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Property-Based Attestation Approach and Virtual TPM

Ahmad-Reza Sadeghi

sadeghi@crypto.rub.de

Horst Görtz Institute for IT-Security

Ruhr-University Bochum, Germany

www.trust.rub.de

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§ Motivation

§ Trusted Virtualization

Motivation

- **Hardware virtualization a (re-discovered / re-invented) useful means to reduce to total cost**
  - apparent in corporate data centers
  - however, workloads should be processed separately due to diversity of security objectives of the involved parties (see [Barham et al 2003, Sailer et al 2005])
- **Combine hypervisors (Virtual Machine Monitors) with hardware-based root of trust**
  - Hypervisors provide isolations of workloads
    - mediating access to physical resources by virtual machines
  - Hardware root of trust is resistant to software attacks and provides a basis for reasoning about the integrity of SW running on a platform

Possible Architecture

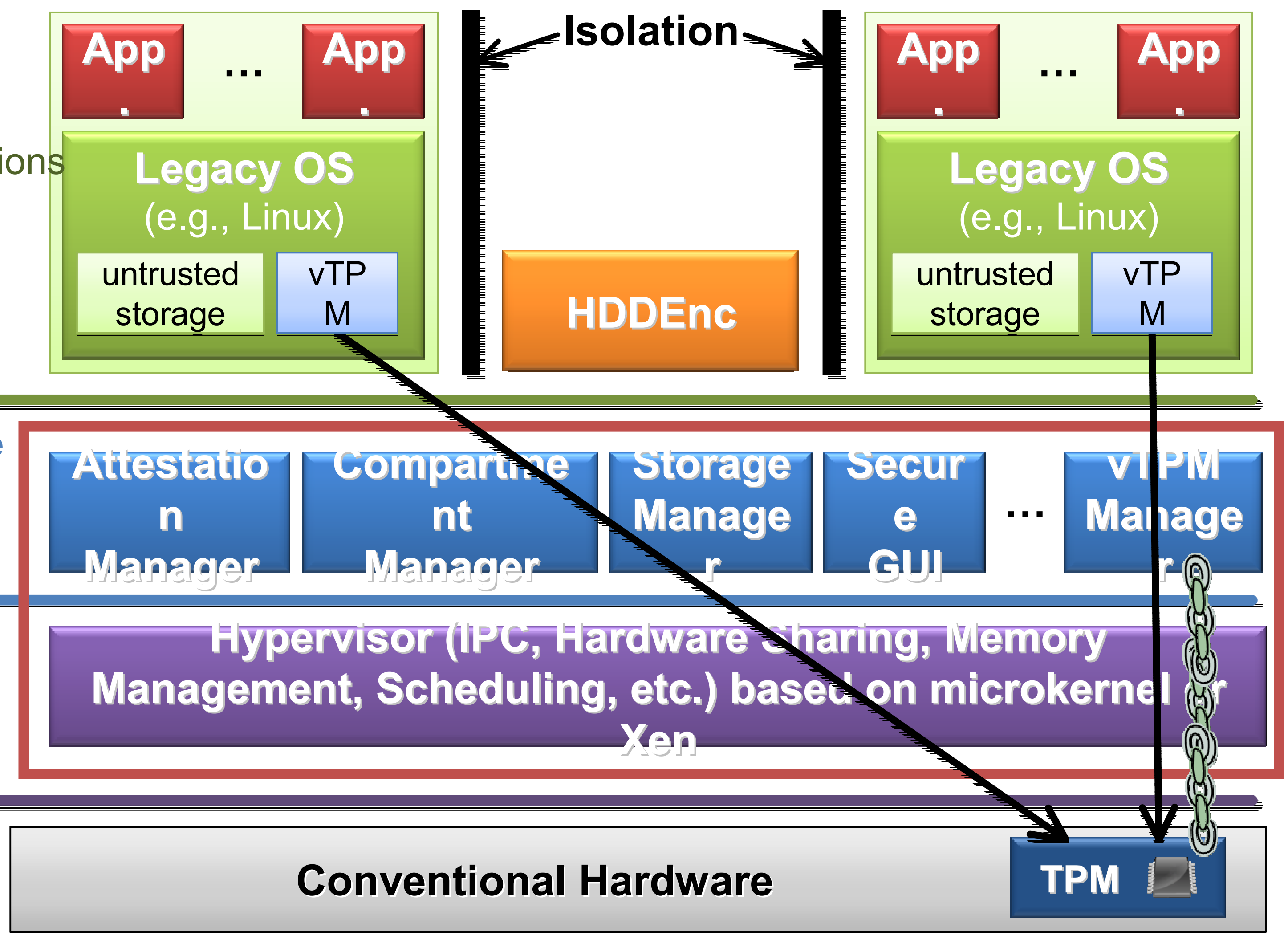
Applications
- Existing OS
- Security applications

Trusted Software Layer

Secure VMM

Virtualization Layer

Hardware
- CPU
- Devices
- Trusted Computing (TC) Technology (TPM, Trusted Execution Technology (TXT) , Presidio, etc.)



Components

- **TC enabled hardware**
- **Trusted Service Layer**
  - Trust Manager: controls access to TPM interface
  - Compartment Manager
    - manages creation, updates, and deletion of compartments
    - measures compartments and assigns unique IDs to them
  - Storage manager
    - guarantees trusted storage, i.e., authenticity, confidentiality and integrity (and freshness) of stored data
    - has access to configuration of clients it is communicating to over trusted channel
  - Secure GUI
    - guarantees a trusted path to application
- **Virtualization Layer**
  - provides abstraction of physical machine
  - Provides isolation between virtual machines

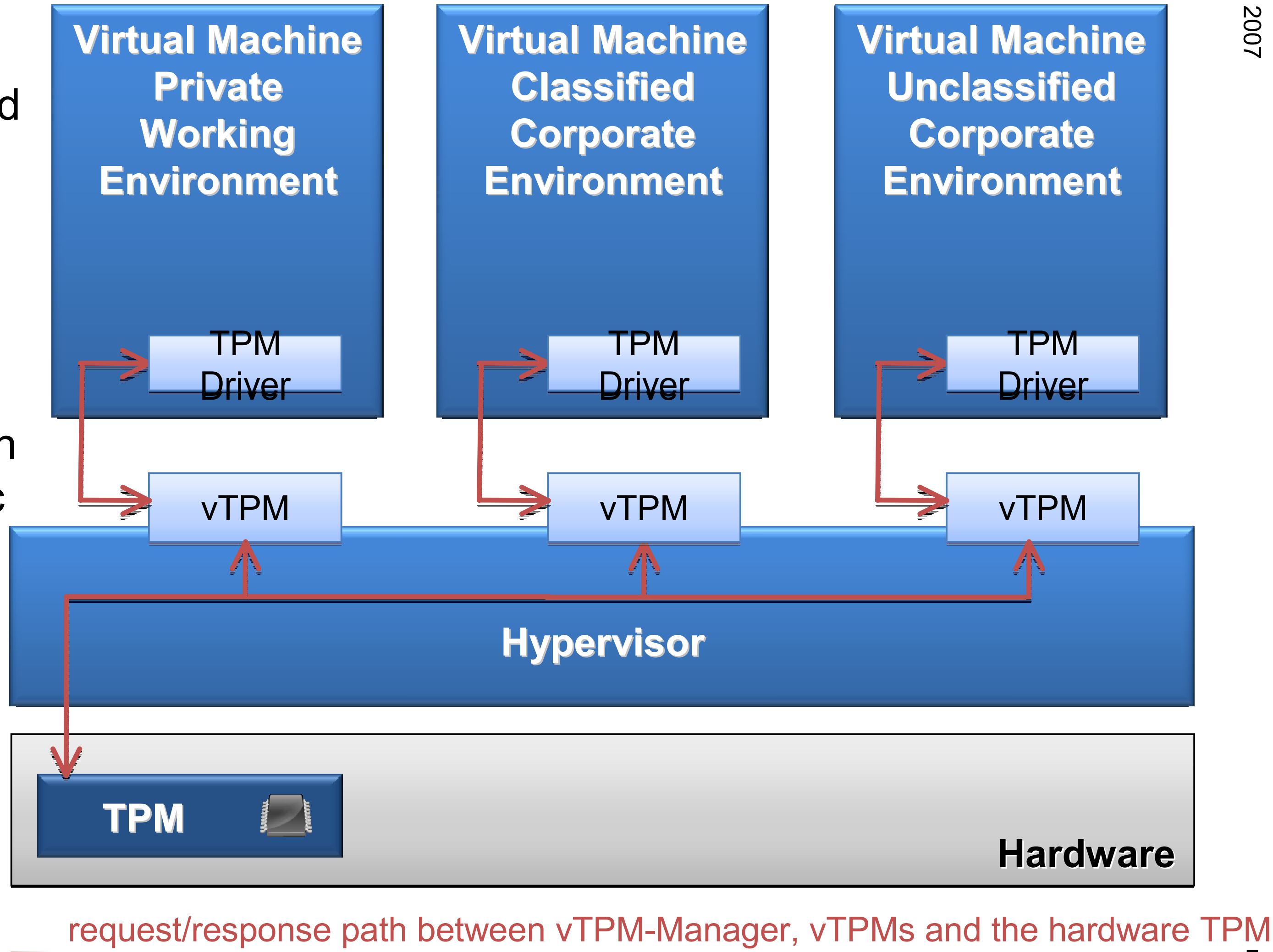
Use Case: Corporate Computing

Private Environment

- e.g., Protection of hard disk encryption application

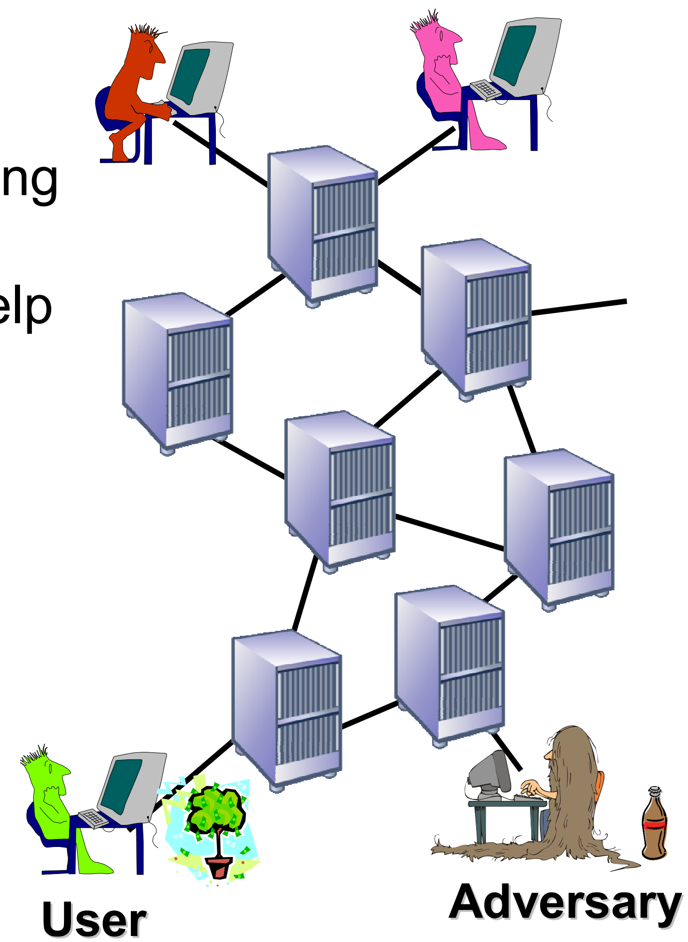
Corporate Environment

- Classified: Stronger security requirement on usage of encryption keys bound to specific hardware
- Unclassified: migrate working environment at home



The Big Picture

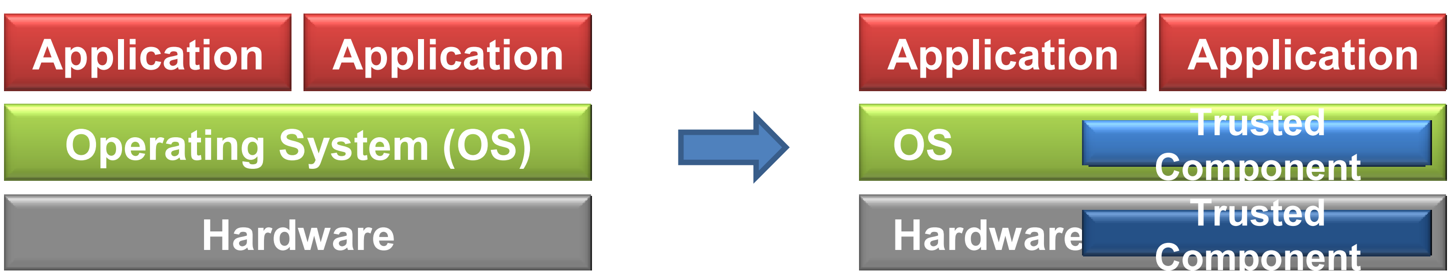
- **Trustworthiness in distributed IT systems**
  - Different parties with potentially conflicting requirements involved
  - Cryptographic methods are of limited help
  - Example applications (signatures, Grid, online voting and banking, ….)
- **How to define „trustworthiness“?**
- **How to determine/verify it?**
- **How could common computing platforms support such functionality?**
  - Even a secure OS cannot verify own integrity
- **The role of Trusted Computing**
  - Enable the reasoning about the



§ TCG Approach to Trusted Computing

Basic Idea for Trusted Platform

- **Trusted components in hardware and software**
- **Provides a variety of functions that must be trusted**
  - in particular a set of cryptographic and security functions
- **Creates a foundation of trust for software**
- **Provides hardware protection for sensitive data**
  - e.g., keys, counters, etc.
- **Desired goals**
  - Trusted Computing Base (TCB) should be minimized
  - Compatibility to commodity systems



Conventional Platform **Trusted Platform**

Trusted Computing Group (TCG)

- **Consortium of IT-Enterprises (since April 2003)**
  - Today more than 120 members [TCG]
    - www.trustedcomputing.org/about/members/
- **Focus on development of hardware-enabled trusted computing and security technology across multiple platforms and devices**
- **Evolved from Trusted Computing Platform Alliance (TCPA)**
  - Formed by Hewlett-Packard (HP), Compaq (today part of HP), IBM, Intel and Microsoft in January 1999
- **Published various specifications**
- **Set up various working groups**

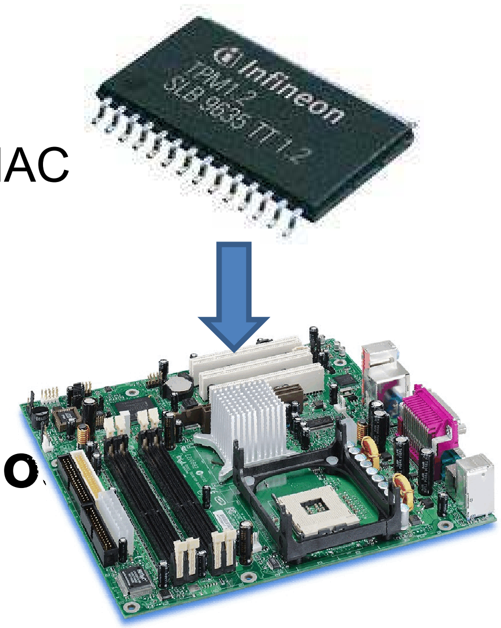
TCG Main Specification

- **Trusted Platform Module (TPM) [TPM2002, TPM2003, TPM2007]**
  - Provides a set of immutable cryptographic and security functions
- **Trusted Software Stack (TSS) [TSS2003, TSS2007]**
  - Issues low-level TPM requests and receives low-level TPM responses on behalf of higher-level applications

§ Trusted Platform Module: Main TCG Specification

Trusted Platform Module (TPM)

- **Current implementation is a cryptographic co-processor**
  - Hardware-based random number generation
  - Small set of cryptographic functions
    - Key generation, signing, encryption, hashing, MAC
- **Offers additional functionalities**
  - Secure storage (ideally tamper-resistant)
  - Platform integrity measurement and reporting
- **Embedded into the platform's motherbo**
- **Acts as a "Root of Trust"**
  - TPM must be trusted by all parties
- **Two versions of specification available**
- **Many vendors already ship their platforms with a TPM [TPMMatrix2006]**



TPM Architecture

System Interface
(e.g., LPC-Bus)

Trusted Platform Module (TPM)

Cryptographic Co-Processor
- Asymmetric en-/decryption (RSA)
- Digital signature (RSA)

SHA-1

HMAC

Random Number Generation

Key Generation
- Asymmetric keys (RSA)
- Symmetric keys
- Nonces

Platform Configuration Registers (PCR)
- Storage of integrity measurements

PCR[23]
:
:
PCR[1]
PCR[0]

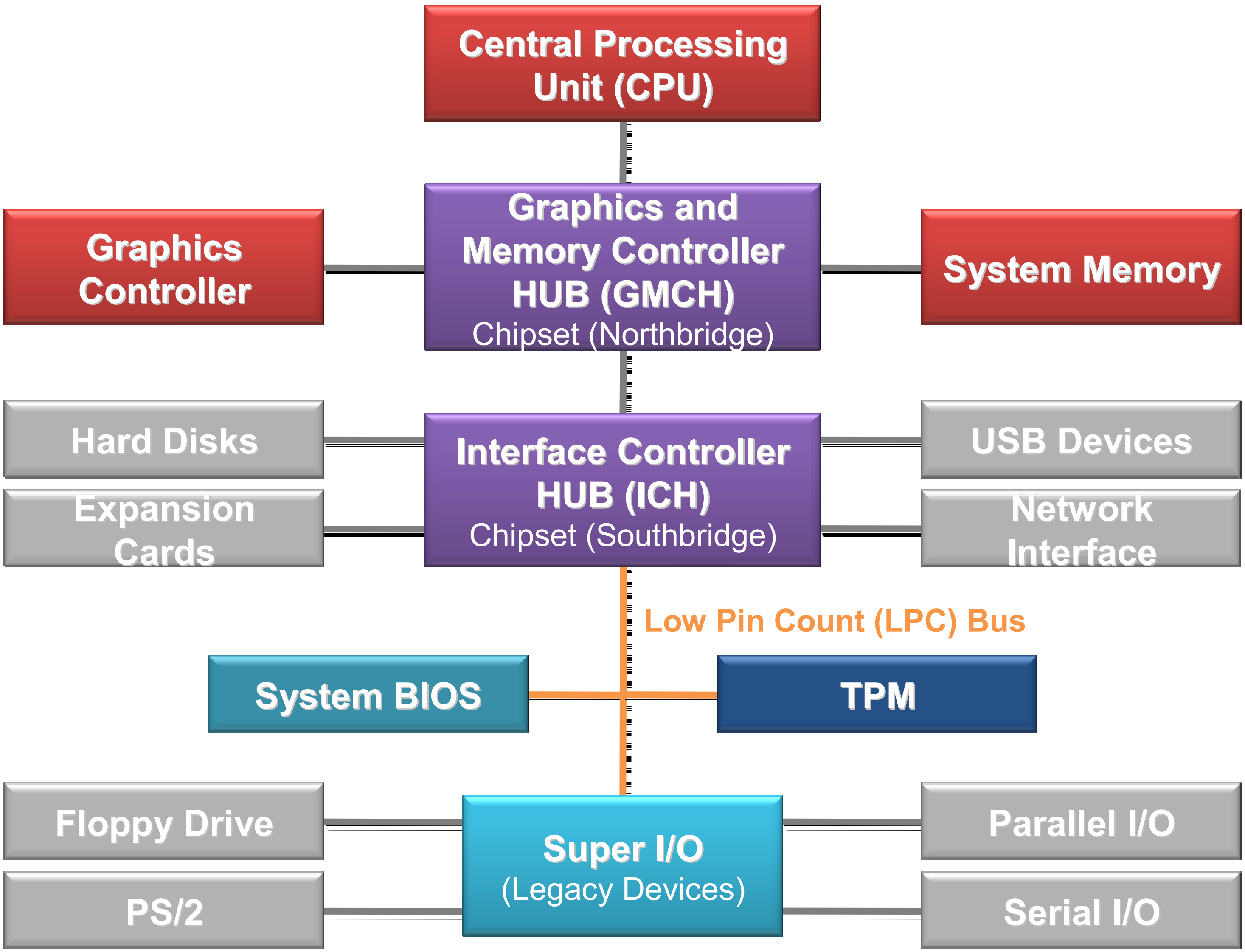
Input/Output
- Protocol en-/decoding
- Enforces access policies

Opt-In
- Stores TPM state information (e.g., if TPM is disabled)
- Enforces state-dependent limitations (e.g., some commands must not be executed if the TPM is disabled)

Execution Engine
- Processes TPM commands
- Ensures segregation of operations
- Ensures protection of secrets

Non-Volatile Memory
- Stores persistent TPM data (e.g., the TPM identity or special keys)
- Provides read-, write- or unprotected storage accessible from outside the TPM

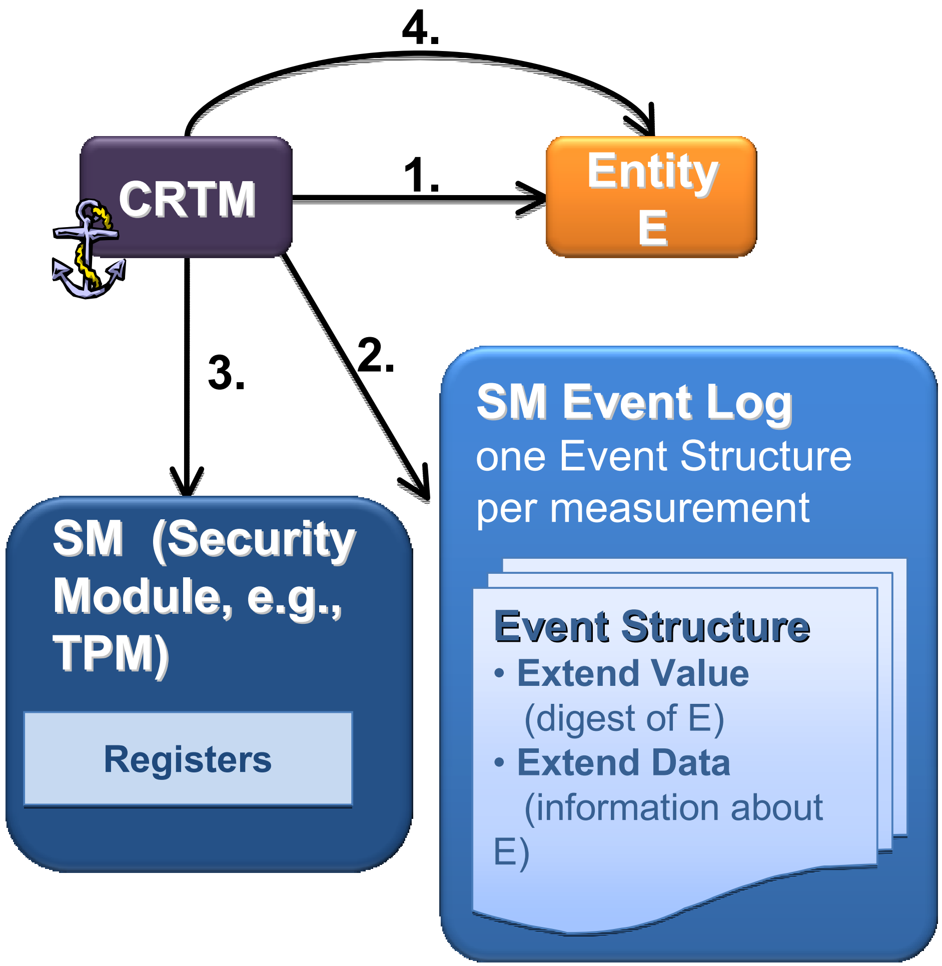
TPM Integration into PC-Hardware



Integrity Measurement

- **Integrity Measurement**
  - Process of obtaining metrics of platform characteristics that affect the integrity (trustworthiness) of a platform and storing digests of those metrics to the TPM's PCRs
    - Platform characteristic = digest of the software to be executed
- **Platform Configuration Registers (PCR)**
  - Shielded location to store integrity measurement values
  - Can only be extended: $PCR_{i+1} \leftarrow SHA\text{-}1(PCR_i, value)$
  - PCRs are reset only when the platform is rebooted
- **Integrity Logging**
  - Storing integrity metrics in a log for later use
  - e.g., storing additional information about what has been measured like software manufacturer name, software name, version, etc.

Performing Integrity Measurements



1. **CRTM measures entity E**
2. **creates Event Structure in TPM Event Log**
   - SML contains the Event Structures for all measurements extended to the SM
   - SM Event Log can be stored on any storage device
     - E.g., hard disk
3. **extends value into Registers**
4. **Executes/passes control to entity E**

CRTM: Core Root of Trust for Measurements

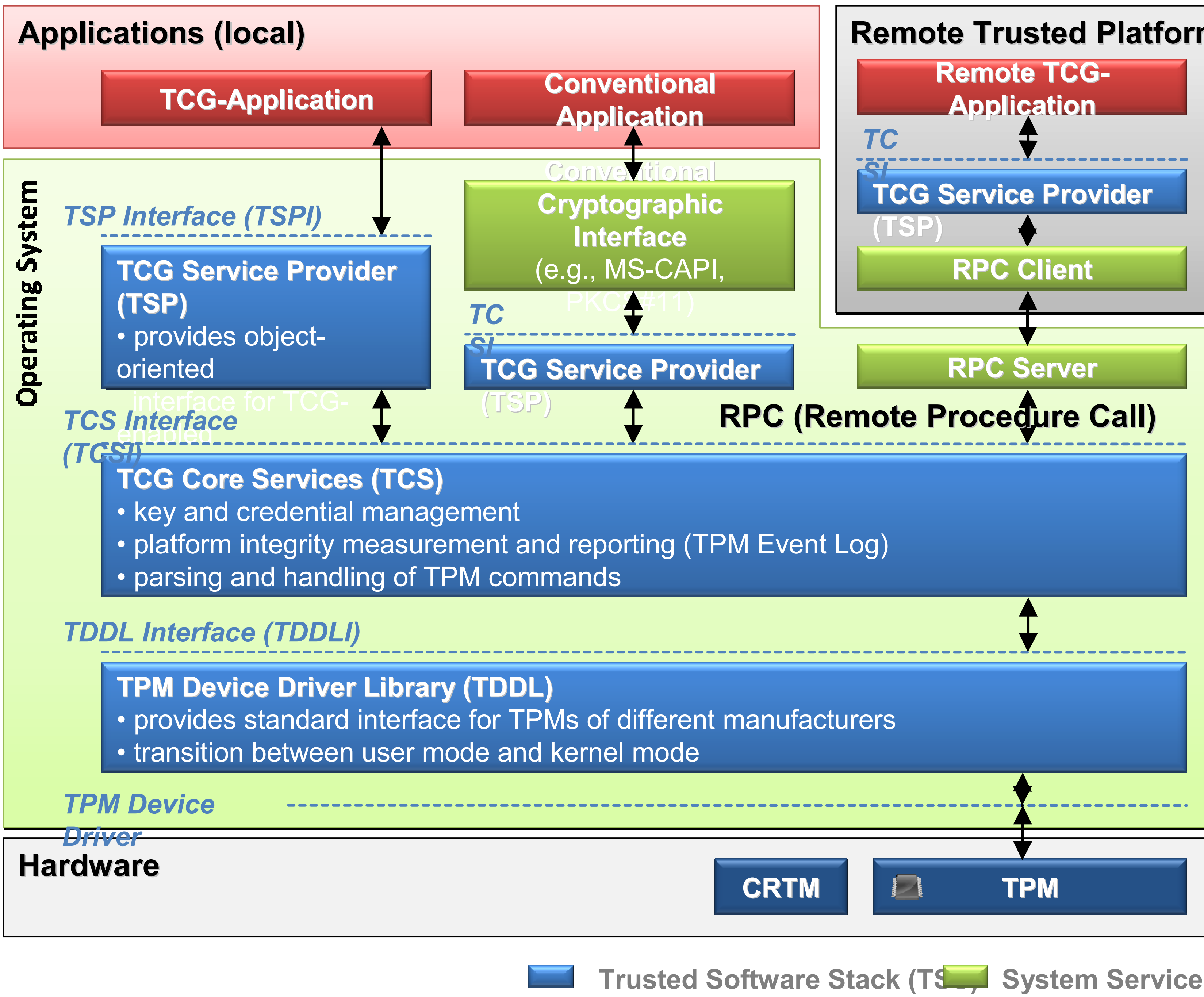
Core Root of Trust for Measurement (CRTM)

- Immutable portion of the host platform's initialization code that executes upon a host platform reset
- Trust in all measurements is based on the integrity of the CRTM
- Ideally the CRTM is contained in the TPM
- Implementation decisions may require to locate it in other firmware (e.g., BIOS boot block)

Two Possible CRTM Implementations

- **CRTM is the BIOS Boot Block**
  - BIOS is composed of a BIOS Boot Block and a POST BIOS
  - Each of these are independent components
    - Each can be updated independent of the other
  - BIOS Boot Block is the CRTM while the POST BIOS is not, but is a measured component of the Chain of Trust
- **CRTM is the entire BIOS**
  - BIOS is composed of a single atomic entity
  - Entire BIOS is updated, modified, or maintained as a single component

TPM Software Integration



TPM Keys

TPM Key Types

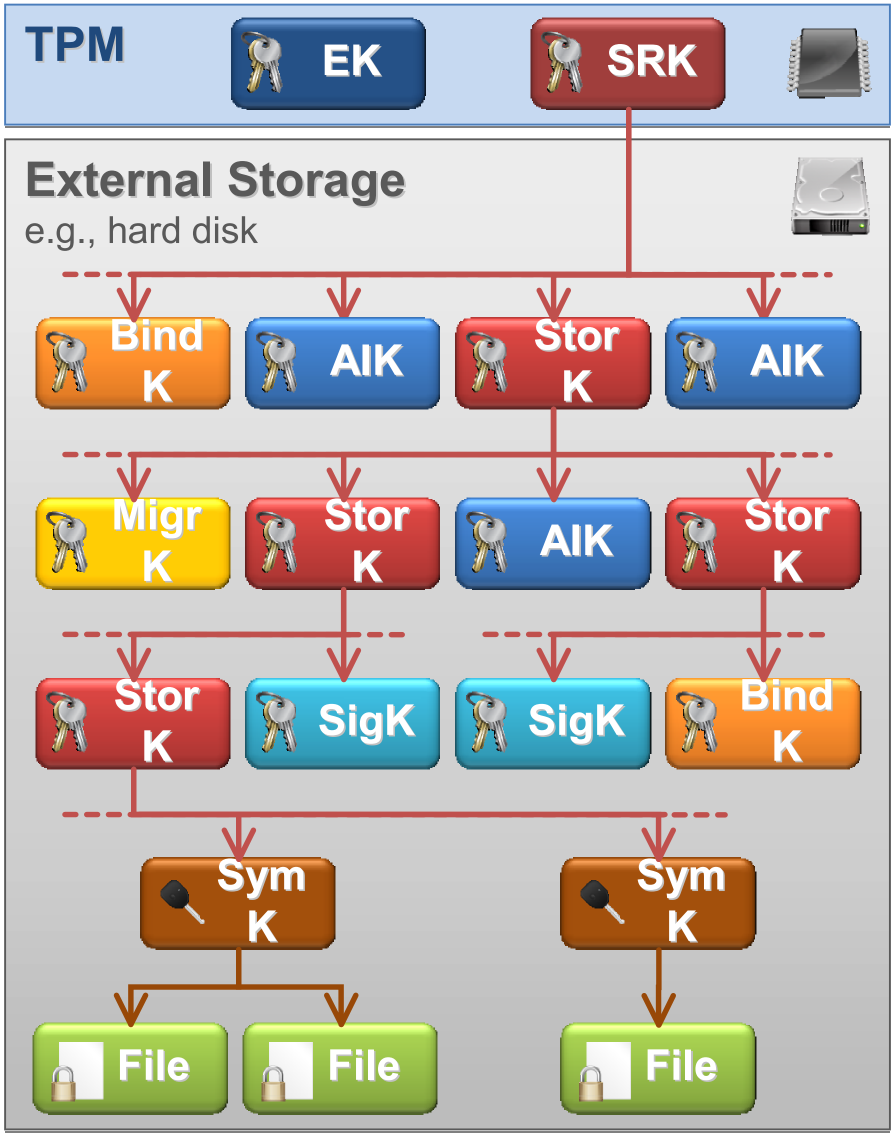
- **TPM provides 9 different types of keys**
  - 3 special TPM key types
    - Endorsement Key, Storage Root Key, Attestation Identity Keys
  - 6 general key types
    - Storage, signing, binding, migration, legacy and "authchange" keys
  - Most important key types explained in following slides
- **Each key may have additional properties, the most important ones are**
  - Migratable, non-migratable, certified migratable
    - e.g., whether the key is allowed to be migrated to another TPM
  - Whether the key is allowed only to be used when the

Special Keys

- **Endorsement key (EK)**
  - TPM identity
  - Generated and certified during manufacturing
  - RSA key
- **Attestation Identity Key (AIK)**
  - Used to sign to current platform configuration
  - Alias for TPM/platform identity EK
  - RSA key
  - TPM/platform may have multiple AIKs
- **Storage Root Key**
  - Secure data storage implemented as a hierarchy of keys
  - Storage Root Key (SRK) is root of this key hierarchy
  - Generated by TPM during process of installing TPM Owner

TPM Key Hierarchy

A → B means A encrypts B
A is called **parent key** of B



- **Depth of hierarchy and number of TPM-protected keys only limited by size of external storage**
- **Storage keys (StoreK) protect all other key types**
  - Attestation ID keys (AIK)
  - Signing keys (SigK)
  - Binding keys (BindK)
  - Migration Keys (MigrK)
  - Symmetric keys (SymK)
- **Transitive protection**
  - SRK indirectly protects

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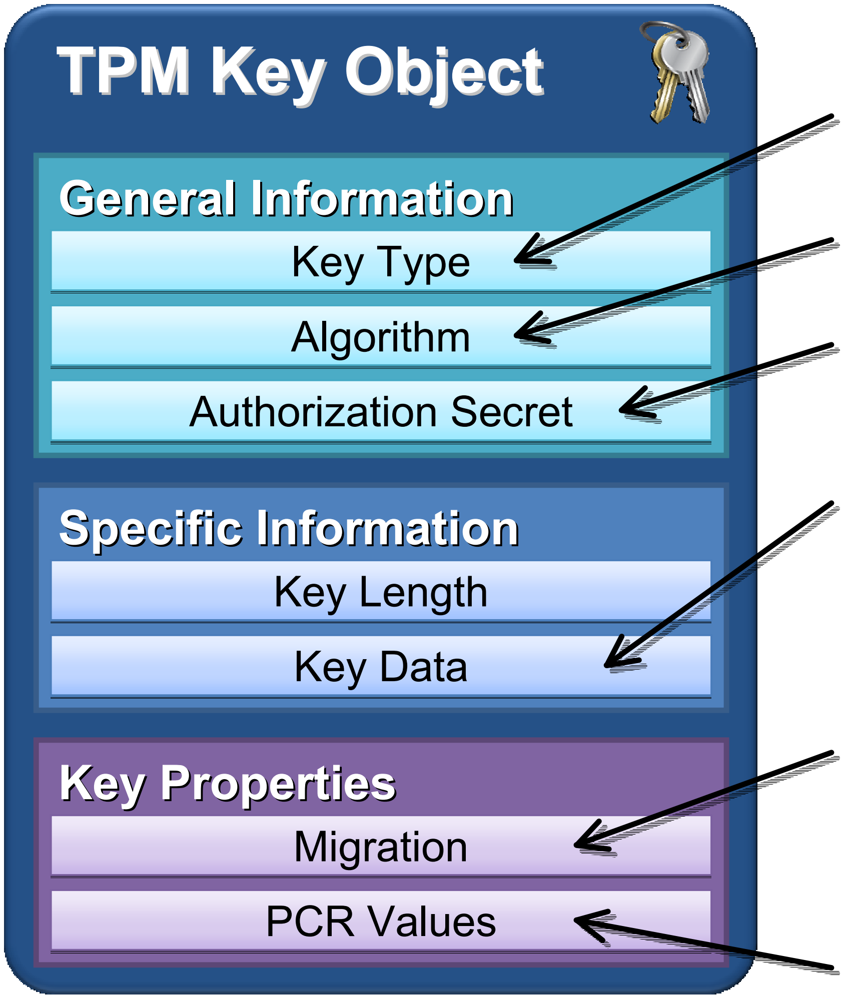
TPM Key Object – Important Fields



e.g., signing key, binding key, storage key, …

e.g., RSA, DSA, HMAC, AES, …

Authorization secret required to use the key

Public and private key, asymmetric key. Secret key data is encrypted with the corresponding parent key.

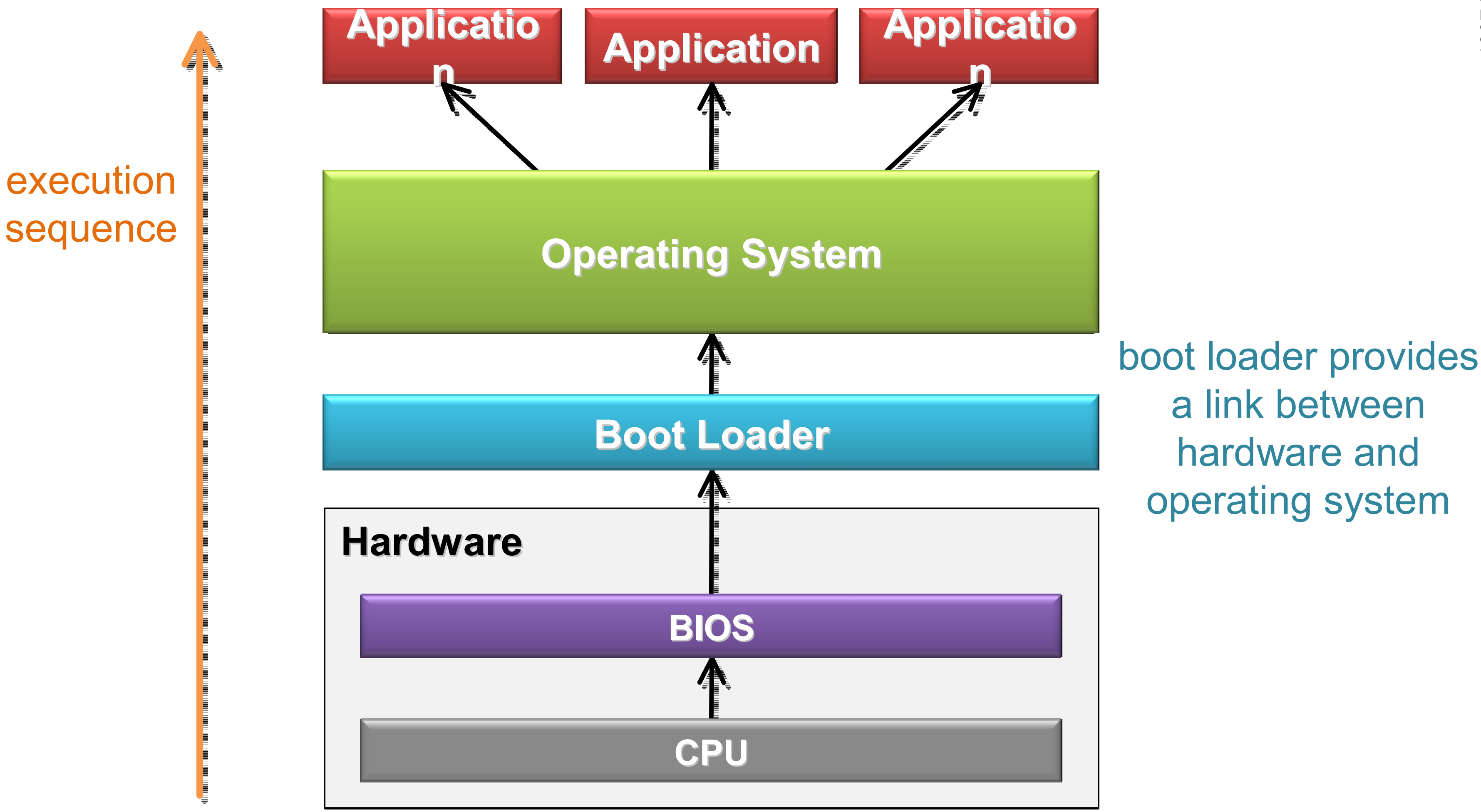
Information about the migratability of the key:
- migratable
- certified mitgratable
- non-migratable

A key can be sealed to specific PCR values. This means that such a key can only be used when the platform is in a specific (trusted) state.

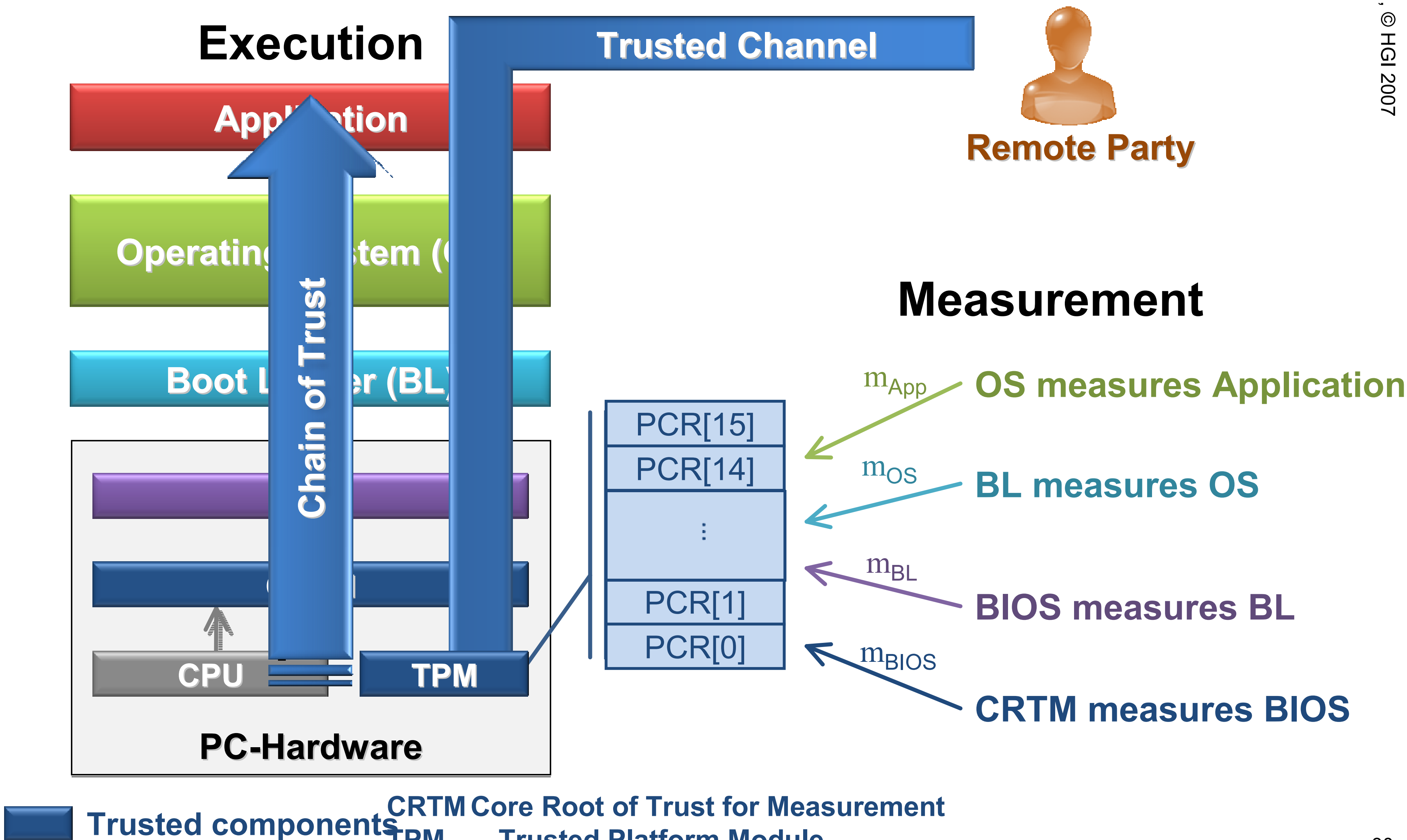
§ Main Functionalities

Authenticated Boot

Bootstrap Architecture in PC

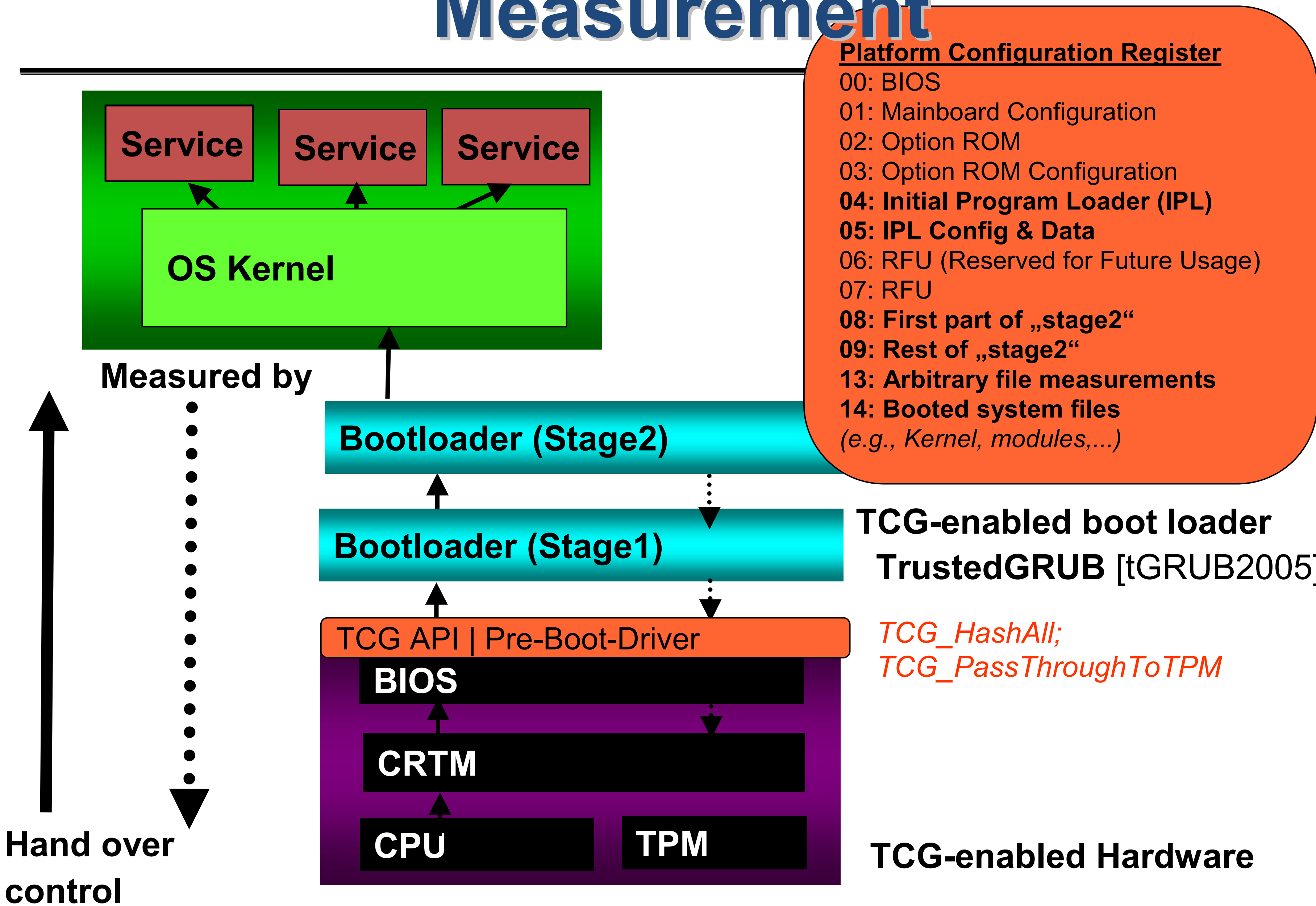


Bootstrap and Integrity Measurement



CRTM Core Root of Trust for Measurement
TPM Trusted Platform Module

Bootstrap and Integrity Measurement



Binding and Sealing

Binding

- Conventional asymmetric encryption
- May be used to bind data to a specific TPM/platform
  - Data encrypted with non-migratable key can only be recovered by TPM that knows corresponding secret key
- Usually no platform binding
  - Since binding can also be used with migratable keys

Sealing (extension of binding)

- Always binds data to a specific TPM/platform
  - Sealing can only be used with non-migratable storage keys
- Configuration of encrypting platform can be verified
  - Ciphertext includes platform's state at the time of encryption
- May bind data to a specific platform configuration
  - Data can be decrypted only if platform is in a pre-defined

Integrity Reporting / Attestation

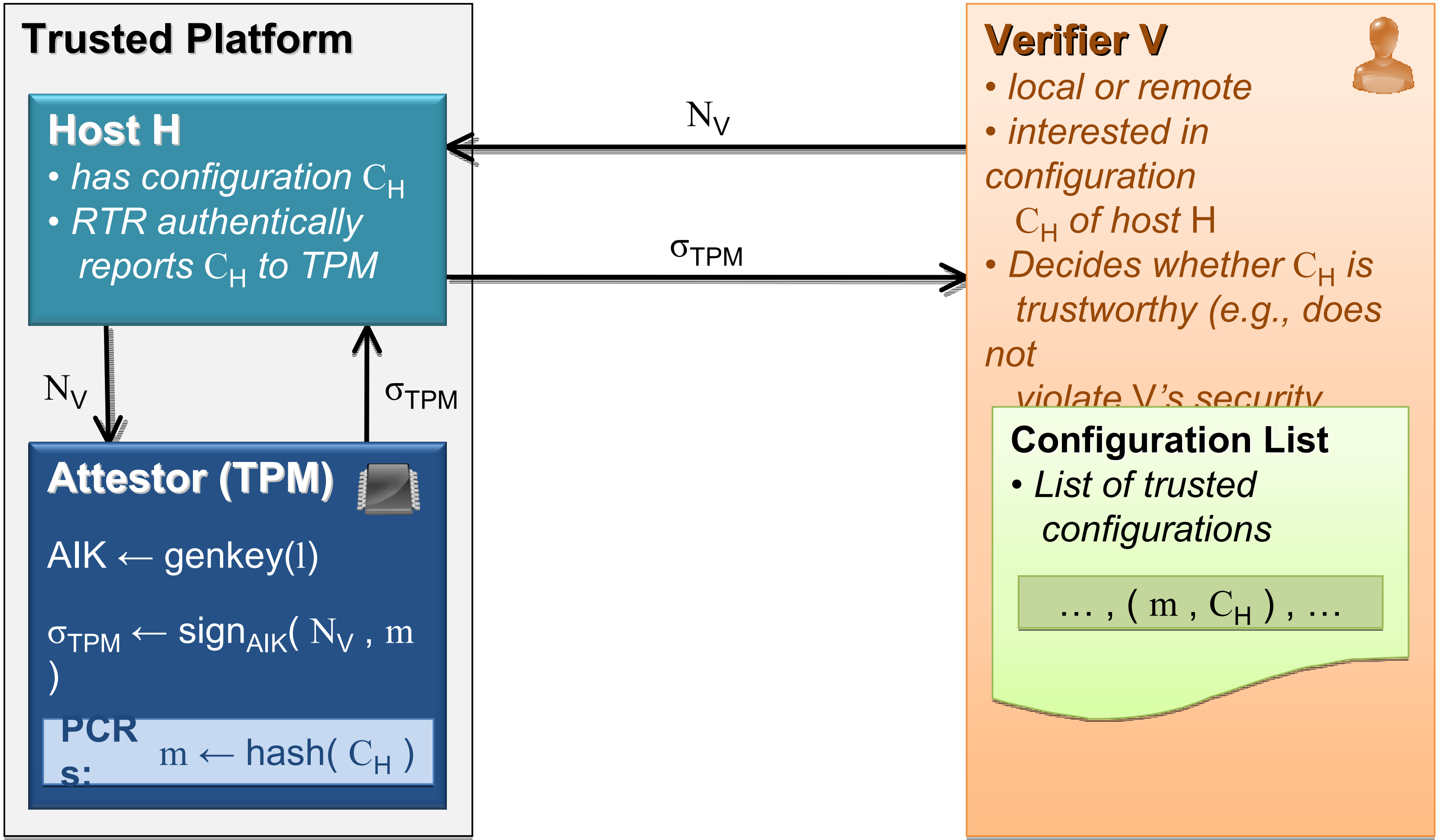
Attestation

- **Authentic report of a platform's state to a (remote) verifier**
  - A local or remote verifier (challenger) is interested in platform configuration (e.g., hard- and software environment)
  - Verifier is able to decide whether it trusts the attested configuration
    - e.g., an online-banking client checks whether the bank's server is in a known secure configuration (e.g., has not been tampered with)
- **TPM and CRTM act as Root of Trust for Reporting**
  - TPM can generate authentic reports of current integrity measurement values (current PCR content)

Requirements on Attestation

- **Attest to all states of entities (machines) capable of affecting the behavior of the entity being attested**
  - e.g., hard- and software environment of the attesting platform including history of all executed program code
- **Attestation platform's state report**
  - Integrity, confidentiality, freshness
- **Authenticity of attestor**
- **Privacy**
  - Regarding information disclosure on system configuration and platform identity

Simplified TCG Attestation Concept



Verify σ_{TPM}

N_V Nonce (anti-replay value) chosen by the verifier
C_H current configuration of host H

Related TPM-Interface

- **Reporting of PCR values signed by the TPM**
  - Command: `TPM_Quote2` and `TPM_Quote` (deprecated)
  - May be called by an attestation system service that handles attestation requests
- **Input to `TPM_Quote2` / `TPM_Quote`**
  - AIK to be used to sign current PCR values
  - Nonce (anti-replay value)
  - Selection of PCRs to be reported
  - Indicator whether the TPM version and revision should be added to the signed report of PCR values
  - Authorization data for using the AIK

More Details about TCG Attestation

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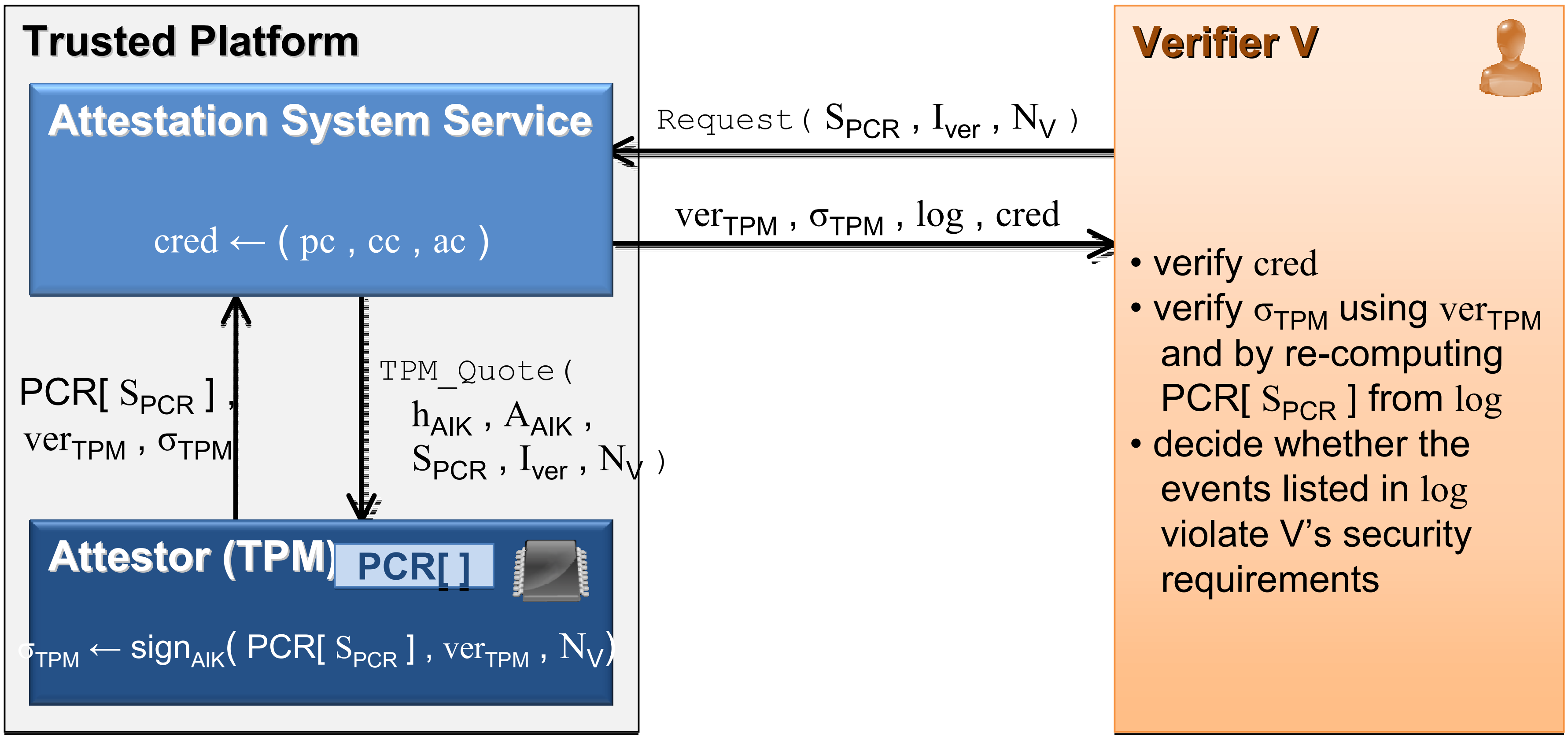


S_{PCR}	selection of PCR values V is interested in
I_{ver}	indicator whether V is interested in TPM version information
N_V	Nonce (anti-replay value) chosen by the verifier
h_{AIK}	pointer (handle) to the AIK to be used
A_{AIK}	authorization secret required to use AIK
ver_{TPM}	TPM version information
pc	platform credential
cc	Conformance Credential
ac	Attestation Credential (e.g., from Privacy C
log	TPM Event Log

AIK Certification: Privacy CA I

TPM Owner

- Prove to third parties that it's platform is in a trustable state
  - E.g., by reporting platform integrity measurements signed with a certified key
- Colluding third parties should not be able to track platform's transactions
  - E.g., by signing every integrity measurement report with a (ideally) different AIK for each

Privacy CA

- Trusted Third Party
- Attests that an AIK belongs to a valid TPM (Attestation Credential)
  - Protocol for certification of an AIK requires disclosure of public EK to Privacy CA

Property-Based Attestation

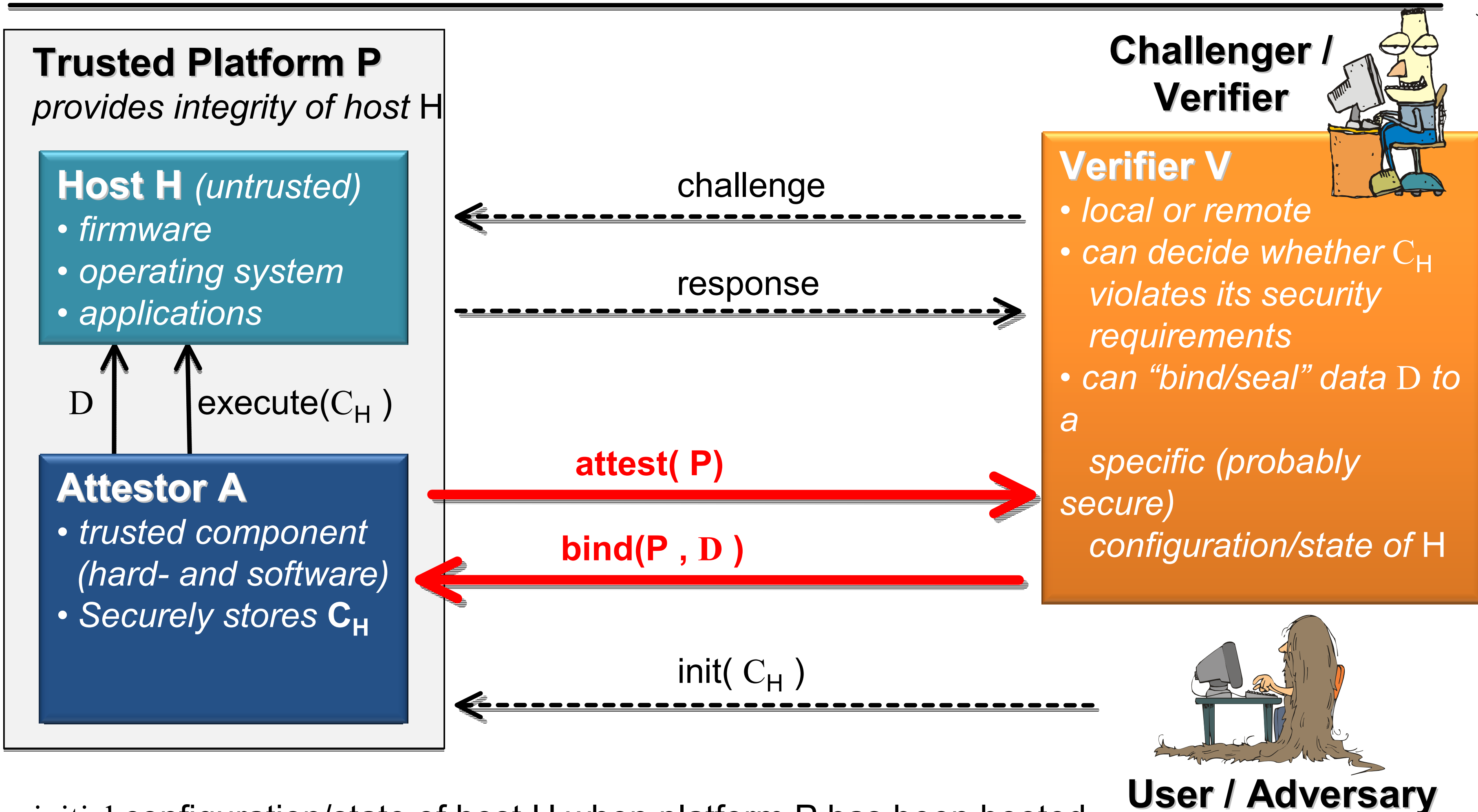
Problems of Binary Attestation/Sealing

- **Discrimination**
  - Binding/Sealing allows content and application providers to enforce usage of a specific platform configuration
  - Application vendors can exclude alternative software
- **Availability**
  - Changed binaries renders sealed data inaccessible
- **Privacy**
  - Verifiers can gain information on platform configurations
- **Management**
  - Hugh number of patches, various compiler options, software versions, development environment
  - Changes in binary values (digests) renders bound/sealed data inaccessible

Overview

- **Verifier usually interested in properties not configuration**
- **Property (informally)**
  - Describes an aspect of the behaviour of an object with respect to certain requirements (e.g., security-related)
- **Properties can be defined on different abstraction levels**
  - Privacy-preserving (built-in measures conform to the privacy laws)
  - Provides Multi-Level Security (MLS)
  - Evaluated by a governmental organisation
- **Choice of a useful property set and its definition depends on the use case and its requirements**

Abstract Model of PBA



C_H initial configuration/state of host H when platform P has been booted

D data to be revealed only if host H is in the (secure) configuration C_H

- - - - insecure channel

——— secure channel

A Possible Approach

- **Delegation-based PBA (DB-PBA)**
  - Property attestor proves that another party has certified the desired properties (e.g., certificates [SaSt2004,KuSeSt2007])
  - Hybrid approach since current TPM is used
  - Offline determination of provided properties
  - Well-suited for enterprise environment
- **How to represent property certificates?**
  - Trusted Third Party T with key pair (SK_T, PK_T)
  - Set of properties p = {p_0, ...p_n}
  - Code with configuration C_H and property p
  - $cert_T$(p, S) := Hash(C_H), p, $Sign_T$(p , cs)

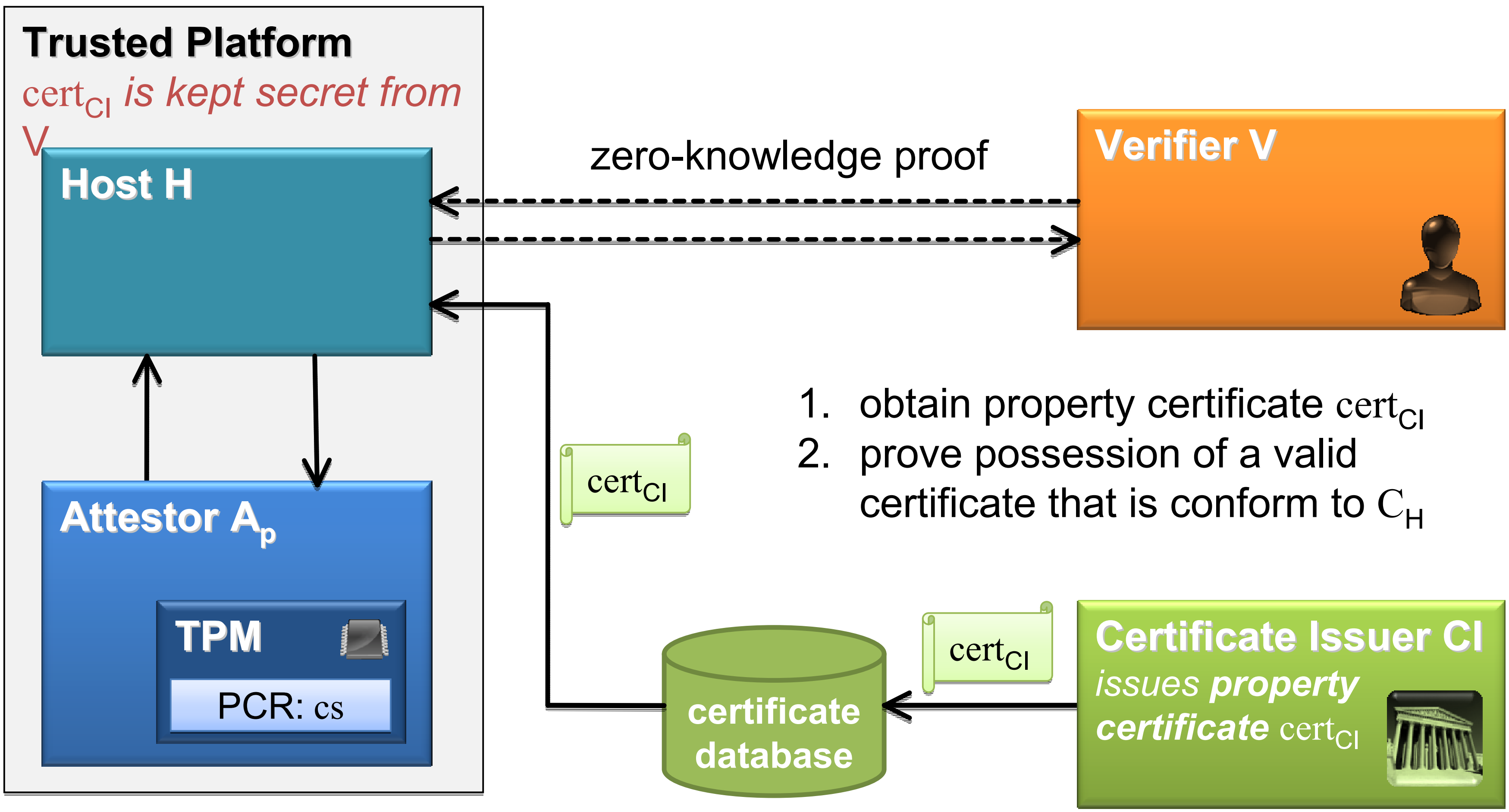
Possible Instantiations of DB-PBA I

- **Trusted Attestation Service**
  - A trusted software service performs necessary actions
  - Software service is binary attested
  - Service must be fully trusted by the verifier
- **Hardware-based certificate verification**
  - TPM evaluates property certificates
  - New TPM commands required

Possible Instantiation of DB-PBA II

- **Group signatures**
  - Public group signature key represents a property while private keys represent different configurations
  - Trusted Third Party generates keys
  - TPM functionality has to be extended
- **Prove possession of a valid certificate**
  - Proof of membership
  - Verifier does not need to trust host

Prove Possession of Valid certificate I

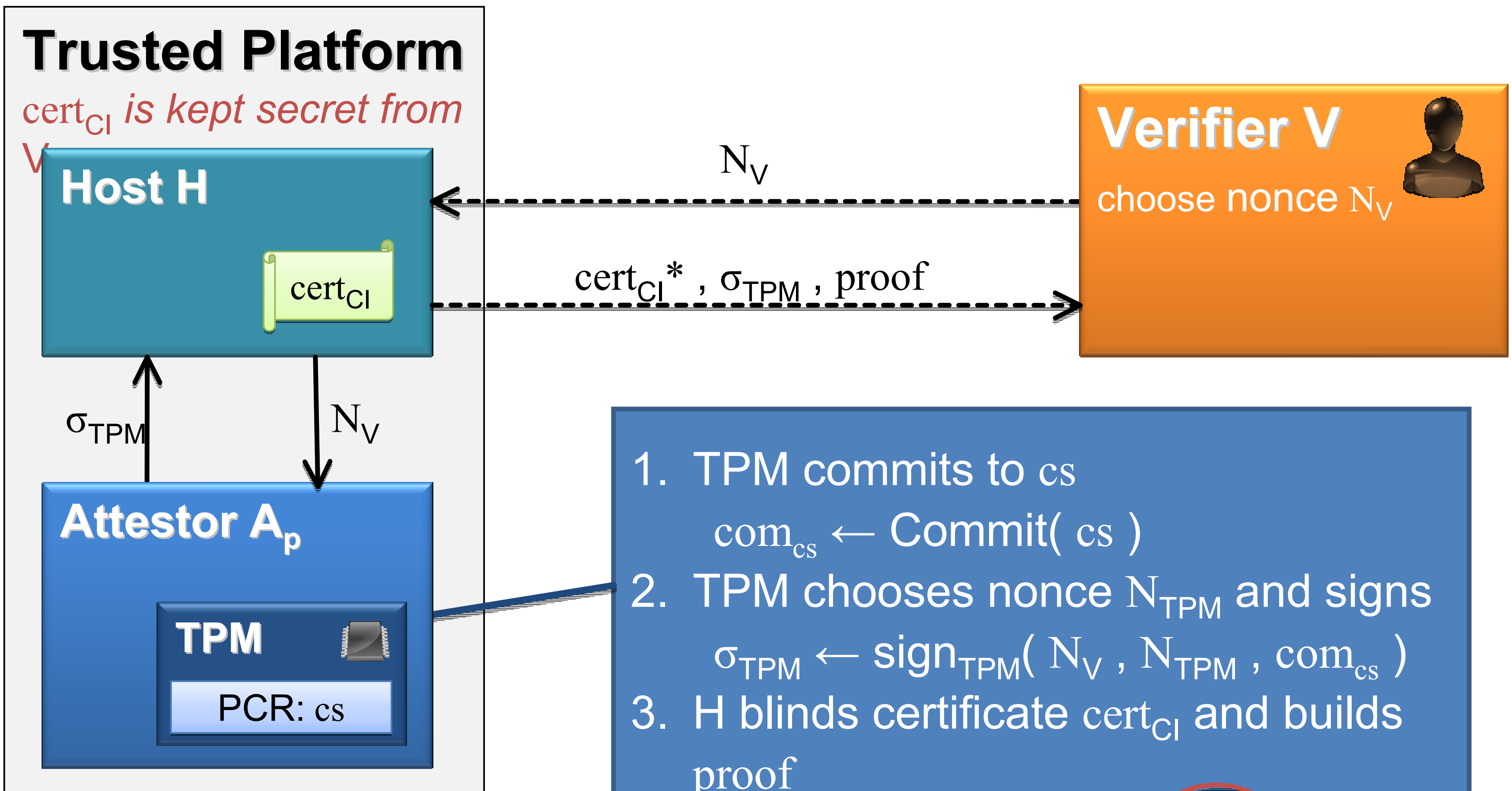


hybrid approach since binary measurements are associated with properties

C_H current configuration of host H
p (security) property of C_H

cs := Hash(C_H)
$cert_{CI}$:= $sign_{CI}$(p , cs)

Prove Possession of Valid certificate II



1. TPM commits to cs
   $com_{cs} \leftarrow$ Commit(cs)
2. TPM chooses nonce N_{TPM} and signs
   $\sigma_{TPM} \leftarrow sign_{TPM}(N_V , N_{TPM} , com_{cs})$
3. H blinds certificate $cert_{CI}$ and builds proof
   $cert_{CI}^* \leftarrow$ Blind($cert_{CI}$) , proof

non-interactive zero-knowledge proof of

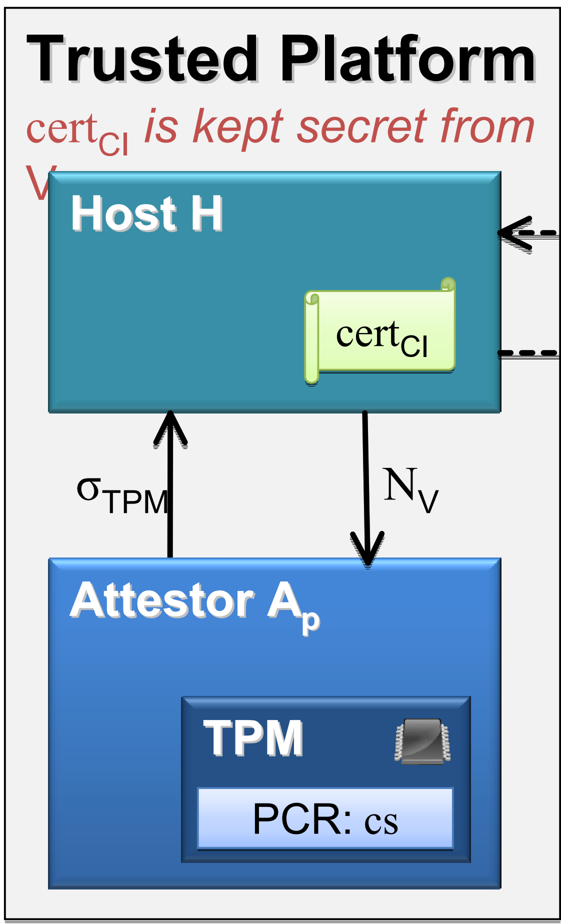
C_H current configuration of host H

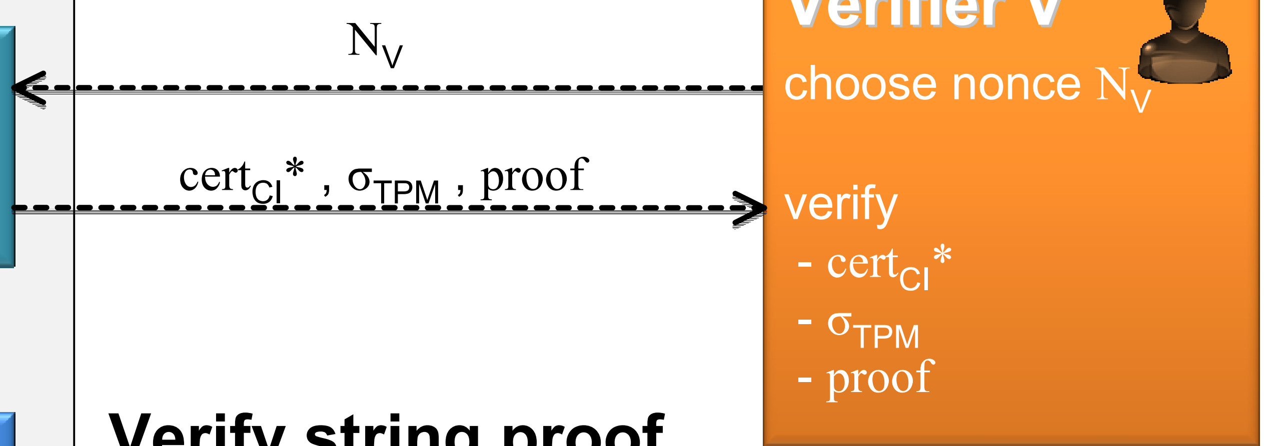
cs := Hash(C_H)

p (security) property of C_H

$cert_{CI}$:= $sign_{CI}$(p , cs)

Cryptographic Proof III





Verify string proof

- is a signature Proof of Knowledge (SPK) (Non-interactive Zero-Knowledge Proof of Knowledge
- porves that the content cs of commitment com_{cs} is in $cert^*_{CI}$ without revealing cs

C_H current configuration of host H

p (security) property of C_H

$cs := Hash(C_H)$

$cert_{CI} := sign_{CI}(p , cs)$

Exploring Other Approaches

- **Code control**
  - Property attestor is trusted to enforce that a machine can only behave as expected
  - e.g., reference monitor to attest both OS and the enforced security policy (e.g., [MaSmBaSt2004] for SE Linux [LoSm2001])
- **Code analysis**
  - Property attestor derives the machine's properties or verifies proof of properties
  - e.g., proof-carrying codes and semantic code analysis (e.g., [Necu2002], [HaChFr2003])

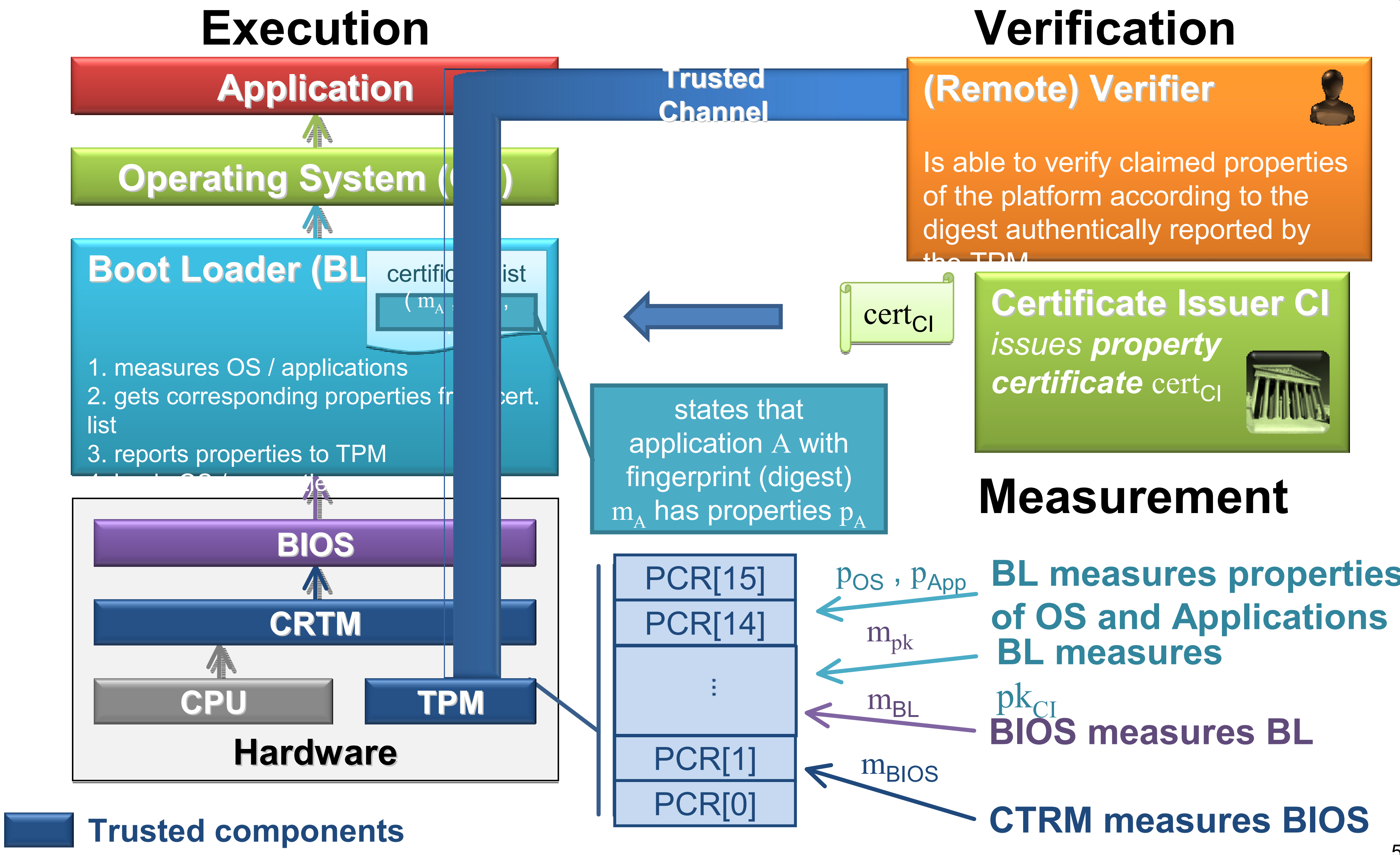
Mapping Properties to PCRs

- **Requirement**
  - reuse existing mechanisms based on PCRs
    - Remote Attestation
    - Sealing, Binding
- **Solution**
  - Use PCRs to store properties instead of binary hash values
  - Instead of extending PCR with H(S):
    - 1) Extend PCR_i with $H(PK_T)$
    - 2) Find $C = cert_T(p,S)$
    - 3) Validate signature in C
    - 4) If valid, extend PCR_j with p, otherwise by 0^{160}

PBA with Bootloader I

- **BIOS measures boot loader and extends PCRs (binary measurement)**
- **For every module to be loaded by the boot loader**
  1) Extend PCR_{b+i} with $H(PK_T)$
  2) Find $C = cert_T(p,S)$
  3) Validate signature in C
  4) If valid, extend PCR_{b+j} with p, otherwise by 0^{160}
- **$PCR_{b+1} \ldots PCR_{23}$ represent properties *p* *certified by T***
- **Attestation, Binding, and Sealing can be used as usual**
- **After a software update, only a new**

Solution with Bootloader II



Virtual TPM (vTPM)

Overview

- Enables virtual machines (VM) on a single hardware platform to use the same physical TPM
- Full software implementation of the TPM specification with additional functionalities to manage virtual TPM (vTPM) instances

Requirements on vTPM I

- **Confidentiality and integrity of vTPM state**
  - it includes Endorsement Key (EK), the Storage Root Key (SRK), the owner's authorization data (i.e., password), and monotonic counters
- **Secure link to chain of trust**
  - Linkage between hardware and software TPM
- **Unclonability and Secure Migration**
- **Freshness**
- **Distinguishability of hardware and software TPM**

Requirements on vTPM II

- **Data availability**
  - Sealed data must be accessible if the security policy is fulfilled, this includes migration
- **Privacy protection**
  - User can decide over the information disclosure on platform’s concrete configuration
- **Flexible key types**

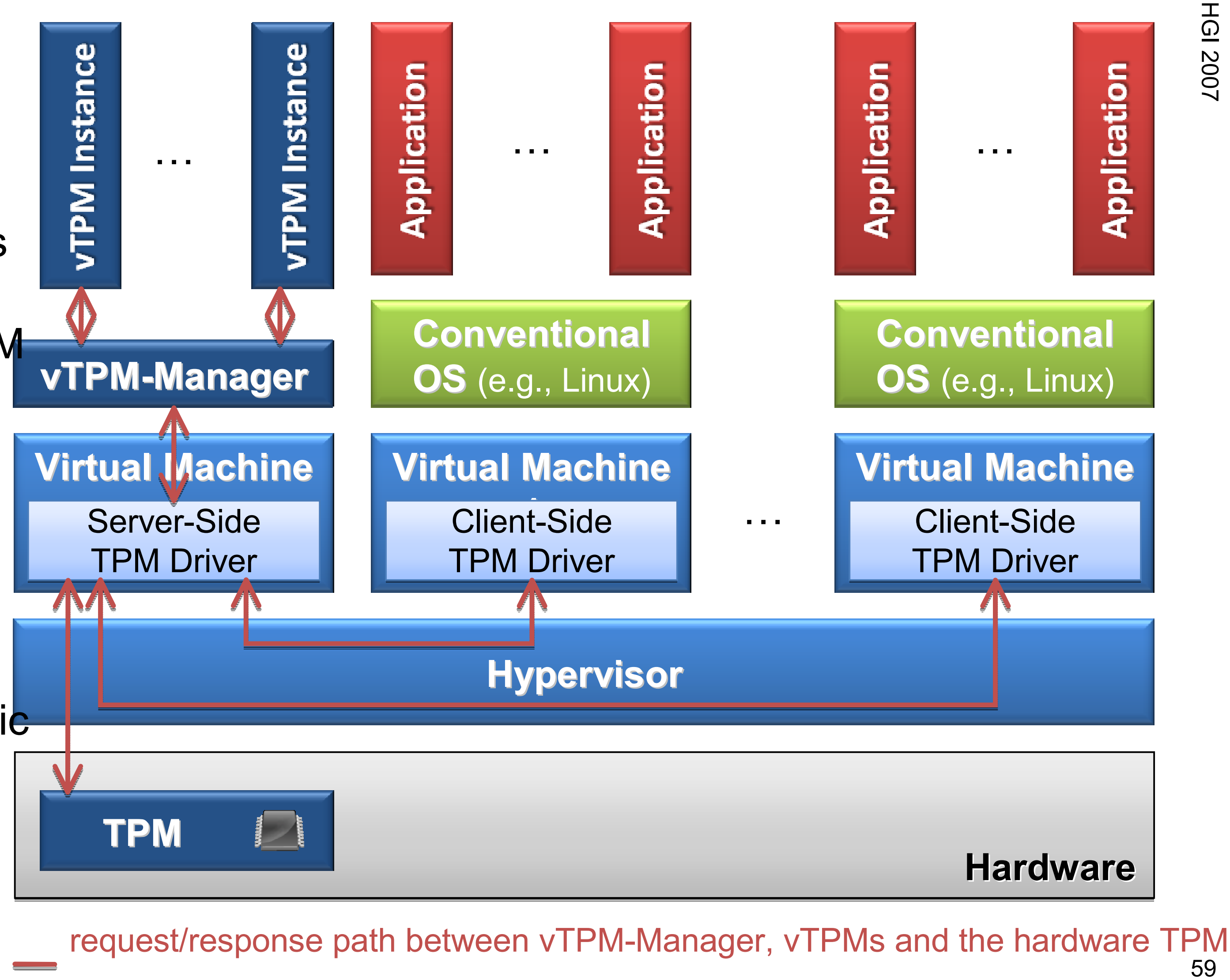
Existing Solutions on vTPM and Open Problems

Possible vTPM Architecture

vTPM Manager
- creates vTPM instances
- multiplexes requests from virtual machines to their associated vTPM instances

Linking vTPM & TCB
- Lower sets of vPCRs contains values from PCR
- Upper set of vPCRs contain values specific to vTPM

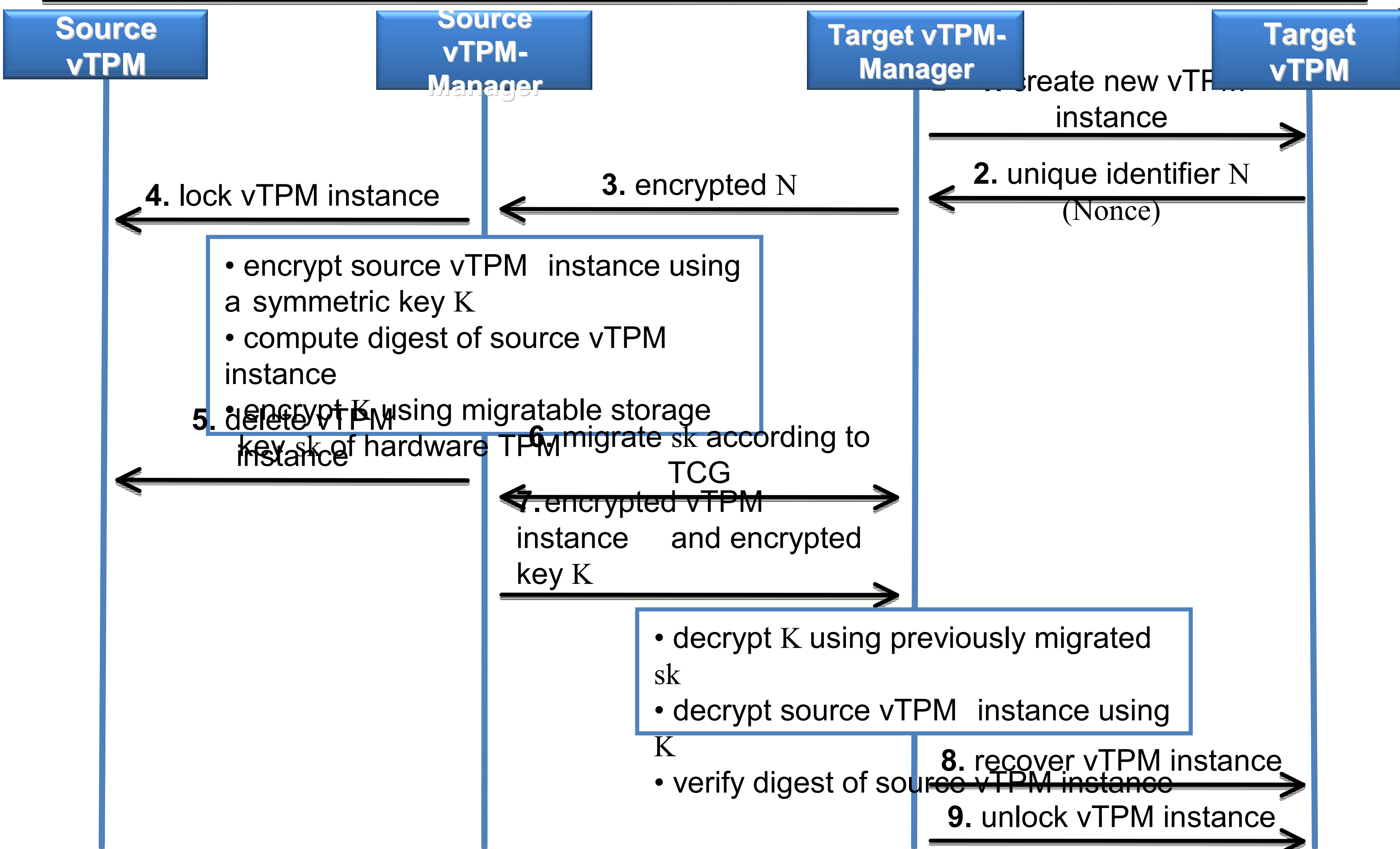
[Berger et al 06]



Linking vTPM to TPM

- **Certified AIK signs vEK and vAIK is certfied by PrivacyCA**
  - Conform to TCG model but needs communication with Privacy CA
- **Certified AIK signs vAIK**
  - Not standard
- **In above solutions AIKs must be invalidated once VM is resumed on the target platform**
- **Alternative: rely on a local authority to issue certificates for EKs of vTPM instances**
  - No direct connection to the TPM
  - But the service can be attested

Migration of vTPMs



Problems Not Solved

- **Migration to platforms with different binary VMM**
  - Binary-based integrity measurement
  - Problems with mapping lower PCRs to lower vPCRs
- **Large TCB**
  - VMM, vTPM Manager, vTPM instances
  - and a whole guest OS in one VM
- **Only one type of TPM keys supported**
- **Software Updates?**

Endorsement Credentials for vTPMs

Information to be included into the Endorsement Credential (EC) for vTPM

$$\text{certInfo}(\ EK_{vTPM}\ ) \leftarrow (\ \text{credType}\ ,\ pk_{EK_{vTPM}}\ ,\ \text{tpmModel}\ ,\ \text{certIssuer}\ ,\ \text{tpmVer}\ ,\ \text{ml}\ )$$

- credType: *indicates that this cert. is an EC*
- $pk_{EK_{vTPM}}$: *public Endorsement Key of vTPM*
- tpmModel: *identifier for vTPM (manufacturer-specific)*
- certIssuer: *identifies issuer of the EC*
- tpmVer: *revision of TPM spec. the vTPM implements*
- ml: *measurement list of the environment of the VM*

Certification of vTPM's EK using an AIK and the `TPM_Quote` command:

$$N \leftarrow \text{SHA-1}(\ \text{certInfo}(\ EK_{vTPM}\ )\ )$$

TCG intended N *to act as anti-replay value (nonce)*

$$\sigma_{TPM} = \text{sign}_{AIK}(\ PCR[\ S_{PCR}\ ]\ ,\ N\ ) \leftarrow \texttt{TPM\_Quote}(\ h_{AIK}\ ,\ A_{AIK}\ ,\ S_{PCR}\ ,\ N\ )$$

- h_{AIK}: *pointer to the AIK to be used to sign* S_{PCR}
- A_{AIK}: *authorization data for using the AIK*
- S_{PCR}: *selection of PCR registers which should be signed (e.g., those containing digests of environment of the VM)*

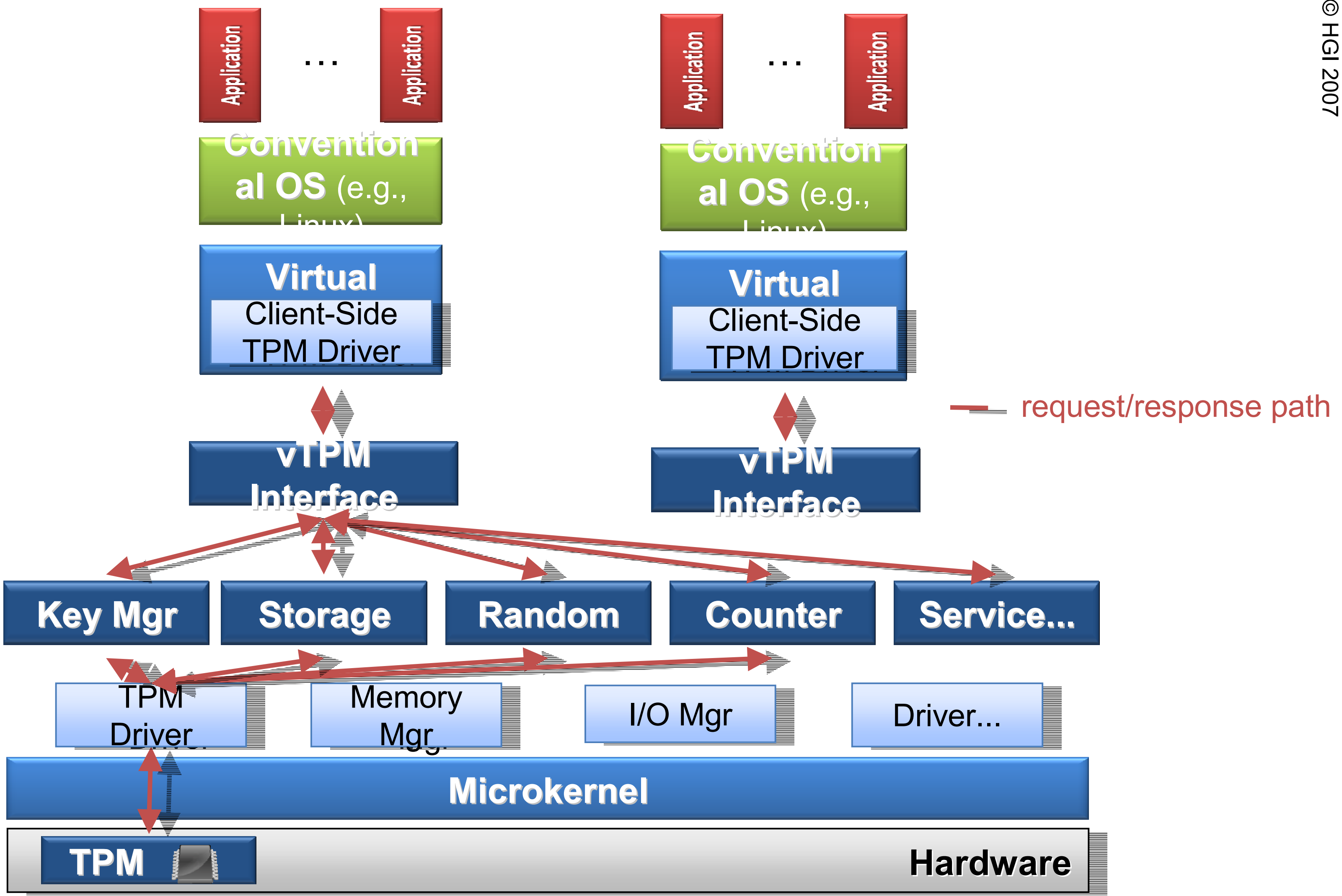
Resulting EC for vTPM:

$$\text{cert}_{AIK}(\ EK_{vTPM}\ ) \leftarrow (\ \text{certInfo}(\ EK_{vTPM}\ )\ ,\ \sigma_{TPM}\ )$$

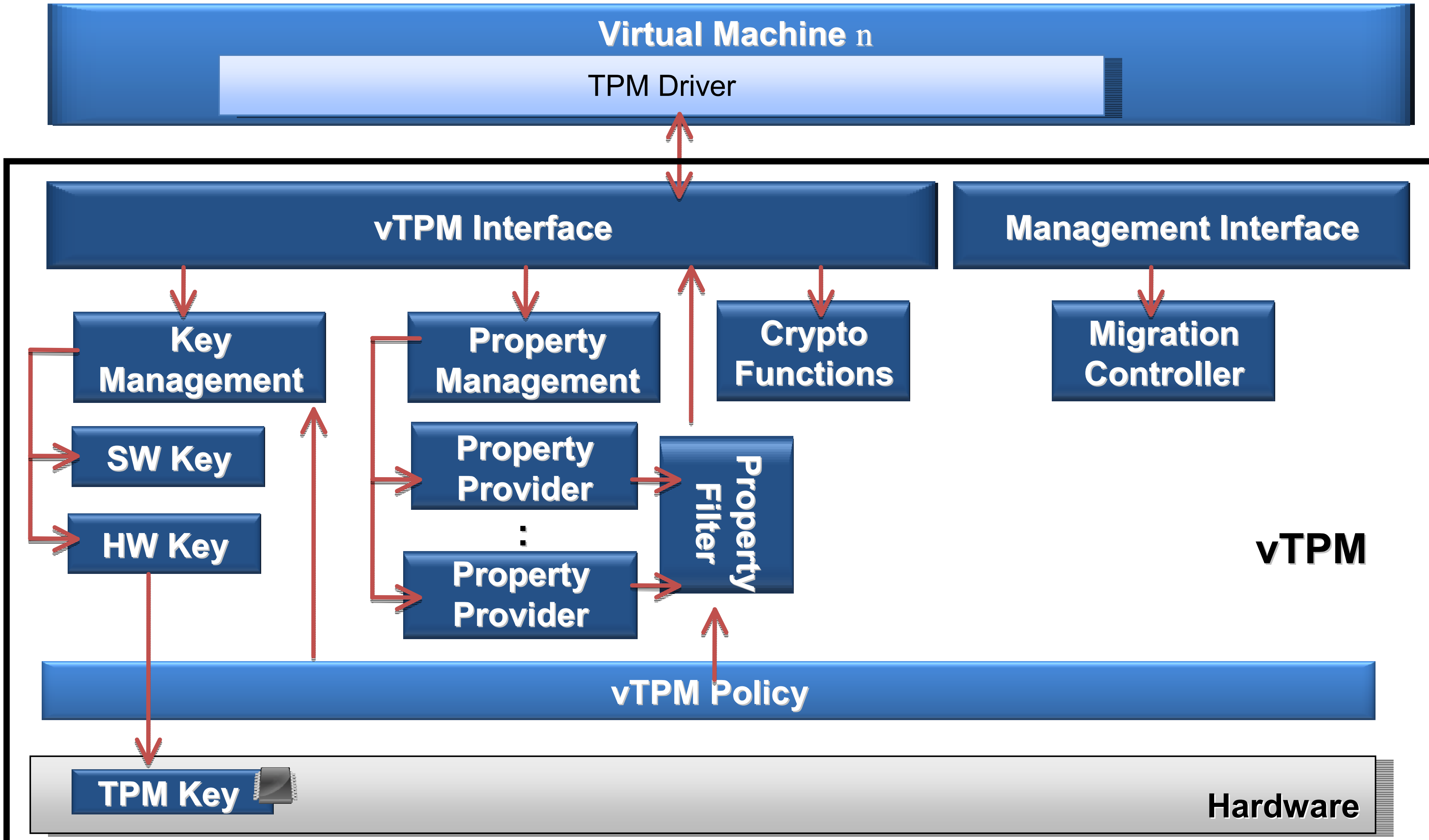
Flexible Key Generation and Usage

- **Both hardware and software keys should be usable by a compartment**
  - Example: Corporate computing at home
    - Boot802.1x (non-migratable) requires a hardware key
    - Other compartments (migratable) require software keys
- **Security kernel should enforce privacy requirements**
  - AIK/DAA management and usage by security service
  - Example: Service creates new AIK for every attestation procedure
- **Decisions should be made by mandatory privacy and security policy!**

Alternative Approach

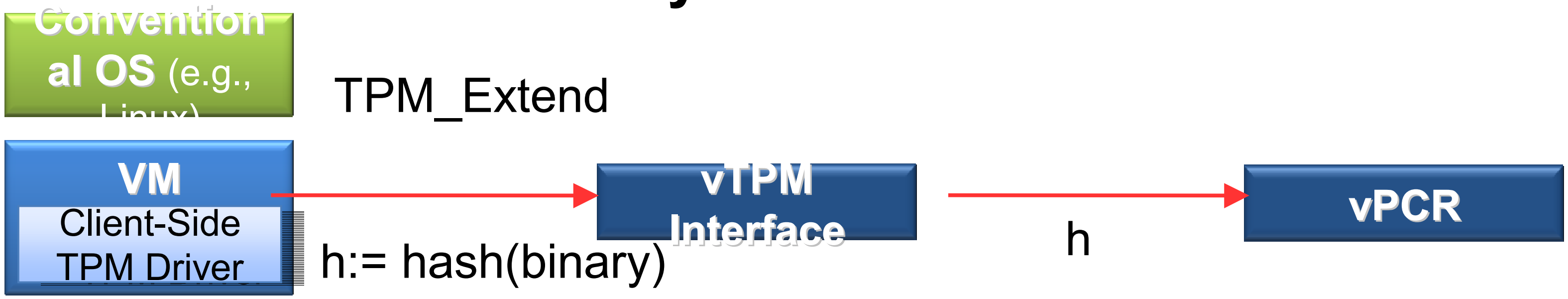


Possible Alternative Solution: Logical vTPM Architecture

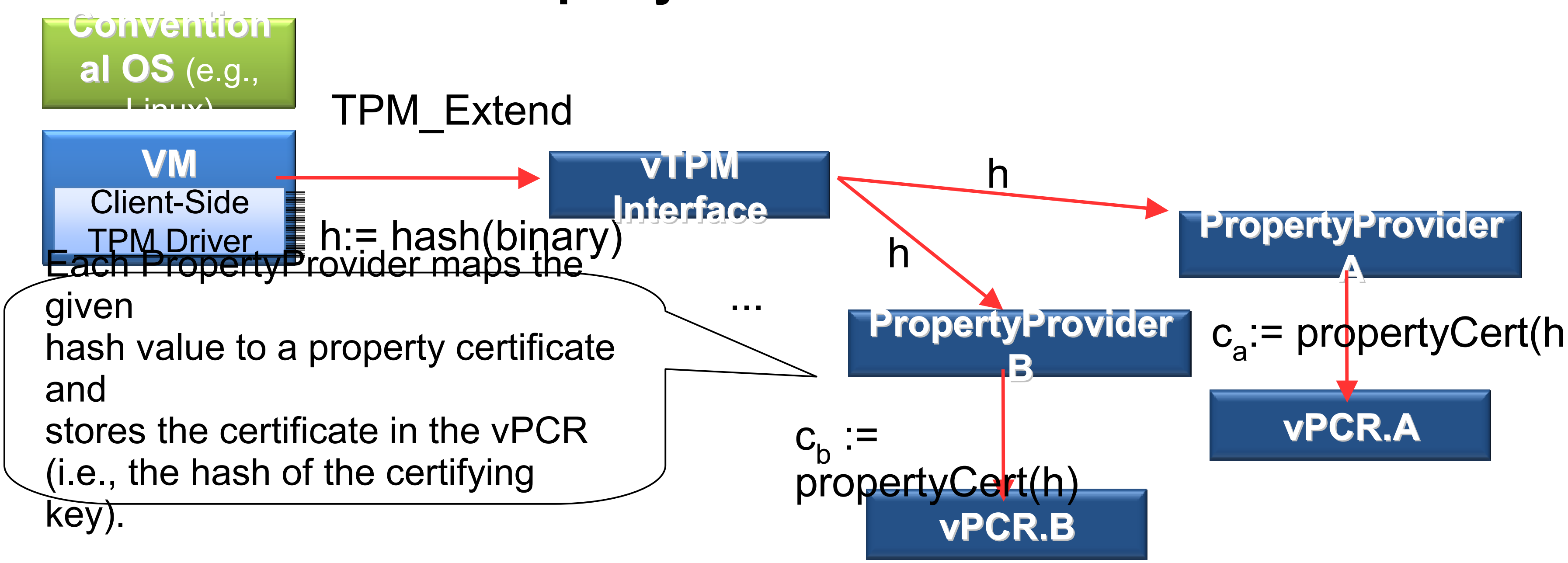


Property Based Approach

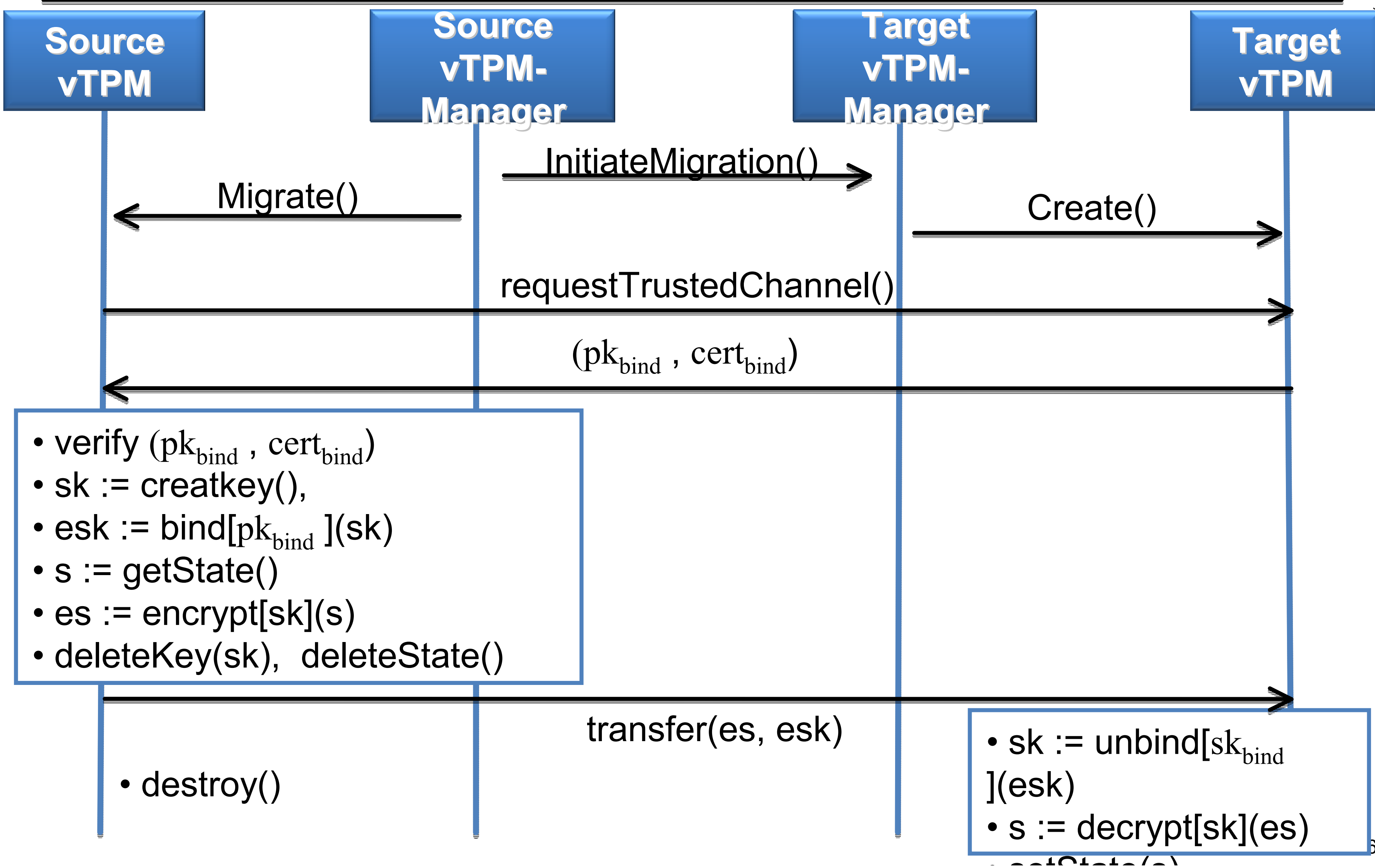
Binary Measurement



Property-based Measurement



Migration of vTPMs



Conclusion and Future Work

- **Trusted Computing is an emerging technology, however, many challenges remain:**
- **Property-based Attestation**
  - What are useful properties? How to formalize them? What are the most efficient approaches for property-based Attestation in practice?
- **TPM**
  - How to design a minimum TPM? How to detect trapdoors and Trojans? More effective revocation and maintenance mechanisms
- **Privacy protecting and anti-discriminating designs**
- **Enabling security protocols with TC functionalities**
- **Trusted Virtual Domain**
- **Applications of multiparty computation for real world**
- **Lightweight TC for embedded systems**
- **Formal proofs in security models**