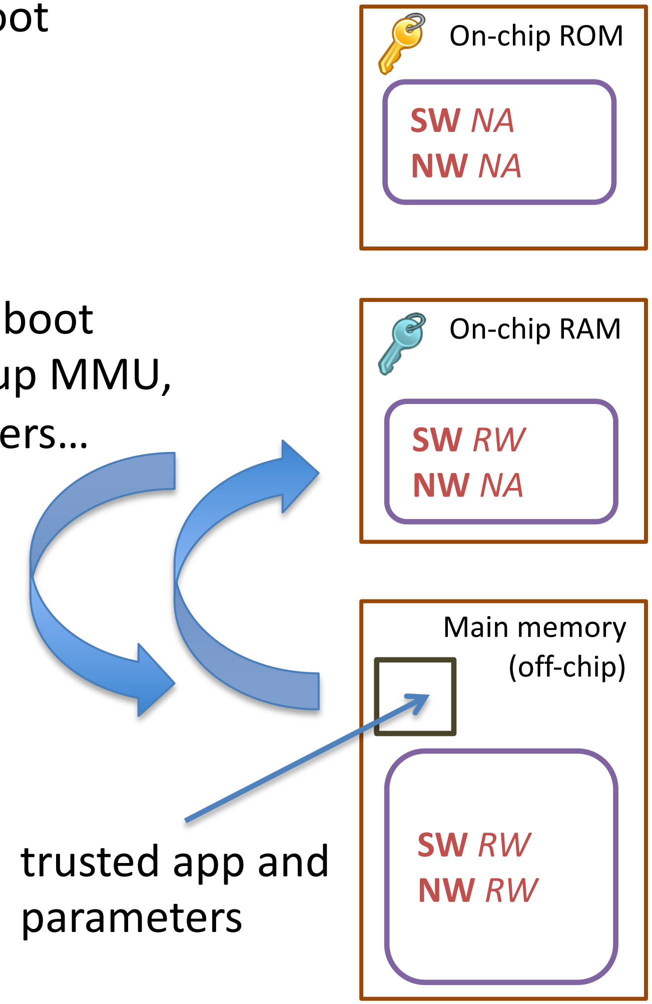
Normal World User

Supervisor

7. Execute trusted application

Normal World Supervisor → Secure World Monitor

SMC,
SCR.NS→0



Skip to GP

TZ-enabled CPUs

- TZ: set of ARM processor extensions
- Combined with other building blocks needed for TEEs
  - Trust root to verify code (e.g., hash of manufacturer's code signing key)
  - Device-secret initialized during chip manufacture
  - Monotonic counter or writable secure memory

Skip to GP

Secure state entry/exit in TrustZone

What happens during entry/exit?

- Store/restore all shared registers
  - Kernel: switching between processor modes
  - Secure monitor: switching between worlds
- Validate/(un)marshal parameters
  - TEE driver
- Reconfigure MMU
  - Secure monitor

Register banking: copies of registers

- Special purpose registers (SP, LR, SPSR)
  - Banked between modes, but not worlds
  - except at **highest privilege mode**
- Ordinary registers are not banked

TEE specifications:
https://www.globalplatform.org/specificationsdevice.asp

GLOBAL PLATFORM

Global Platform (GP)

GP standards for smart card systems used many years

- Examples: payment, ticketing
- Card interaction and provisioning protocols
- Reader terminal architecture and certification

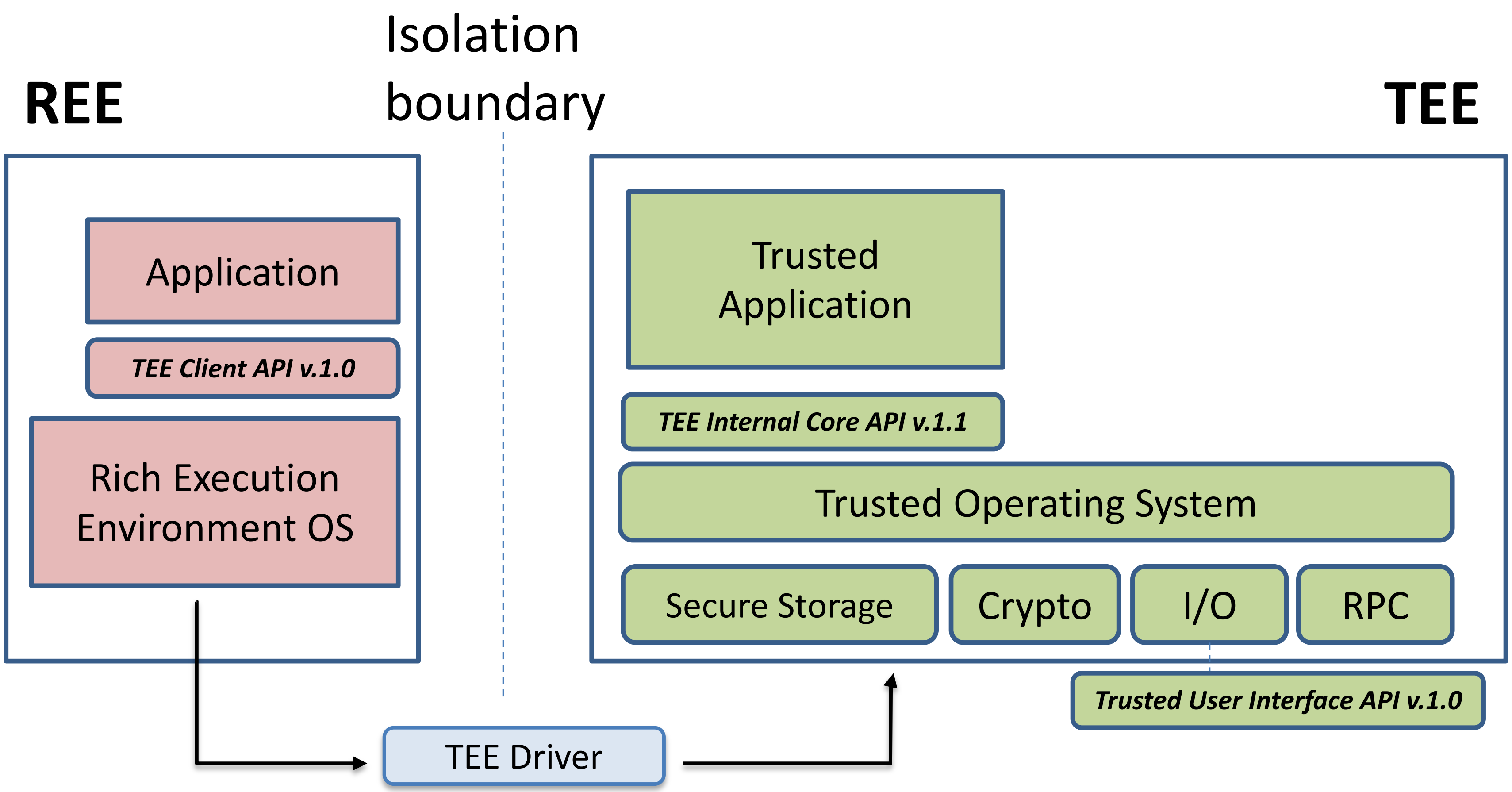
Recently GP has released standards for mobile TEEs

- Architecture and interfaces

http://www.globalplatform.org/specificationsdevice.asp

- TEE System Architecture
- TEE Client API Specification v.1.0
- TEE Internal Core API Specification v1.1
- Trusted User Interface API v 1.0

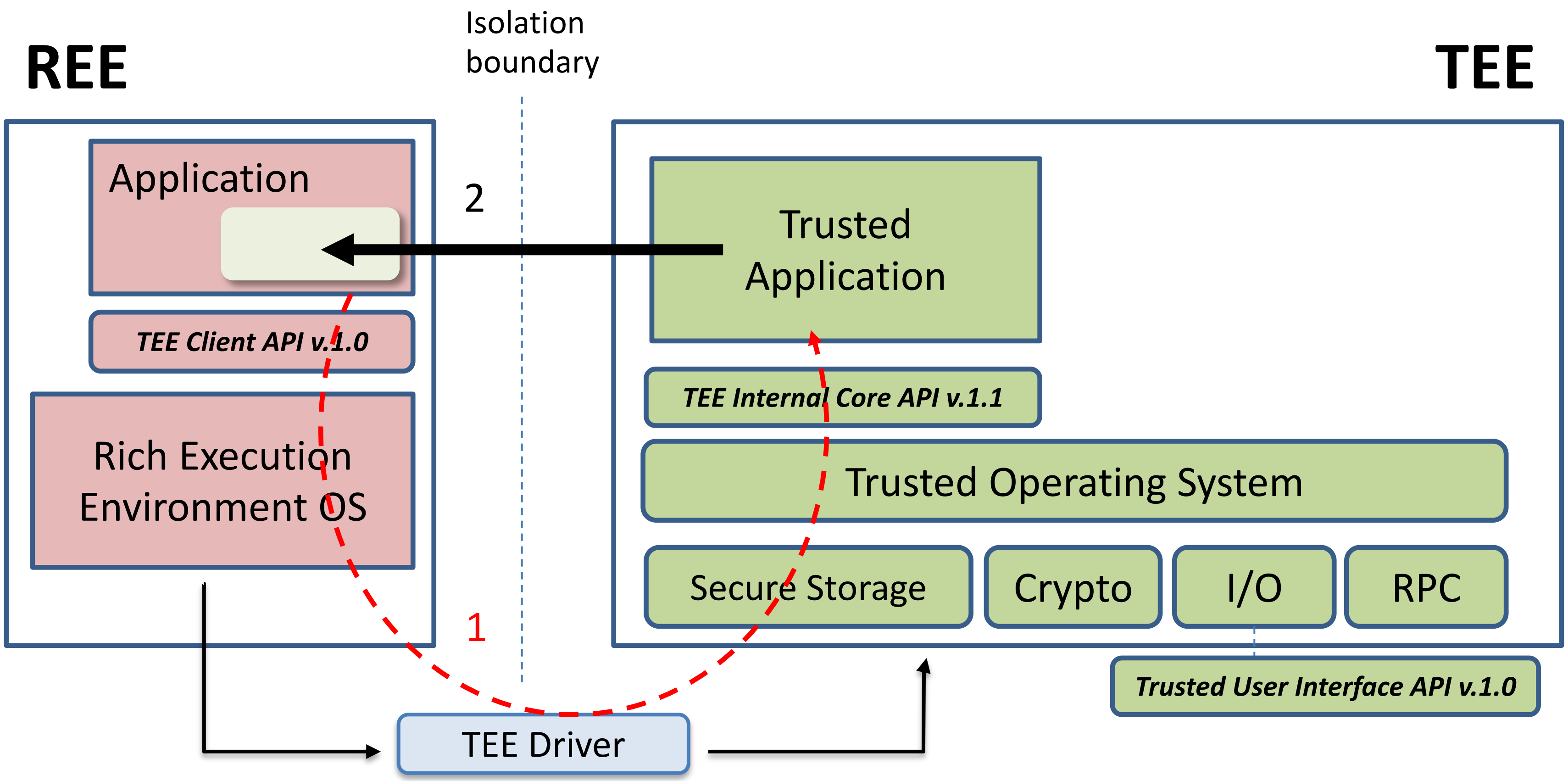
GP TEE System Architecture



Interaction with Trusted Application

REE App provides a pointer to its memory for the Trusted App

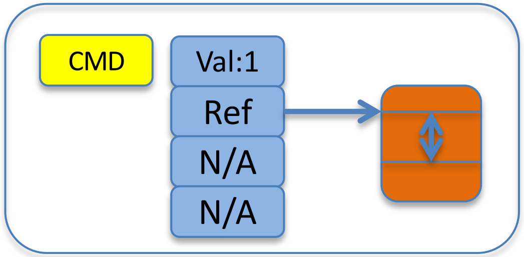
- Example: Efficient in place encryption



TEE Client API example

```c
// 1. initialize context
TEEC_InitializeContext(&context, …);

// 2. establish shared memory
sm.size = 20;
sm.flags = TEEC_MEM_INPUT | TEEC_MEM_OUTPUT;
TEEC_AllocateSharedMemory(&context, &sm);

// 3. open communication session
TEEC_OpenSession(&context, &session, …);

// 4. setup parameters
operation.paramTypes = TEEC_PARAM_TYPES(TEEC_VALUE_INPUT, …);
operation.params[0].value.a = 1;              // First parameter by value
operation.params[1].memref.parent = &sm;      // Second parameter by reference
operation.params[1].memref.offset = 0;
operation.params[1].memref.size = 20;

// 5. invoke command
result = TEEC_InvokeCommand(&session, CMD_ENCRYPT_INIT, &operation, NULL);
```

Parameters:



TEE Internal Core API example

```
// each Trusted App must implement the following functions…

// constructor and destructor
TA_CreateEntryPoint();
TA_DestroyEntryPoint();

// new session handling
TA_OpenSessionEntryPoint(uint32_t param_types, TEE_Param params[4],
                         void **session)
TA_CloseSessionEntryPoint (…)

// incoming command handling
TA_InvokeCommandEntryPoint(void *session, uint32_t cmd,
                           uint32_t param_types, TEE_Param params[4])
{
    switch(cmd)
    {
      case CMD_ENCRYPT_INIT:
        ....
    }
}
```

In Global Platform model Trusted Applications are command-driven

Storage and RPC (TEE internal Core API)

Secure storage: Trusted App can persistently store memory and objects

```
TEE_CreatePersistentObject(TEE_STORAGE_PRIVATE, flags, ..., handle)

TEE_ReadObjectData(handle, buffer, size, count);
TEE_WriteObjectData(handle, buffer, size);
TEE_SeekObjectData(handle, offset, ref);
TEE_TruncateObjectData(handle, size);
```

RPC: Communication with other TAs

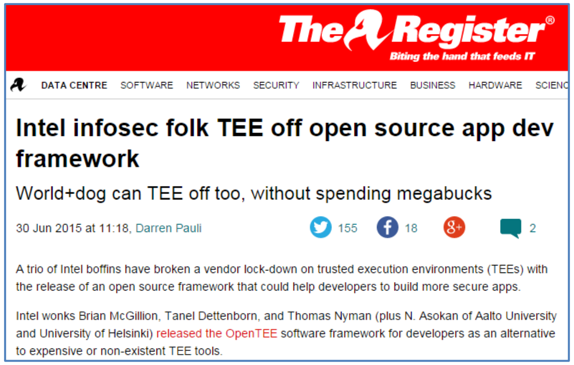
```
TEE_OpenTASession(TEE_UUID* destination, …,  paramTypes, params[4], &session);
TEE_InvokeTACommand(session, …, commandId, paramTypes, params[4]);
```

Also APIs for **crypto**, **time**, and **arithmetic** operations…

Legend:
OEM: Original Equipment Manufacturer

GP standards summary

- Specifications provide sufficient basis for TA development
- Issues
  - Application installation (provisioning) model not yet defined
  - Access to TEE typically controlled by the manufacturer
  - User interaction
- Open-TEE
  - Original intent: virtual TEE platform for TA developers
    - Implements GP interfaces: TA development w/ standard Linux tooling
  - Port for Android (requested by an OEM)
  - https://github.com/Open-TEE


The Register®
Biting the hand that feeds IT

DATA CENTRE SOFTWARE NETWORKS SECURITY INFRASTRUCTURE BUSINESS HARDWARE SCIENC

Intel infosec folk TEE off open source app dev framework

World+dog can TEE off too, without spending megabucks

30 Jun 2015 at 11:18, Darren Pauli 155 18 2

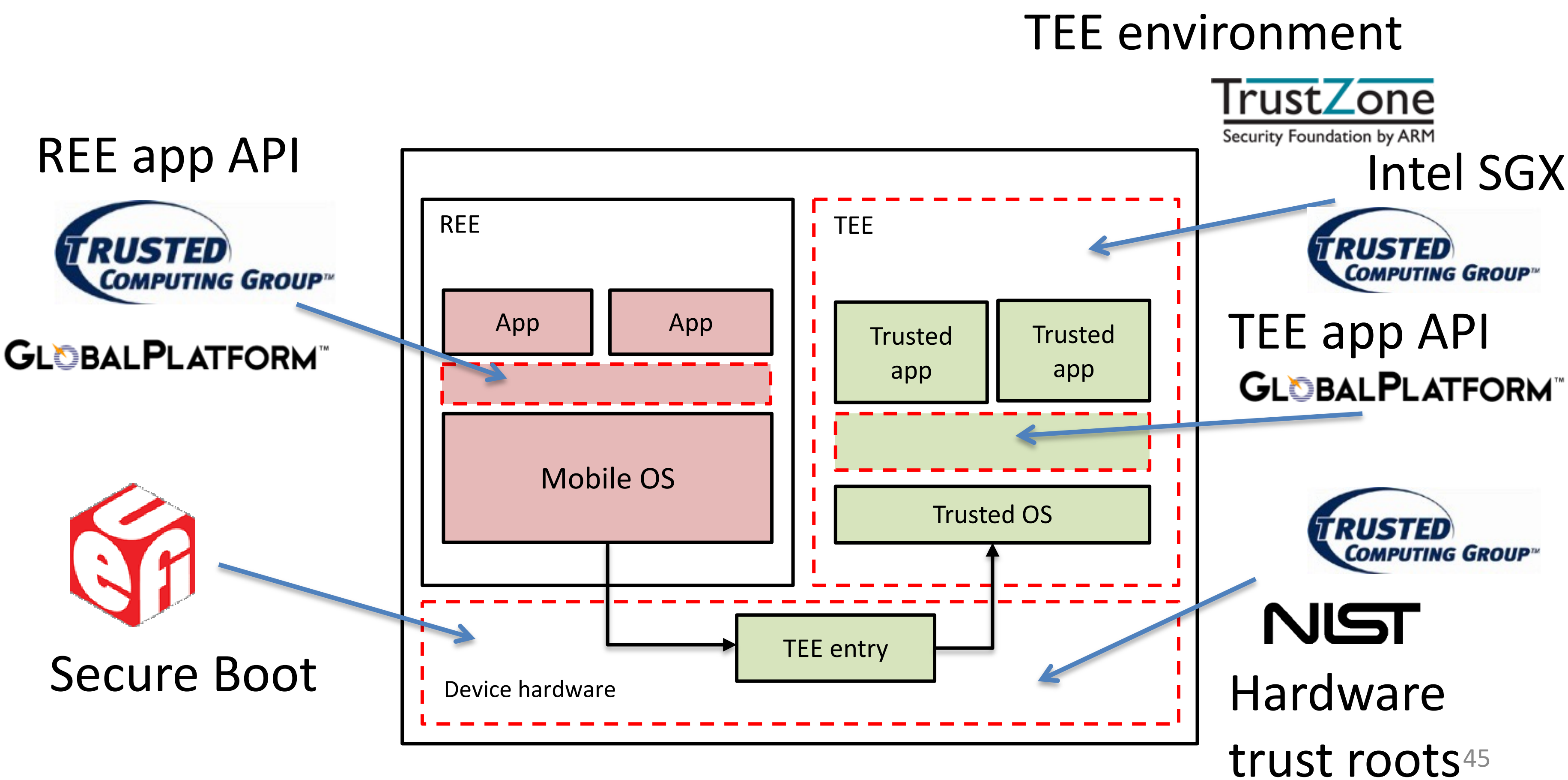
A trio of Intel boffins have broken a vendor lock-down on trusted execution environments (TEEs) with the release of an open source framework that could help developers to build more secure apps.

Intel wonks Brian McGillion, Tanel Dettenborn, and Thomas Nyman (plus N. Asokan of Aalto University and University of Helsinki) released the OpenTEE software framework for developers as an alternative to expensive or non-existent TEE tools.

http://www.theregister.co.uk/2015/06/30/opentee_an_open_virtual_trusted_execution_environment/

TEE standards and specifications

- First versions of standards already out
- Goal: easier development; better interoperability



Standards summary

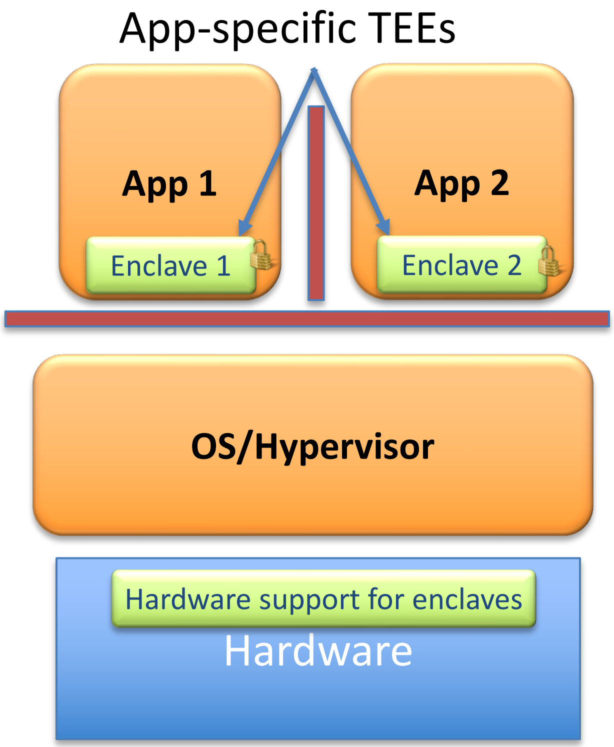
- Global Platform Mobile TEE specifications
  - Sufficient foundation to build trusted apps for mobile devices
- TPM 2.0 library specification
  - TEE interface for various devices (also Mobile Architecture)
  - Extended Authorization model is (too?) powerful and expressive
  - Short tutorial on TPM 2.0: **Citizen Electronic Identities using TPM 2.0**
- Mobiles can combine UEFI, NIST, GP and TCG standards
- Developers do not yet have full access to TEE functionality

TEE instances

INTEL SOFTWARE GUARD EXTENSIONS (SGX)

Skip to end

Intel Software Guard Extensions

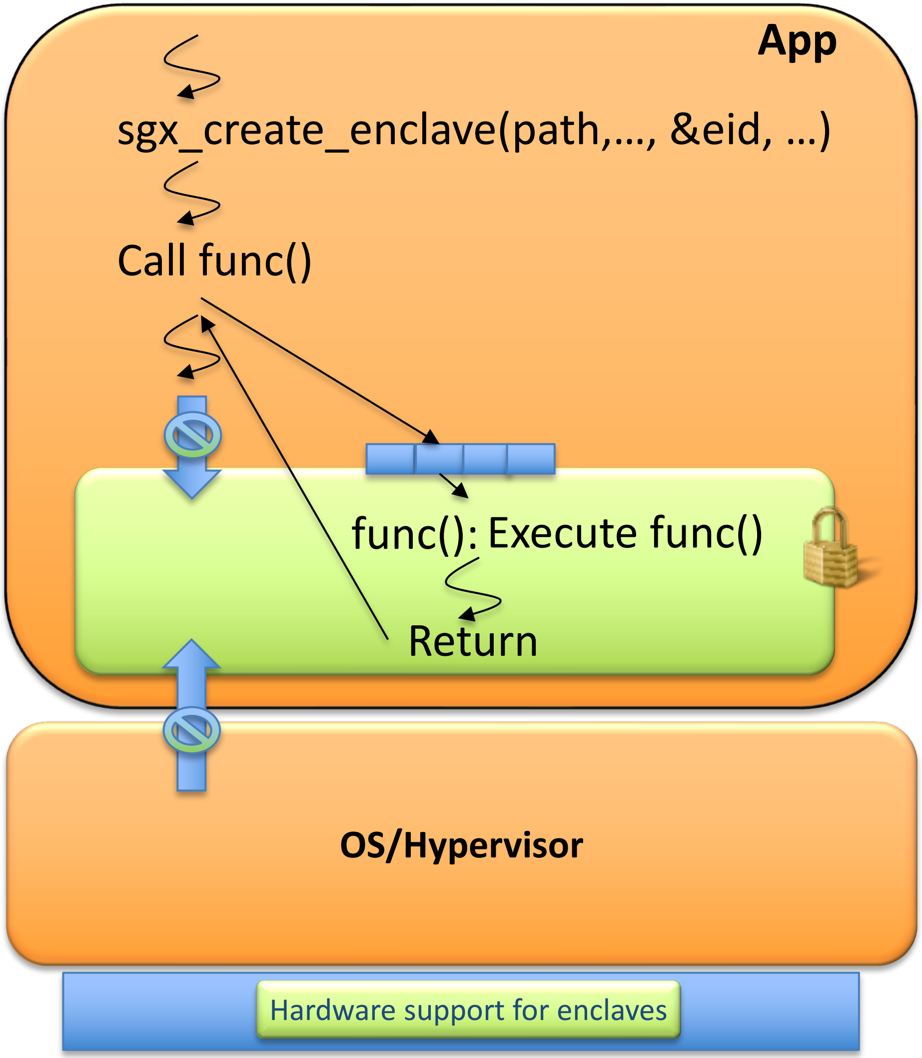


- HW-supported TEE functionality in ring-3
- Enclave code/data encrypted by HW
- Supports attestation and sealing

Intel Software Guard Extensions :
"Theory of Operations": https://software.intel.com/en-us/sgx/resource-library
Academic papers: https://software.intel.com/en-us/sgx/academic-research

Skip to SGX attestation

How does SGX work?



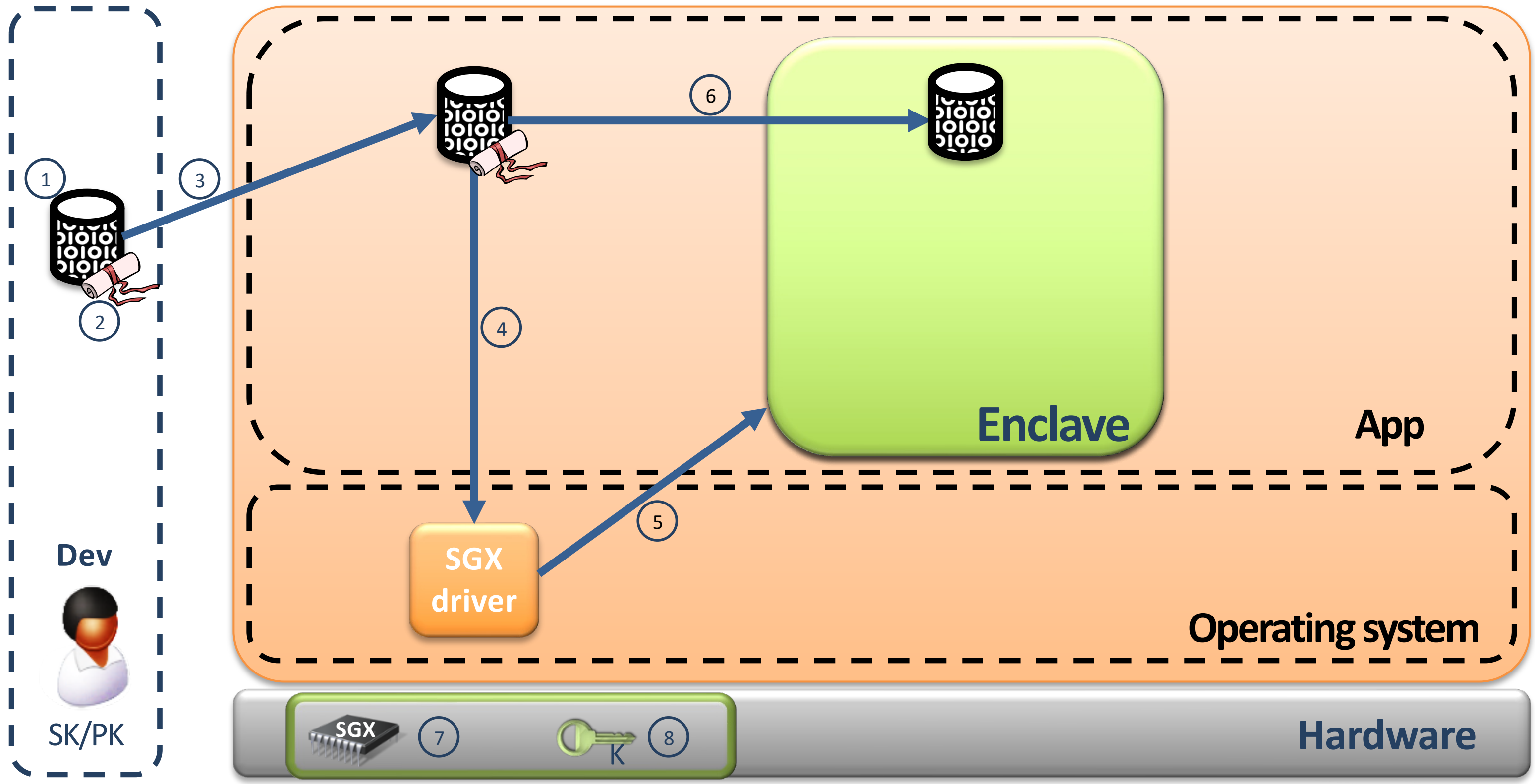
ECREATE, EADD, EEXTEND, EINIT

EENTER

EEXIT

Skip to SGX attestation

SGX – Create Enclave

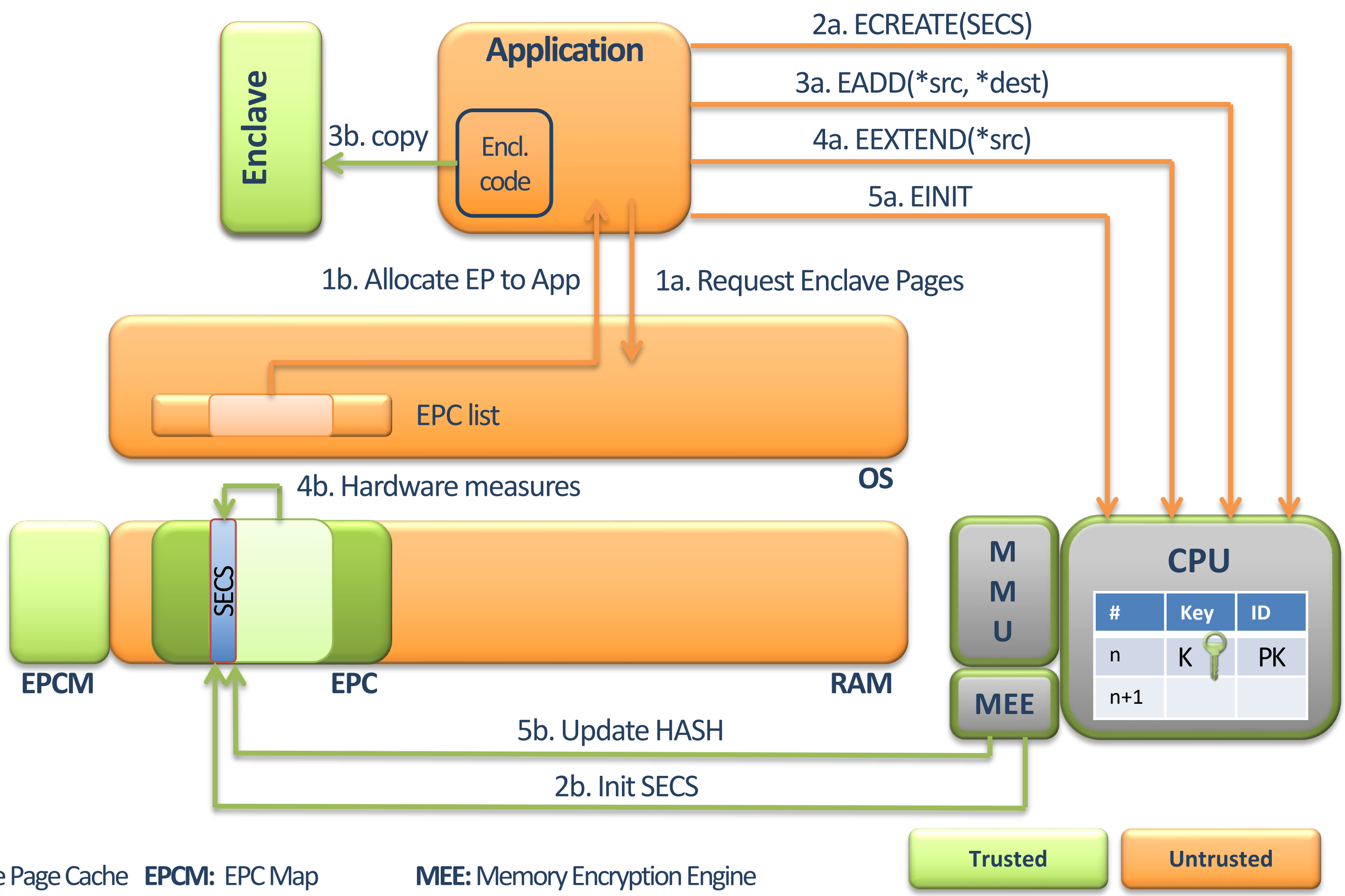


1. Create App
2. Create app certificate (includes HASH(App) and Dev PK)
3. Upload App
4. Create enclave
5. Allocate enclave pages
6. Load & measure enclave
7. Validate certificate and enclave integrity
8. Generate enclave **K** key
9. Protect enclave

Trusted | Untrusted

[Skip to SGX attestation](#)

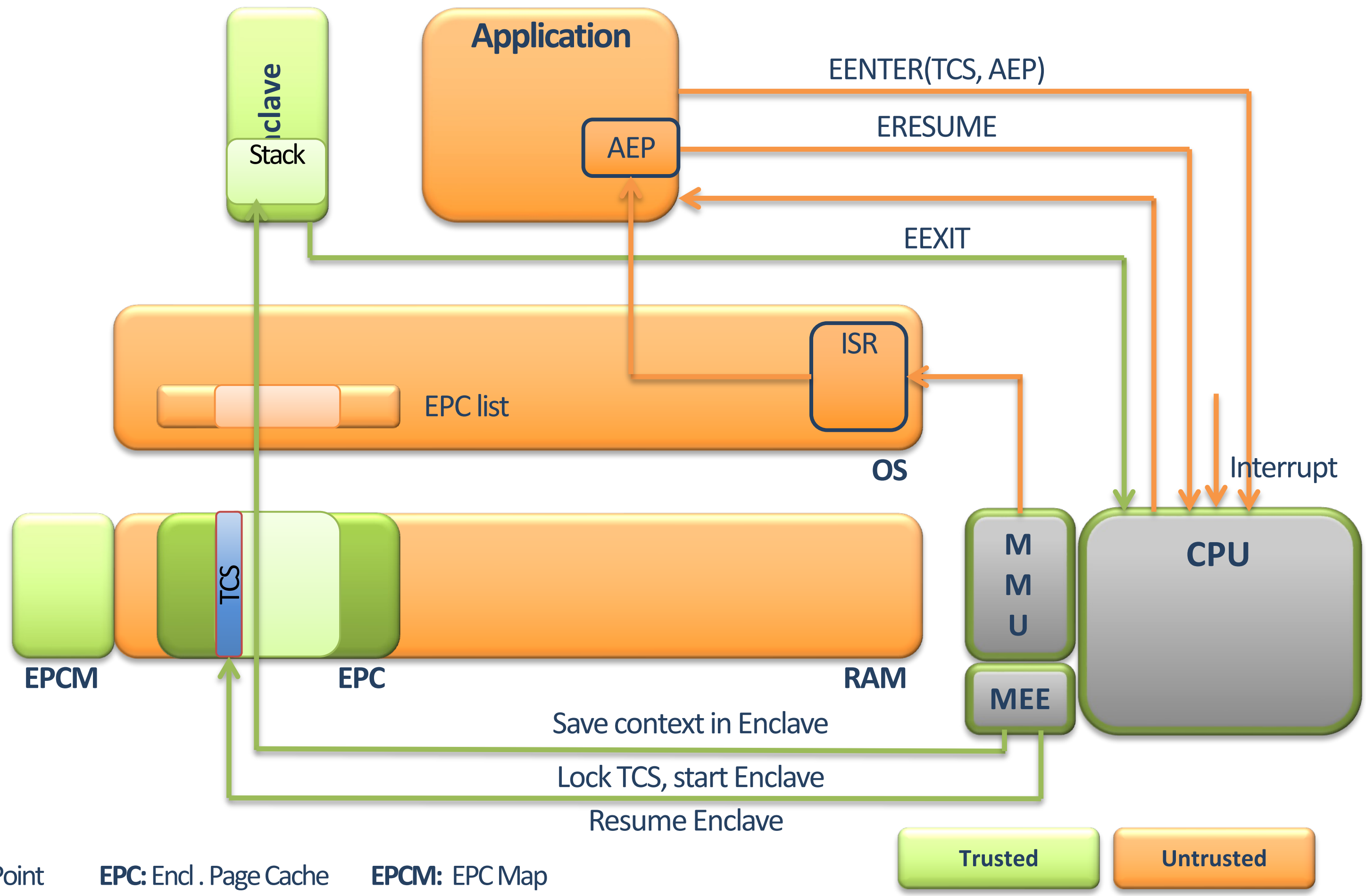
Enclave Creation – Details



EPC: Enclave Page Cache **EPCM:** EPC Map
MMU: Memory Management Unit
MEE: Memory Encryption Engine
SECS: SGX Enclave Control Structure

[Skip to SGX attestation]

Enclave Entry and Exit – Details



AEP: Async Exit Point
ISR: Int. Service Routine
EPC: Encl . Page Cache
MEE: Mem. Enc. Engine
EPCM: EPC Map
TCS: Thread Control Structure

Attestation in SGX

- Local Attestation: one enclave verifies another on the same device

- Remote Attestation: a remote party verifies an enclave

Enclave Identity

Identity of an enclave:

- Enclave's **initial state**
- **sealing identity**

Initial State

- *Enclave measurement* representing:
  - Contents of enclave pages (initial code/data)
  - Relative position of enclave's pages
- Determined during enclave creation:
  - Log activities during enclave creation
  - Digest of log contents in *MRENCLAVE*
  - Only CPU can modify the MRENCLAVE

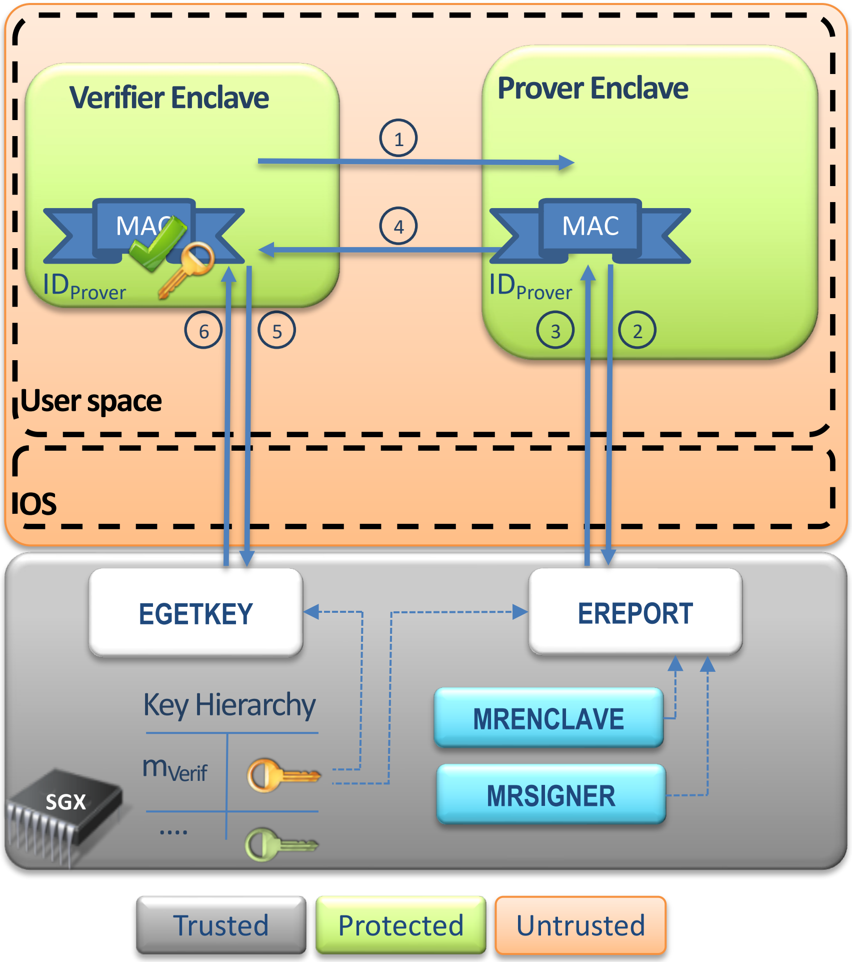
Sealing Identity

- *Sealing authority (SA)* signs enclaves prior to distribution:
  - Signature on trusted (expected) value of initial state
  - Signature and SA's public key sent to devices that need to run the enclave
- During enclave creation on device:
  - signed measurement
    - verified using SA's public key
    - compared with local measurement
    - If matched, sealing identity (hash of the SA's public key) stored in the MRSIGNER register

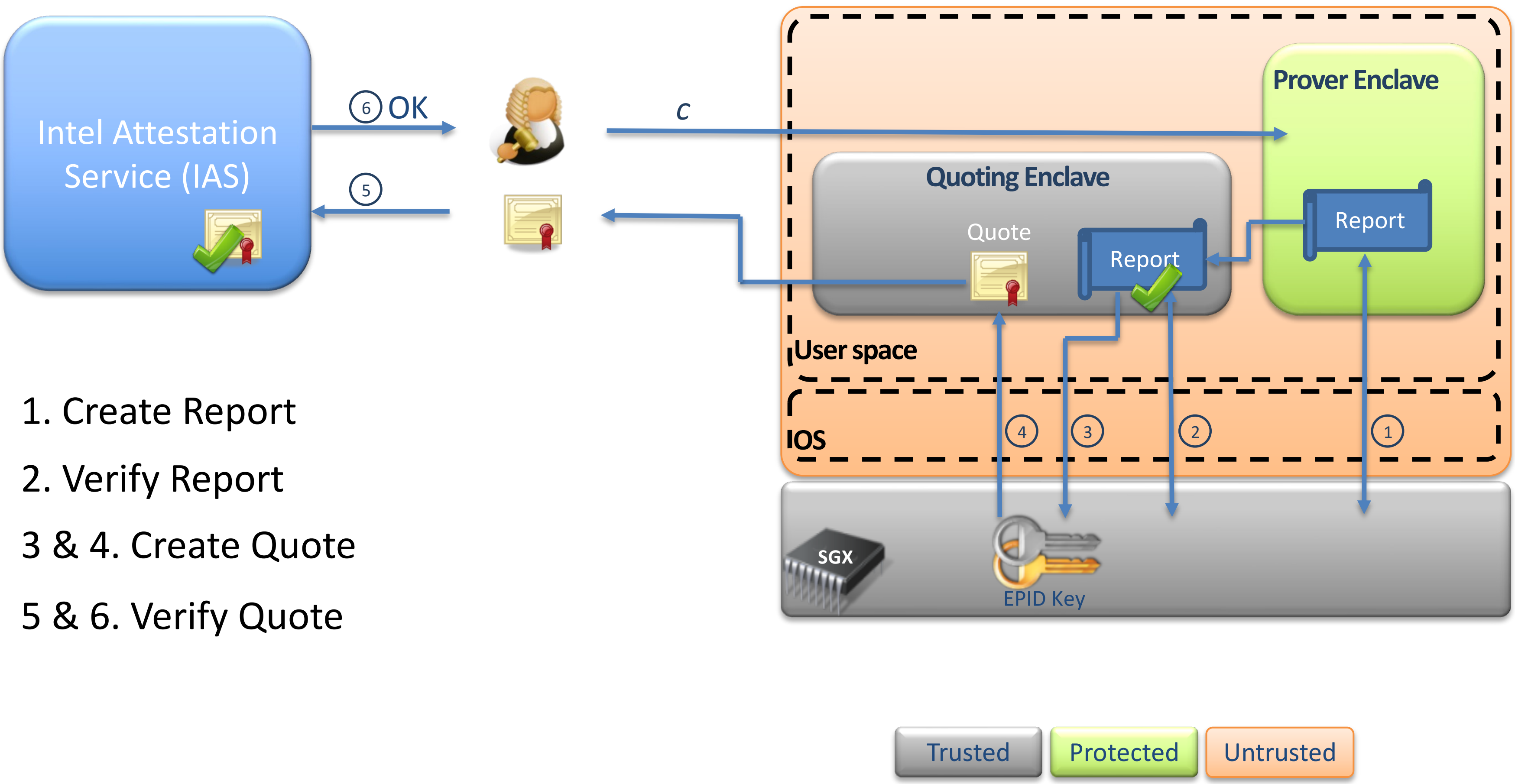
Local Attestation

1. Verifier sends measurement (m_{Verif}) to prover
2. Prover calls *EREPORT*, with m_{Verif} as parameter, to create report
3. Prover's report (ID and MAC generated using the verifier's *report key)* returned

   Report := ID_{Prover}, $MAC(ID_{Prover})_{RepKey_{Verifier}}$
4. Report transferred to verifier
5. Verifier calls *EGETKEY* (for reports)
6. Verifier's *report key* is returned
7. MAC included in Report verified using received *report key*



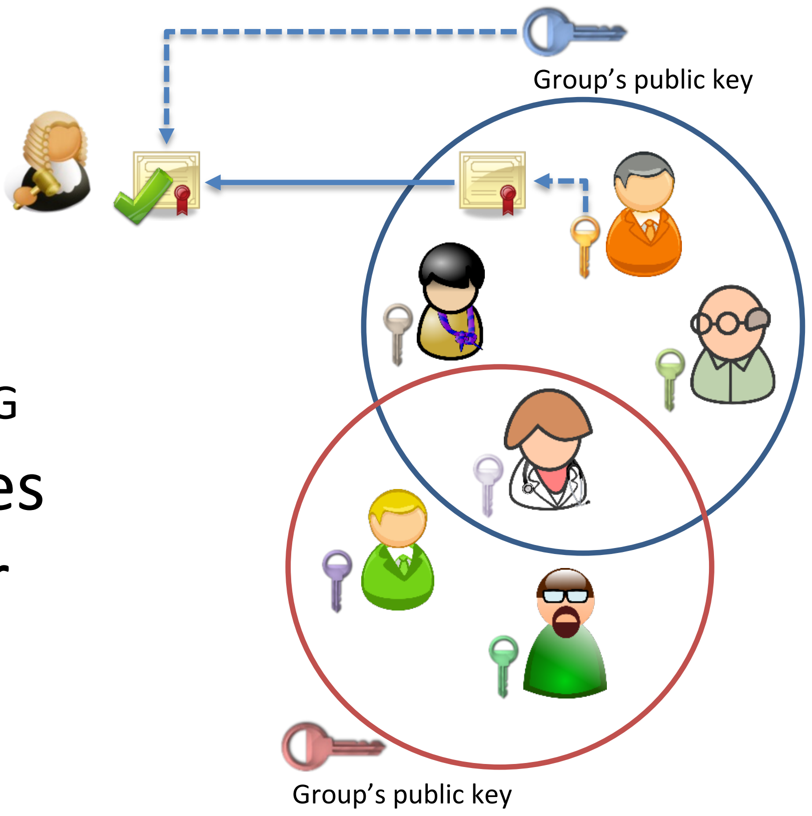
Remote Attestation



1. Create Report
2. Verify Report
3 & 4. Create Quote
5 & 6. Verify Quote

Intel Enhanced Privacy ID (EPID)

- Group signature scheme
- Each signer
  - owns a secret key
  - belongs to a group
- Group has a public key PK_G
- Use PK_G to verify signatures generated by any member



Sealing

- Store persistent data securely
- Enclaves get sealing keys via EGETKEY
- Two modes:
  - Sealing to Enclave-Identity
    - key derived from contents of MRENCLAVE
  - Sealing to Sealing-Identity
    - key derived from contents MRSIGNER