Policy Enforcement and Compliance Proofs for Xen Virtual Machines

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Broader Problem: Security Management of VMs

- **Complicating Factors**
  - **VMs on same physical host may belong to diverse organizations**
  - **VMs on same physical host may have different security requirements**
  - **Weaker isolation boundary between VMs than physical machines**
  - **Security verification & confidentiality may be opposing goals**

- **Our focus is on Integrity Management**
  - **Protecting VM security policies from modification throughout VM life-cycle**
  - **Verifying that a VM is compliant with specified security requirements**

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Contributions

- **Formal model for *generalized* integrity management of VMs**
  - **Extends TPM (Trusted Platform Module) based mechanisms to cover**
    - **VMs and virtual devices**
    - **Wider and finer-grained policies**
    - **any policy that can be expressed as predicate on system log entries**
- **PEV (Protection, Enforcement, and Verification) Integrity Architecture**
  - **Extensibility: verify compliance even if new virtual devices are added to VMs**
  - **Flexibility: user can specify which aspects of system's integrity state are of interest**
    - **obtains only information corresponding to those aspects for compliance verification**
  - **Blinding technique for enforcing access restrictions to the system integrity state**
- **Xen-based prototype**

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Outline

- **Formal model for *generalized* integrity management**
- **PEV Integrity Architecture & Associated Protocols**
- **Xen-based prototype**
- **Use-cases**

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Trusted Platform Module: Background

- Tamper-evident, smartcard-like hardware chip
- Hardware implementation of multiple roots-of-trust
  - Root-of-trust (assumption): always behaves as expected; trusted by local & remote parties
  - E.g., root-of-trust for storage, for integrity reporting, for integrity measurement
- 160-bit Platform Configuration Registers (PCRs)

- Operations
  - Extension: Replace content of PCR with hash (old PCR content + input)
  - Measurement: Compute the SHA-1 hash of the binary code of a component
  - Attestation: Challenge-response style cryptographic protocol
    - Allows a remote party to query the recorded platform measurement values (stored in PCRs)
    - Allows the platform to reliably report the requested values
      - Using the TPM_Quote command to obtain signature on PCR value
  - Sealing: Bind data item to PCR values
    - Ensure that a sensitive data item is accessible only under certain platform config.
  - Unsealing: Reveals specified data item only if current PCR value(s) = PCR value(s) at sealing time

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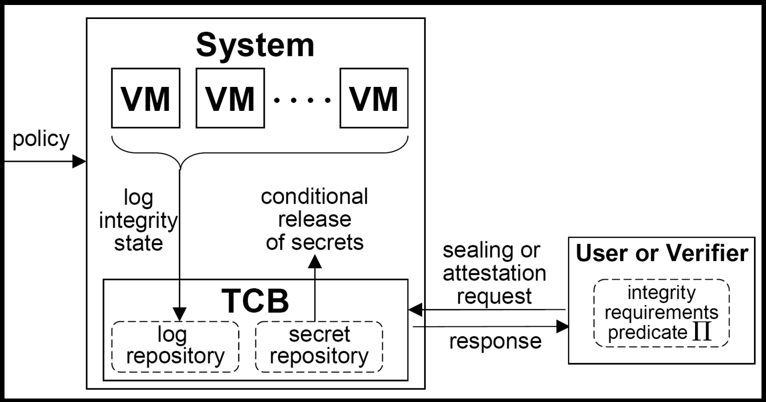
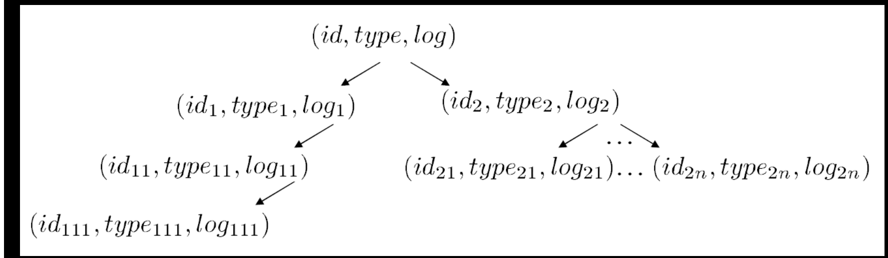
Formal Integrity Model



Log Tree, T



- **Secure Write-Only Log Repository**
  - **log data contains integrity state of the system**
- **Log contents stored in a tree structure, called *log tree***
  - **One node for each system component**
  - **Node = (id, type, *vector* of log values)**
  - **Extensible**
- **Secret Repository for conditional release of secrets**
  - **Store sensitive data item and associated condition, such that the data item is released only if the log data satisfies condition**
- **Integrity Requirements**
  - **Expressed using predicates & projections on log data**
  - **Projection function, p (T)**
    - **returns a subset of the tree nodes and a subset of the vector elements from the log vector of each node**
    - **models specific aspects of the system's integrity state that is of interest to user/verifier**
  - **Predicate, Π**
    - **used for specifying integrity conditions**

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Formal Integrity Model: Generalized Sealing to Protect Integrity

- **TPM-Based Solution**
  - **Sealing: encrypt data item, tie it to values in specified subset of PCRs**
  - **Unsealing: decryption only if those PCRs have same values as those at sealing time**
- **Generalization to protect integrity of a data item**
  - **by making it inaccessible unless specified integrity conditions hold**
  - **Sealing Operation**
    - ***Input:* data item, projection $\mathbf{p}(\ )$, sealing predicate Π , public part of encryption key**
    - ***Action:* Log both $\mathbf{p}(\ )$ and Π, then encrypt data item using key**
  - **Unsealing Operation**
    - ***Input:* encrypted data item, log tree**
    - ***Output:* reveal data item, only if $\Pi\ (\mathbf{p}\ (\mathbf{T})\ )$ holds**

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Formal Integrity Model: Generalized Attestation to Verify Integrity

- **TPM-based solution**
  - **query and obtain values in a specified subset of PCRs**
- **Generalization**
  - **Verifier specifies which aspects of system's integrity state are of interest**
    - **Via attestation predicate Π , and projection function $\mathbf{p}$ ()**
  - **Input: challenge $\mathbf{c}$, Π, $\mathbf{p}$ (), secret key K**
  - **Output: sign_K [Π ($\mathbf{p}$ ($\mathbf{T}$)), $\mathbf{c}$]**
- **Specialization**
  - **to obtain TPM-based binary attestation**
    - **predicate is simply the identity function**
    - **projection function specifies which subset of PCRs to use**
  - **property-based attestation**
    - **predicate extracts high-level properties from the result of $\mathbf{p}$ ($\mathbf{T}$)**

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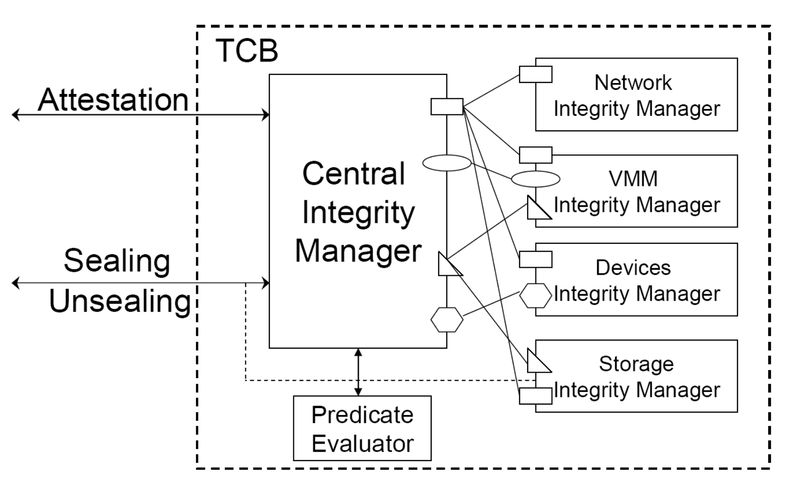
PEV Integrity Architecture: Key Elements



Flexibility: plug-in modules to encode arbitrarily complex log projection functions

Extensibility: integrity state of newly added VMs/virtual devices can be covered by adding new plug-in modules to TCB

- **Central Integrity Manager**
  - **Implements one master plug-in module for each p (T)**
  - **Invokes appropriate component plug-in modules and aggregates their output**
- **Component Integrity Managers**
  - **One per each system component that is of interest from an integrity perspective**
  - **manages part of the log tree corresponding to the component**
  - **e.g., Storage Integrity Manager is responsible for storage sub-tree of the log tree**
  - **contains component plug-in modules that implement log projection functions**
  - **mapping between plug-in identifier and plug-in functionality is made public**

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PEV Integrity Architecture: Sealing-Unsealing Protocol

- Input
  - Data item to be encrypted
  - Key (public part is used for encryption; private part is revealed only if unsealing is successful)
  - Identifiers of plug-ins (which implement the log projection function)
    - Which aspects of the system's integrity state are of interest to the user and need to be verified
  - Predicate
    - Condition for revealing the private part of sealing key
- Key sealed against [state of TCB + hash(plug-in IDs + predicate)]
  - State of TCB stored in non-resettable PCRs
  - Hash stored in resettable PCR, which ensures that
    - TCB is aware of conditions to be satisfied before revealing key during unseal operation
    - these conditions are not changed prior to unsealing
- Unseal operation
  - Stage 1
    - TPM reveals key to Integrity Manager if state of TCB is unchanged
    - TCB checks whether resettable PCR still contains hash
  - Stage 2
    - Integrity Manager invokes Predicate Evaluator
    - if predicate holds, Integrity Manager reveals key to user

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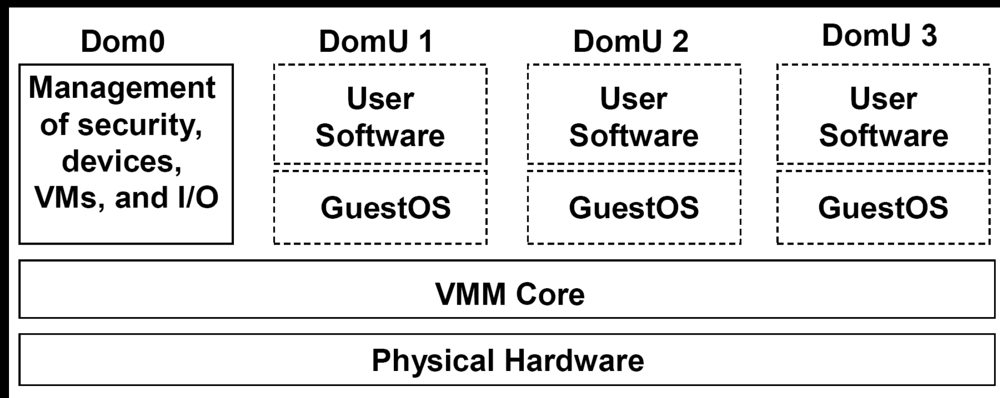
Xen: Background



- Domains = running instances of VMs
- Dom0
  - the first domain created
  - a special domain that controls other domains, called DomUs or user domains
- Device virtualization
  - For a given physical device, the native device driver is part of at most one VM
  - VM with native device driver exports a *back-end driver*
  - Any VM that wants to share the device exports a *front-end (virtual) device driver*
  - Front-end driver connected to back-end driver through *device channels*

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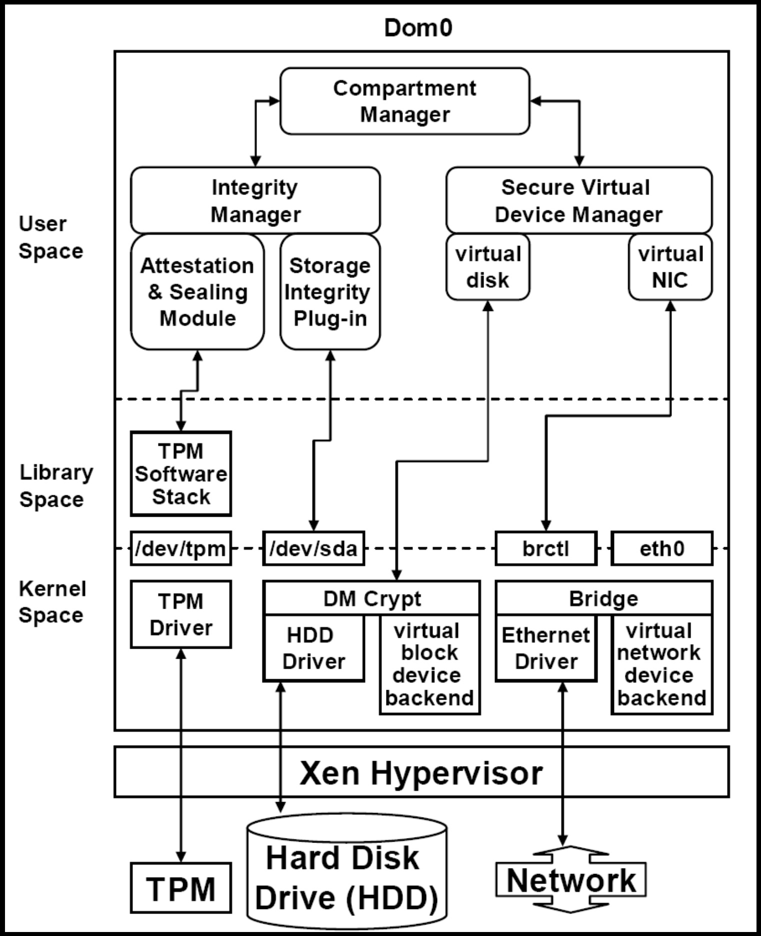
Xen-based Prototype

- Compartment Manager (CM)
  - VM life cycle management
  - orchestrator of IM and SVDM
- Integrity Manager (IM)
  - Storage Integrity Plug-In (SIP)
    - measures disk images, files
  - Attestation & Sealing Module (ASM)
    - performs sealing, attestation protocols
    - invokes TPM operations
- Secure Virtual Device Manager (SVDM)
  - Managing virtual devices
  - Consists of two specialized low-level component plug-in modules
    - one for virtual encrypted hard disk
    - one for virtual network interface card



Model		Xen-based Prototype
Projection	p()	component measurement plug-in
Predicate	Π	XSLT stylesheet

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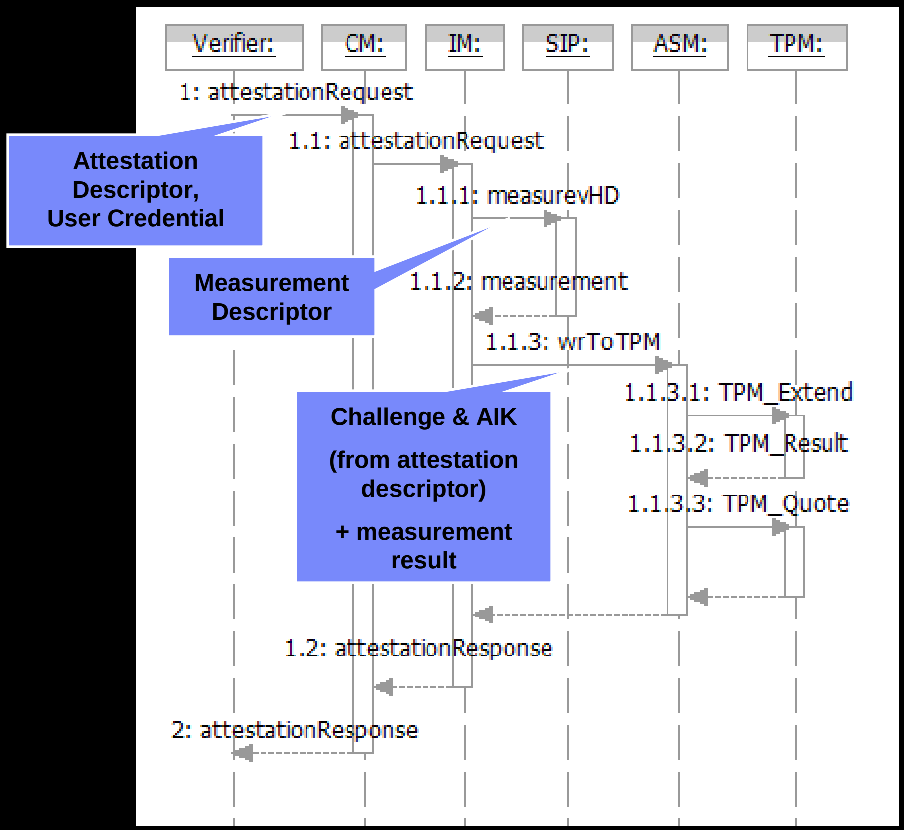
Use Case 1: Attestation the Status of a VM Disk Image



- Attestation Descriptor
  - XML structure which tells which log projection function to choose
  - contains measurement descriptor(s)
  - what is to be measured?
    - which measurement plug-in modules to invoke?
    - e.g., VM disk image
  - where to store measurement results?
    - e.g., PCR 16
- attestationResponse
  - TPM_Quote result
  - relevant log files
- Verifier can check result
  - recompute hash over the relevant log files
  - compare result with PCR value in attestationResponse

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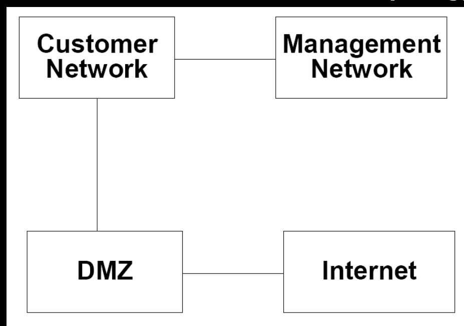
Use Case 2: Compliance Proof for Correct Network Configuration

Desired Virtual Network Topology



XML Representation of Flow Control Policy

```
<flow-policy>
  <zone id="customer-net">
    <permit id="mgmt-net" />
    <permit id="dmz" />
  </zone> ...
</flow-policy>
```

XSLT Stylesheet Encoding Conditions to be Checked (used at verifier)

```
<xsl:template
  match="/flow-policy/zone[@id='customer-net']">
  <xsl:choose> <xsl:if
      test="count(*[@id='dmz'])=1
            and count(*[@id='mgmt-net'])=1">
      <true />
    </xsl:if>
  </xsl:choose>
</xsl:template>
```

Goal: Validate the Config. Of Virtual Networking Sub-system on a given Host in the Customer Network

- **Similar sequence of steps as in Use Case 1.**
- **Instead of invoking the SIP, the IM invokes the network measurement plug-in.**
- **Plug-in outputs measurement results as XML structure**
  - Indicates the flow control policy in place
- **Compliance proof = attestation of [TCB + plug-in output]**
- **Verifier uses XSLT stylesheet on XML output of network measurement plug-in to validate that the network policy at the host reflects the desired network topology**

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Summary

- **Introduced a formal model that generalizes TPM-based integrity management**
  - **Log data stored in extensible tree structure**
  - **Projection functions allow choosing specific aspects of the system's integrity state**
  - **Predicates allow encoding arbitrarily complex integrity conditions**

- **PEV integrity architecture for policy enforcement and compliance checking**
  - **Flexibility: plug-in modules to encode arbitrarily complex projection functions**
  - **Extensibility: integrity state of newly added VMs/virtual devices can be covered by adding new plug-in modules to TCB**

- **Xen-based prototype**
  - **demonstrated capabilities using multiple use-cases**

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