Systems and Internet Infrastructure Security

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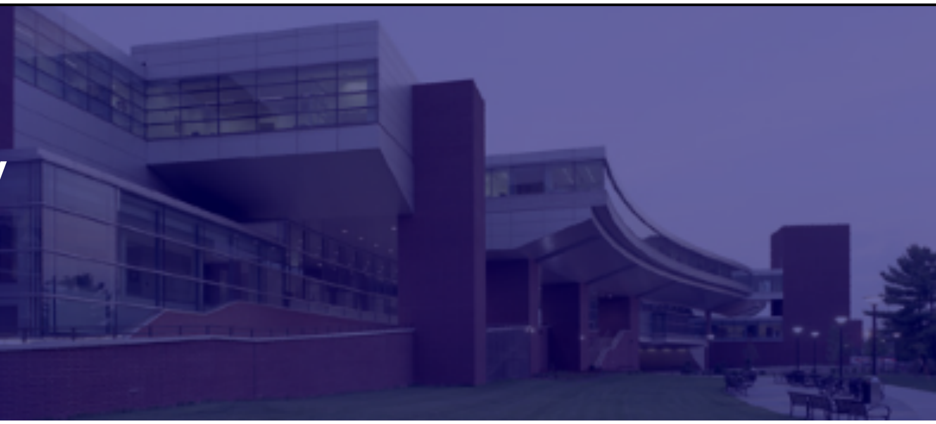

Advanced Systems Security: Intel SGX

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Remaining Problems

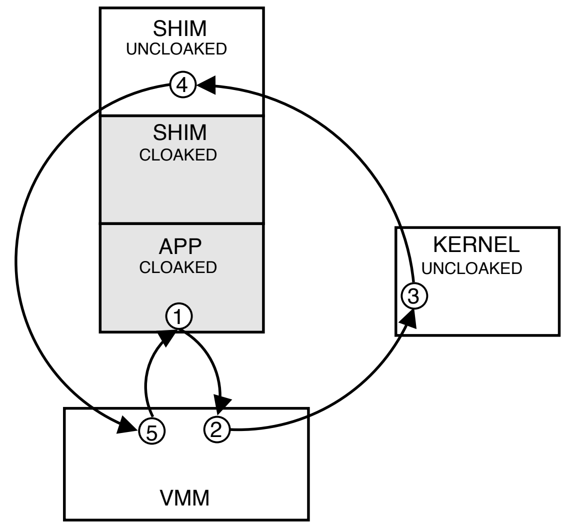
- Deploying a custom OS is painful
  - Building a special kernel is non-trivial
- And it may not be secure itself
  - Still need a methodology to determine code correctness and tamperproofing
- What if you want to eliminate trust in the OS altogether?

Insight: Shadowing Memory

- VMMs need to manage physical to virtual mapping of memory
- This is done with a shadow page table
- Multi-shadowing give context-aware views of this memory
  - Use encryption instead

Memory Cloaking

- Not new idea
  - XOM, LT
- Encrypt the pages in memory
  - For each page, (IV, H) meta data
  - What should the "secure hash" be?
- OS can operate on encrypted pages
  - But can't read them

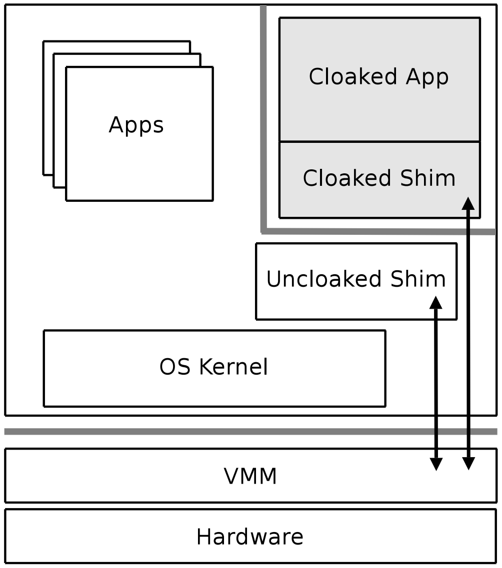


Tasks of the Overshadow

- Mediate all application interaction with OS to ensure correct cloaking of memory
  - Context Identification
  - Secure Control Transfer
  - System Call Adaptation
  - Mapping Cloaked Resources
  - Managing Protection Metadata

Shim baby Shim

- The key to Overshadow is the Shim
  - Manages transitions to and from VMM via a hypercall
- Shim Memory protects application
  - CTC protects control registers
- Uncloaked Shim
  - Neutral ground
  - Trampoline!



Loading Applications

- The Shim uses a Loader program
- Sets up the cloaked memory with a hypercall
- The loader / shim must be trusted
  - Metadata on the CTC checks for compromise
  - Here is the meat of the problem
    - Is it even used?
- Propagate shims to spawned applications

Its not that easy…

- Lot of OS interfaces that must be handled
- Faults / Interrupts
- System Calls
  - Pass control to the VMM
  - The shim catches this and stores registers
    - Clear the registers to prevent side channels

Complex Syscalls

- Some syscalls are easy
  - No *side effects*
  - Nice, getpid, sync
- Others, less so…
  - Pipe, r/w (kernel sees zero data, VMM needs to fix)
  - Clone – must keep cloaked cloaked
  - Fork
  - Signal Handling – cannot signal cloaked code arbitrarily, so VMM must signal shim

Performance

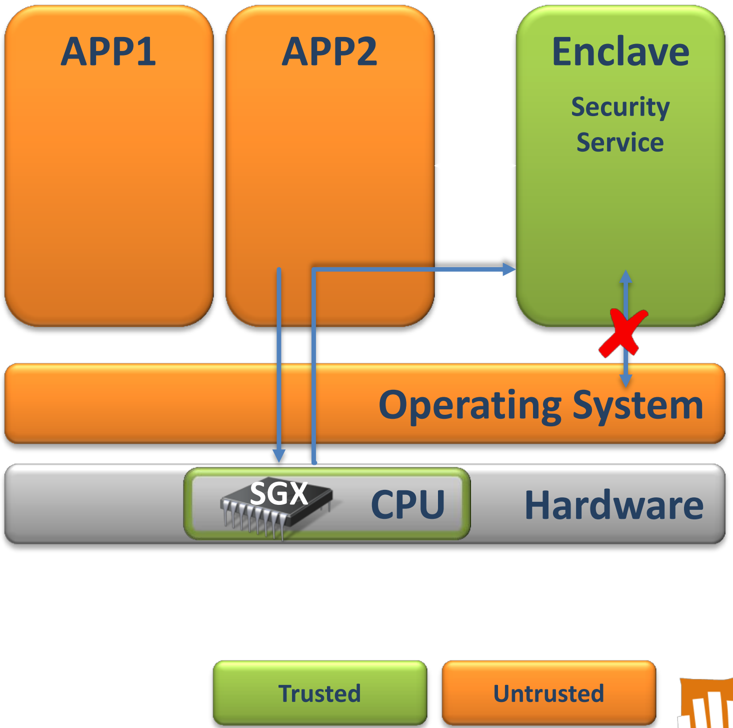
- Microbenchmarks
  - Not so hot 15-60%
  - Although a lot better than Proxos
- Application Benchmarks
  - SPEC isn't so bad
  - High bandwidth hits some bottlenecks
  - Why?

Intel Software Guard Ext

Intel® Software Guard Extensions (SGX)

[McKeen et al, Hoekstra et al., Anati et al., HASP'13]

- **Security critical code isolated in enclave**
- **Only CPU is trusted**
  - Transparent memory encryption
  - 18 new instructions
- **Enclaves cannot harm the system**
  - Only unprivileged code (CPU ring3)
  - Memory protection
- **Designed for Multi-Core systems**
  - Multi-threaded execution of enclaves
  - Parallel execution of enclaves and untrusted code
  - Enclaves are interruptible
- **Programming Reference available**



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SGX Enclaves

- **Enclaves are isolated memory regions of code and data**
- **One part of physical memory (RAM) is reserved for enclaves**
  - It is called **Enclave Page Cache (EPC)**
  - EPC memory is encrypted in the main memory (RAM)
  - Trusted hardware consists of the CPU-Die only
  - EPC is managed by OS/VMM

RAM: Random Access Memory
OS: Operating System
VMM: Virtual Machine Monitor (also known as Hypervisor)

SGX Memory Access Control

- **Access control in two direction**
  - From enclaves to “outside“
    - Isolating malicious enclaves
    - Enclaves needs some means to communicate with the outside world, e.g., their “host applications”
  - From “outside“ to enclaves
    - Enclave memory must be protected from
      - Applications
      - Privileged software (OS/VMM)
      - Other enclaves

OS: Operating System
VMM: Virtual Machine Monitor (also known as Hypervisor)

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SGX MAC from enclaves to “outside“

- **From enclaves to “outside“**
  - All memory access has to conform to segmentation and paging policies by the OS/VMM
    - Enclaves cannot manipulate those policies, only unprivileged instructions inside an enclave
  - Code fetches from inside an enclave to a linear address outside that enclave will results in a #GP(0) exception

MAC: Memory Access Control
#GP(0): General Protection Fault

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SGX MAC "outside" to enclaves

- **From "outside" to enclaves**
  - Non-enclave accesses to EPC memory results in abort page semantics
  - Direct jumps from outside to any linear address that maps to an enclave do not enable enclave mode and result in a about page semantics and undefined behavior
  - Hardware detects and prevents enclave accesses using logical-to-linear address translations which are different than the original direct EA used to allocate the page. Detection of modified translation results in #GP(0)

MAC: Memory Access Control
EA: Enclave Access
#GP(0): General Protection Fault

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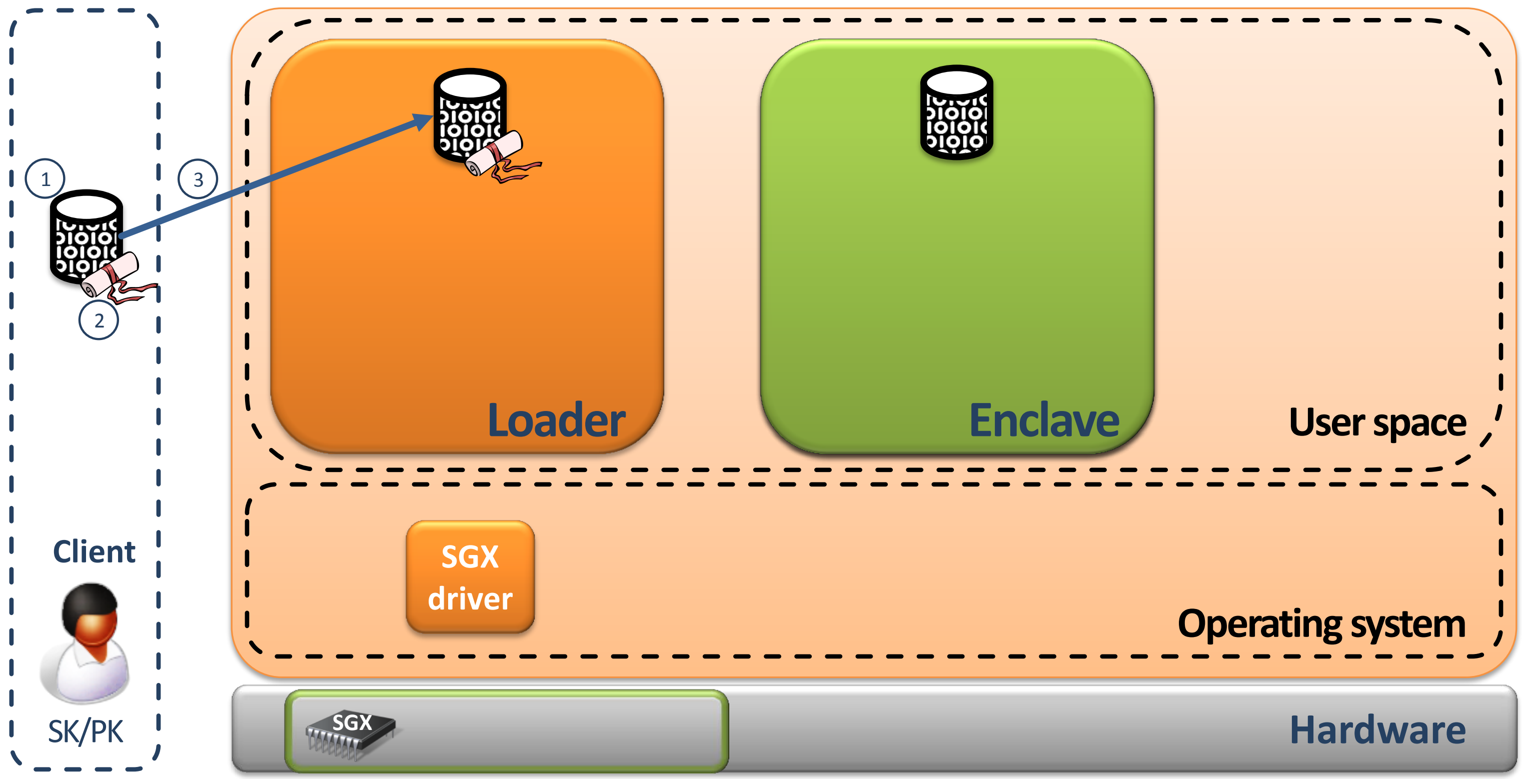
SGX – Create Enclave

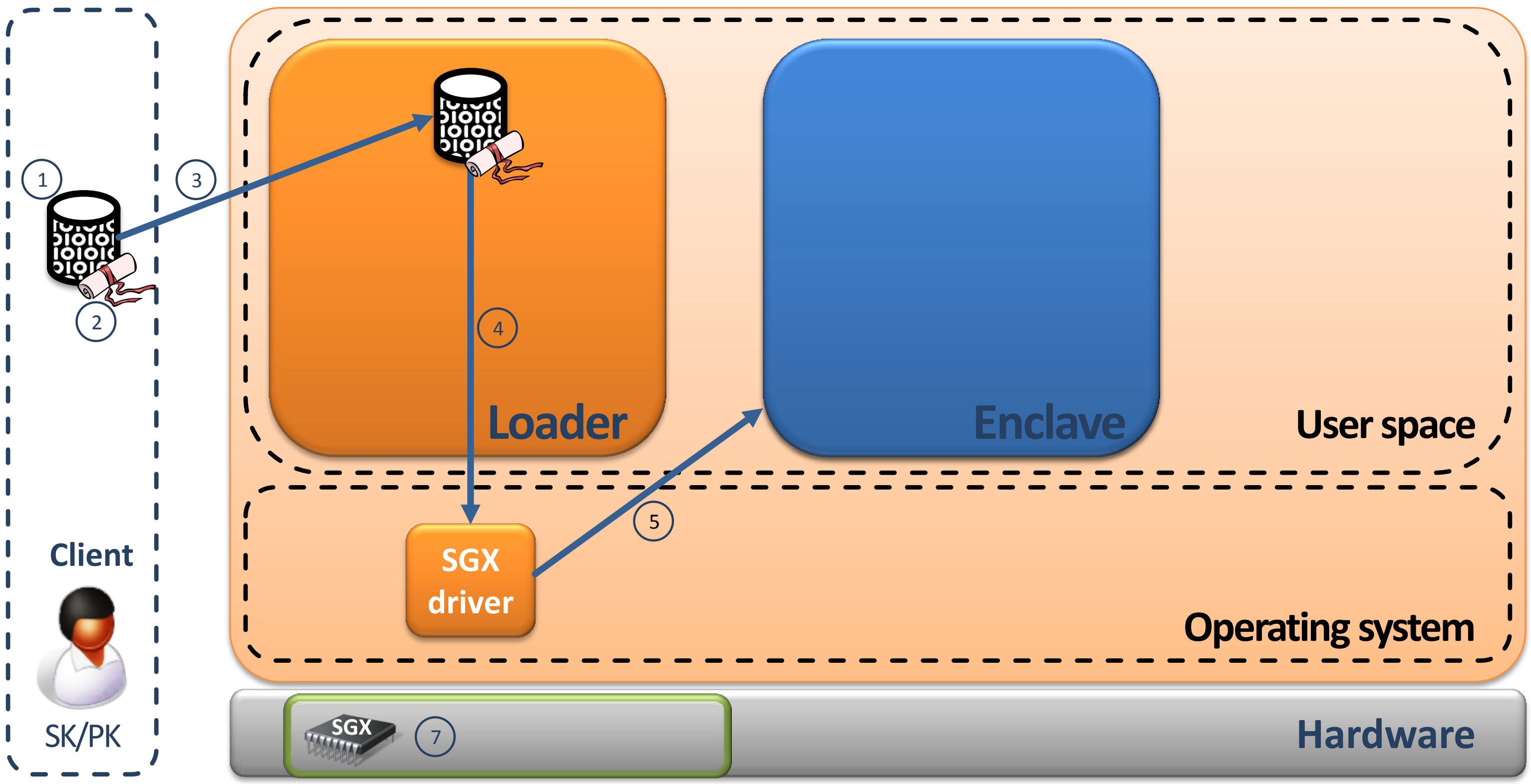


1. Create App   2. Create app certificate (includes HASH(App) and Client PK)   3. Upload App to Loader

Trusted   Untrusted

Intel Software Guard Ext

SGX – Create Enclave



1. Create App
2. Create app certificate (includes HASH(App) and Client PK)
3. Upload App to Loader
4. Create enclave
5. Allocate enclave pages

Trusted | Untrusted

Intel Software Guard Ext

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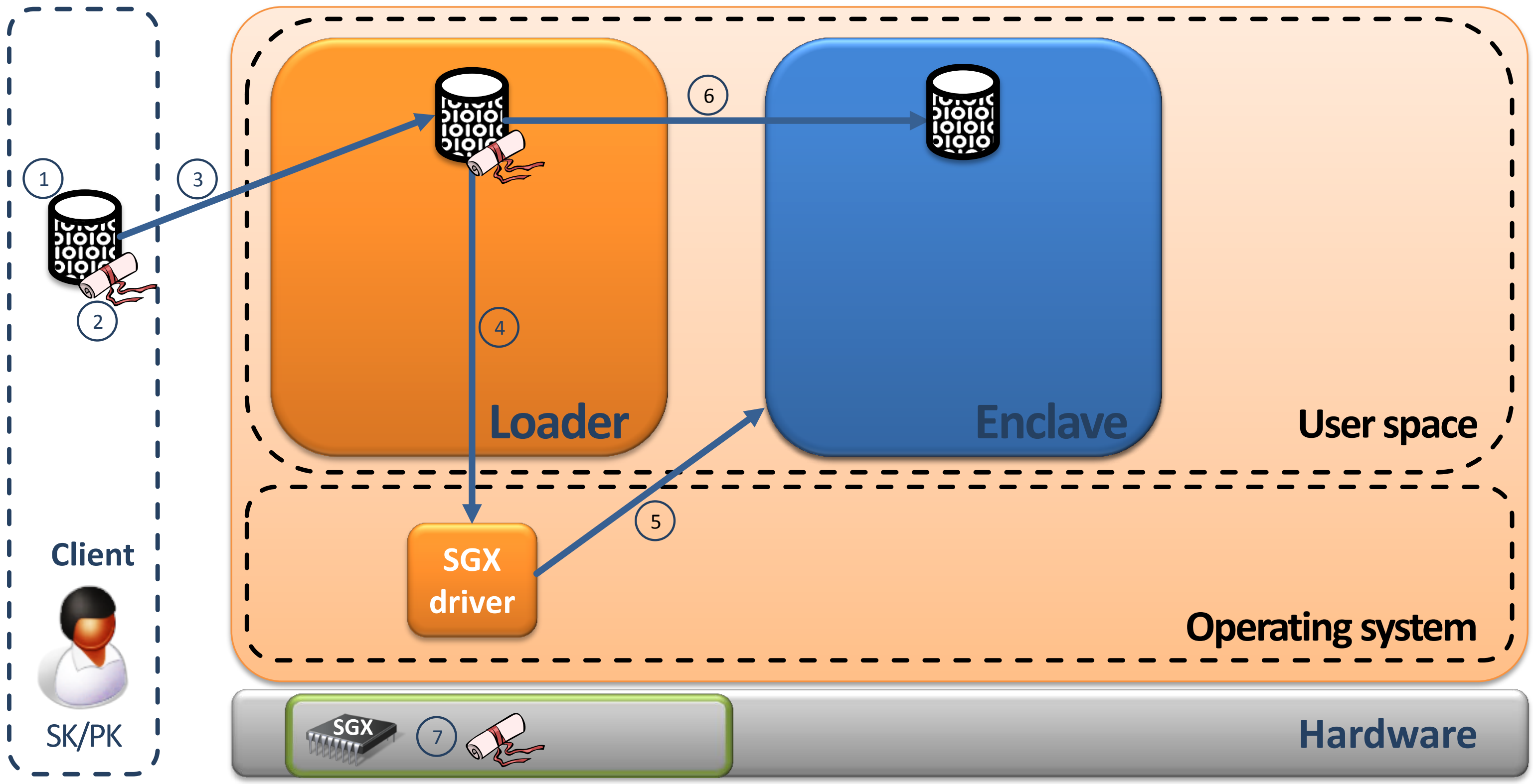
SGX – Create Enclave



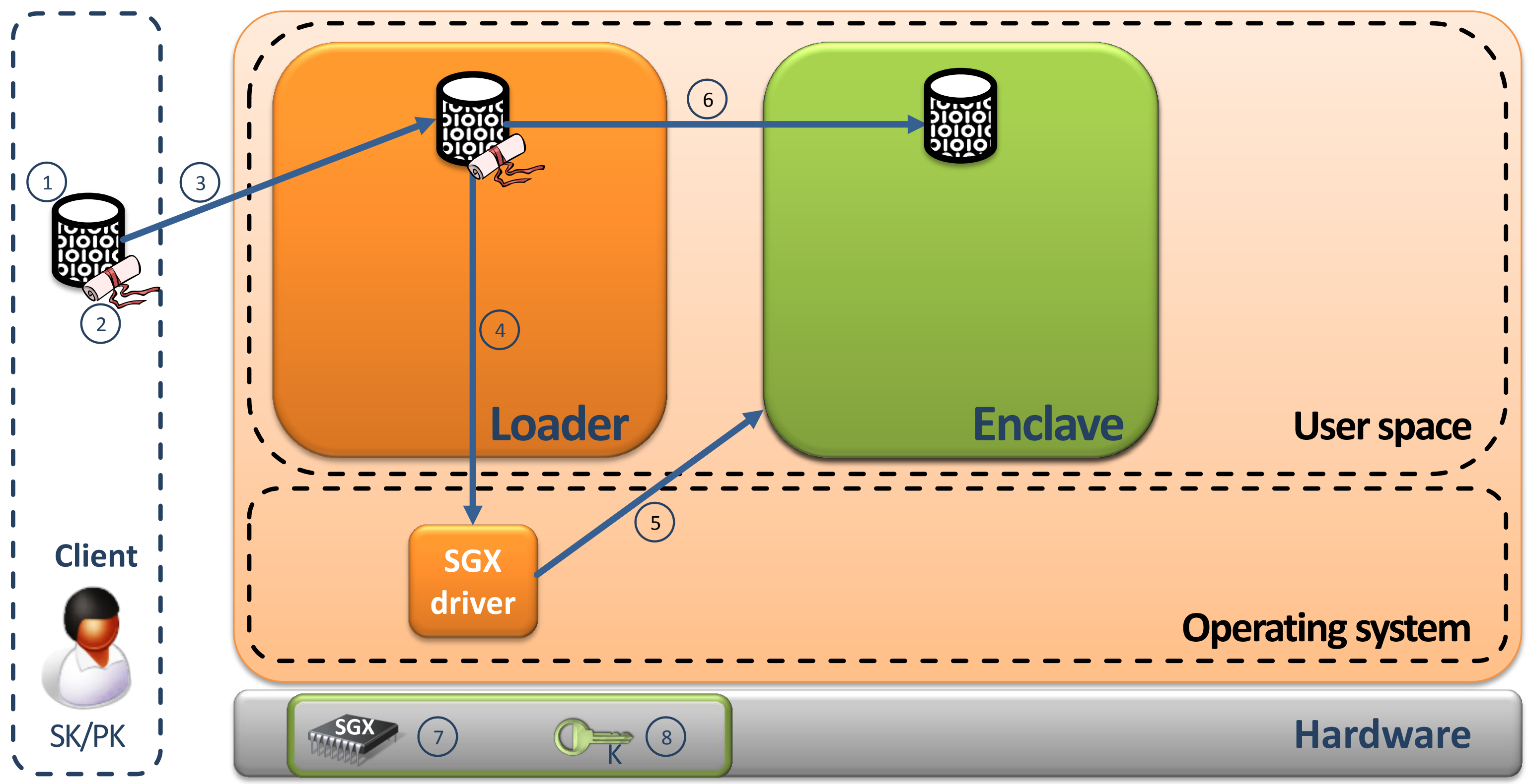
1. Create App 2. Create app certificate (includes HASH(App) and Client PK) 3. Upload App to Loader
4. Create enclave 5. Allocate enclave pages 6. Load & Measure App 7. Validate certificate and enclave integrity

Trusted Untrusted

A.-R. Sadeghi ©TU Darmstadt, 2007-2014 Slide Nr. 21, Lecture Embedded System Security, SS 2014 Trusted Execution Environments / Intel SGX

Intel Software Guard Ext

SGX – Create Enclave



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

Trusted Untrusted

A.-R. Sadeghi ©TU Darmstadt, 2007-2014 Slide Nr. 22, Lecture Embedded System Security, SS 2014 Trusted Execution Environments / Intel SGX

A Problem

- My computer is running a process
- It makes a request to your computer
  - Asks for some secret data to process
  - Provides an input you depend on
- How do you know it is executing correctly?
- Example
  - ATM machine is uploading a transaction to the bank
  - How does the bank know that this ATM is running correctly, so the transaction can be considered legal?

Question You Might Ask?

- Who owns the remote computer?
  - Does this tell you whether the computer has malware?
- Is the computer protected from ever running malware?
  - How would we know this?
- What is actually running on the computer?
  - How can get this information securely?
- Would any of these things enable you to determine whether to supply your personal information to the remote computer?

What would you do?

- Proof by authority (Certificates)
  - Validate the source of messages from the remote system
  - Tells you who and what (maybe), but how
- Constrain the system (Secure Boot)
  - Remote system boots using only trusted software
  - Is only running if secure
- Inspect the runtime state (Authenticated Boot)
  - Remote system produces record of software run
  - You validate whether you trust the software

Secure Boot

- Why not just boot from a floppy (DVD now)?

Secure Boot

- Check each stage in the boot process
  - Is code that you are going to load acceptable?
  - If not, terminate the boot process
- Must establish *a* ***Root-of-Trust***
  - A component trusted to speak for the correctness of others
  - Assumed to be correct because errors are **undetectable**

AEGIS

- AEGIS architecture (1997)
  - ROM checks the BIOS
  - BIOS checks expansion ROMs and boot block
  - Boot Loader checks the OS
- What is the root of trust?
- What can it verify?
- How do we know it booted securely?

Authenticated Boot

- Secure boot enforces requirements and uses special hardware to ensure a specific system is booted
  - Implied verification (Good because it is)
- By contrast, we can **measure** each stage and have a **verifier** authenticate the correctness of the stage
  - Verifier must know how to verify correctness
  - Behavior is uncertain until verification
- What is root-of-trust for authenticated boot?

Secure v Authenticated Boot

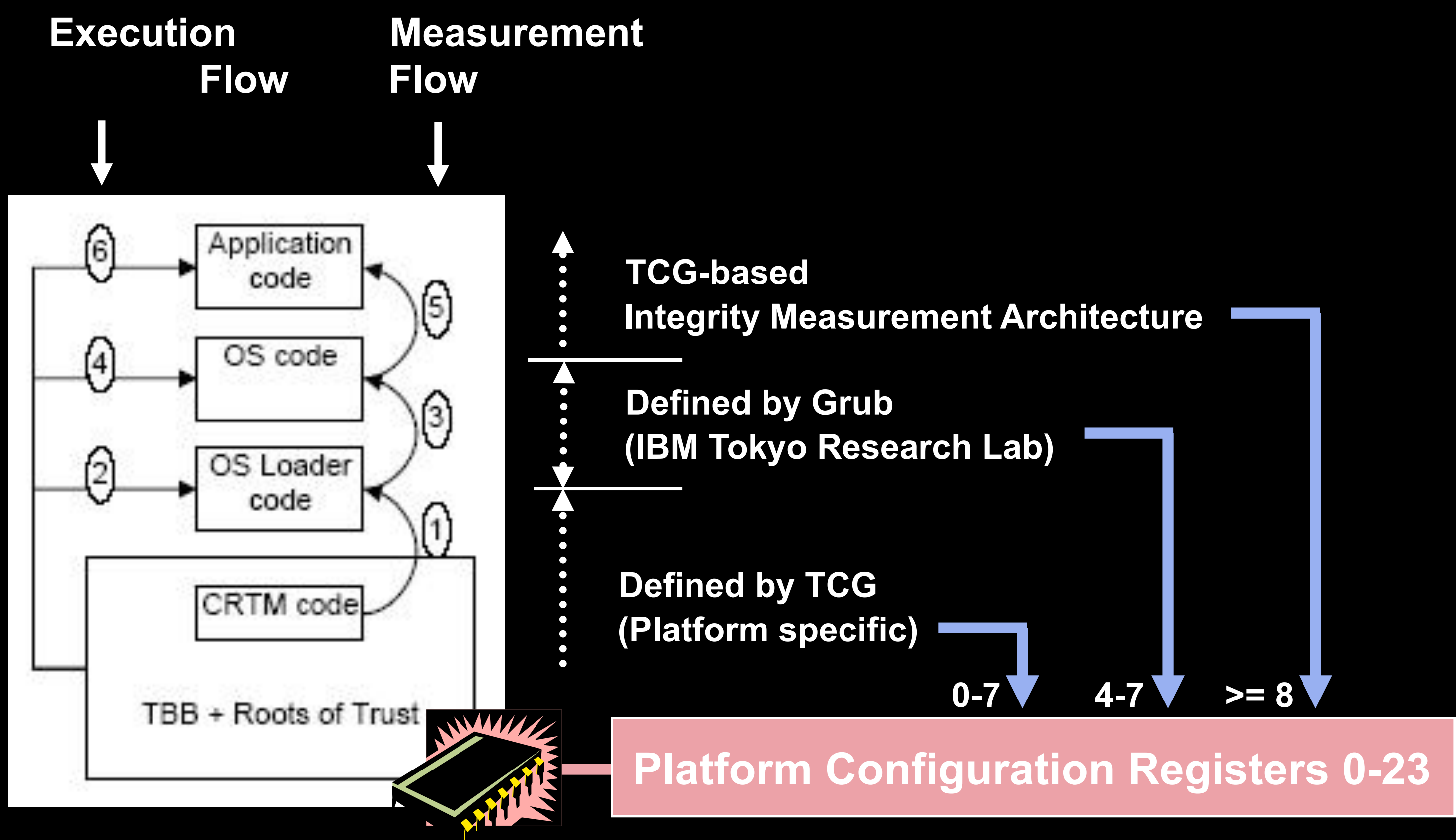
- Odd implications of each
- Secure boot enables you to tell if your machine is secure
  - But remote parties cannot tell
- Authenticated boot enables remote parties to tell if your machine is secure
  - But you cannot tell by using it yourself

Trusted Computing

- The Trusted Platform Module (TPM) brought authenticated boot into the mainstream
- Essentially, the TPM offers few primitives
  - Measurement, cryptography, key generation, PRNG
  - Controlled by physical presence of the machine
  - BIOS is Core Root of Trust for Measurement (CRTM)
- Spec only discussed how to measure early boot phases and general userspace measurements

Trusted Computing

Trusted Computing Group Architecture

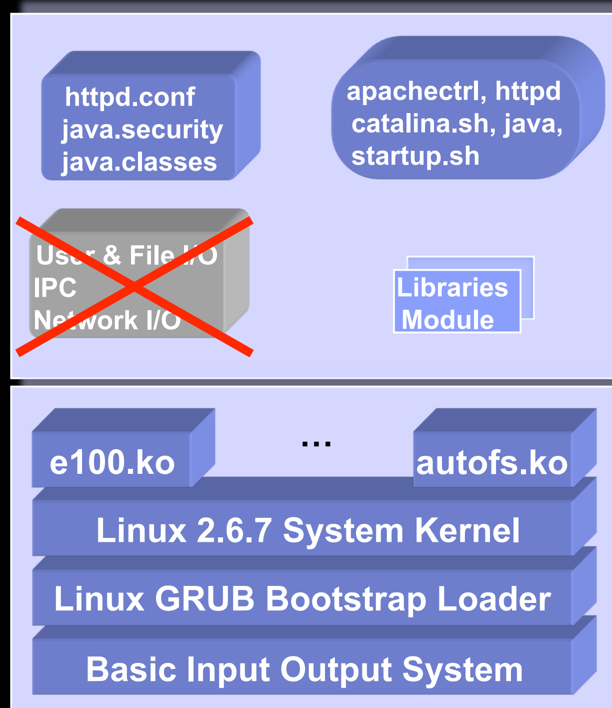


Trusted Computing

- What would you measure in the following system to prove it is running correctly to remote verifiers?

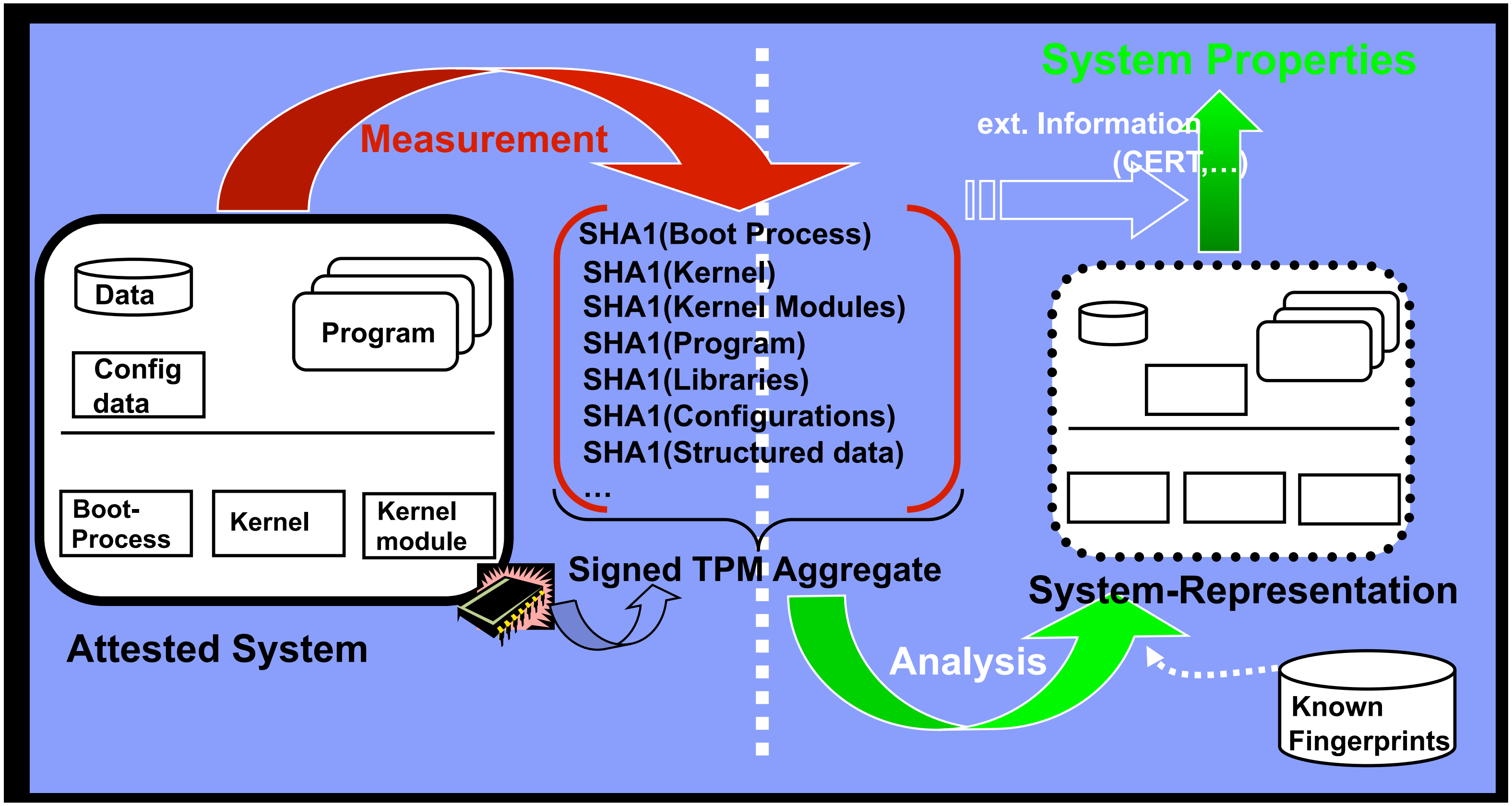
Example: Web Server

- **Executables** (Program & Libraries)
  - apachectrl, httpd, java, ..
  - mod_ssl.so, mod_auth.so, mod_cgi.so,..
  - libc-2.3.2.so libjvm.so, libjava.so, …
- **Configuration Files**
  - httpd.conf, html-pages,
  - httpd-startup, catalina.sh, servlet.jar
- **Unstructured Input**
  - HTTP-Requests
  - Management Data



Trusted Computing

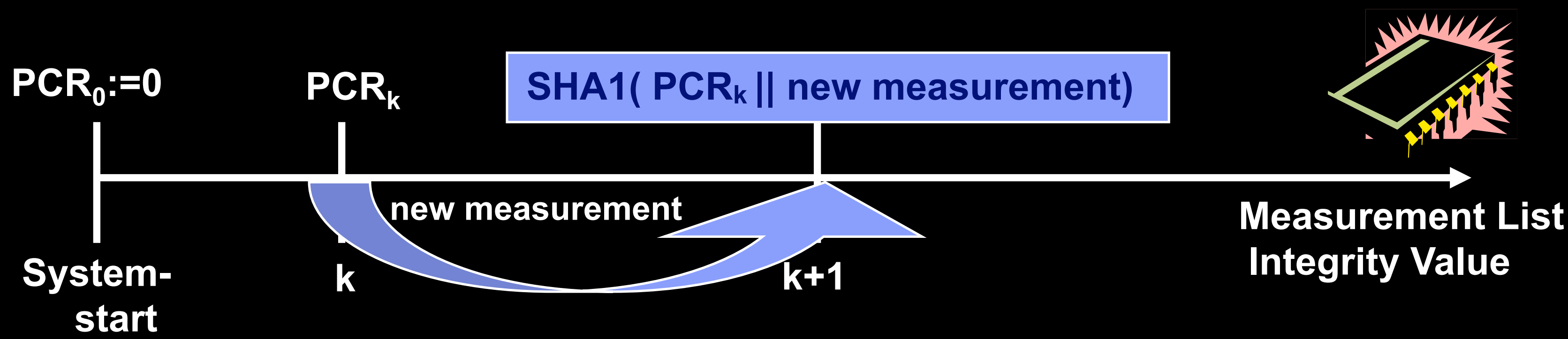
- How would you measure code and static files to prove system is running correctly to remote verifiers?



Linux Integrity Measurement

Measurement list aggregation:

- **Compute** 160bit-SHA1 over the contents of the data (measurement)
- **Adjust** Protected hw Platform Configuration Register (PCR) to maintain measurement list integrity value
- **Add** measurement to ordered measurement list
  - → Executable content is recorded before it impacts the system
  - → That is, before it can corrupt the system



IMA Implementation

- Place hooks throughout Linux kernel
  - Later added more general LIM hooks
- Extend TPM PCR at file load-time
  - PCR = SHA1(File || PCR)
- Extend kernel-stored measurement list
  - List of SHA1 hashes taken by kernel
  - Including those requested by user space applications
- Generate attestation using TPM hardware
  - $S(K^{-}_{TPM}, PCR+nonce)$

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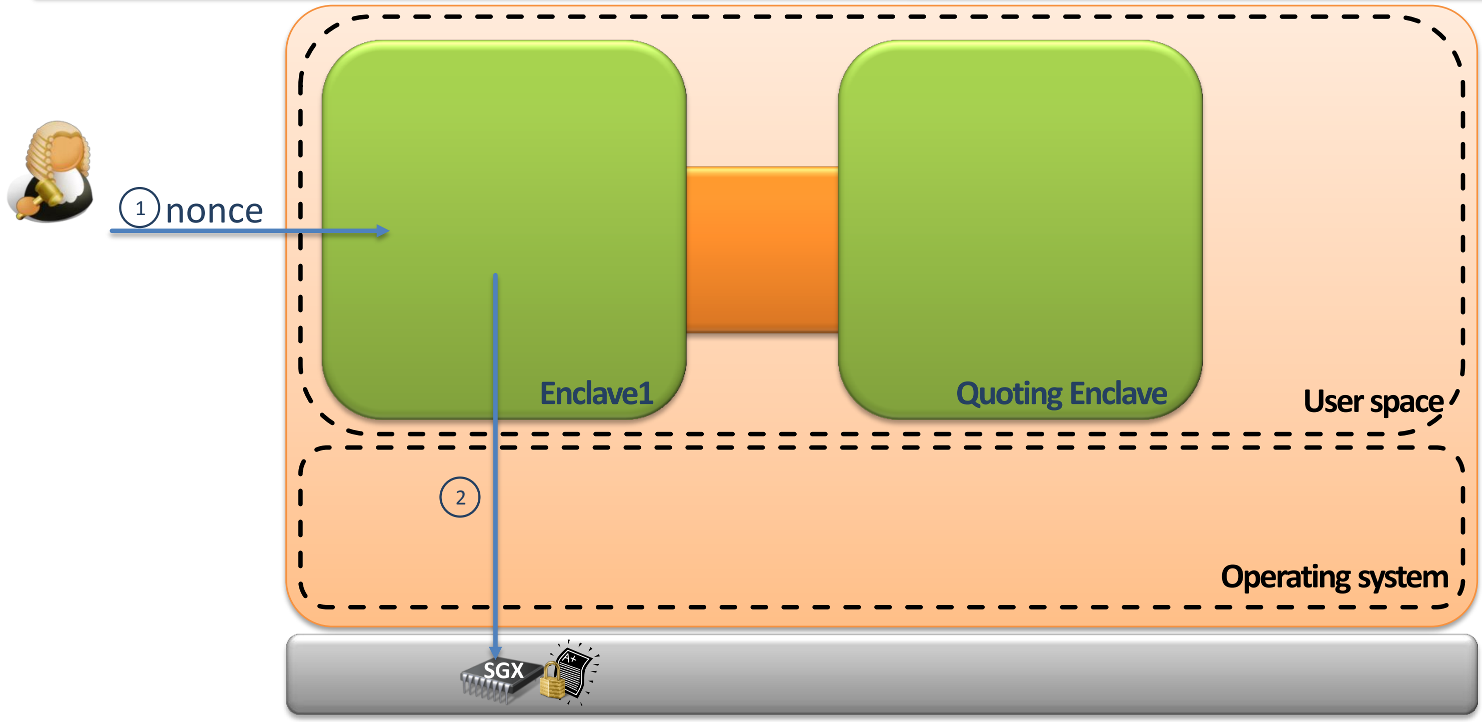
SGX – Remote Attestation



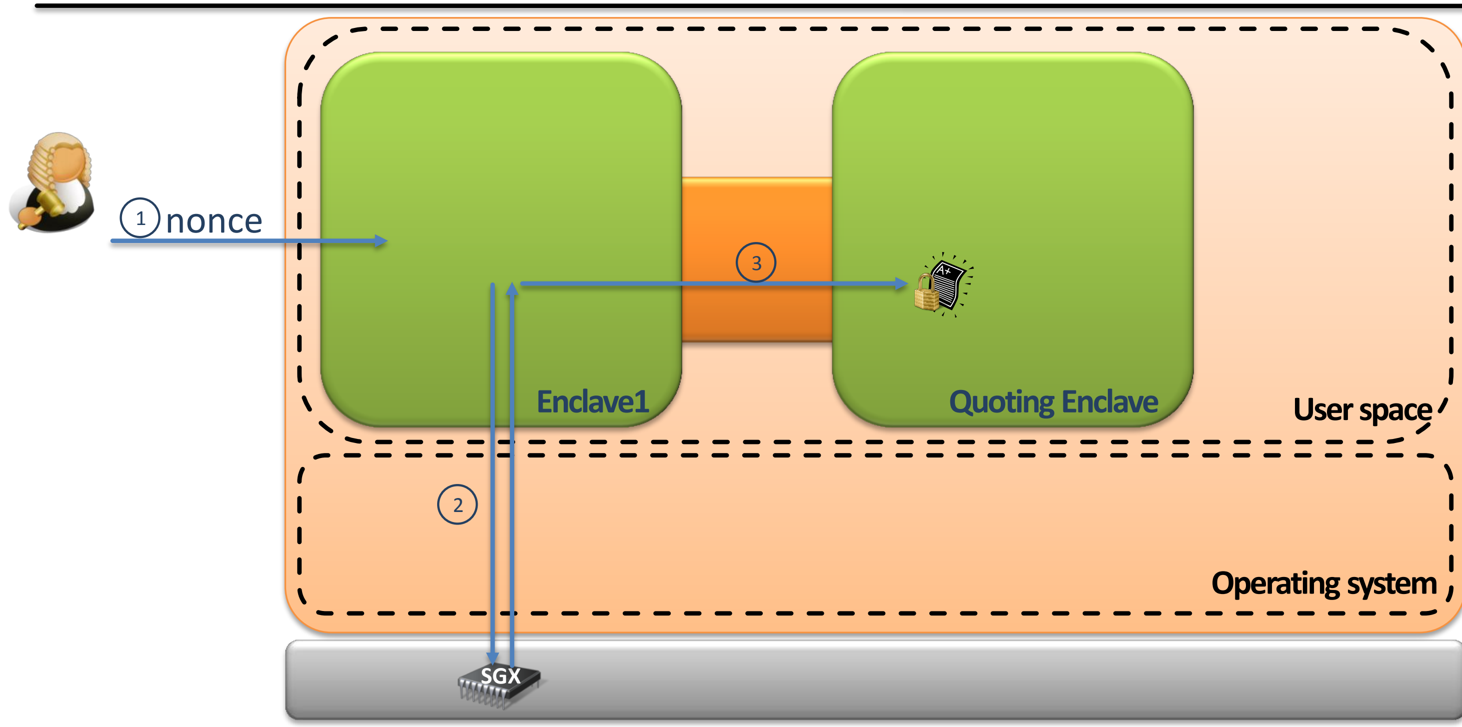
1. Verifier sends nonce

2. Generate Report = (HASH(Enclave1), ID-QuotingEnclave, nonce)

Trusted Untrusted

Intel Software Guard Ext

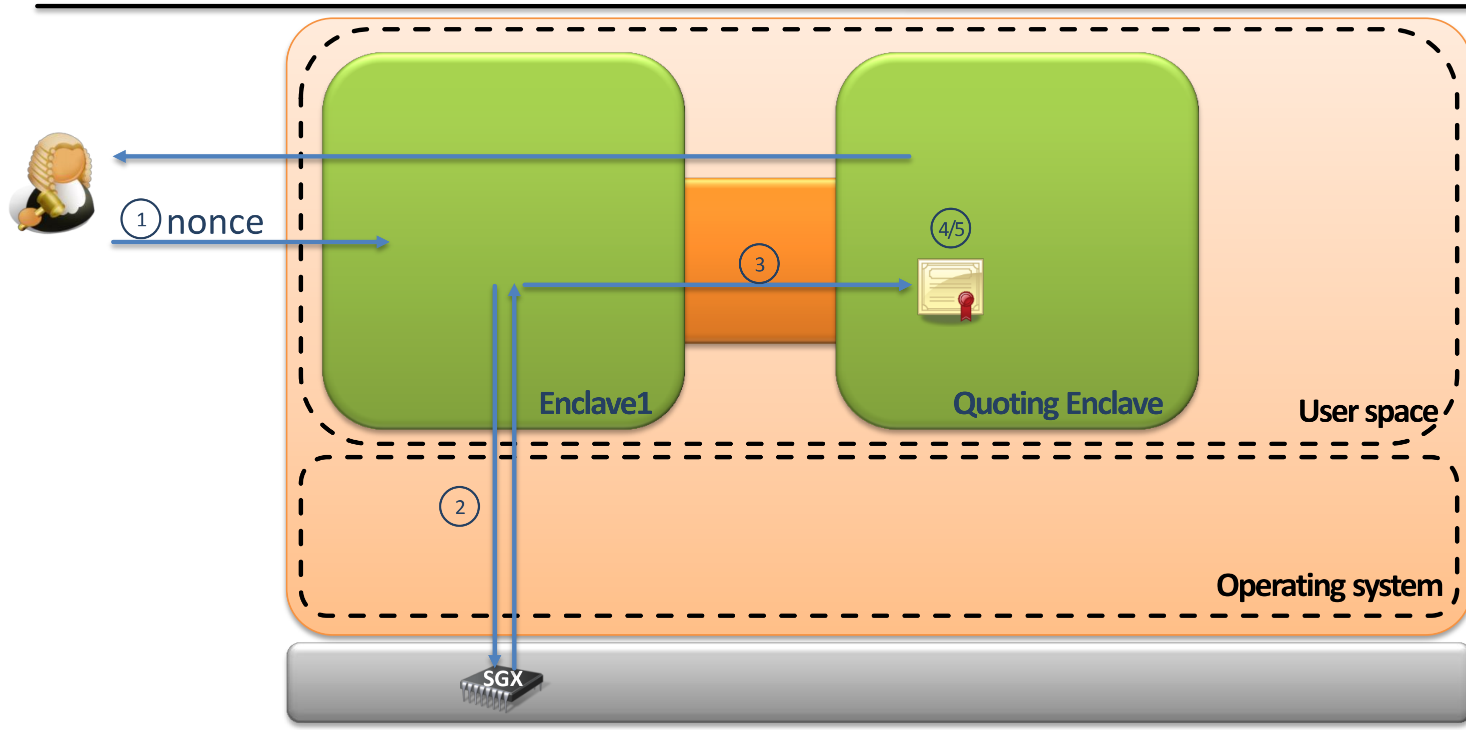
SGX – Remote Attestation



1. Verifier sends nonce
2. Generate Report = (HASH(Enclave1), ID-QuotingEnclave, nonce)
3. Pass Report to Quoting Enclave

Trusted | Untrusted

SGX – Remote Attestation



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5. Signs Report with "Platform Key"
6. Signed Report is send to verifier

Trusted | Untrusted

Intel Software Guard Ext

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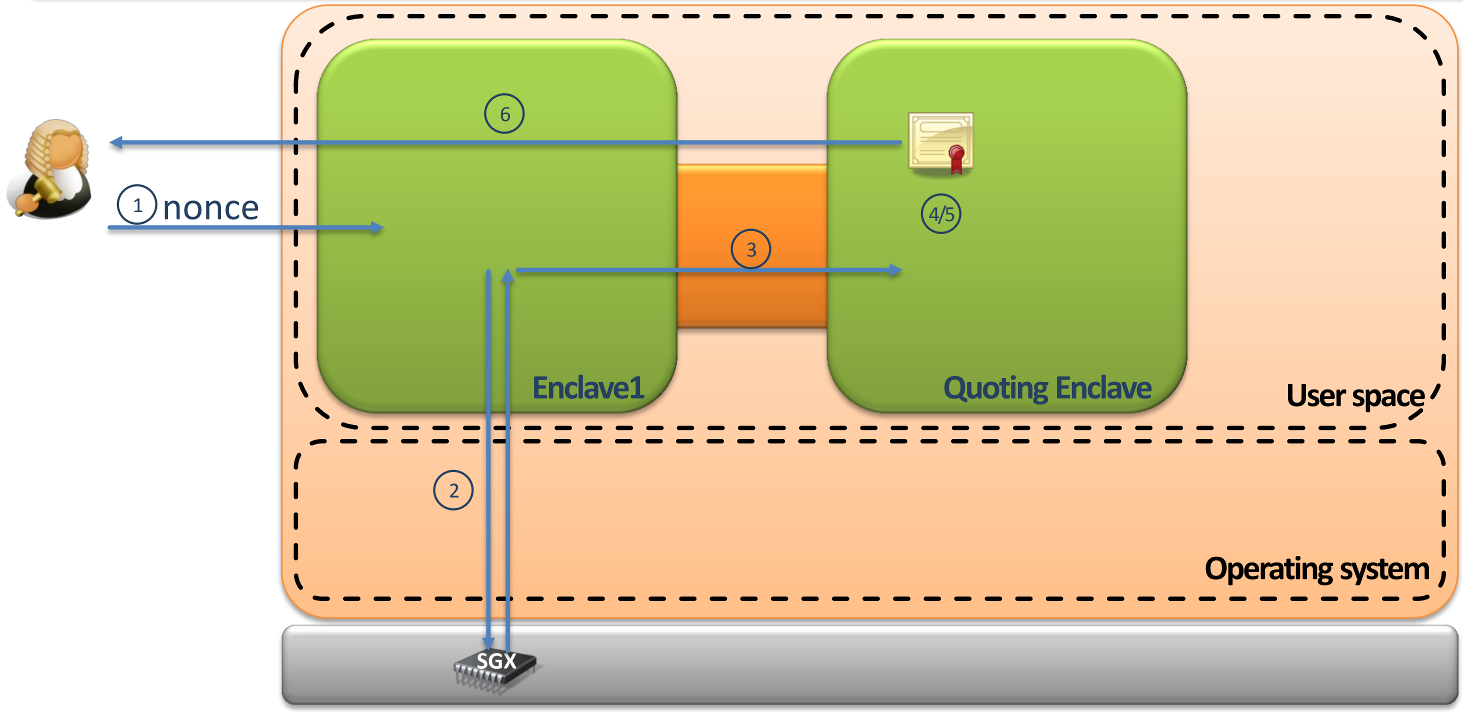

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Trusted Untrusted

Take Away

- Problem: Do not want to trust systems software
  - Idea: Cloak memory from system software
- Overshadow – Virtualization-based implementation of cloaking
- Intel SGX
  - Hardware-based memory cloaking
  - Hardware-based attestation to prove properties
- VC3 – Application of Intel SGX for cloud computing