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Shadow-Box v2:

The Practical and Omnipotent Sandbox for ARM

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Who Are We?

- Senior security researcher at NSR (National Security Research Institute of South Korea)
- Speaker at Black Hat Asia 2017 and HITBSecConf 2016/2017
- Author of the book series titled “64-bit multi-core OS principles and structure, Vol.1&2”
- a.k.a kkamagui, @kkamagui1

- Senior security researcher at NSR
- Embedded system engineer
- Interested in firmware security and IoT security
- a.k.a davepark, @davepark312

Last Year We Presented…

We introduced Shadow-box v1

Goal of This Year is…

Linux	Linux IMA
Shadow-Box for x86	Shadow-Box for ARM
VT-x, VT-d (Virtualization Technology)	TrustZone (Virtualization Technology)
intel	ARM

We will introduce Shadow-box v2

Background

Design

Implementation

Demo. and Conclusion

(with Black Hat Sound Bytes)

REMIND:
Linux Kernel is Everywhere!

REMIND:

Security Threats of Linux Kernel

- **The Linux kernel suffers from rootkits and security vulnerabilities**
  - Rootkits: EnyeLKM, Adore-ng, Sebek, suckit, kbeast, and so many descendants
  - Vulnerabilities: CVE-2014-3153, CVE-2015-3636, CVE-2016-4557, CVE-2017-6074, etc.

Devices that use Linux kernel share security threats

REMIND:

Melee Combats at the Kernel-level

- **Kernel-level (Ring 0) protections are not enough**
  - Lots of rootkits and exploits work in the Ring 0 level
  - Protections against them are often easily bypassed and neutralized
    - Kernel Object Hooking (KOH)
    - Direct Kernel Object Manipulation (DKOM)

Protections need
an even lower level (Ring -1)

REMIND:

Taking the Higher Ground

- **Leveraging virtualization technology (VT)**
  - VT separates a machine into a host (secure world) and a guest (normal world)
  - The host in Ring -1 can freely access/control the guest in Ring 0 (the converse doesn't hold)
  - VT-equipped HW: Intel VT-x, AMD AMD-v, **ARM TrustZone**

Shadow-Box v2 focuses on ARM TrustZone!

ARM TrustZone and Trusted Execution Environment

- **ARM TrustZone**
  - is a security extension of ARM processor and hardware-based security
  - separates a machine into the secure world and normal world
- **Trusted Execution Environment (TEE)**
  - is a secure area of ARM processor
  - protects integrity and confidentiality of data in memory and storage

Lords of the TEE

SAMSUNG

OH, NO...

RED OCEAN...

QUALCOMM

Restrictions on Lords of the TEE (1)

- **TEEs are proprietary**
  - Their source codes are not published
  - Use of the source code is restricted
- **TEEs are not portable**
  - They are designed for their own processors
  - So, they are not applicable in different processors

Restrictions on Lords of the TEE (2)

- **To wrap it up, their TEEs are not suitable for various ARM-based devices**
  - There are so many ARM processor vendors such as Broadcom, NXP, MediaTek, Allwinner, etc.
  - Manufacturers choose low-cost ARM SoC for their products
    - The types and vendors of ARM SoC in products are different depending on manufacturing date

We need

an open source and portable TEE!

OP-TEE: Open Portable TEE (1)

- **OP-TEE is an open source TEE**
  - You can change everything that you want
  - Linaro supports and maintains OP-TEE
    - Linaro is an association of ARM, Freescale, IBM, Samsung, ST, TI

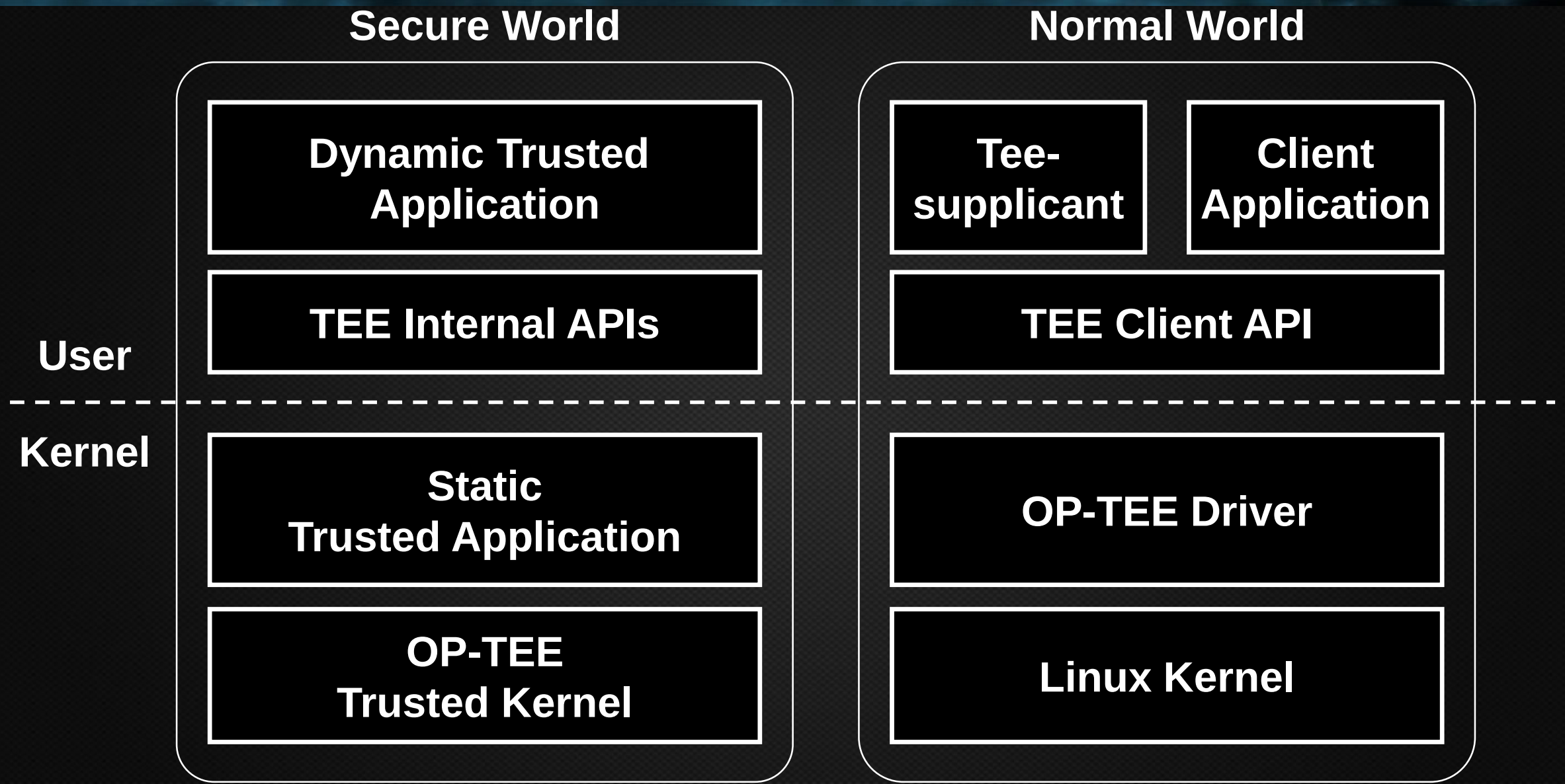
OP-TEE .org

- **OP-TEE supports many kinds of SoCs and devices**
  - OP-TEE supports more than fourteen devices including Raspberry Pi 3 and QEMU
  - OP-TEE has well-defined architecture, so you can port OP-TEE to your device easily

OP-TEE: Open Portable TEE (2)

- **OP-TEE follows GlobalPlatform specifications**
  - GloabalPlatform makes Trusted Execution Environment (TEE) specifications
  - GlobalPlatform is an association of Samsung, Qualcomm, AMD, APPLE, Trustonic, NXP
  - Many companies follow the specifications, so you can port your trusted application to other TEE

Architecture of OP-TEE



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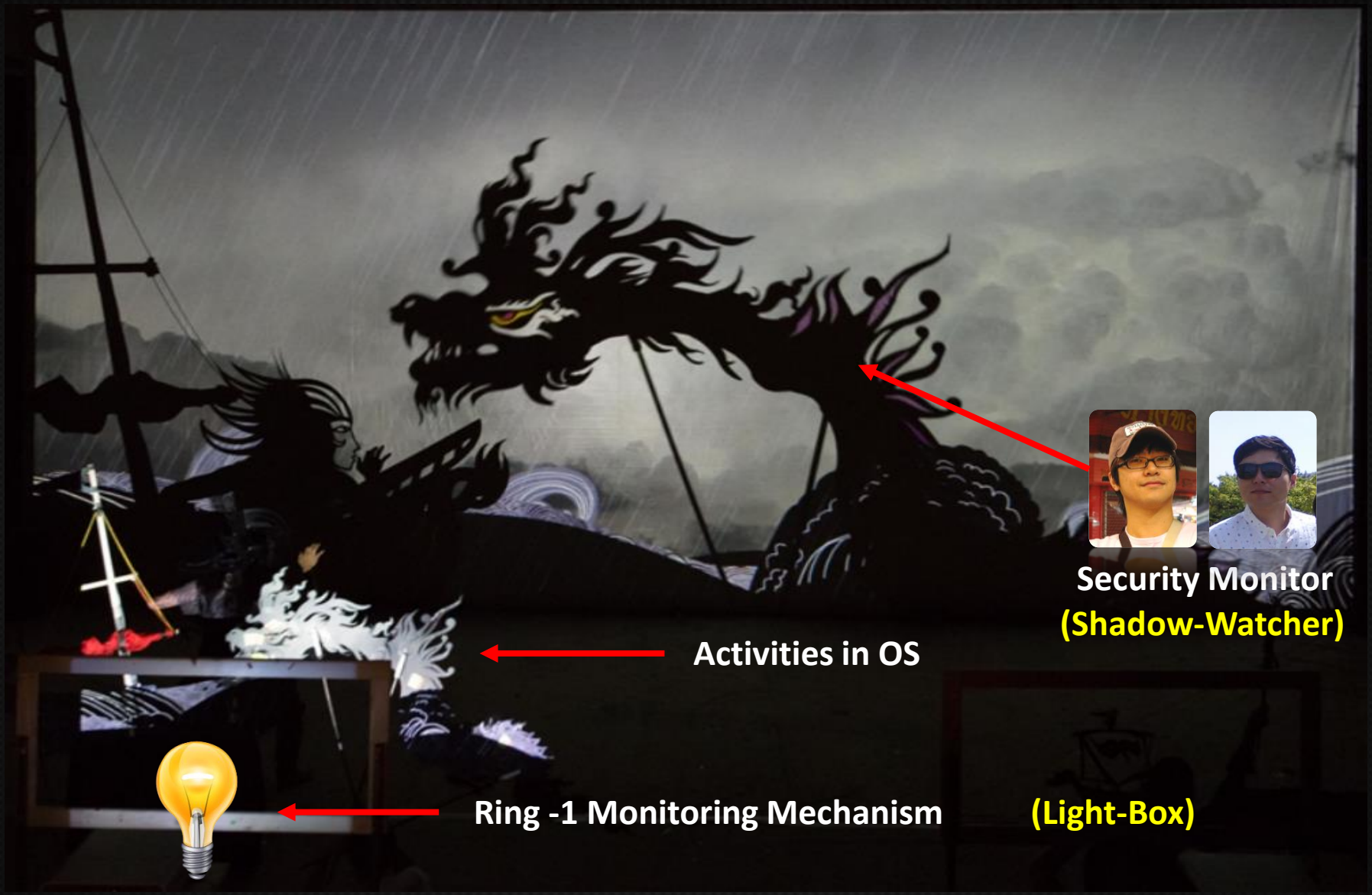
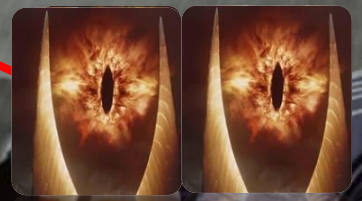
REMIND:
Security Architecture in Shadow Play



REMIND:
Security Architecture in Shadow Play

We named this architecture
"Shadow-box"

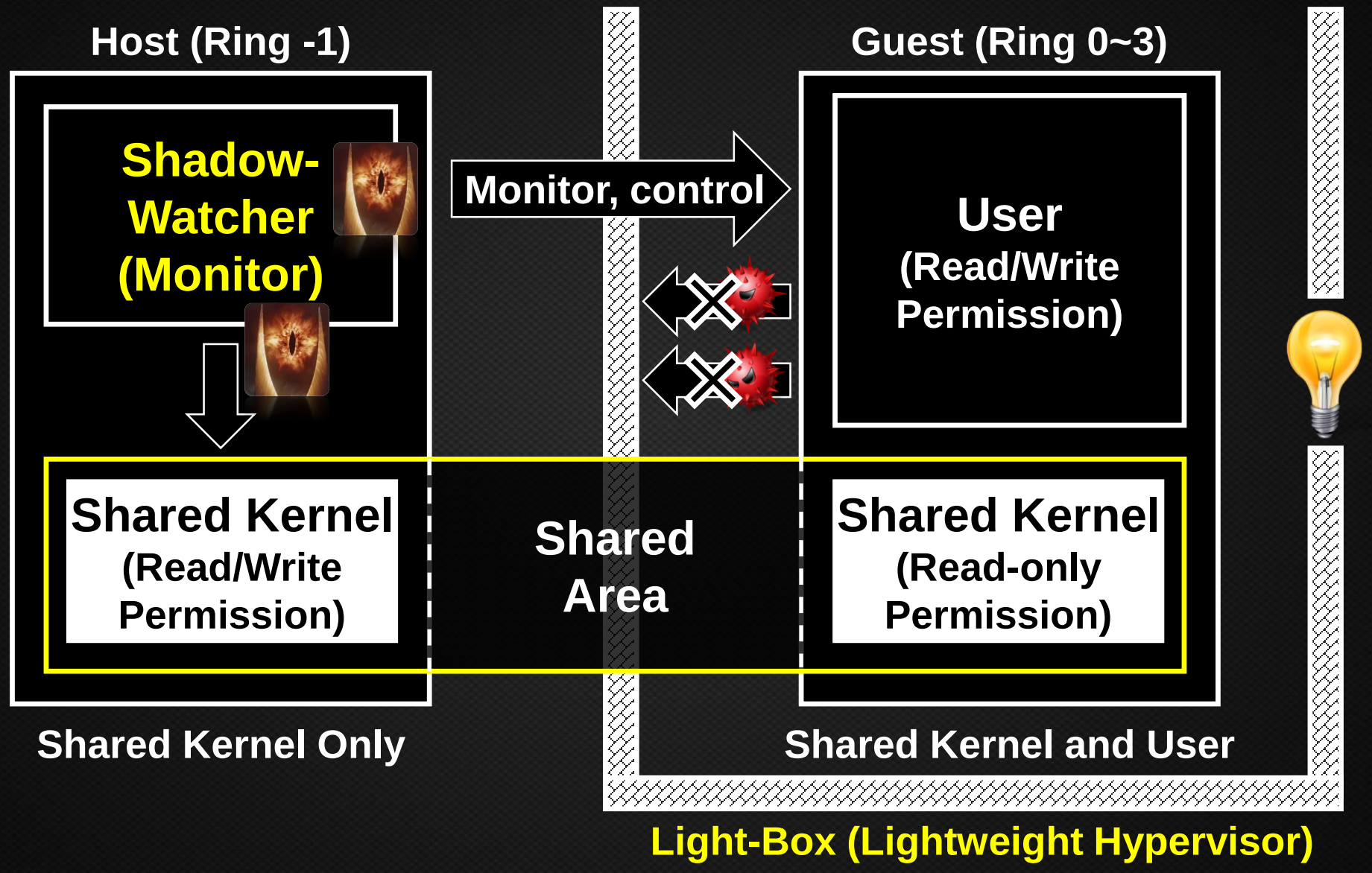


Security Monitor
(Shadow-Watcher)

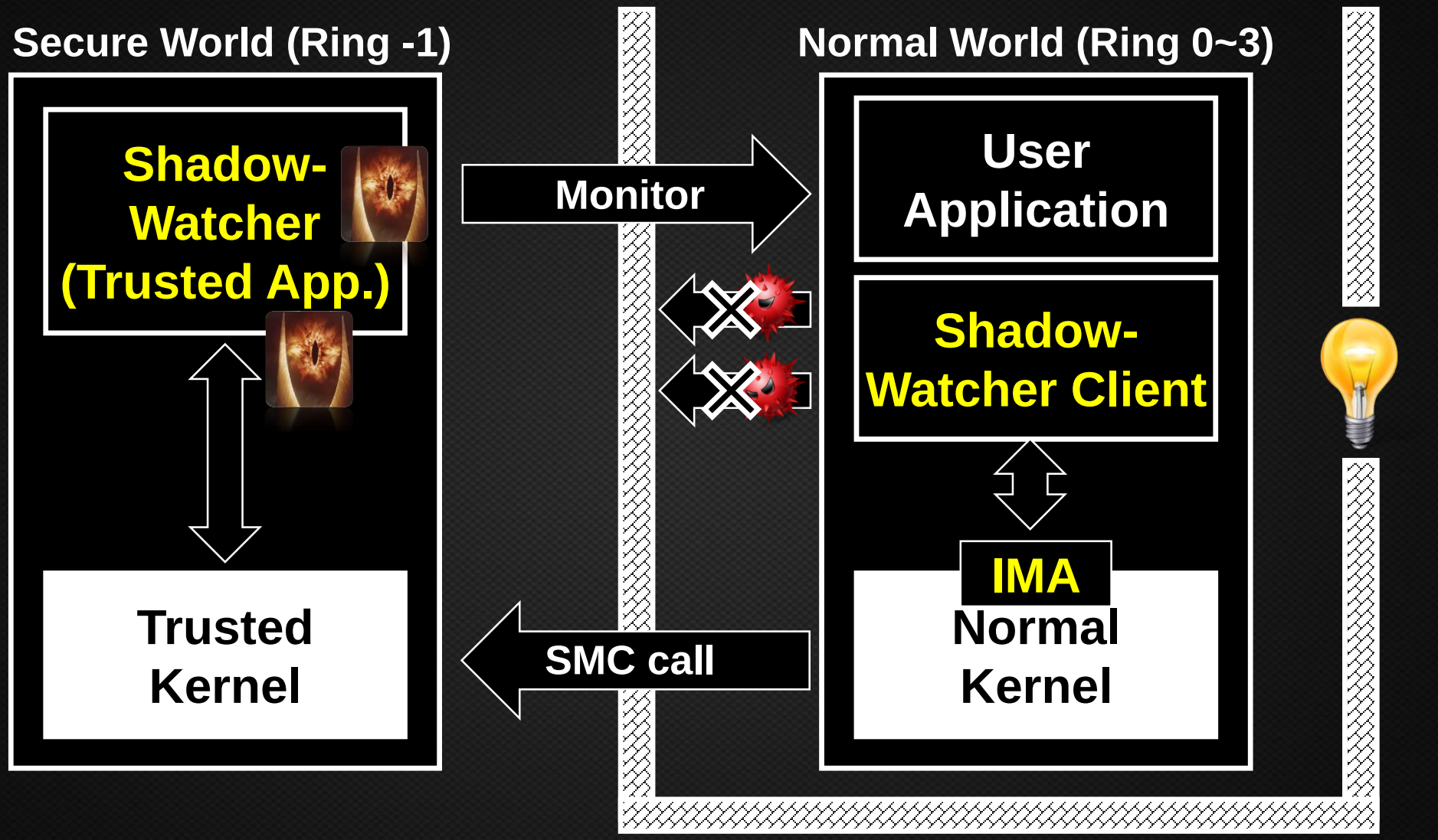
Activities in OS

Ring -1 Monitoring Mechanism (Light-Box)

Architecture of Shadow-Box for x86



Architecture of Shadow-Box for ARM



Light-Box (Trusted App. and Trusted Kernel)

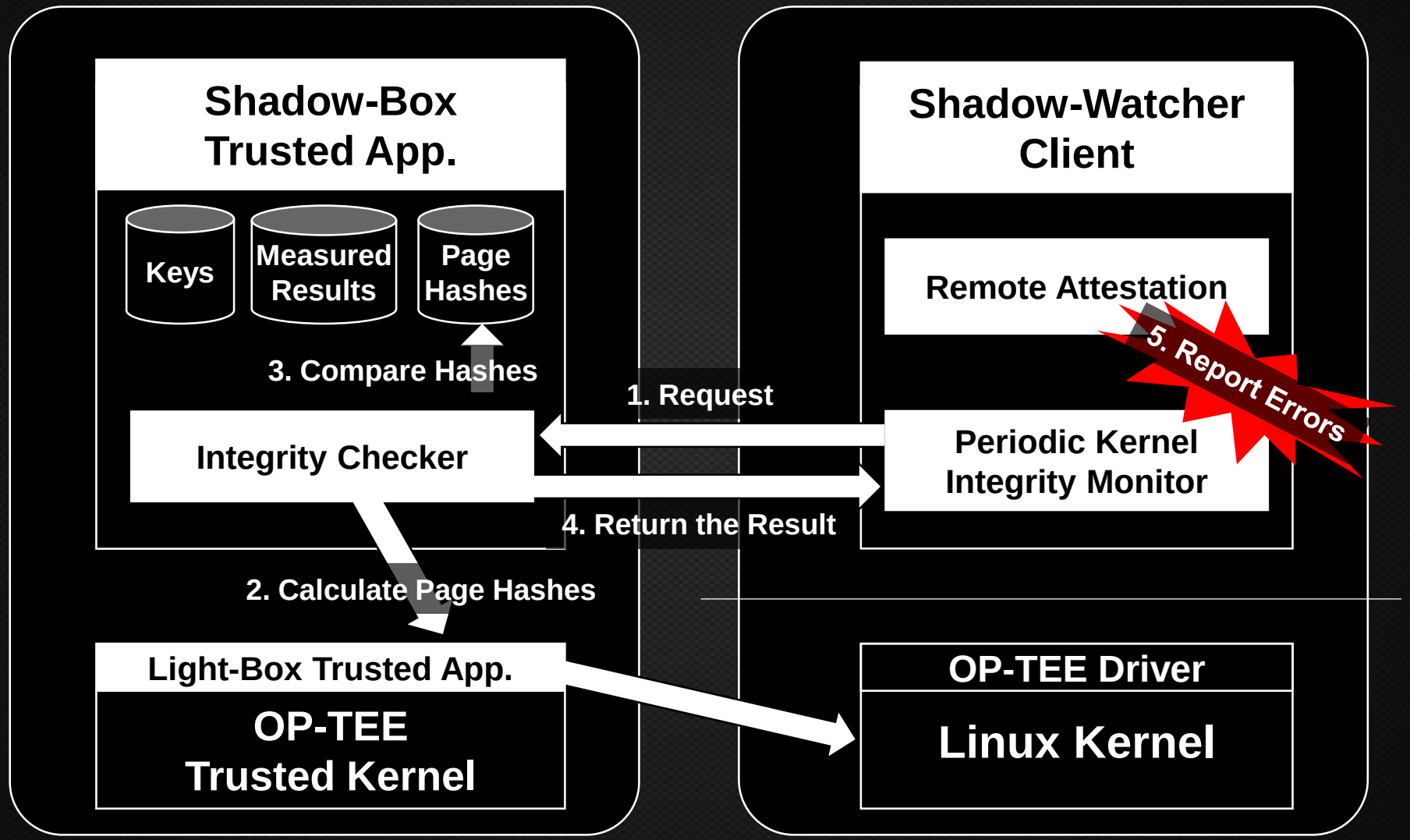
Integrity Measurement Architecture

- **Integrity Measurement Architecture (IMA)**
  - Can check hashes or signatures of files and prevent the system from unauthorized executable files
  - Can store measurement value in Trusted Platform Module (TPM)
  - Is included Linux Kernel since 2.6.30!
- **IMA needs to manage hashes or signatures**
  - You need to make hashes or signatures of good executable files
  - IMA is hard to be used for general purpose environment, but it is good for special purpose environment such as embedded systems

What can Shadow-Box v2 Do?

- Shadow-box v2 (for ARM) protects Linux kernel from
  - Unauthorized executable file attacks
    - IMA in kernel verifies signatures of executable files
  - Static kernel object attacks
    - Static kernel object = immutable at runtime
    - Code modification and system table modification attacks
  - Dynamic kernel object attacks (x86 only and future work!)
    - Dynamic kernel object = mutable at runtime
    - Process hiding and module hiding, function pointer modification attacks

Static Kernel Object Protection (1)

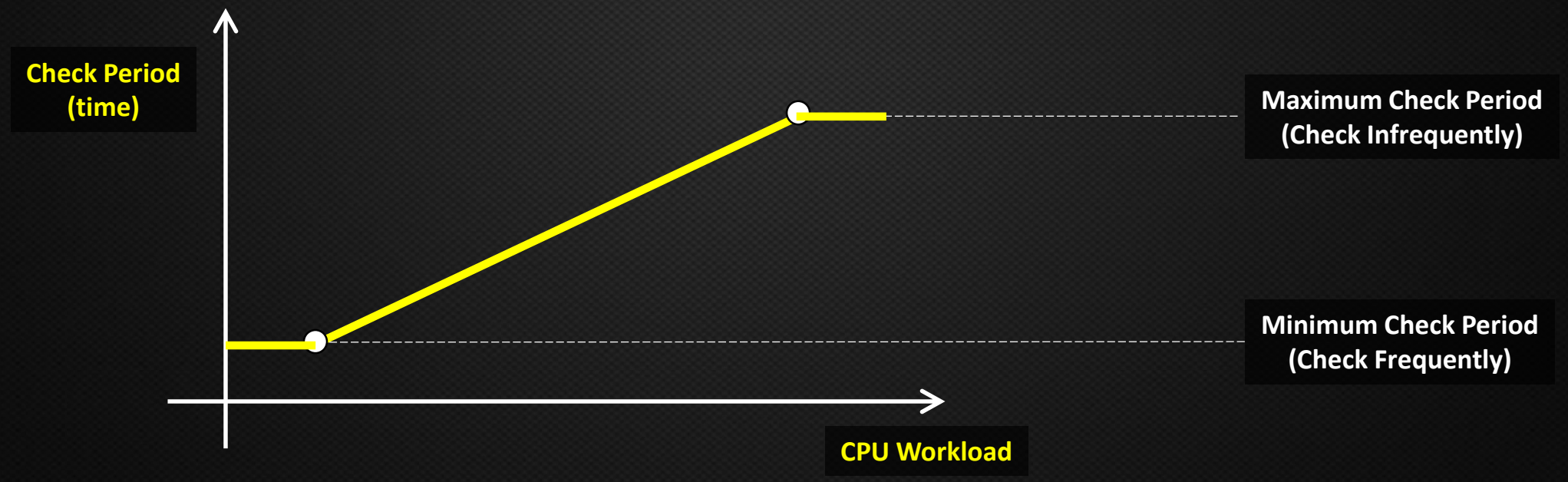


Static Kernel Object Protection (2)

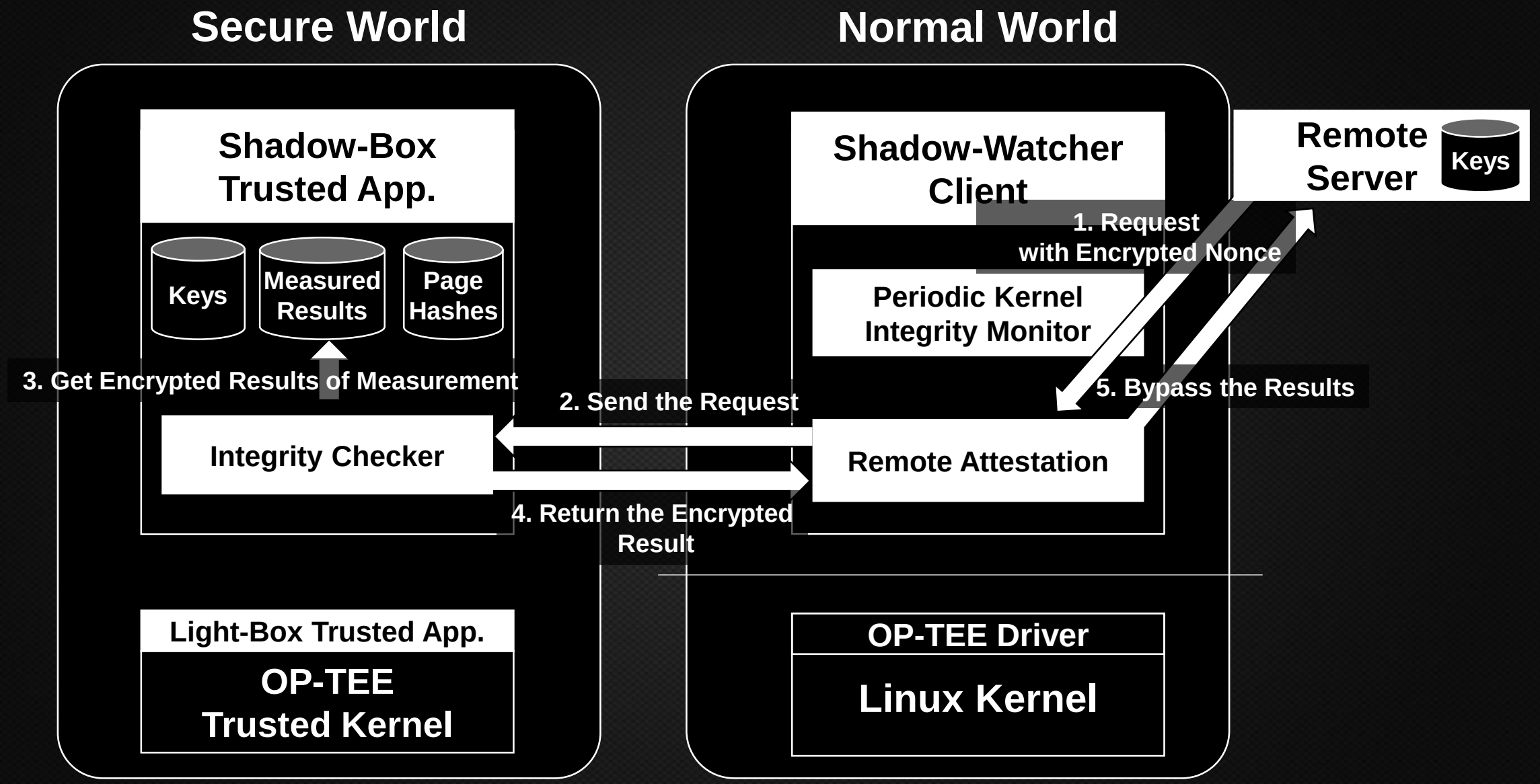
- **Page hash-based integrity monitor**
  - Is a simple and intuitive mechanism which is widely used!
    - But, the attacker can guess when the page is measured and do transient attack!
  - Needs a mechanism to randomize the measurement timing
- **So, Shadow-Box randomizes page order**
  - Shadow-watcher trust application shuffles pages after integrity measurement is completed

Workload-Concerned Kernel Monitoring

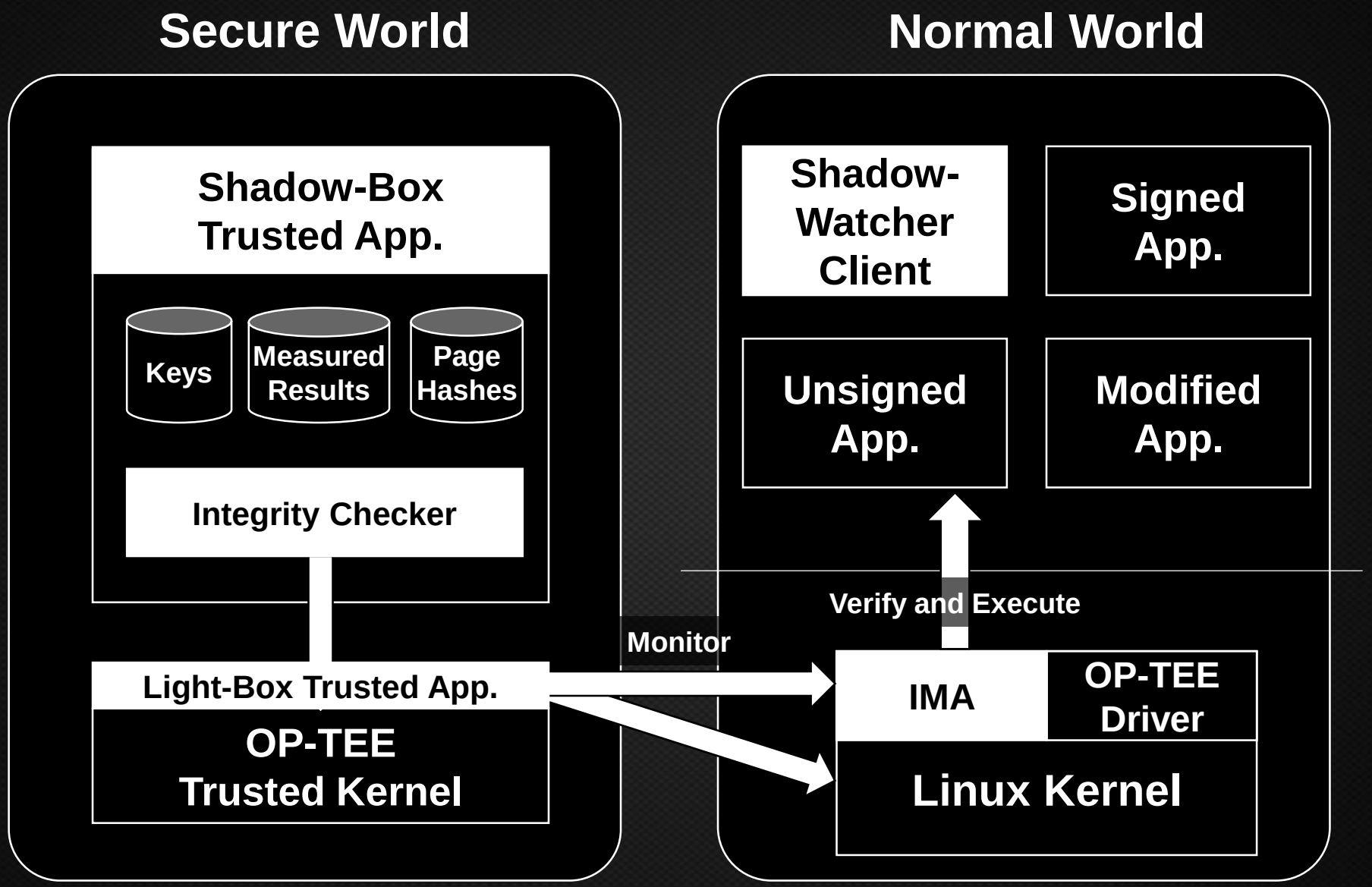
- **Adaptive mechanism**
  - Changes check period for measurement depending on system workload
  - Increases the period to keep performance as workload increases



Remote Attestation



Executable File Verification with IMA



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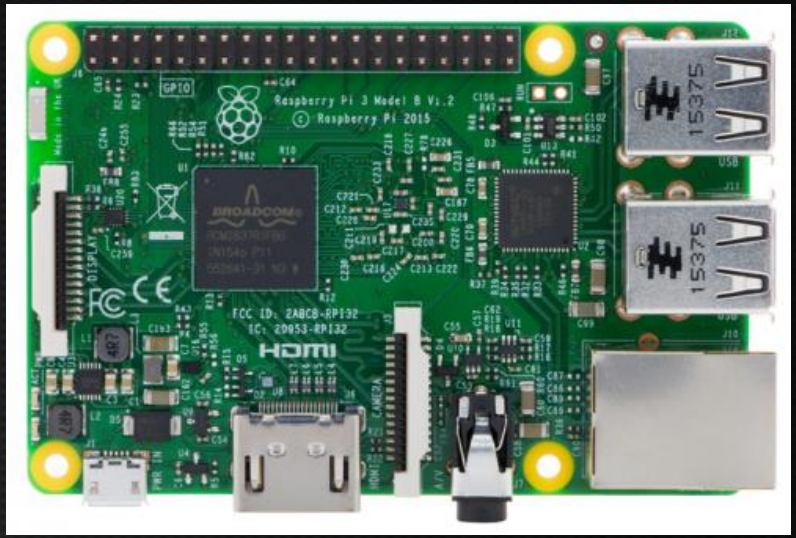
Target Board: Raspberry Pi 3

- **Raspberry Pi board**
  - Is the most famous embedded hardware
  - Supports many kinds of OS such as Raspbian, Ubuntu, and Windows 10 core



- **Raspberry Pi 3 model B specification**
  - Quad Core 1.2GHz Broadcom BCM2837
  - 1GB RAM and HDMI
  - BCM43438 wireless LAN and bluetooth
  - 40-pin extended GPIO

Raspbian

Limitation of Raspberry Pi 3

- **Raspberry Pi is the best board for a prototype, but…**
  - CPU supports ARM TrustZone feature only
  - DRAM and flash controller do not support it
  - Raspberry Pi does not have secure boot feature
  - The secure world is not really secure and just for a prototype!
- **If you want a fully-featured board, choose another board!**
  - OP-TEE supports many kinds of embedded boards such as Juno board, HiKey board, ATSAMA5D2-XULT board, and i.MX7Dual SabreSD Board

How to Integrate Shadow-Box with Raspberry Pi

Raspbian OS

\- Raspbian's Kernel

\+ OP-TEE's Kernel with IMA Patch

\+ OP-TEE's Secure Kernel

\+ Shadow-Box

= Secure Pi

Secure Pi is

an **OPEN SOURCE** project!

We always welcome your

CONTRIBUTIONS!

https://github.com/kkamagui/shadow-box-for-arm

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Porting x86 Rootkits to ARM (1)

- **Rootkits need to patch kernel code and read-only data**
  - They usually hide themselves by patching kernel code or function pointers
  - But, kernel has page protection mechanism
  - In x86 case, they disable page write protection in the CR3 register!
  - In ARM case, they also need to disable page protection, too!

```
/* Disable write-protection, bit 16 */
unsigned clear_return_cr0(void)
{
        unsigned cr0 = 0;
        unsigned ret;
        asm volatile ("movl %%cr0, %%eax"
        :"=a"(cr0)
        );
        ret = cr0;
        cr0 &= 0xfffeffff;
        asm volatile ("movl %%eax, %%cr0"
        :
        :"a"(cr0)
        );
        return ret;
}
```

Porting x86 Rootkits to ARM (2)

- **Do we really need to know about the page protection mechanism for patching kernel?**
  - Paging mechanism is too much complicated
  - ARM processors have various paging mechanism
- **Use live kernel patch functions instead!**
  - Linux kernel has kernel patch functions for a live patch
    - x86: text_poke(void *addr, const void *opcode, size_t len)
    - ARM: patch_text(void *addr, unsigned int insn)
  - You do not worry about the paging mechanism anymore!

Porting x86 Rootkits to ARM (2)

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DEMO

Conclusion and Black Hat Sound Bytes

- **Kernel-level (ring 0) threats should be protected in a more privileged level (ring -1)**
  - Rootkits can neutralize kernel-level (ring 0) protection
  - We create a ring -1 level protection mechanism with ARM TrustZone
- **Shadow-box v2 is practical and portable**
  - Shadow-box v2 protects the kernel from rootkits using IMA and OP-TEE
  - We made a reference implementation with Raspberry Pi 3
  - We named it “Secure Pi” and opened as an open source project

Questions ?

CONTRIBUTION!

Project : https://github.com/kkamagui/shadow-box-for-arm
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