black hat USA 2021
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BRIEFINGS

Alcatraz:

A Practical Hypervisor Sandbox to Prevent Escapes from the KVM/QEMU and KVM-Based MicroVMs

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Who Am I?

- **Senior security researcher** at the Affiliated Institute of ETRI
- **Review board member** of **Black Hat Asia** and **KimchiCon**
- **Speaker** at **USENIX Security**, **Black Hat Asia/Europe**, **HITBSecConf**, **BlueHat Shanghai**, **TyphoonCon**, **KimmchiCon**, **BECS, etc.**
- **Author** of “64-bit multi-core OS principles and structure, Vol.1&2”
- **Debian Linux maintainer** and **Linux kernel contributor**
- a.k.a kkamagui, @kkamagui1

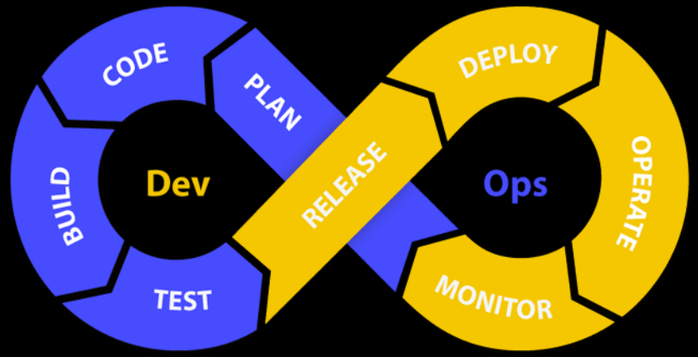
Goal of This Talk

- **I present escape paths of KVM/QEMU and KVM-based microVMs**
  - KVM-based hypervisors are widely used from VMs to containers
  - KVM has higher privilege than the kernel and can be used for escapes
- **I introduce a new tool, Alcatraz, to prevent escapes**
  - It downgrades KVM’s privilege (Ring -1) to the guest hypervisor (Ring 0)
  - It makes a sandbox for the KVM and monitors system calls to prevent escapes
    - Process creation, kernel code modification, and privilege escalation

There was JUST a security researcher

(not a CEO or CTO, not even a new CSO or manager)

A New Era of Cloud Platforms has come



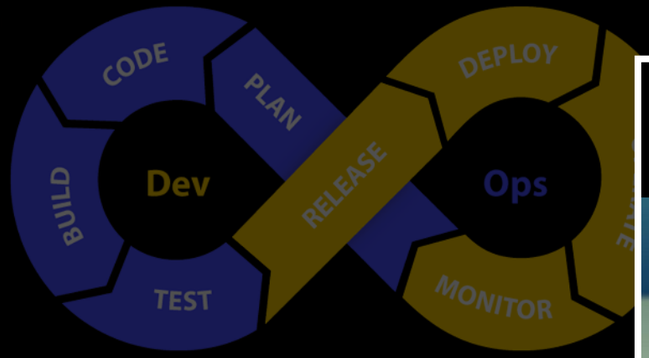
DevOps

Serverless

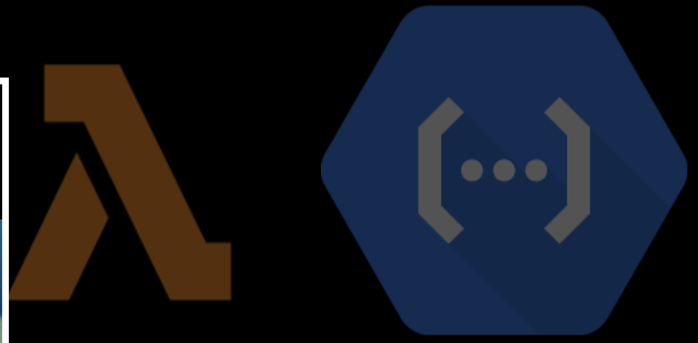
VM-based Technology

Container-based Technology

A New Era of Cloud Platforms has come



DevOps

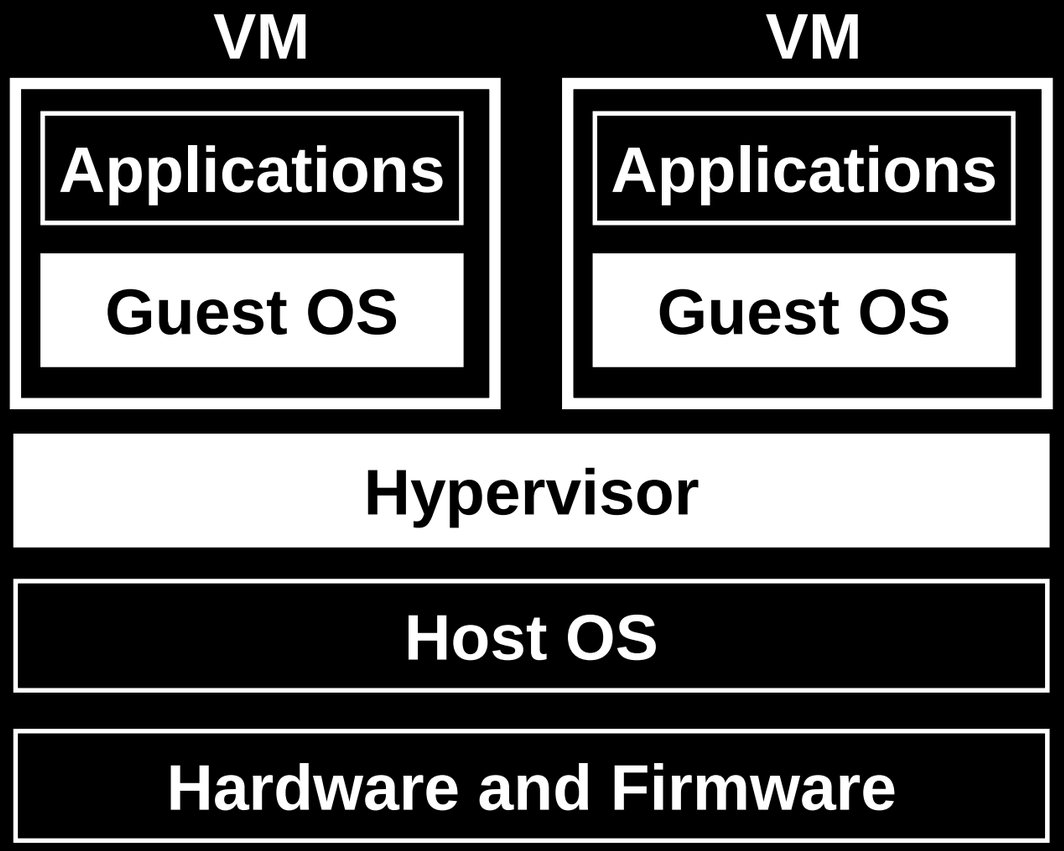


Serverless

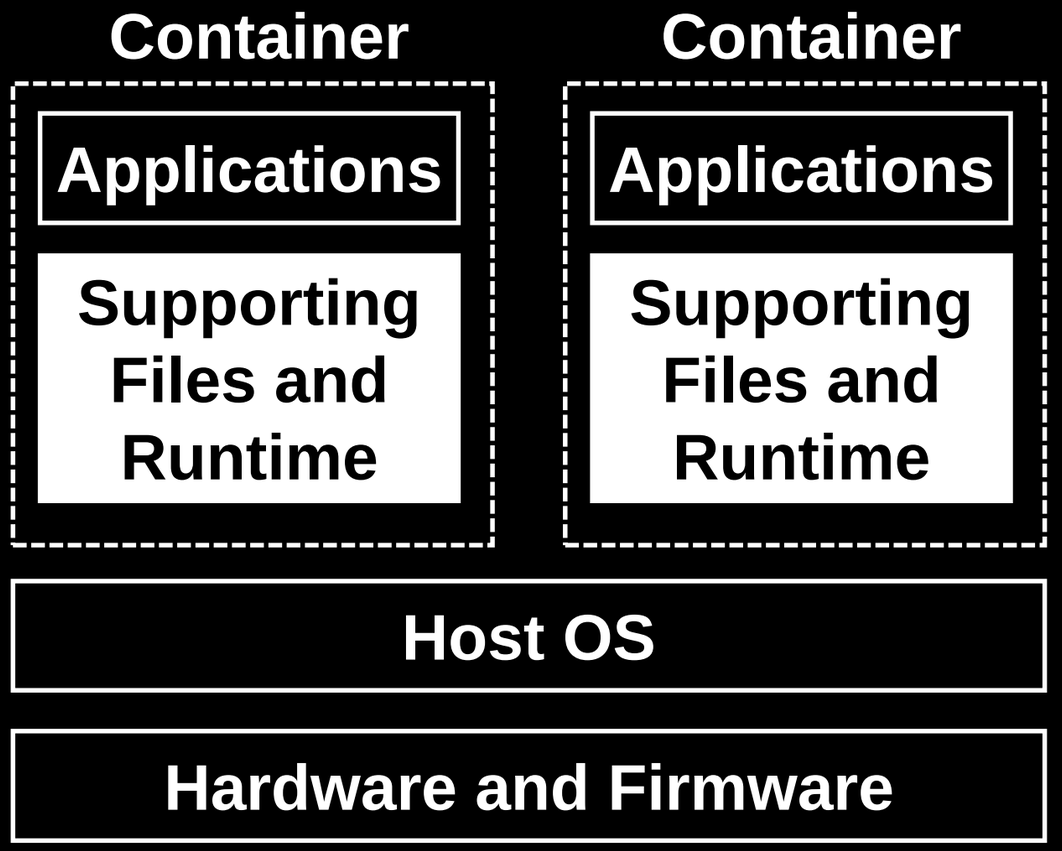
VM-based Technology

Container-based Technology

Virtual Machine (VM) vs Container (1)

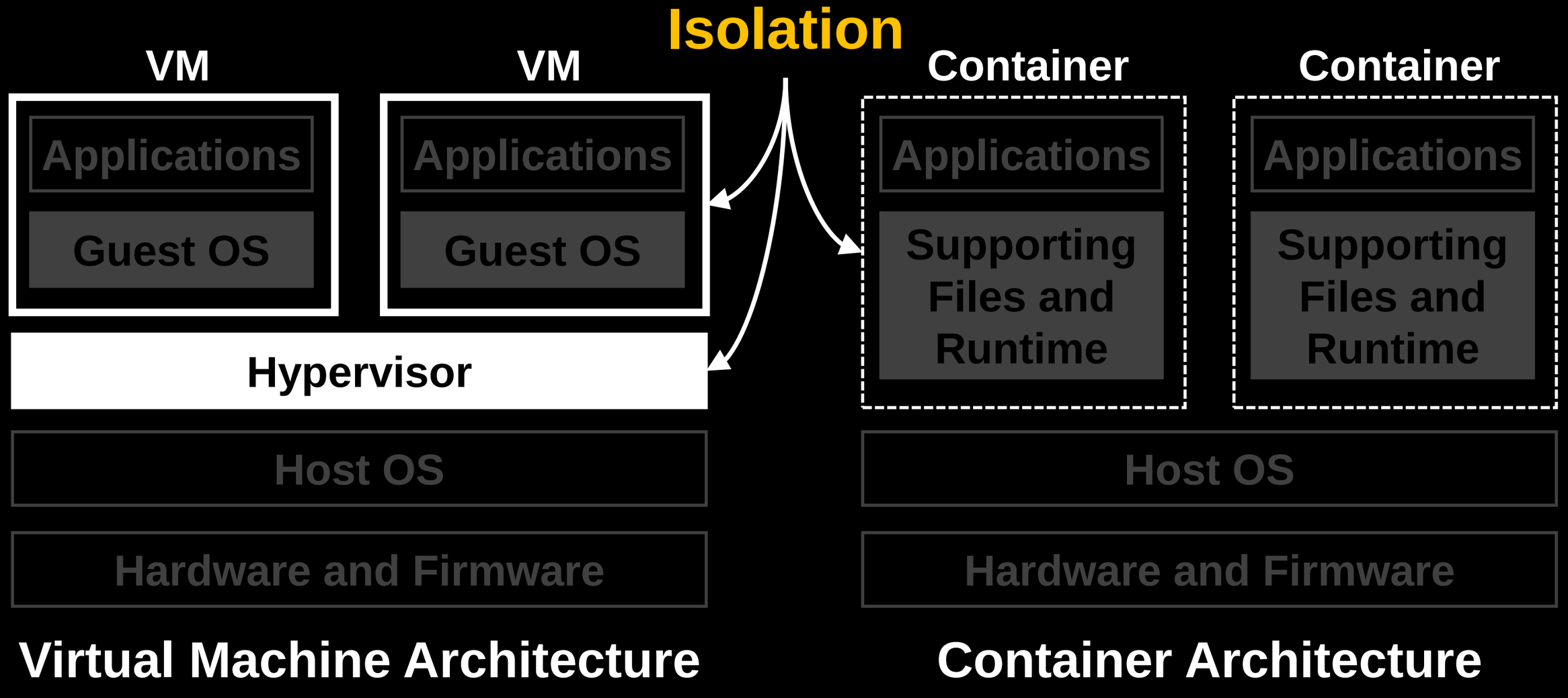


Virtual Machine Architecture

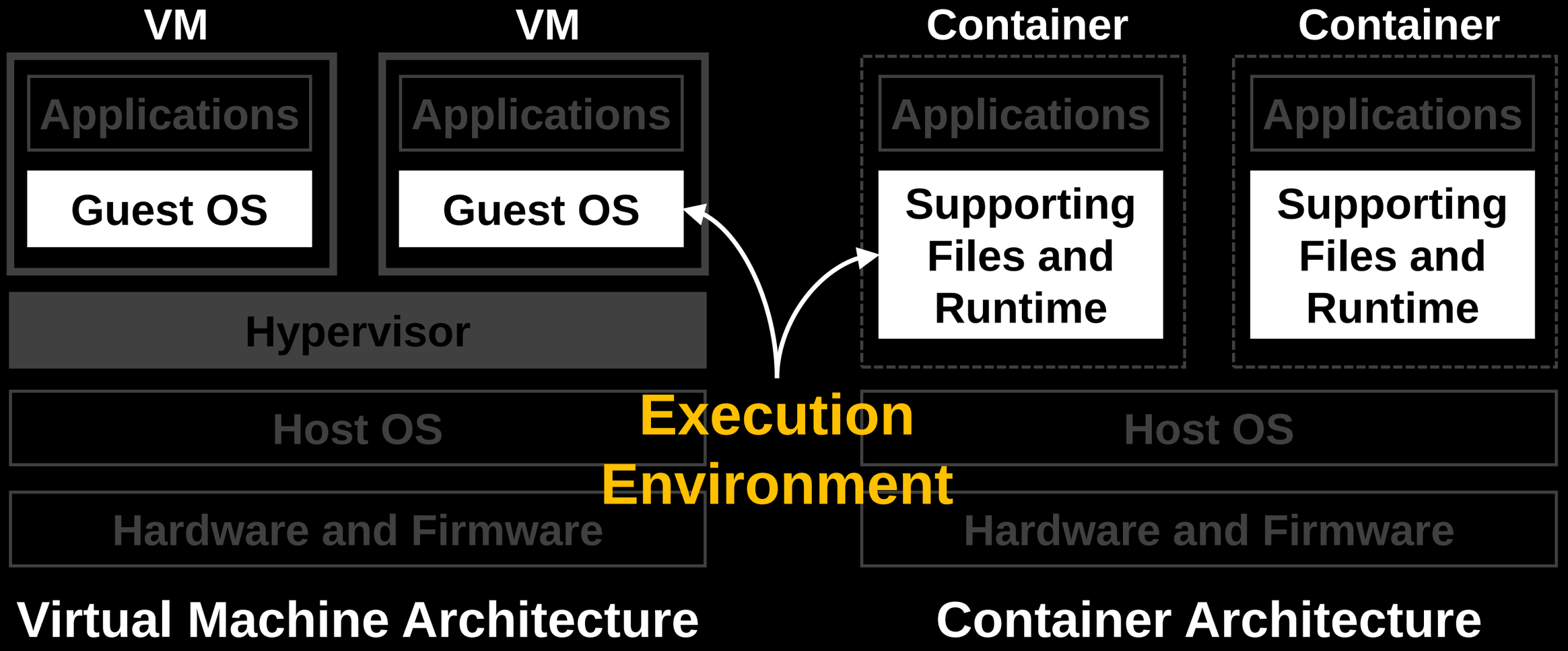


Container Architecture

Virtual Machine (VM) vs Container (1)



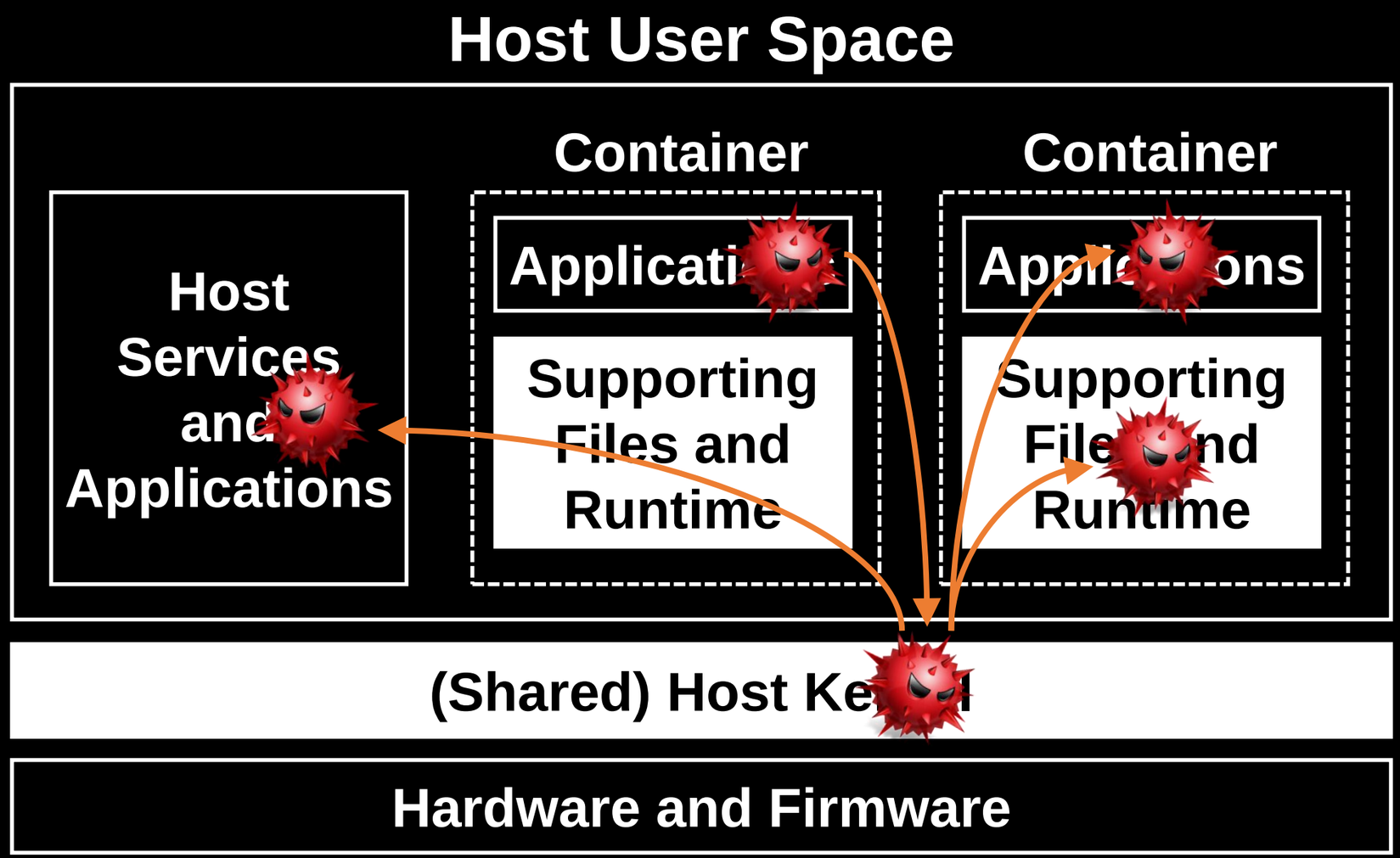
Virtual Machine (VM) vs Container (1)



Virtual Machine (VM) vs Container (2)

- **Virtual machine architecture**
  - uses Virtual Machine Monitor (VMM), a.k.a. hypervisor
  - provides strong isolation with virtualized hardware
    - A guest OS is needed, and performance overhead is high
  - has each execution environment, such as kernel and user space
- **Container architecture**
  - uses namespace and cgroup features of Linux kernel
  - provides weak isolation with the kernel
    - Supporting files are needed, and performance overhead is low
  - shares the kernel and has its own user space only

The container is good, but the problem is …



Container Architecture

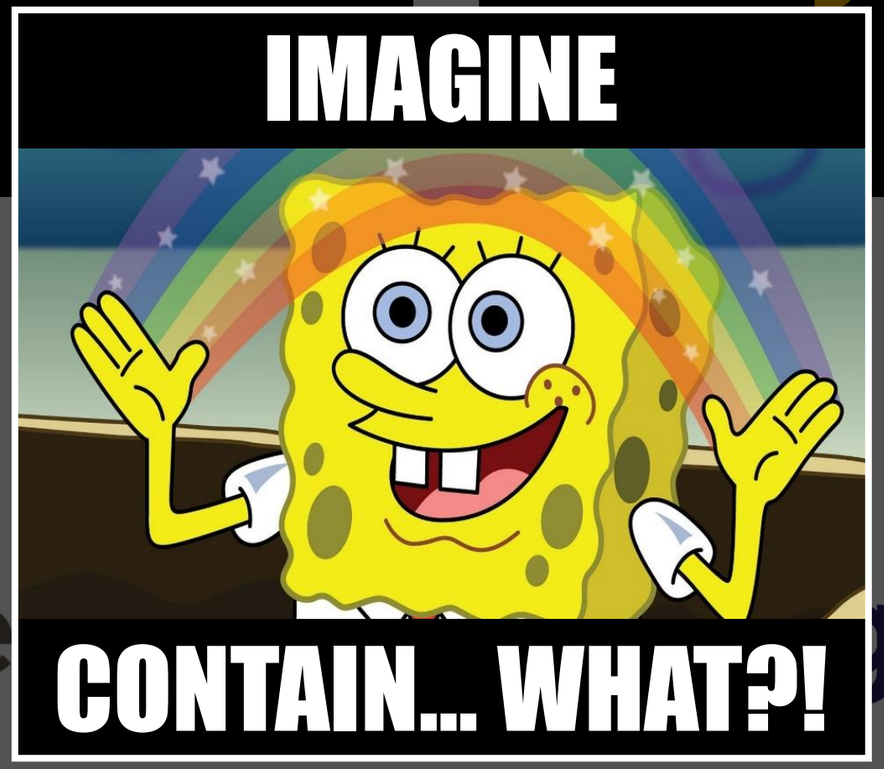
Containers are indispensable!

But, **strong isolation** is needed

to **prevent** the **ESCAPES**

Container ⊤ Hypervisor

Container ⊥ Hypervisor



Fire

gVisor

To be or not to be,
that is the question

- William Shakespeare

So, the security researcher realized …

To be a container or not to be a container,
that is NOT the question

- Anonymous Researcher

The REAL question is …

How can we prevent escapes?

- Background
- Analysis of Critical Paths of Escapes
- Design and Implementation of Alcatraz
- Evaluation and Demo
- Conclusion and Black Hat Sound Bytes

- **Background** 

- Analysis of Critical Paths of Escapes

- Design and Implementation of Alcatraz

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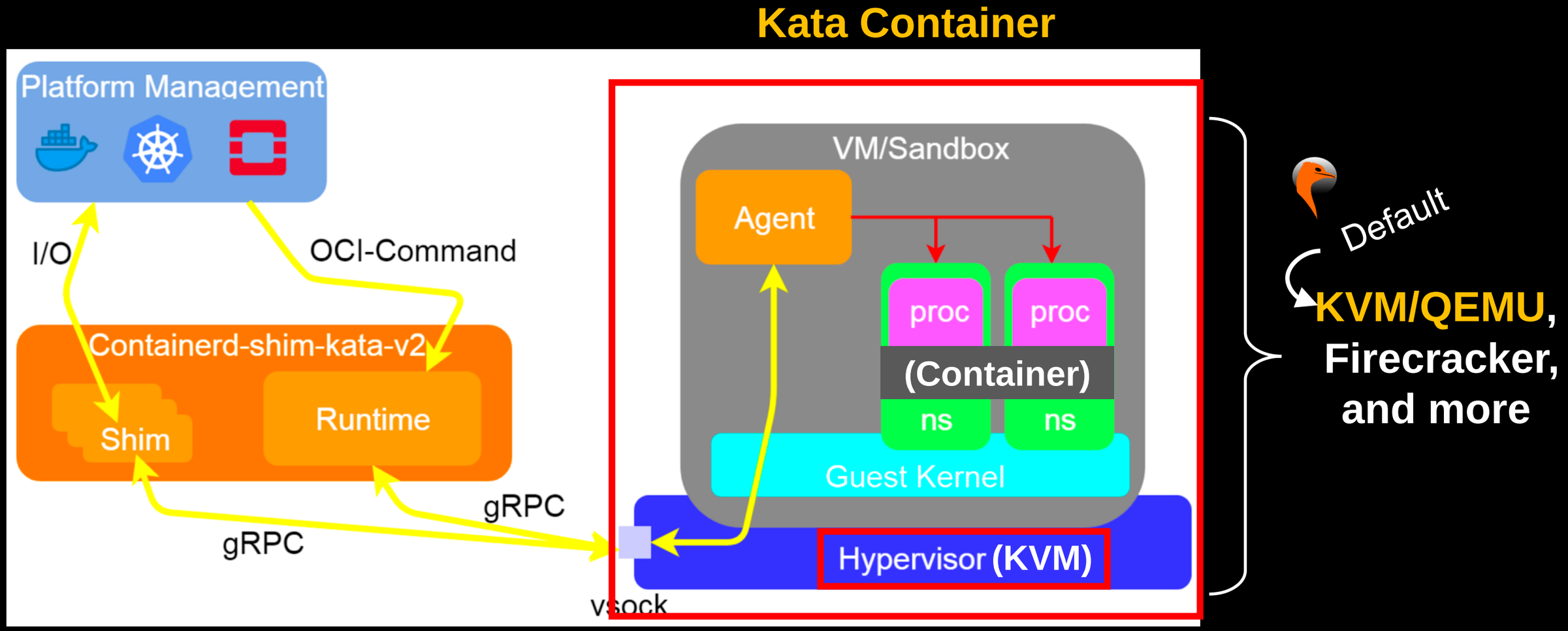
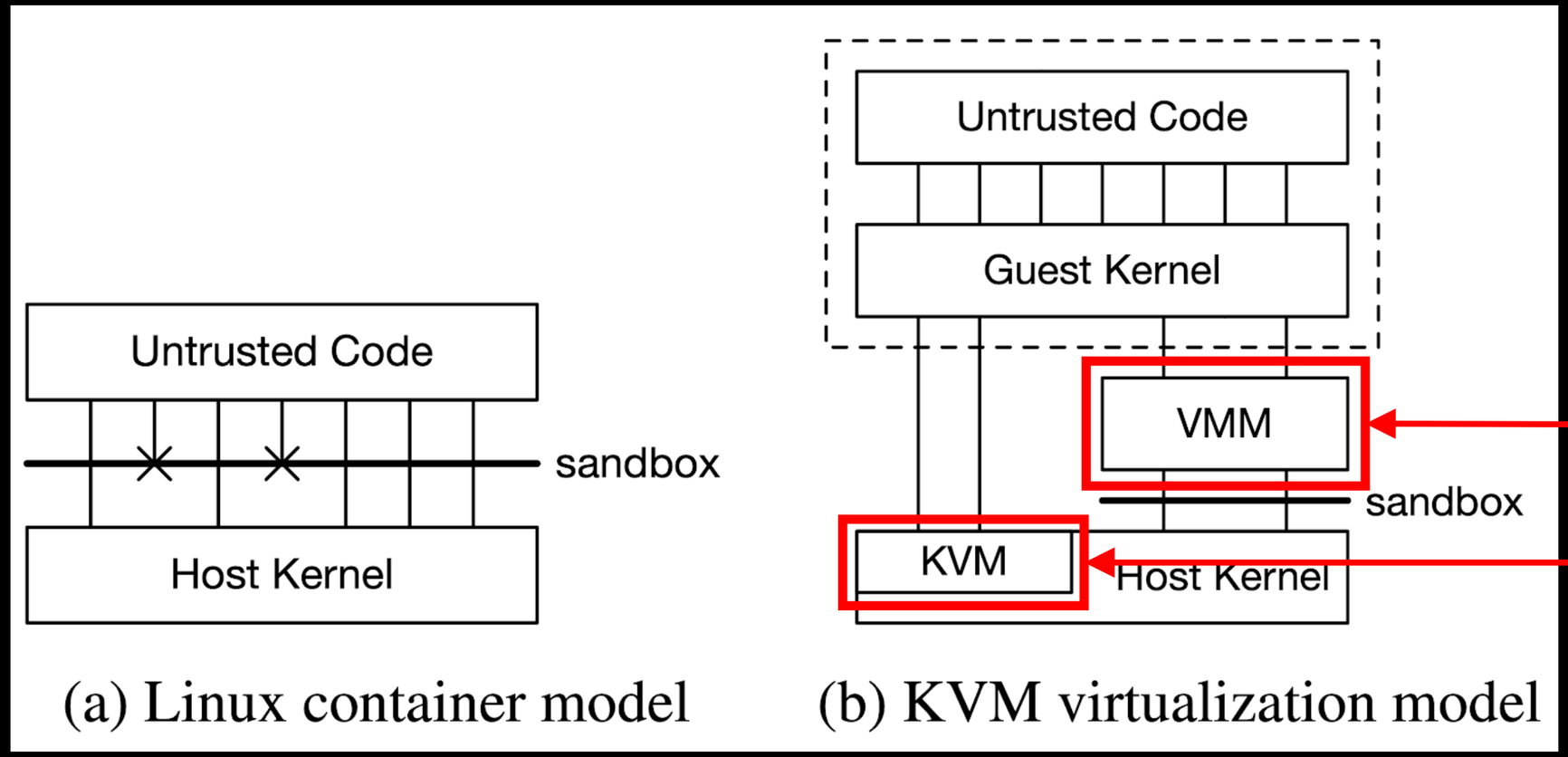
Kata Container



Kata Architecture - Kata Containers: An Emerging Architecture for Enabling MEC Services in Fast and Secure Way

Amazon Firecracker

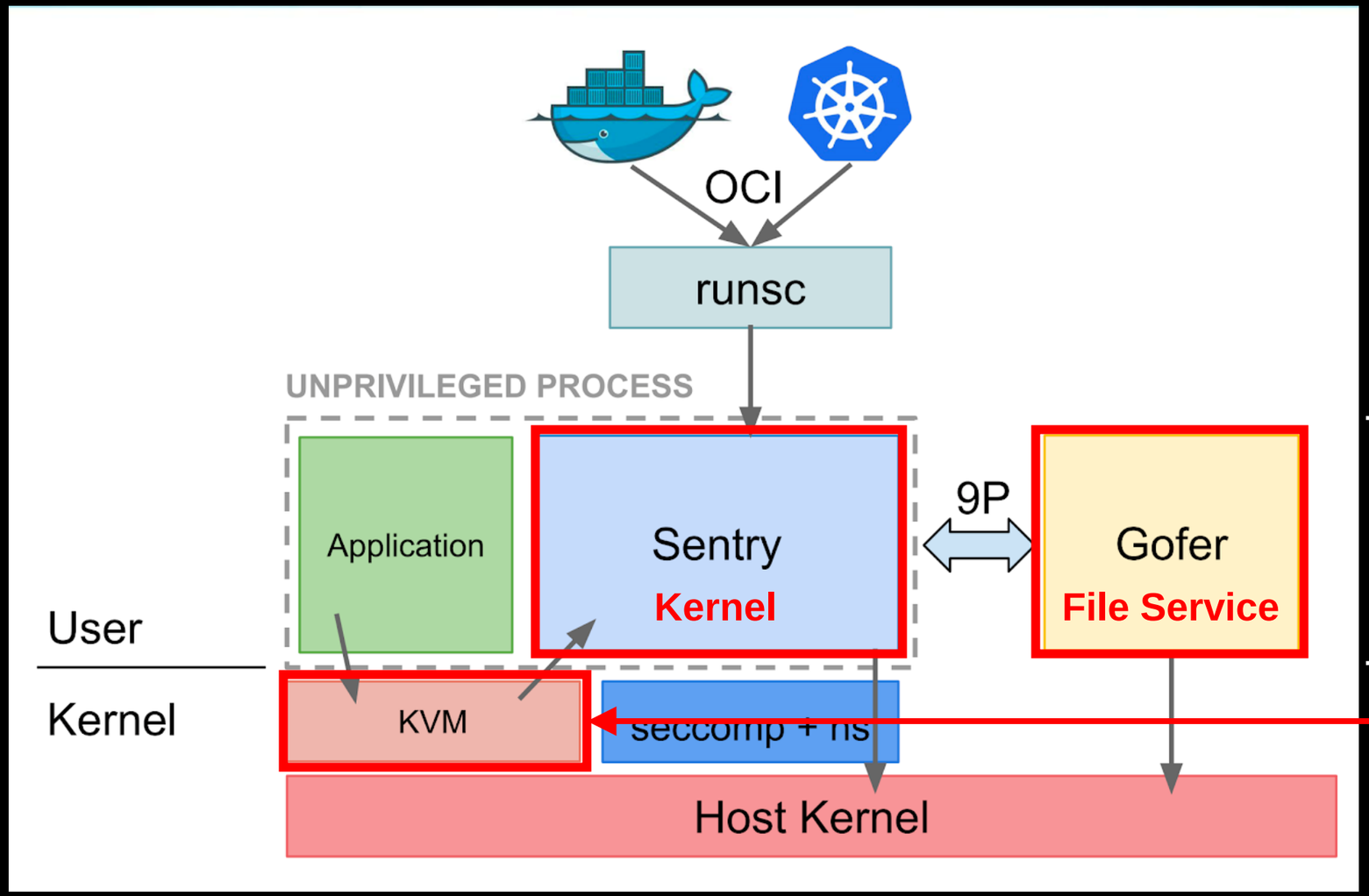


MicroVM
(Minimal Set for a Serverless Compute Service)

Firecracker
(written in Rust)

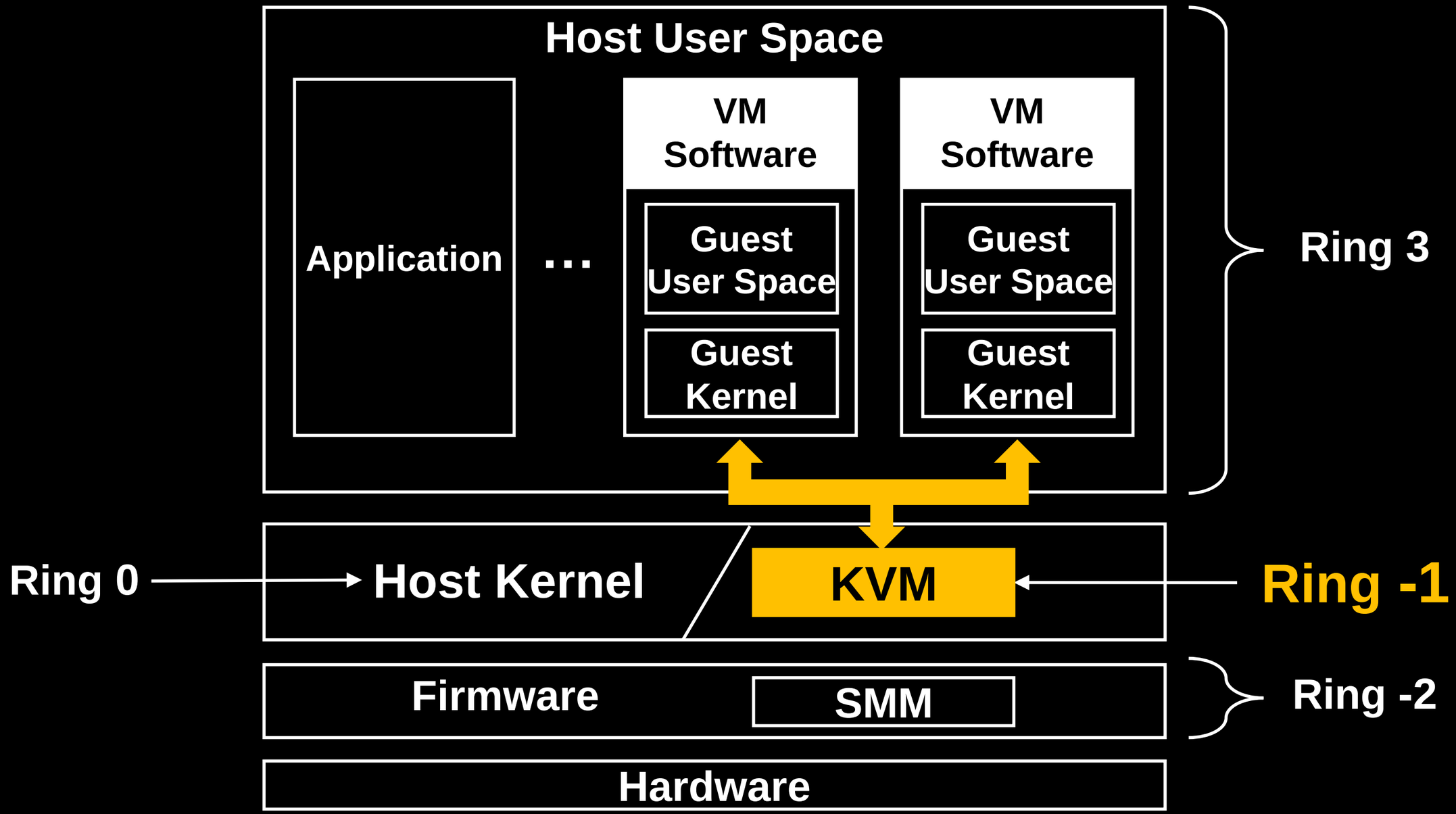
The Security Model of Linux Containers - Firecracker: Lightweight Virtualization for Serverless Applications

Google gVisor

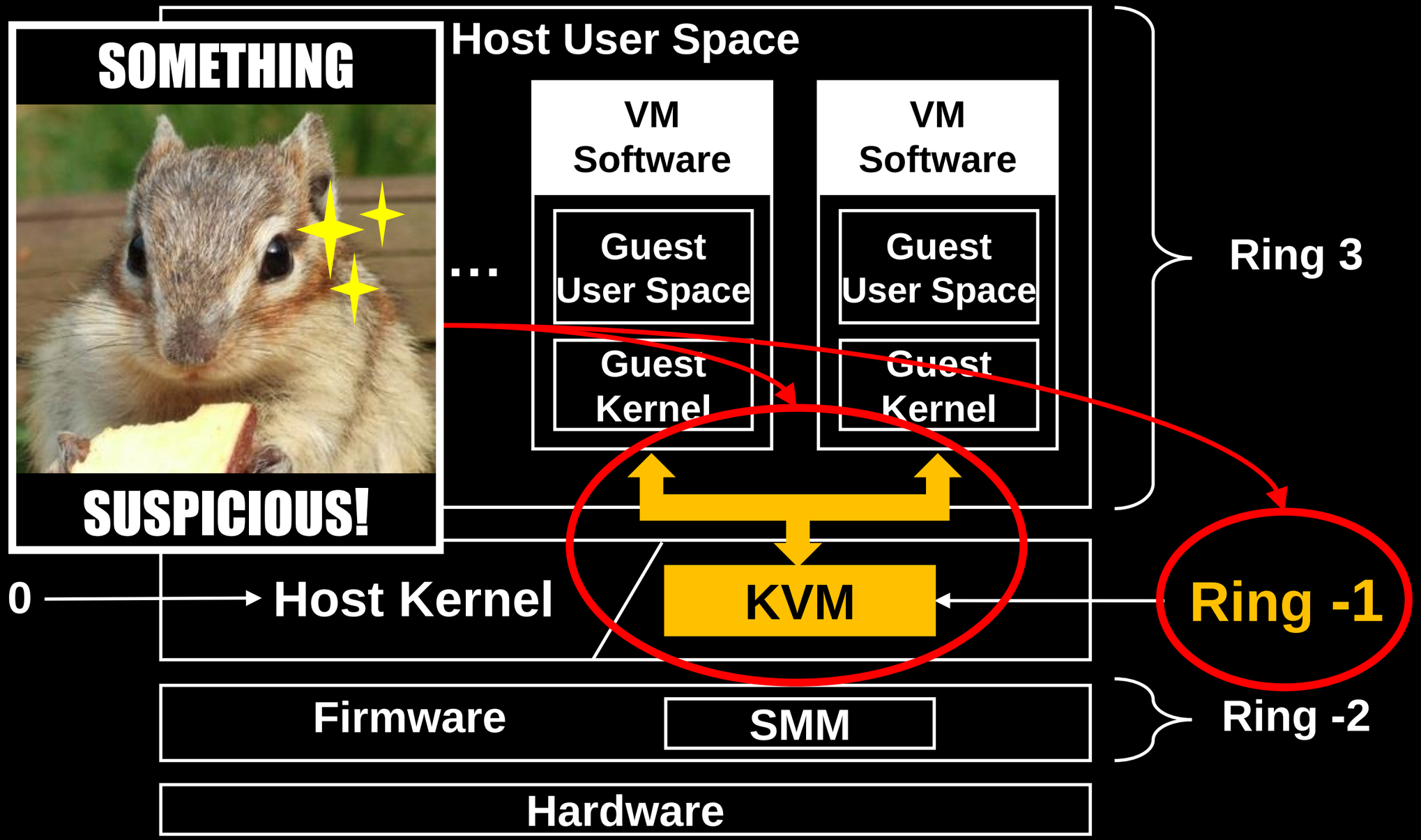


An OCI runtime powered by gVisor-Container Isolation at Scale (... and introducing gVisor)

Kernel-based Virtual Machine (KVM)



Kernel-based Virtual Machine (KVM)



A hypervisor attaches to VMs tightly

It has Ring -1 privilege!

The attacker can escape from the VM

with a KVM vulnerability

(and subvert the system)

Fortunately,

I was not the only one who was worried about

the excessive privilege of a hypervisor!

Previous Works

HyperSentry: Enabling Stealthy In-context Measurement of Hypervisor Integrity *

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ABSTRACT

This paper presents *HyperSentry*, a novel framework to enable integrity measurement of a running hypervisor (or any other highest privileged software layer on a system). Unlike existing solutions for protecting privileged software, HyperSentry does not introduce a higher privileged software layer below the integrity measurement target, which could start another race with malicious attackers in obtaining the highest privilege in the system. Instead, HyperSentry introduces a software component that is properly isolated from the hypervisor to enable *stealthy* and *in-context* measurement of the runtime integrity of the hypervisor. While stealthiness is necessary to ensure that a compromised hypervisor does not have a chance to hide the attack traces upon detecting an up-coming measurement, in-context measurement is

we implement a prototype of the framework along with an integrity measurement agent for the Xen hypervisor. Our experimental evaluation shows that HyperSentry is a low-overhead practical solution for real world systems.

Categories and Subject Descriptors

D.4.6 [**Operating Systems**]: Security and Protection—*invasive software*

General Terms

Security

Keywords

Virtualization, Hypervisor Integrity, Integrity Measurement

1. INTRODUCTION

Preventing and Detecting Xen Hypervisor Subversions

Joanna Rutkowska & Rafał Wojtczuk
Invisible Things Lab

Black Hat USA 2008, August 7th, Las Vegas, NV

intel

CHIPSET BASED APPROACH TO DETECT VIRTUALIZATION MALWARE a.k.a. DeepWatch

Yuriy Bulygin

Joint work with David Samyde

Security Center of Excellence / PSIRT @ Intel Corporation

me/learningnets

Protecting Cloud Virtual Machines from Commodity Hypervisor and Host Operating System Exploits

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Abstract

Hypervisors are widely deployed by cloud computing providers to support virtual machines, but their growing complexity poses a security risk as large codebases contain many vulnerabilities. We have created HypSec, a new hypervisor design for retrofitting an existing commodity hypervisor using microkernel principles to reduce its trusted computing base while protecting the confidentiality and integrity of virtual machines. HypSec partitions the hypervisor into an untrusted host that performs most complex hypervisor functionality without access to virtual machine data, and a trusted core that provides access control to virtual machine data and performs basic CPU and memory virtualization. Hardware virtualization support is used to isolate and protect the trusted core and execute it

maintenance effort. For example, KVM [44] is integrated with Linux and Hyper-V [56] is integrated with Windows. The result is a huge potential attack surface with access to VM data in CPU registers, memory, I/O data, and boot images. The surge in outsourcing of computational resources to the cloud and away from privately-owned data centers further exacerbates this security risk of relying on the trustworthiness of complex and potentially vulnerable hypervisor and host OS infrastructure. Attackers that successfully exploit hypervisor vulnerabilities can gain unfettered access to VM data, and compromise the privacy and integrity of all VMs—an undesirable outcome for both cloud providers and users.

Recent trends in application design and hardware virtualization support provide an opportunity to revisit hypervisor design requirements to address this crucial security problem.

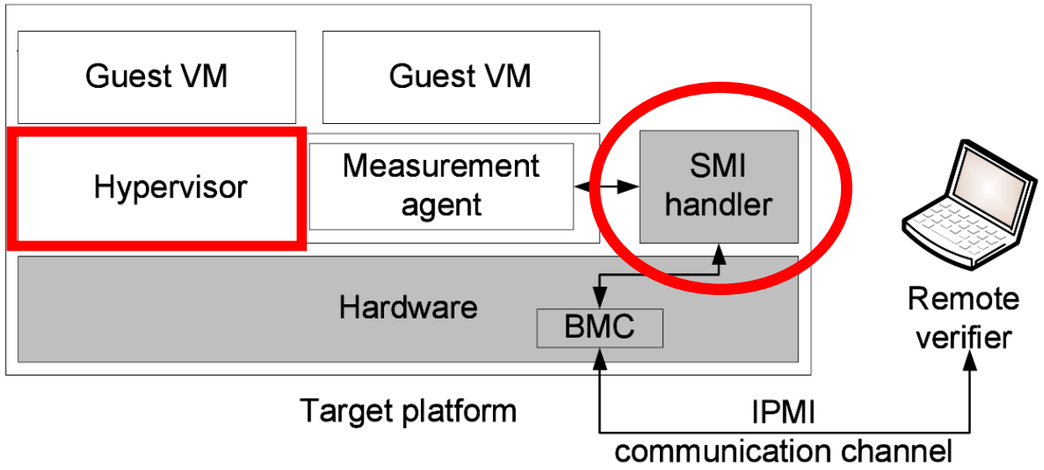
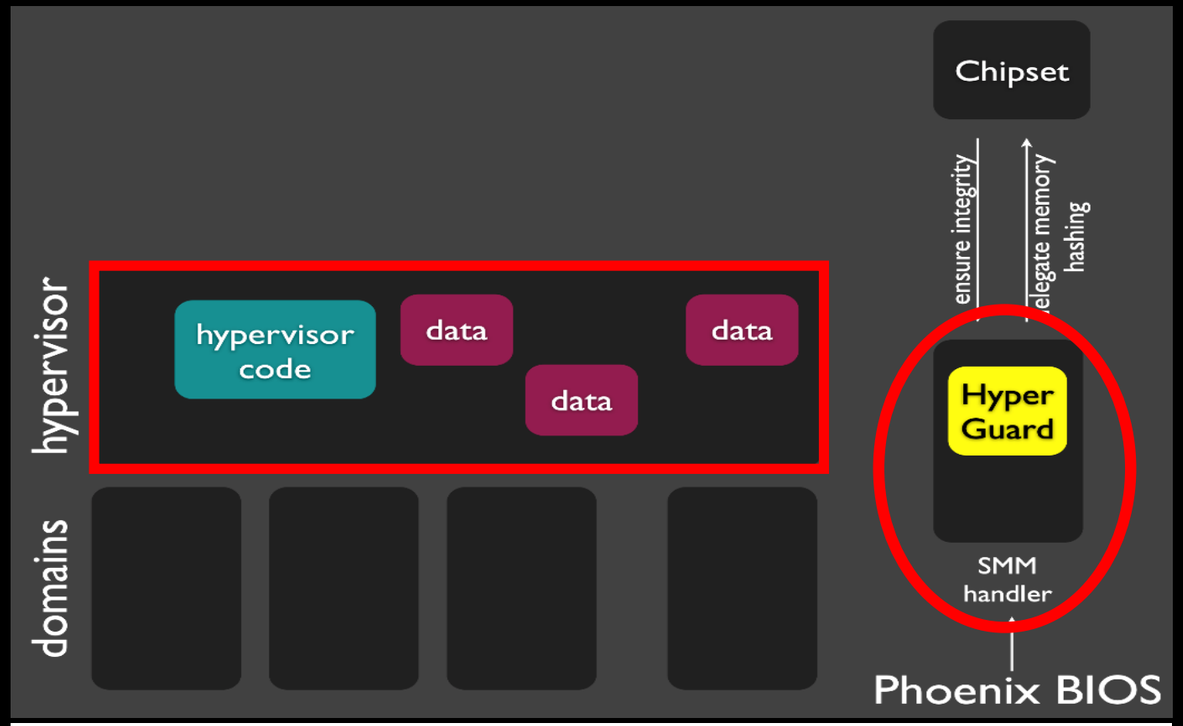
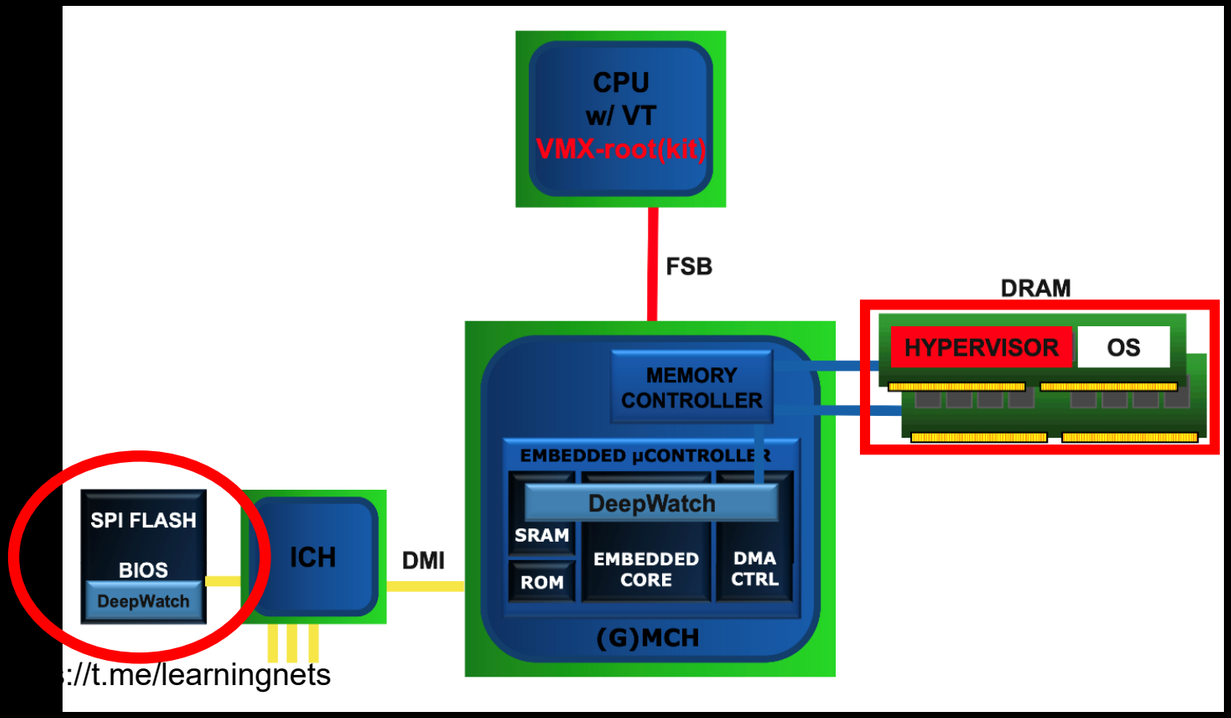


Figure 1: HyperSentry's architecture (Trusted components are shown in gray.)





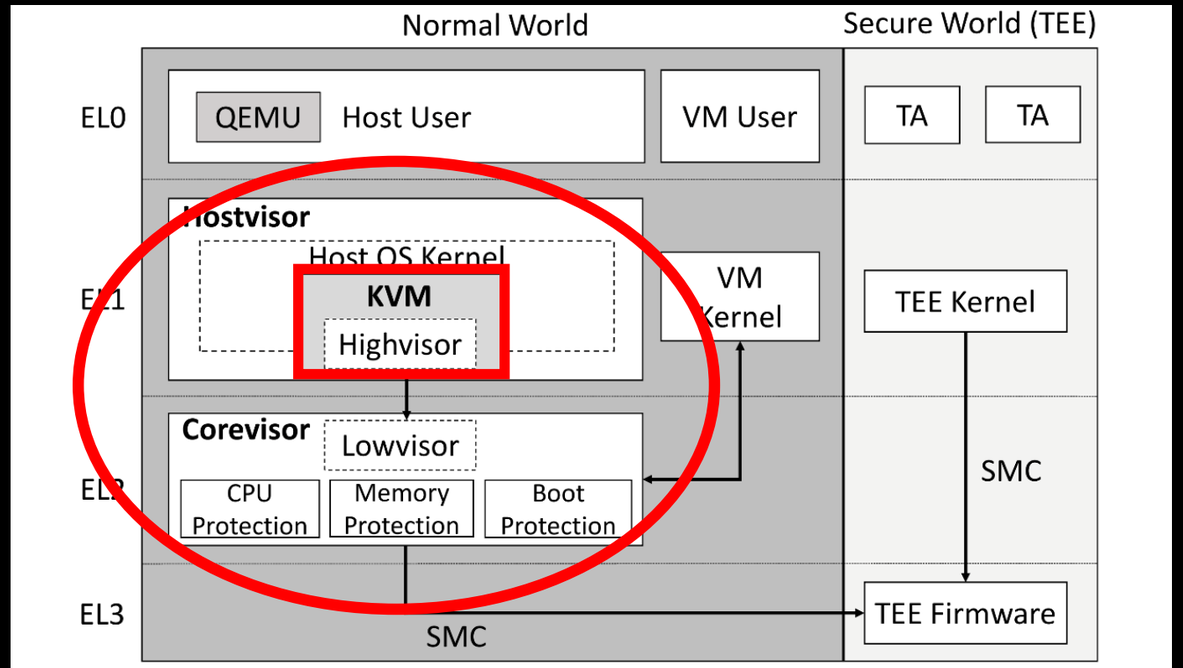
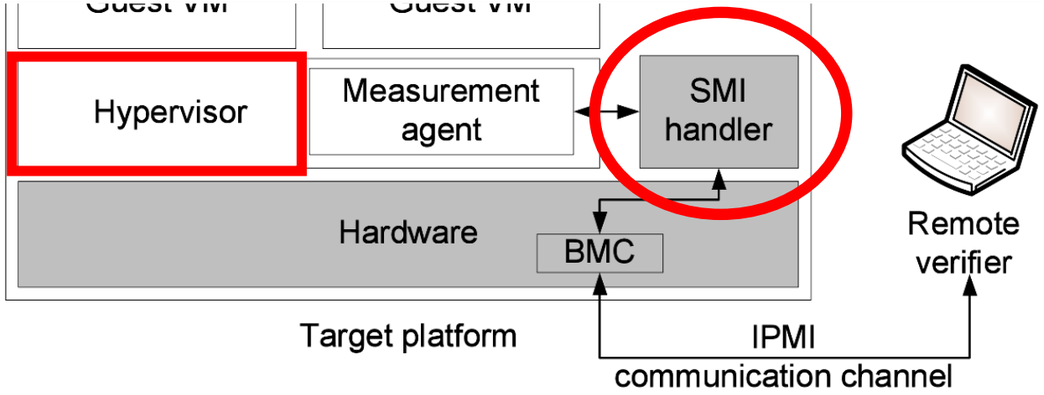


Figure 3: HypSec on KVM/ARM

Firmware Modification



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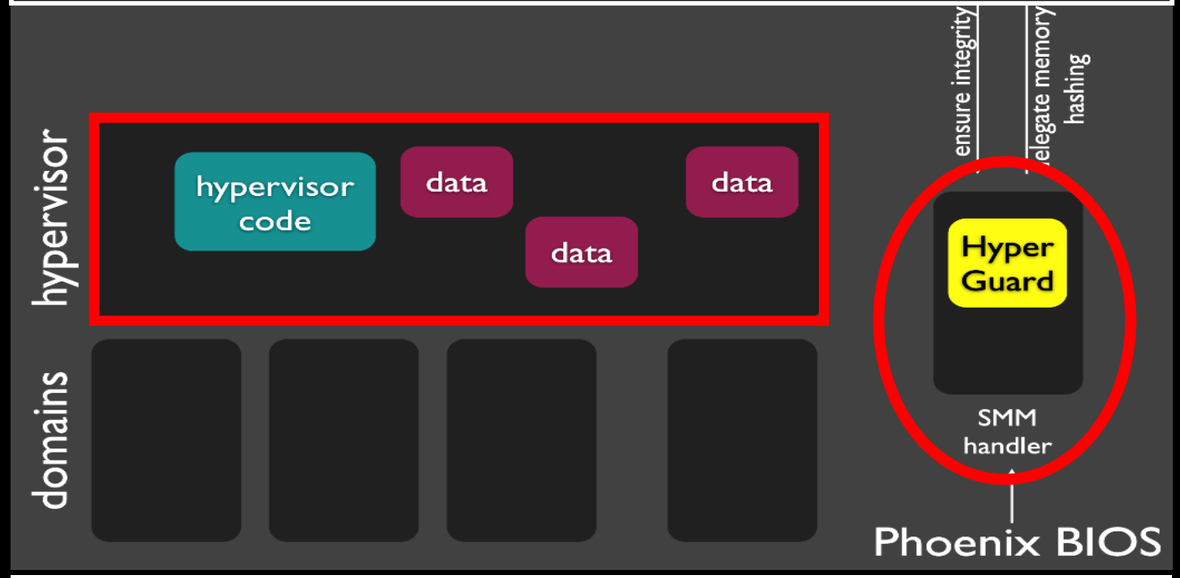

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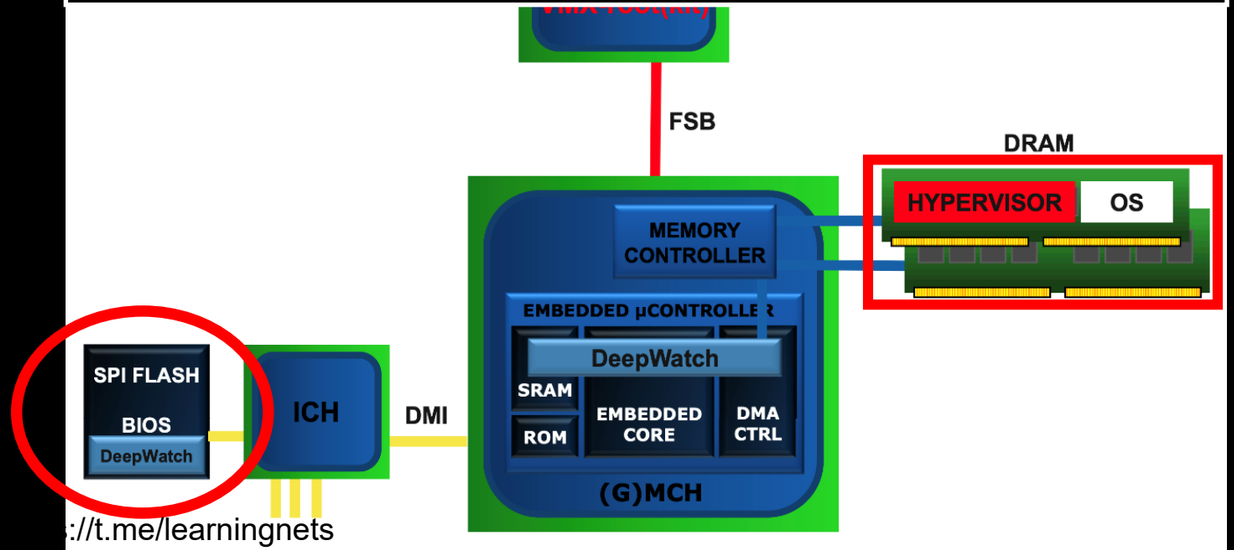
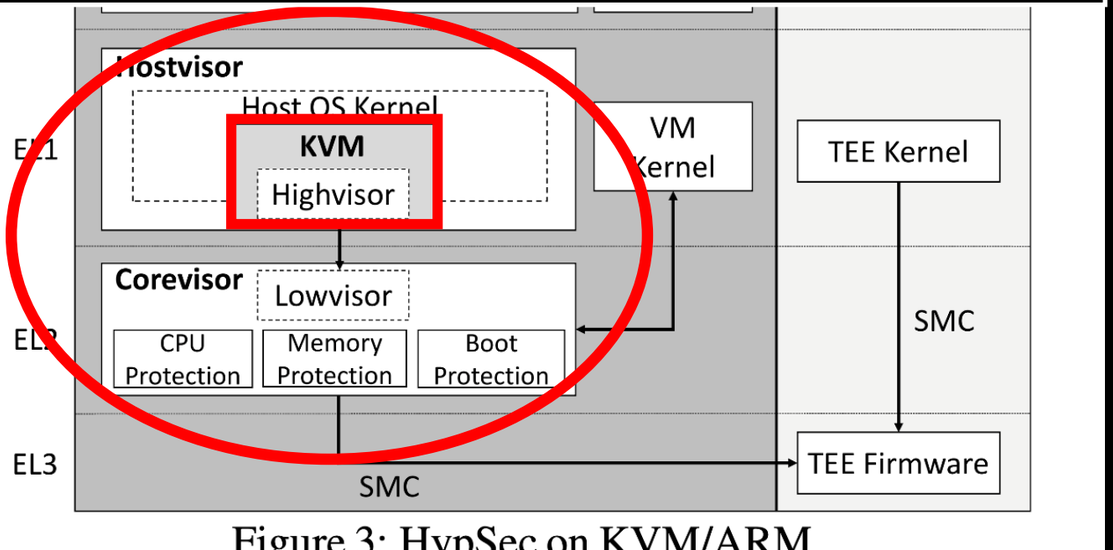


Hypervisor Retrofit



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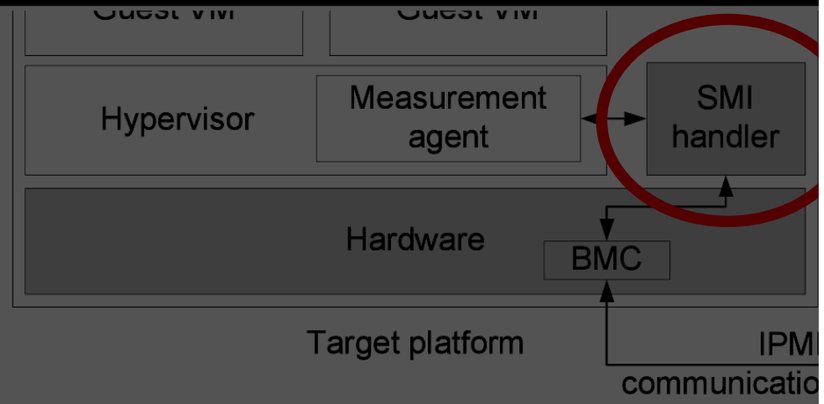

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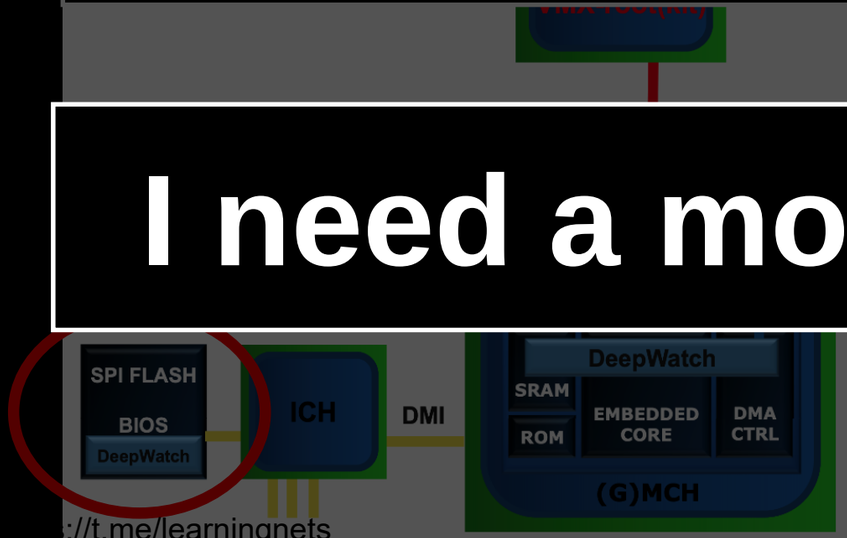
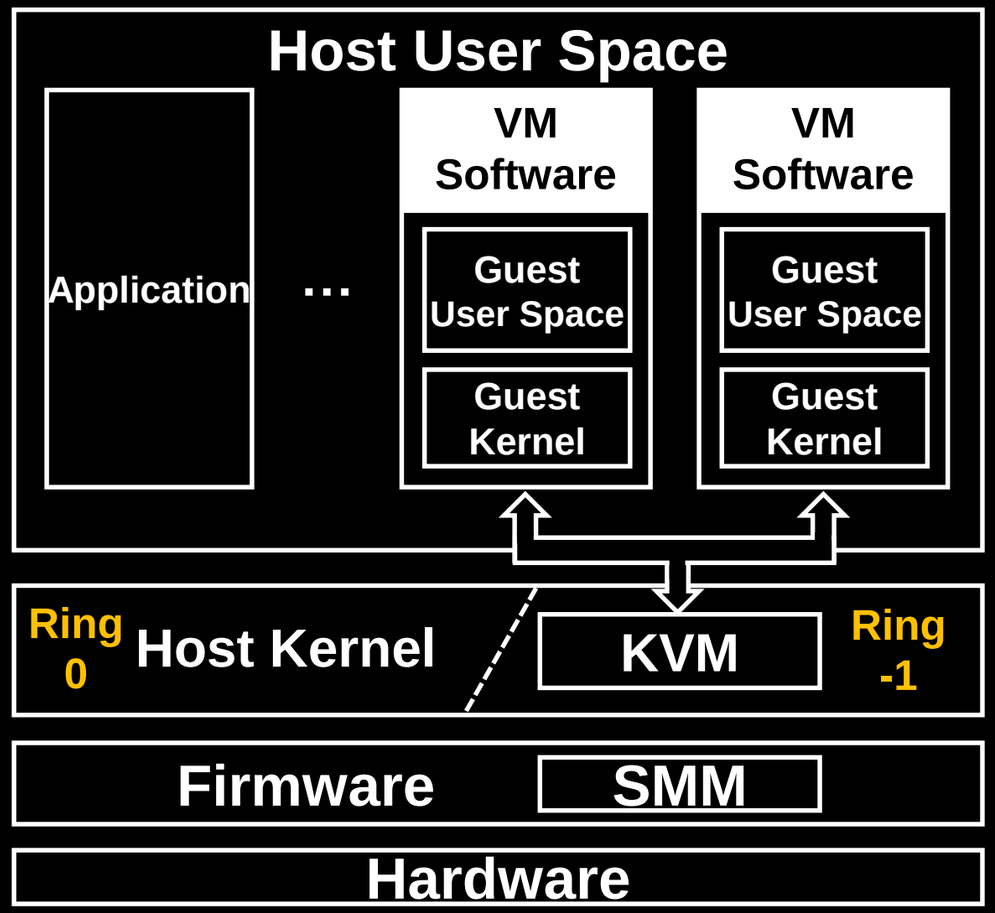


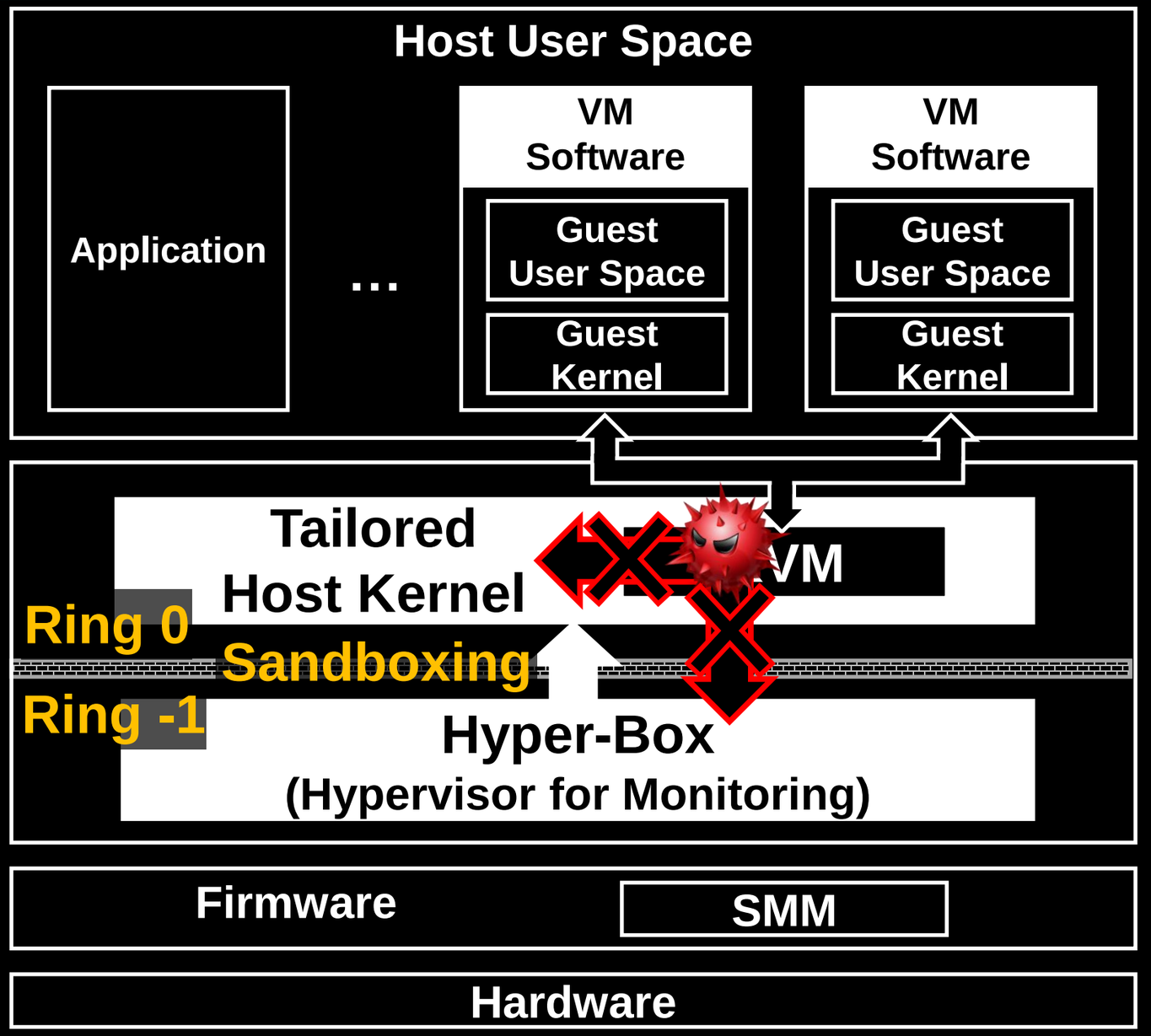
ypervisor Retrofit

Figure 3: HypSec on KVM/ARM

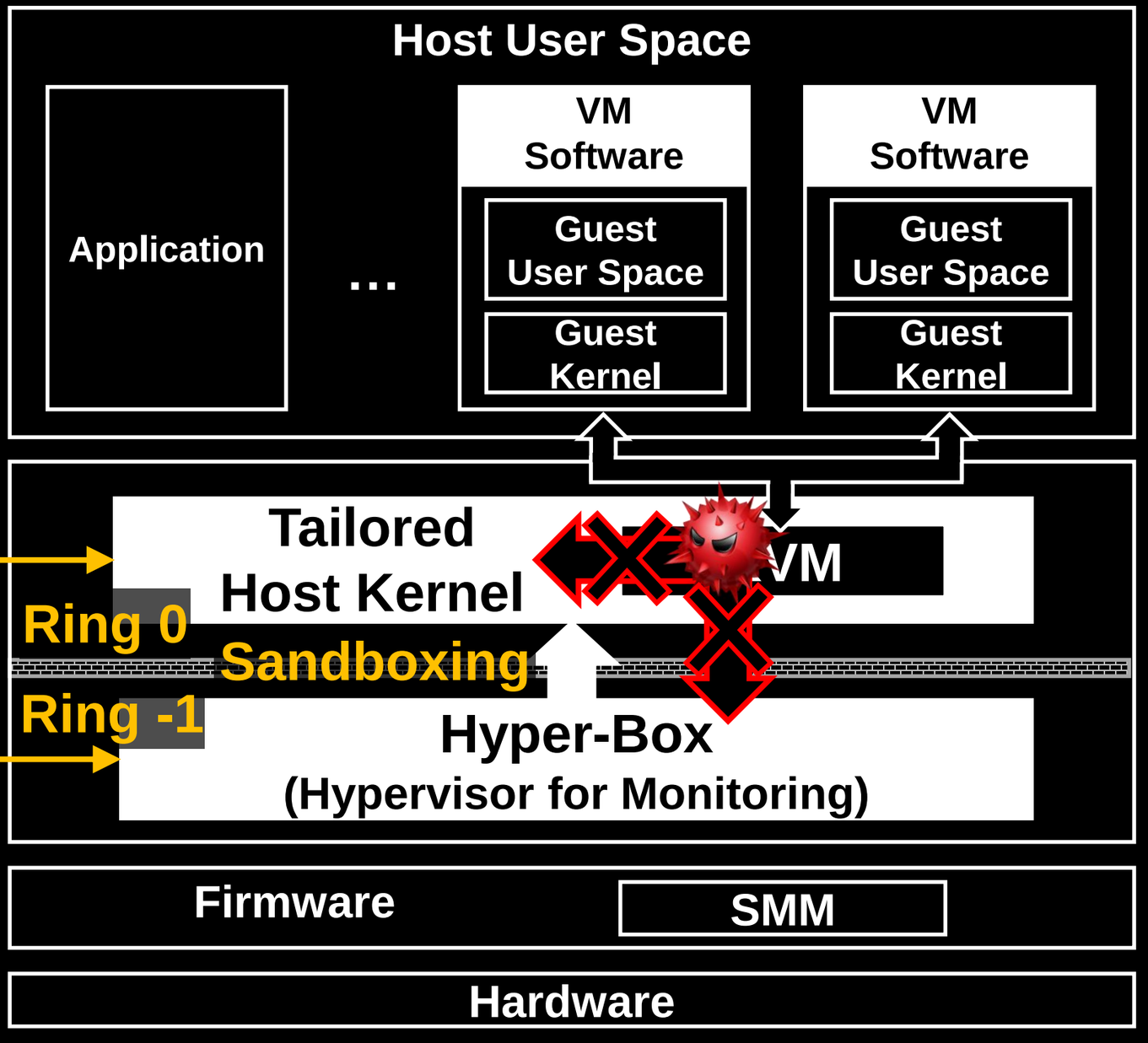
I need a more PRACTICAL solution!

The Solution: Sandboxing Hypervisor





The Solution: Sandboxing Hypervisor



- Background
- **Analysis of Critical Paths of Escapes** 
- Design and Implementation of Alcatraz
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CVE-2021-20181: TOCTOU in 9pfs of QEMU, privilege escalation
CVE-2021- 3546: OOB in VIRTIO in QEMU, code execution
CVE-2021- 3409: OOB in SDC of QEMU, code execution
CVE-2020-35506: UAF in SCSI of QEMU, code execution
CVE-2020-17380: OOB in SDC of QEMU, code execution
CVE-2020-15863: OOB in NET of QEMU, code execution
CVE-2020-14364: OOB in USB of QEMU, code execution
CVE-2020- 1711: OOB in iSCSI of QEMU, code execution
CVE-2019-18389: OOB in VIRTIO-GPU in QEMU, code execution
CVE-2019-14835: OOB in KVM, privilege escalation
CVE-2019-14821: OOB in MMIO of KVM, privilege escalation
CVE-2019- 7221: UAF in HR timer of KVM, code execution
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CVE-2017- 5931: Integer overflow in VIRTIO of QEMU, code execution
CVE-2017- 5667: OOB in SDC of QEMU, code execution
CVE-2017- 2630: Stack overflow in NBD of QEMU, code execution
CVE-2017- 2620: OOB in display of QEMU, code execution
CVE-2017- 2615: OOB in display of QEMU, code execution
CVE-2016-10150: UAF in KVM, local privilege escalation
CVE-2016- 9777: Improper IOAPIC handing in KVM, privilege escalation
CVE-2016- 9603: OOB in display of QEMU, code execution
CVE-2016- 7161: OOB in NET of QEMU, code execution
CVE-2016- 6351: OOB in SCSI of QEMU, code execution
CVE-2016- 5338: OOB in SCSI of QEMU, code execution
CVE-2016- 5126: OOB in iSCSI of QEMU, code execution
CVD-2016- 4440: Improper APICv handling of KVM, code execution
CVE-2016- 4439: OOB in SCSI of QEMU, code execution
CVE-2016- 4002: OOB in NET of QEMU, code execution
CVE-2016- 3710: OOB in VESA VGA of QEMU, code execution
CVE-2016- 1714: OOB in NVRAM of QEMU, code execution
CVE-2016- 1586: OOB in IDE of QEMU, code execution
CVE-2016- 0749: OOB in SPICE of QEMU, code execution
CVE-2015- 7512: OOB in NET of QEMU, code execution
CVE-2015- 7504: OOB in NET of QEMU, code execution
CVE-2015- 5279: OOB in NET of QEMU, code execution
CVE-2015- 5278: OOB in NET of QEMU, code execution
CVE-2015- 5260: OOB in SPICE of QEMU, code execution
CVE-2015- 5225: OOB in VNC of QEMU, code execution
CVE-2015- 5154: OOB in IDE of QEMU, code execution
CVE-2015- 3456: OOB in FDC of QEMU (VENOM), code execution
CVE-2015- 3214: OOB in PIT of QEMU, code execution
CVE-2015- 3209: OOB in NET of QEMU, code execution
CVE-2014- 8106: OOB in display of QEMU, code execution
CVE-2014- 7840: OOB in migration function of QEMU, code execution
CVE-2014- 3461: OOB in USB of QEMU, code execution
CVE-2014- 0182: OOB in VIRTIO of QEMU, code execution
CVE-2014- 0150: Integer overflow in VIRTIO-NET of QEMU, code execution
CVE-2014- 0144: OOB in CLOOP of QEMU, code execution
CVE-2014- 0049: OOB in KVM, code execution
CVE-2013- 6399: OOB in VIRTIO of QEMU, code execution
CVE-2013- 4544: OOB in NET of QEMU, code execution
CVE-2013- 4587: OOB in KVM, local privilege escalation
CVE-2013- 4542: OOB in SCSI of QEMU, code execution
CVE-2013- 4541: OOB in USB of QEMU, code execution
CVE-2013- 4540: OOB in GPIO of QEMU, code execution
CVE-2013- 4539: OOB in Audio of QEMU, code execution
CVE-2013- 4538: OOB in Display of QEMU, code execution
CVE-2013- 4537: OOB in SDC of QEMU, code execution
CVE-2013- 4536: OOB in PIC of QEMU, code execution
CVE-2013- 4532: OOB in NET of QEMU, code execution
CVE-2013- 4529: OOB in PCI of QEMU, code execution
CVE-2013- 4527: OOB in HPET of QEMU, code execution
CVE-2013- 4526: OOB in AHCI of QEMU, code execution
CVE-2013- 4151: OOB in VIRTIO of QEMU, code execution
CVE-2013- 4150: OOB in VIRTIO-NET of QEMU, code execution
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CVE-2016- 4439: OOB in SCSI of QEMU, code execution
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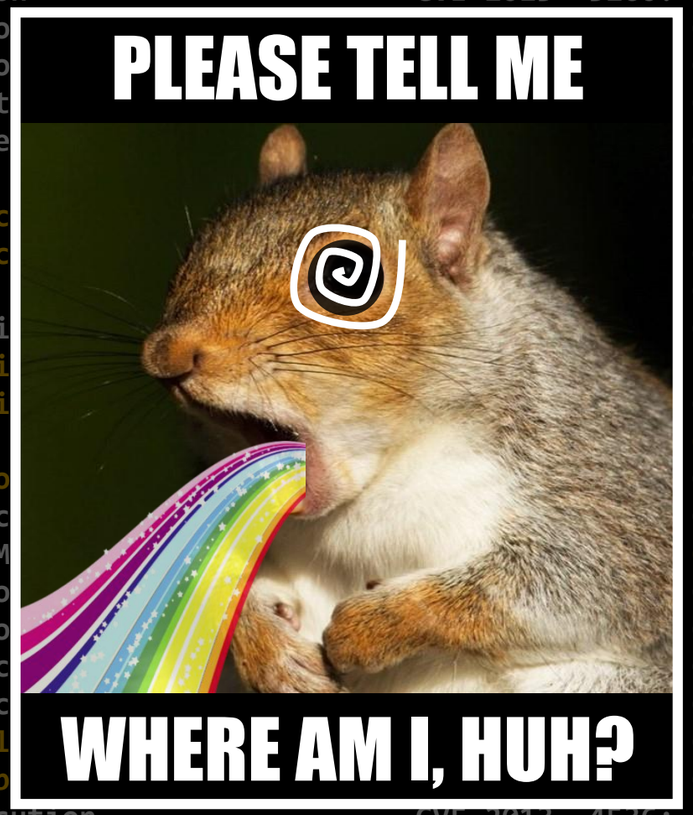
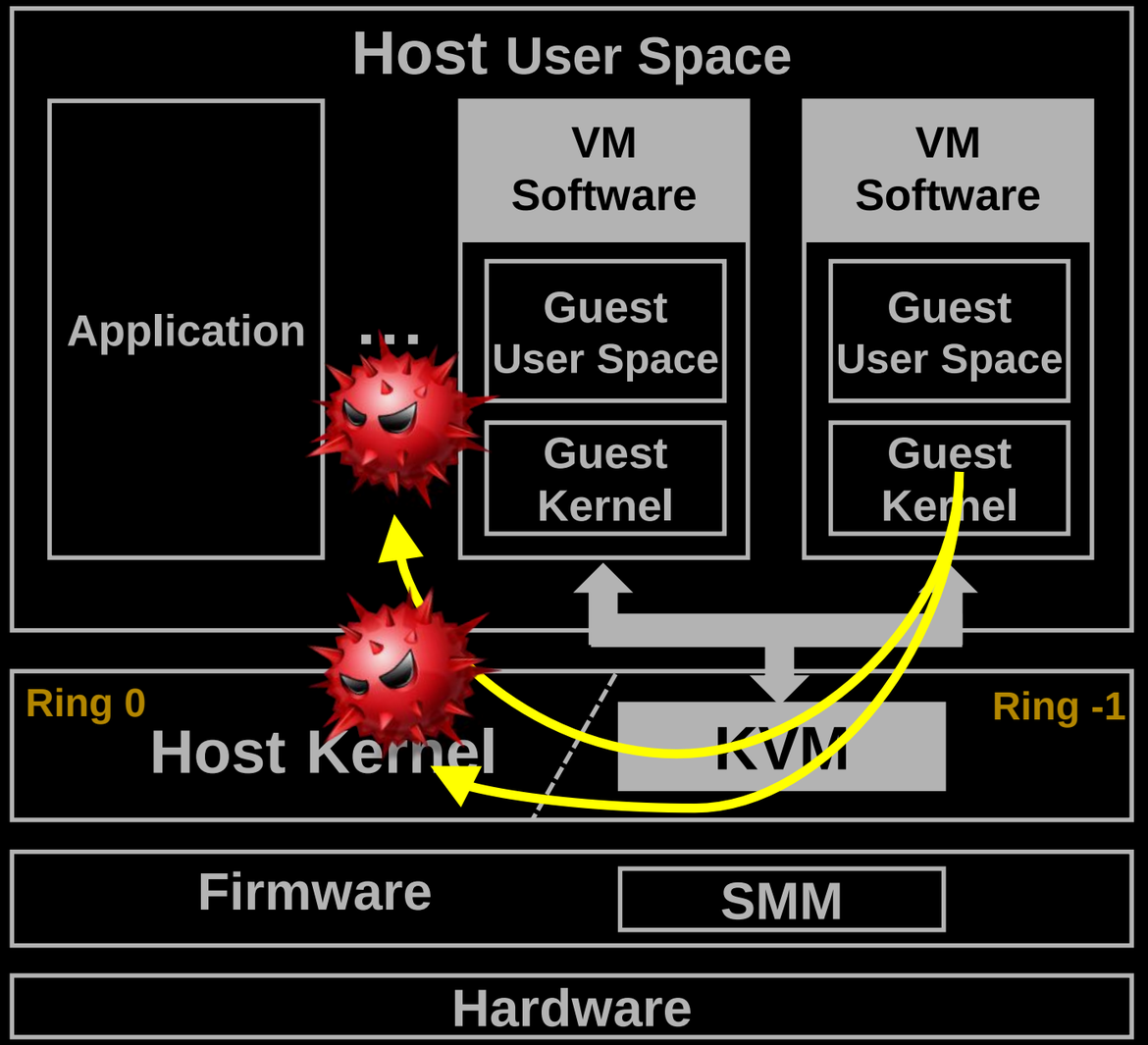
CVE-2016- 3710: OOB in VESA VGA of QEMU, code execution
CVE-2016- 1714: OOB in NVRAM of QEMU, code execution
CVE-2016- 1586: OOB in IDE of QEMU, code execution

CVE-2016- 0749: OOB in SPICE of QEMU, code execution
CVE-2015- 7512: OOB in NET of QEMU, code execution
CVE-2015- 7504: OOB in NET of QEMU, code execution
CVE-2015- 5279: OOB in NET of QEMU, code execution
CVE-2015- 5278: OOB in NET of QEMU, code execution
CVE-2015- 5260: OOB in SPICE of QEMU, code execution
OOB in VNC of QEMU, code execution
OOB in IDE of QEMU, code execution
OOB in FDC of QEMU (VENOM), code execution
OOB in PIT of QEMU, code execution
OOB in NET of QEMU, code execution
OOB in display of QEMU, code execution
OOB in migration function of QEMU, code execution
OOB in USB of QEMU, code execution
OOB in VIRTIO of QEMU, code execution
Integer overflow in VIRTIO-NET of QEMU, code execution
OOB in CLOOP of QEMU, code execution
OOB in KVM, code execution
OOB in VIRTIO of QEMU, code execution
OOB in NET of QEMU, code execution
OOB in KVM, local privilege escalation
OOB in SCSI of QEMU, code execution
OOB in USB of QEMU, code execution
OOB in GPIO of QEMU, code execution
OOB in Audio of QEMU, code execution
OOB in Display of QEMU, code execution
OOB in SDC of QEMU, code execution
CVE-2013- 4536: OOB in PIC of QEMU, code execution
CVE-2013- 4532: OOB in NET of QEMU, code execution
CVE-2013- 4529: OOB in PCI of QEMU, code execution
CVE-2013- 4527: OOB in HPET of QEMU, code execution
CVE-2013- 4526: OOB in AHCI of QEMU, code execution
CVE-2013- 4151: OOB in VIRTIO of QEMU, code execution
CVE-2013- 4150: OOB in VIRTIO-NET of QEMU, code execution
CVE-2013- 4149: OOB in VIRTIO-NET of QEMU, code execution
CVE-2013- 4148: OOB in VIRTIO-NET of QEMU, code execution
CVE-2013- 1943: Improper page handling of KVM, local privilege escalation
CVE-2013- 0311: Improper descriptor handling of KVM, privilege escalation



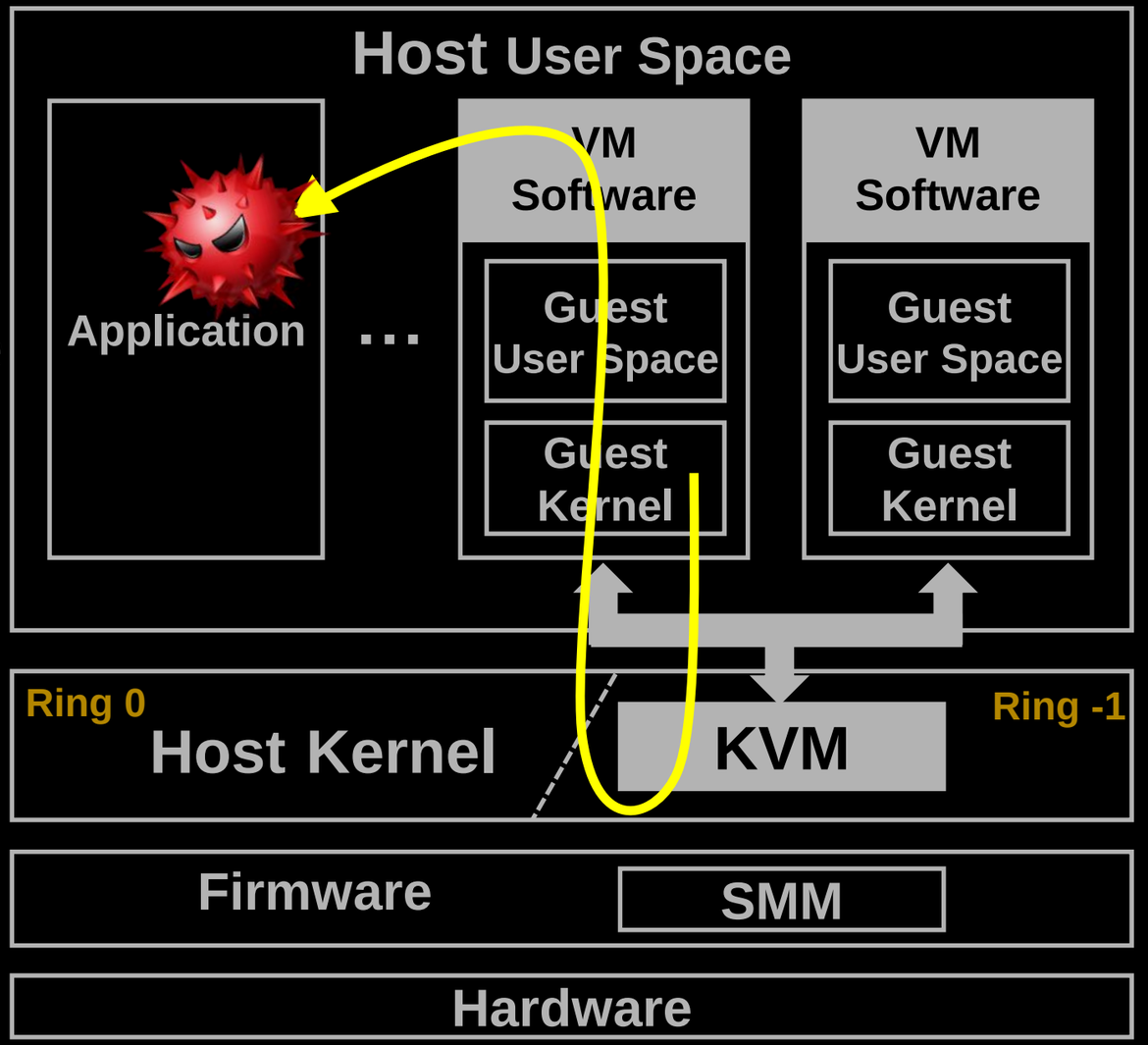
Extracting Escape Paths from CVEs (1)
Code Execution with a KVM Vulnerability

- **Executes code outside of a VM**
  - Small shellcode is used for creating a ROOT privilege process of a host
    - Process creation: Guest → Host
    - Privilege escalation: Host user → root
  - It is also possible to modify kernel or KVM code
    - But, disabling security features are needed! 😞



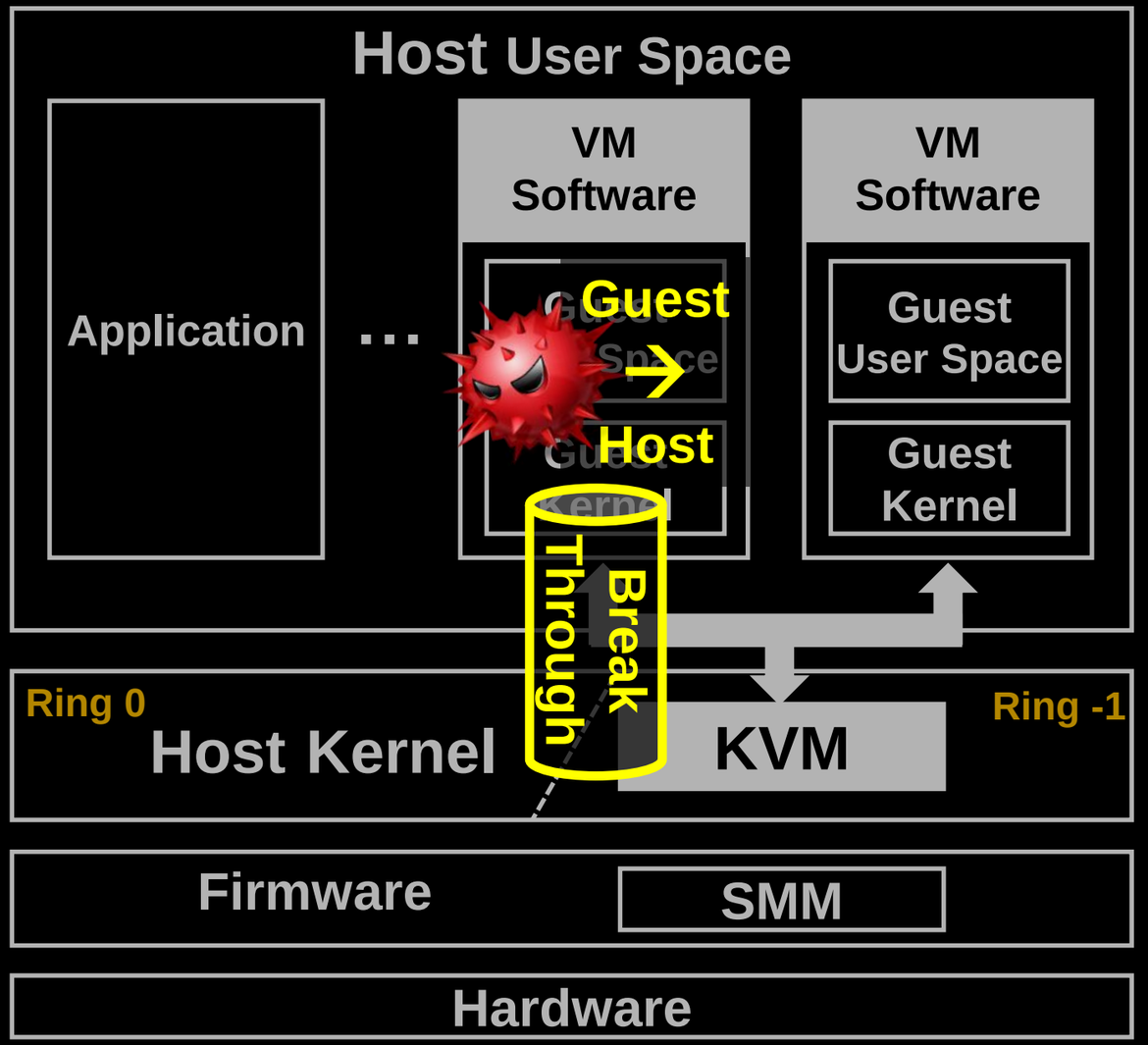
Extracting Escape Paths from CVEs (2)
Code Execution with a VM Vulnerability

- **Also executes code outside of a VM**
  - A VM software has lots of code for services and hardware emulations
    - Full-featured VMs (QEMU) has a large code base
    - Others have smaller ones, but … 😞
  - Small shellcode is used for creating a USER privilege process of a host
    - Process creation: Guest → Host
    - Privilege escalation is needed!



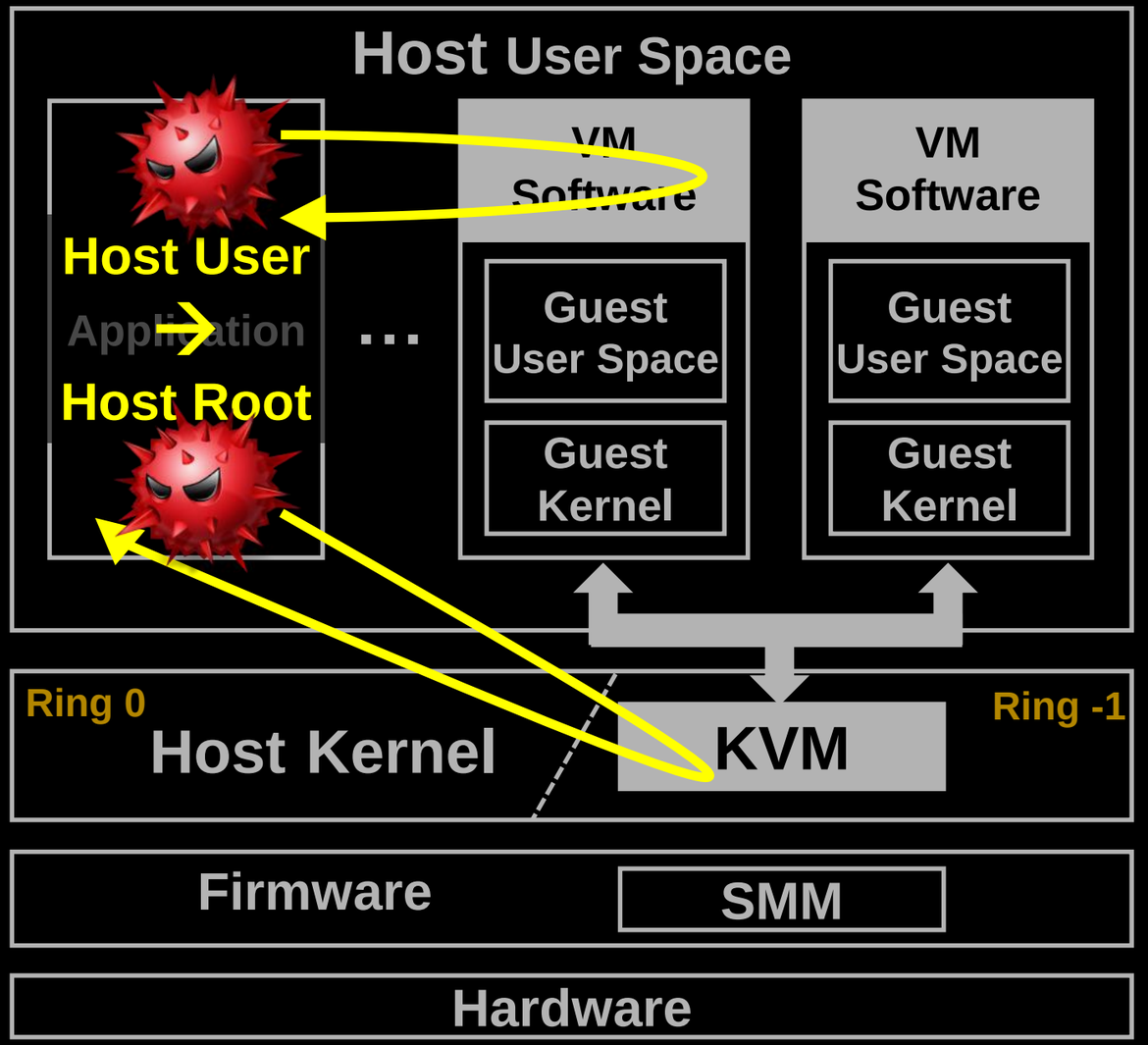
Extracting Escape Paths from CVEs (3)
Privilege Escalation with a KVM Vulnerability

- **Elevates the privilege of a VM**
  - A VM is a process and runs in the guest privilege of a host
  - But, improper handlings give HOST privilege to the VM
    - Page tables, interrupts, registers, etc.
  - It is possible to create a root privilege process of a host and modify kernel code



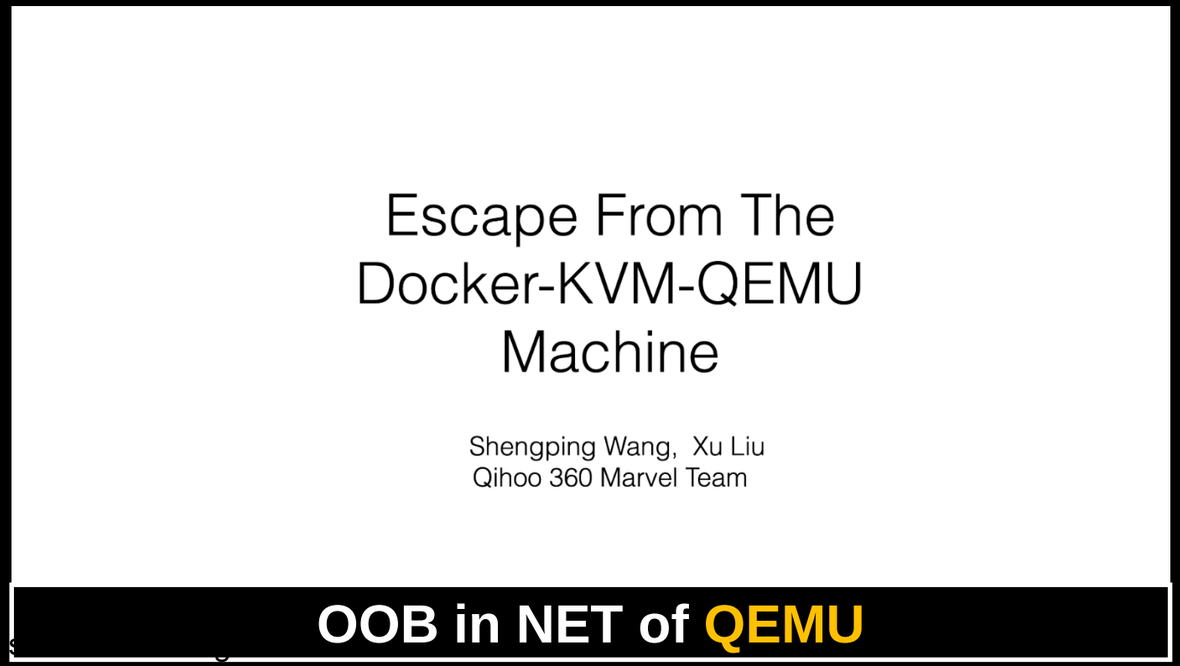
Extracting Escape Paths from CVEs (4)
Local Privilege Escalation with a KVM and VM Vuln.

- **Elevates the privilege of a process**
  - Some KVM vulnerabilities can be exploited through /dev/kvm
    - It can be used to elevate privilege (and create a root privilege process)
  - Some VM vulnerabilities can be used for privilege escalation if the VM or related daemon runs in root privilege
    - But, a VM usually runs in user privilege for security reasons 😞

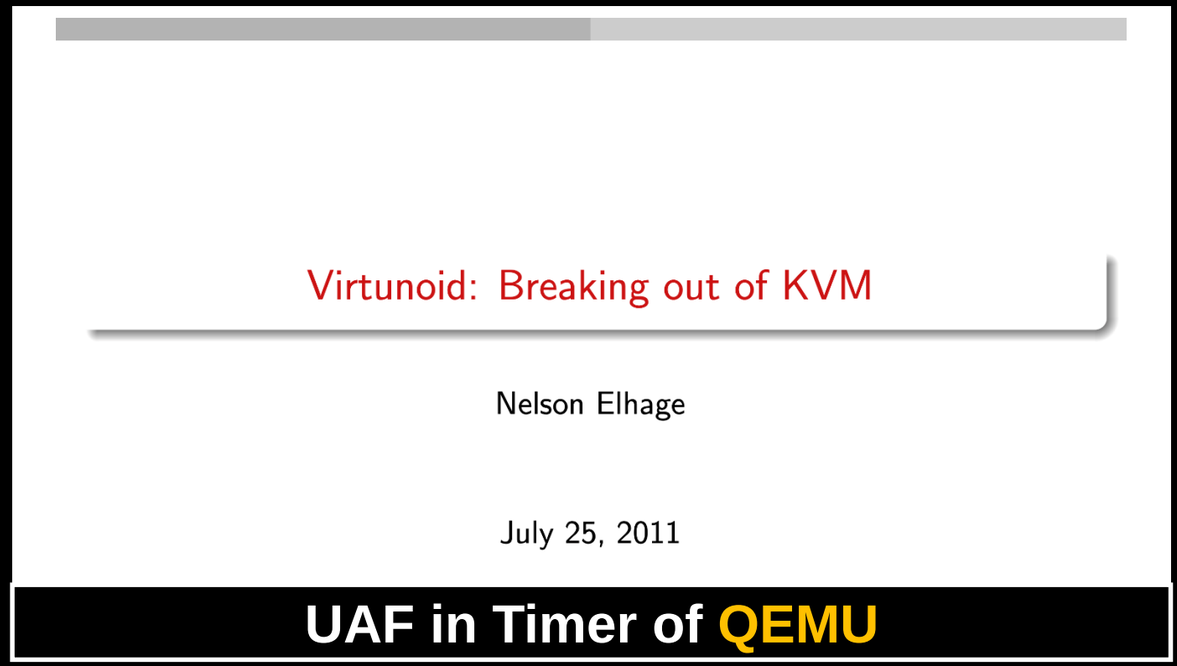


OOB in VIRTIO-GPU of QEMU

OOB in FDC of QEMU

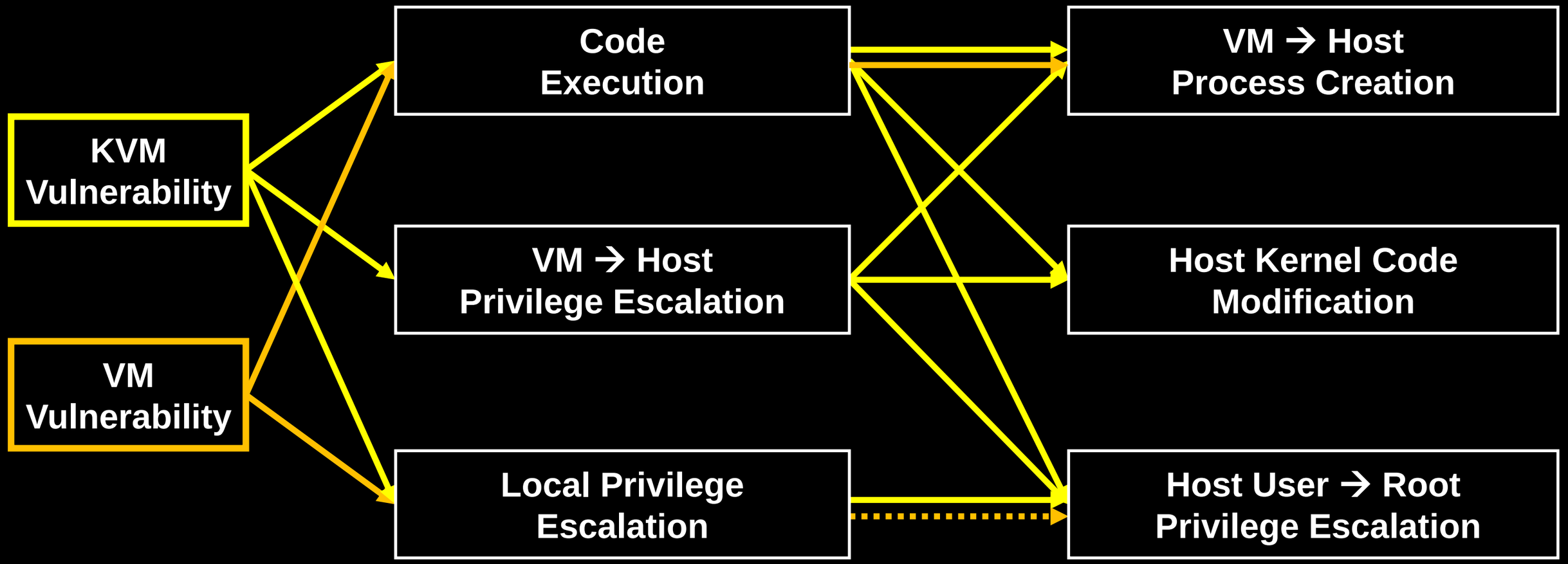


OOB in NET of QEMU

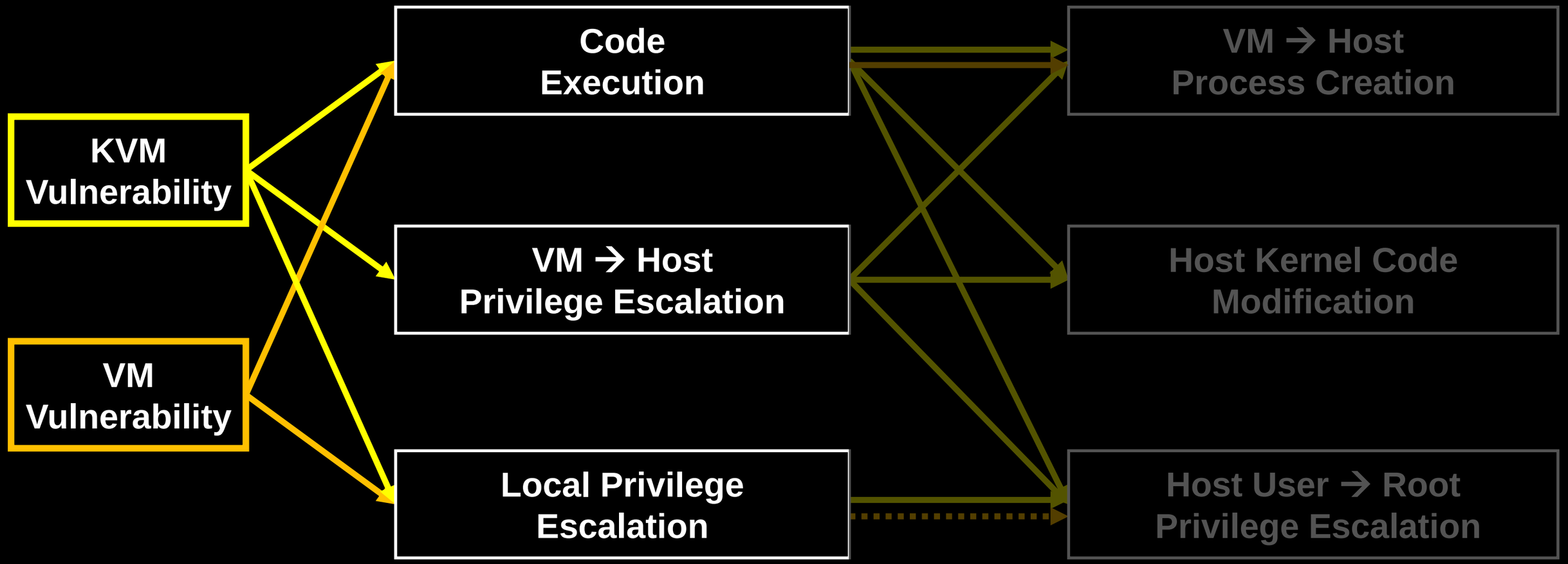


UAF in Timer of QEMU

So, critical paths of escapes are ...



So, critical paths of escapes are ...



No one knows

until the vulnerability is revealed

So, critical paths of escapes are ...

KVM Vulnerability

VM Vulnerability

VM → Host Process Creation

Host Kernel Code Modification

Host User → Root Privilege Escalation

We can detect

SYMPTOMS

- Background

- Analysis of Critical Paths of Escapes

- **Design and Implementation of Alcatraz** 

- Evaluation and Demo

- Conclusion and Black Hat Sound Bytes

What is Alcatraz?

- **Alcatraz is a practical hypervisor sandbox to prevent escapes**
  - It does not need SMM and retrofits of the hypervisor
  - It downgrades KVM’s privilege and makes a sandbox with Intel VT
- **Alcatraz consists of Hyper-box and tailored Linux kernel**
  - Hyper-box is a pico hypervisor made from scratch
    - It has core mechanisms for preventing escapes
  - Tailored Linux kernel has only one system call interface for x86_64
    - It narrows the attack surface and monitoring points

Hyper-Box (1)

- **Makes a sandbox with the memory and register protection techniques**
  - It leverages the Extended Page Table (EPT) of Intel VT
    - Guest Physical Address (PA) are translated to host PA with EPT
    - EPT can prevent code and RO data modifications!
  - It protects security-related bits of control registers (CRs)
    - Write Protect (WP) of CR0, Supervisor Mode Execution Protection (SMEP) of CR4
- **Monitors system calls and prevents unauthorized behaviors**
  - It sets H/W breakpoints to the system call entry point, fork, exit, and cred functions
    - wake_up_new_task(), cgroup_release(), entry_SYSCALL_64(), and commit_creds()
  - It detects and prevents unauthorized behaviors
    - code modification, process creation, and privilege escalation

Hyper-Box (2)

- **Emulates VMX instructions for nested virtualization**
  - It downgrades KVM's privilege (Ring -1) to a guest hypervisor (Ring 0)
  - So, It has to emulate VMX instructions of KVM because Ring 0 cannot execute them
    - However, performance overhead is high
- **Uses VT features to reduce the performance overhead**
  - Virtual Machine Control Structure (VMCS) shadowing
    - It allows a guest hypervisor to execute VMREAD and VMWRITE directly
    - So, emulations or interventions are reduced!
  - Virtual Process ID (VPID)
    - It gives unique ID to vCPU and Translation Lookaside Buffer (TLB)
    - It prevents TLB flushes when VMExit occurs!

Hyper-Box (2)

- **Emulates VMX instruc ualization**
  - It downgrades KVM's priv t hypervisor (Ring 0)
  - So, It has to emulate VMX cause Ring 0 cannot execute them
    - However, performance
- **Uses VT features to re ce overhead**
  - Virtual Machine Control S wing
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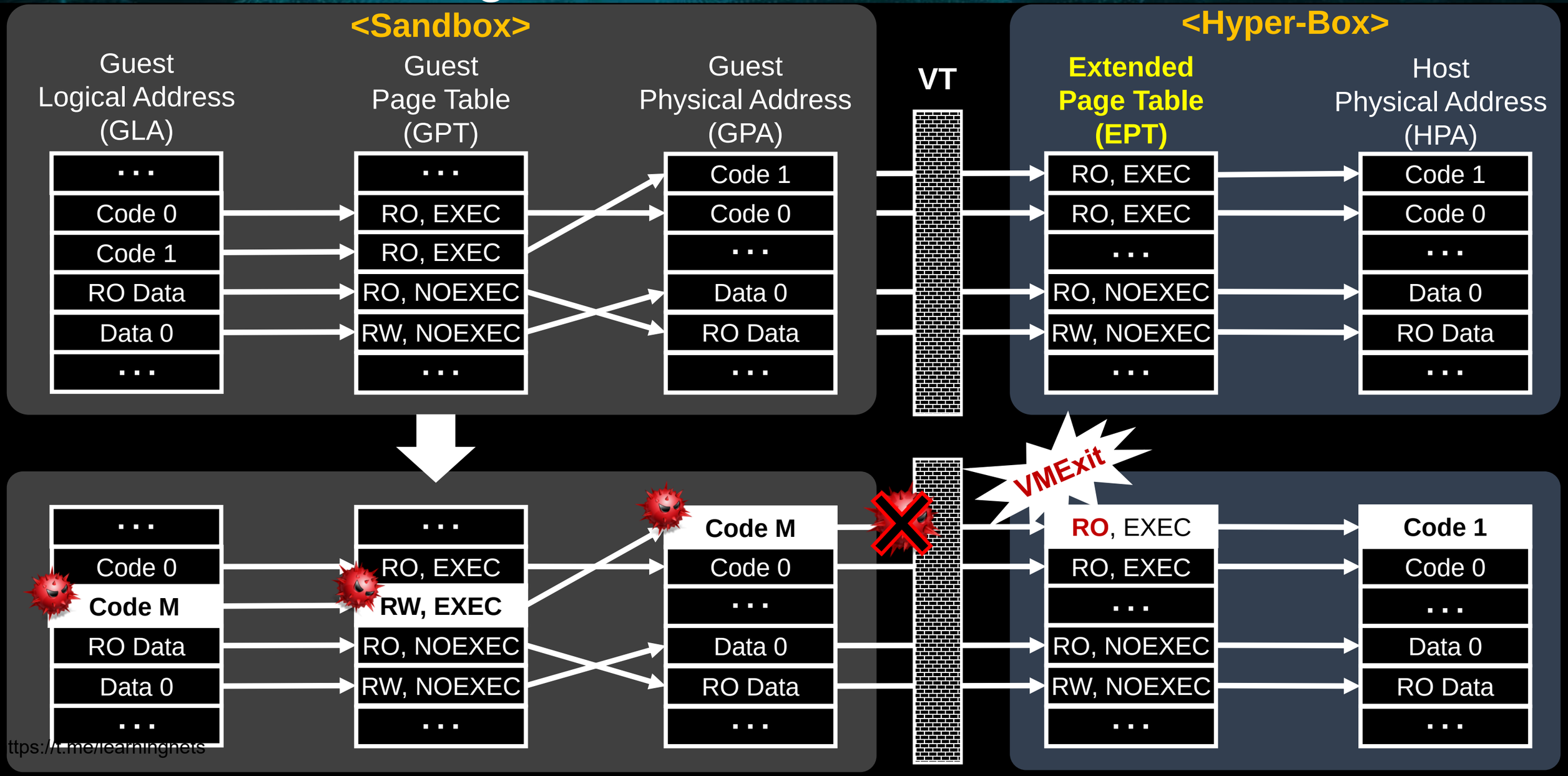
    - It gives unique ID to vCPU and Translation Lookaside Buffer (TLB)
    - It prevents TLB flushes when VMExit occurs!

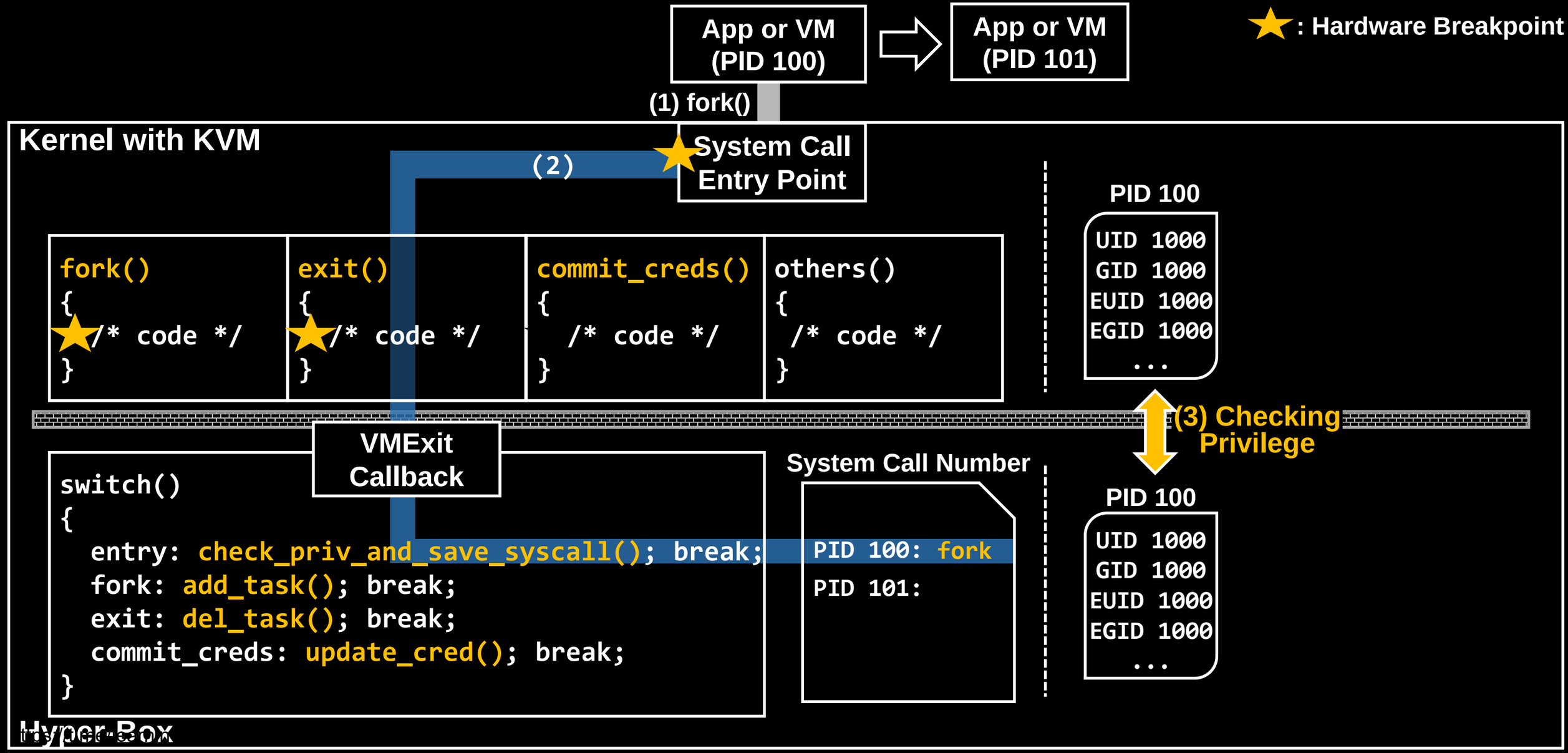
Hyper-Box Design

Preventing Unauthorized Code Modification



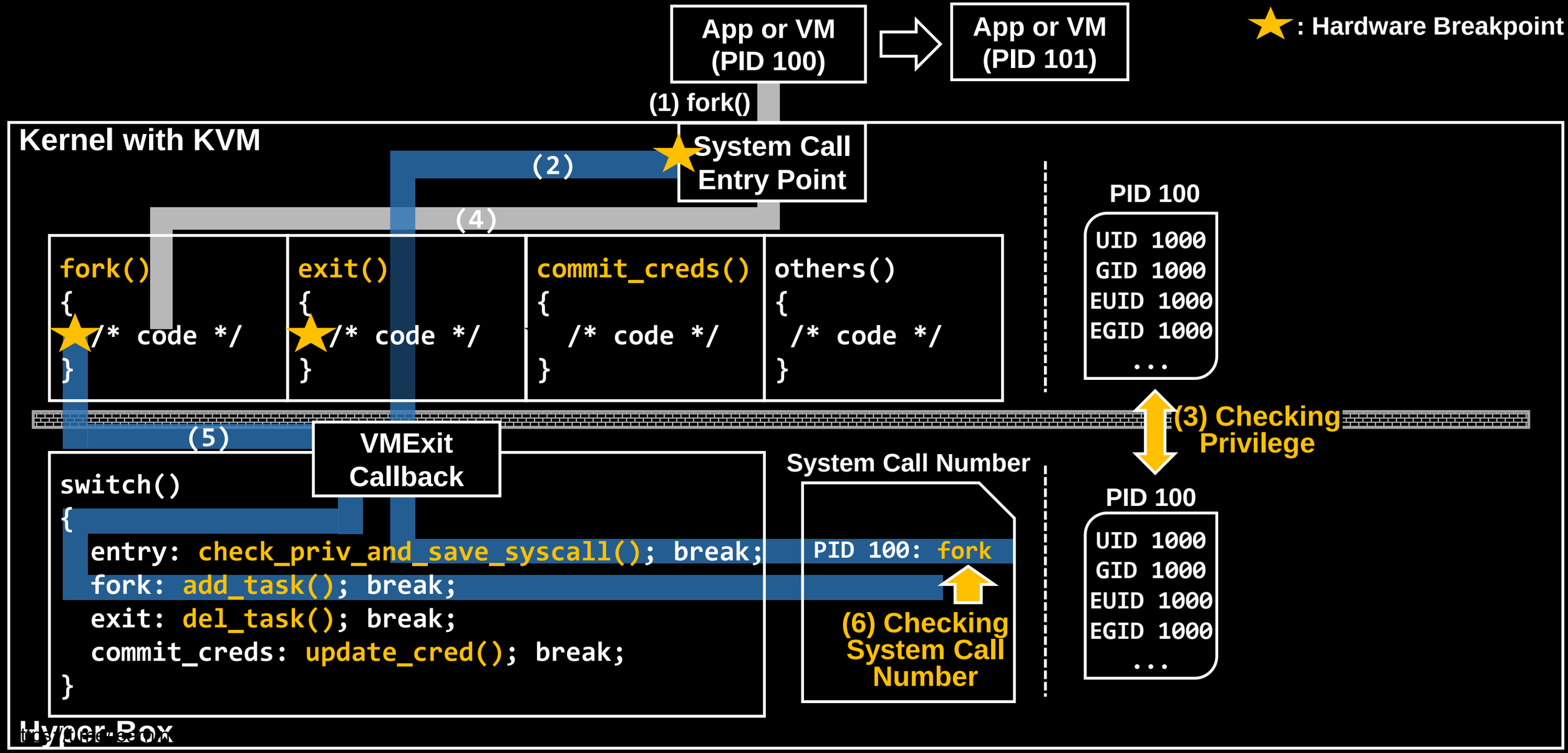
Hyper-Box Design

Preventing Unauthorized Process Creation (1)



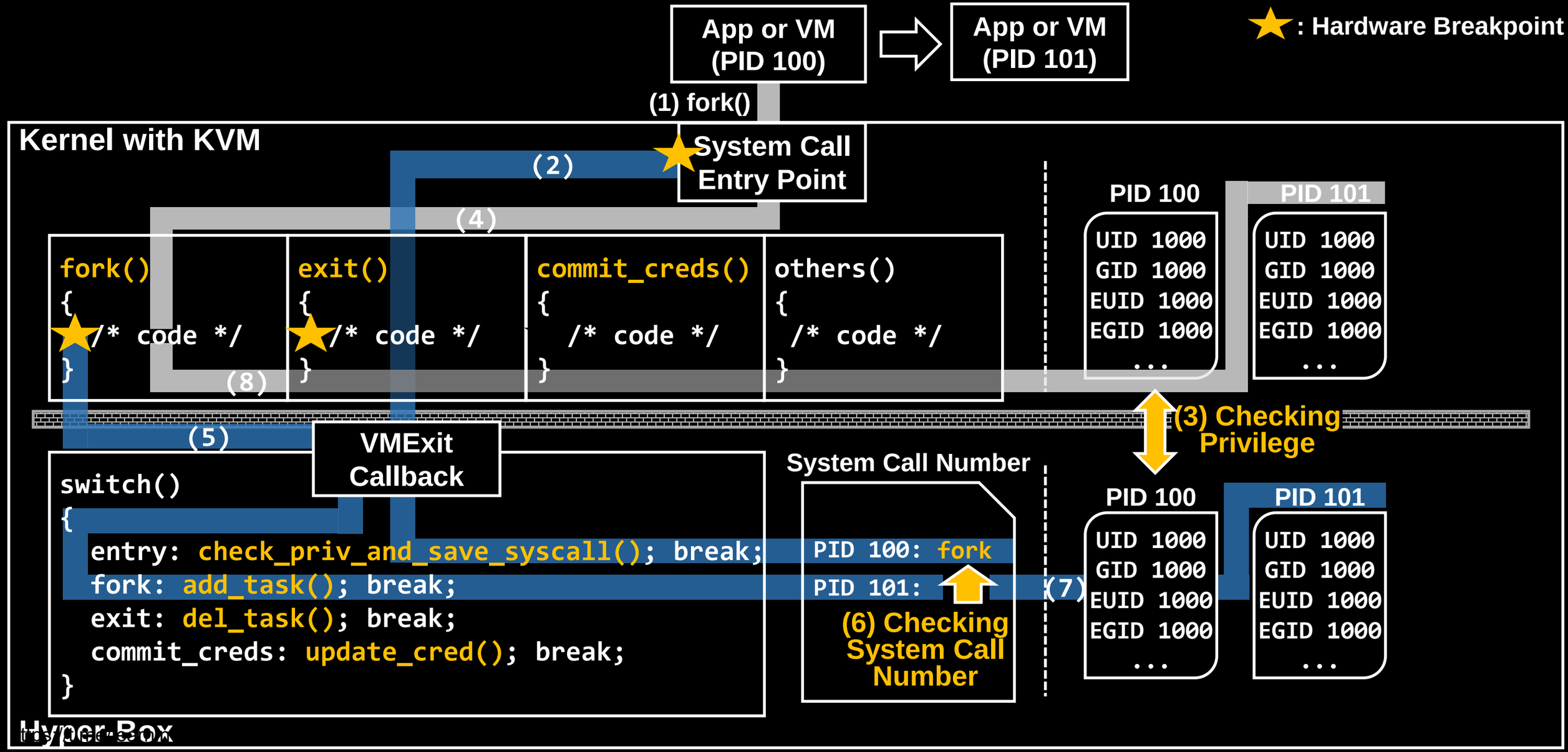
Hyper-Box Design

Preventing Unauthorized Process Creation (1)



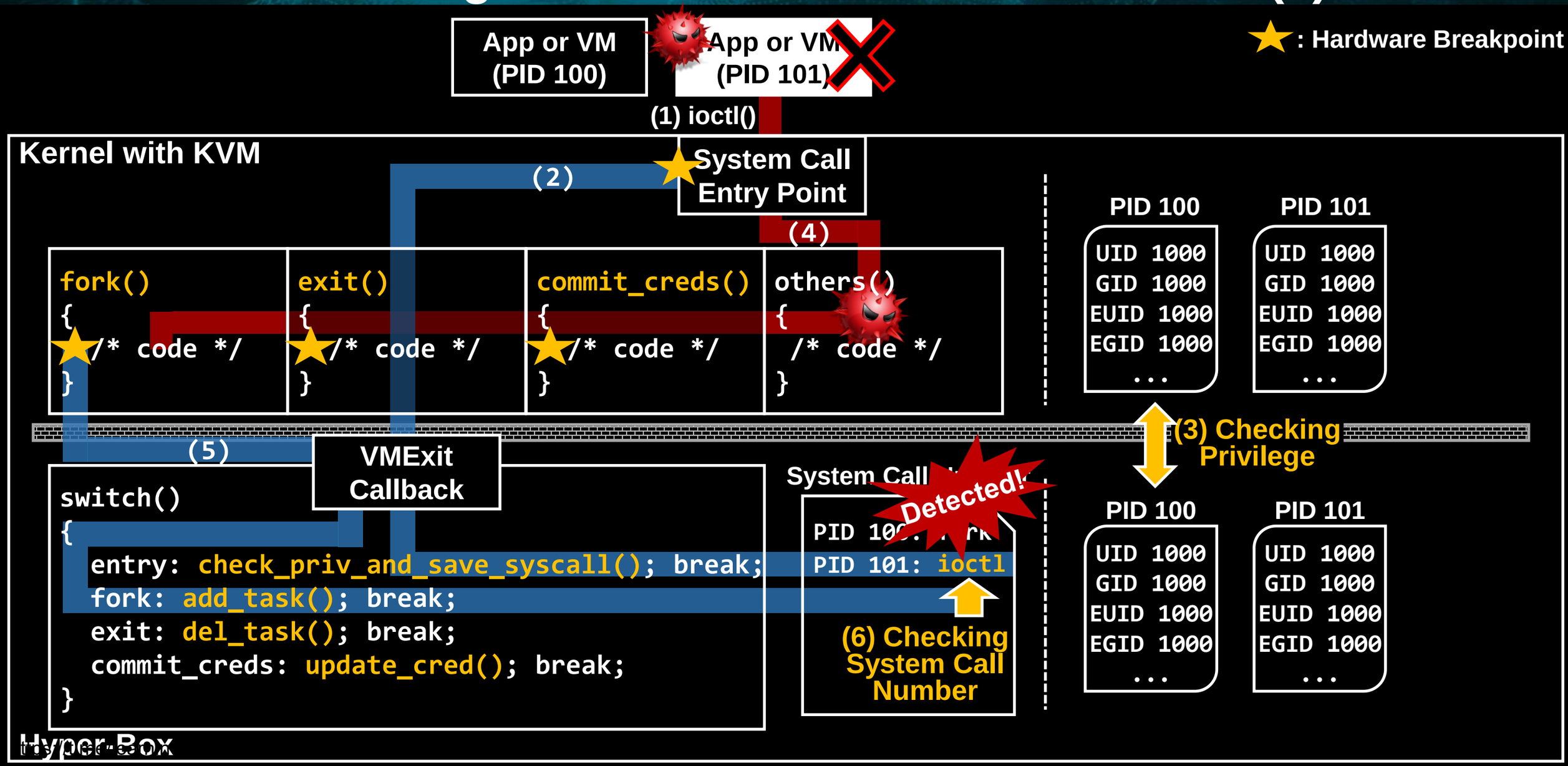
Hyper-Box Design

Preventing Unauthorized Process Creation (1)



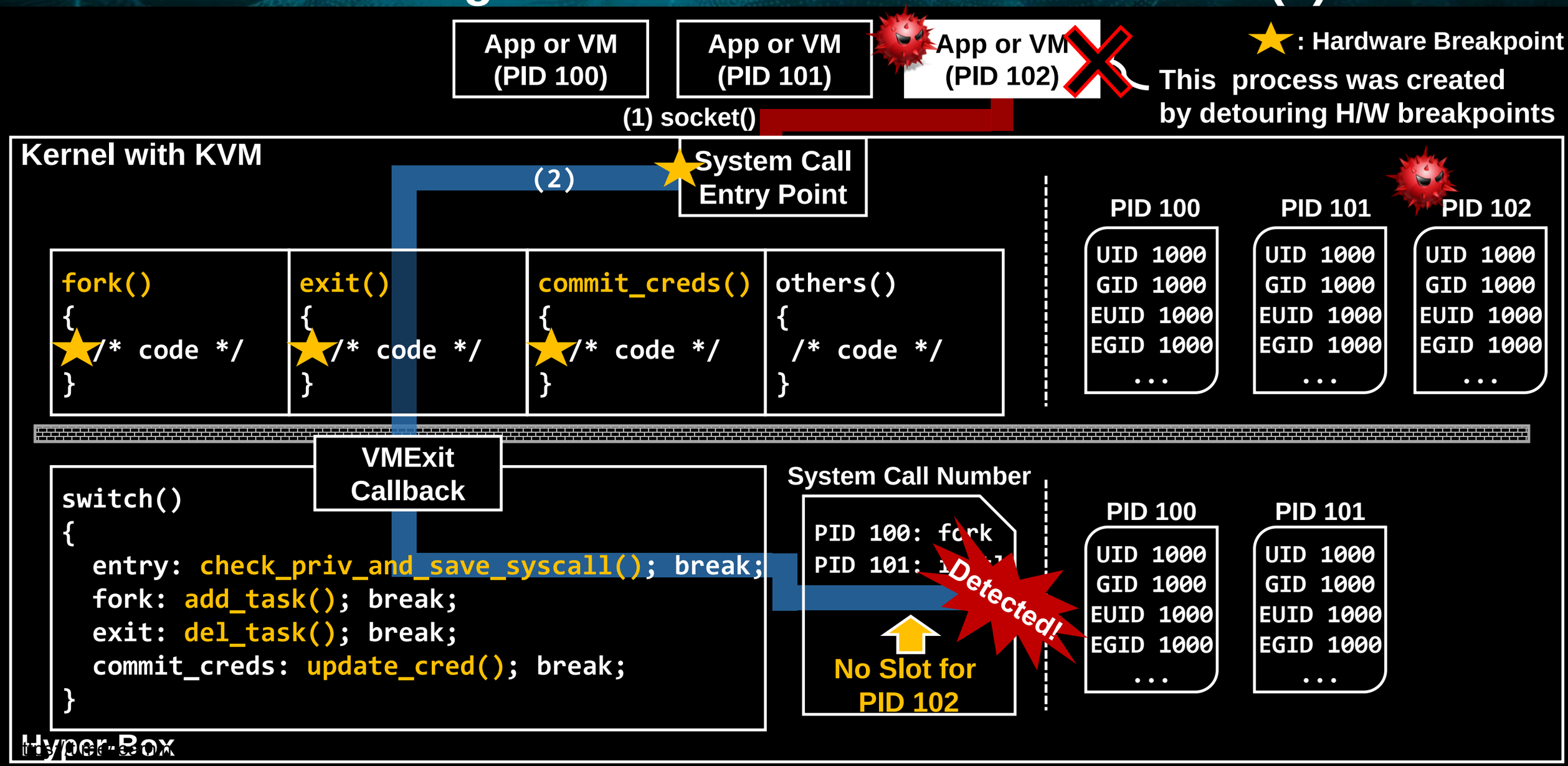
Hyper-Box Design

Preventing Unauthorized Process Creation (2)



Hyper-Box Design

Preventing Unauthorized Process Creation (3)



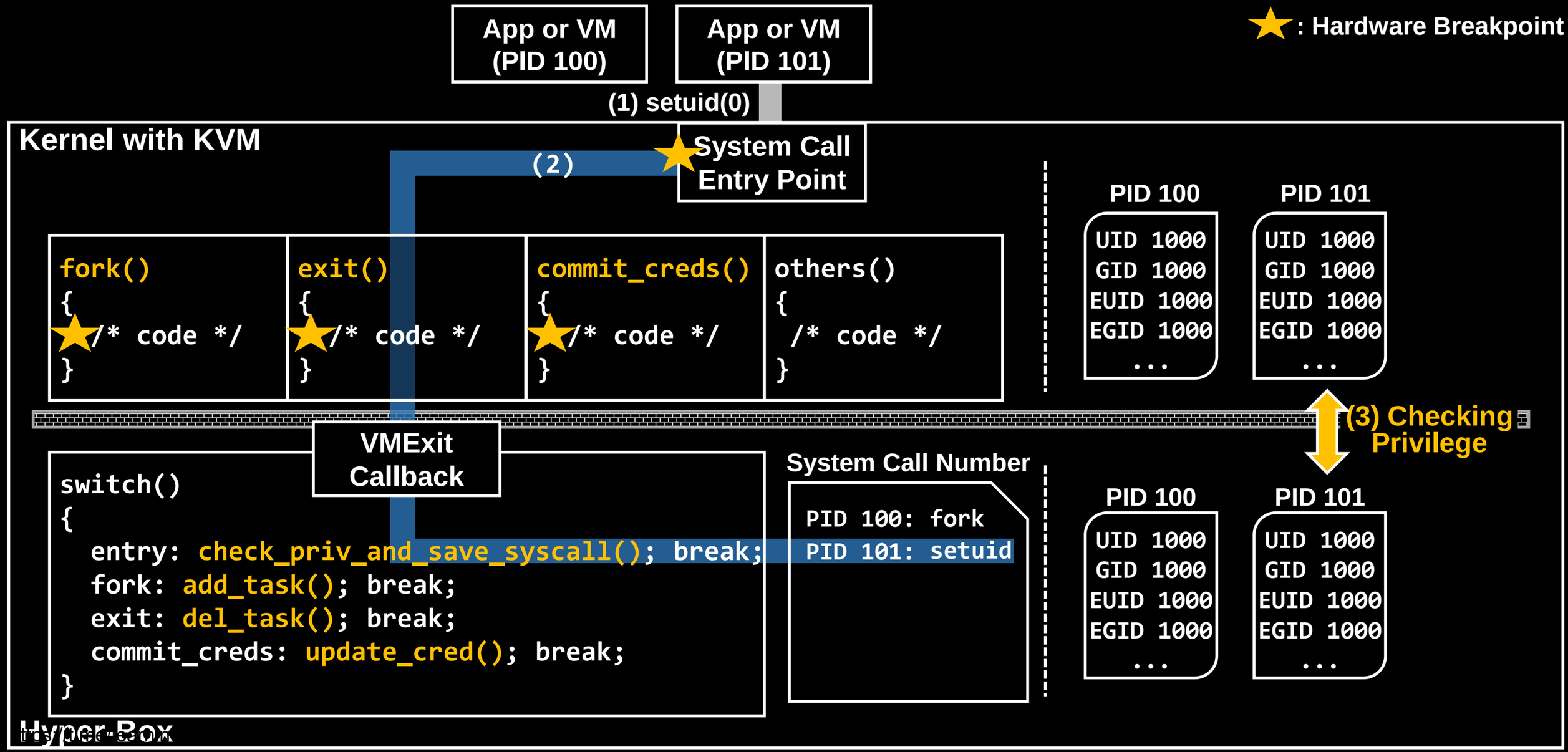
Hyper-Box Design

Preventing Unauthorized Process Creation (4)

- **Some processes are not allowed to create a child process**
  - QEMU process cannot create it for security reasons
  - Hyper-box has a disallowed list that contains process names
    - It checks the list for every system call and blocks the request
- **Some kernel drivers load other modules with a kernel thread**
  - They call call_usermodehelper(), and the function creates a kernel thread
  - The kernel thread executes modprobe (/usr/bin/kmod) with kernel API
    - It means the system call number is unknown, but modprobe is created!
  - Hyper-box has a workaround feature that allows the kernel thread to execute a process
    - But, the feature is only for logging and not recommended
    - **Load all necessary modules before Alcatraz or include modules to the kernel!**

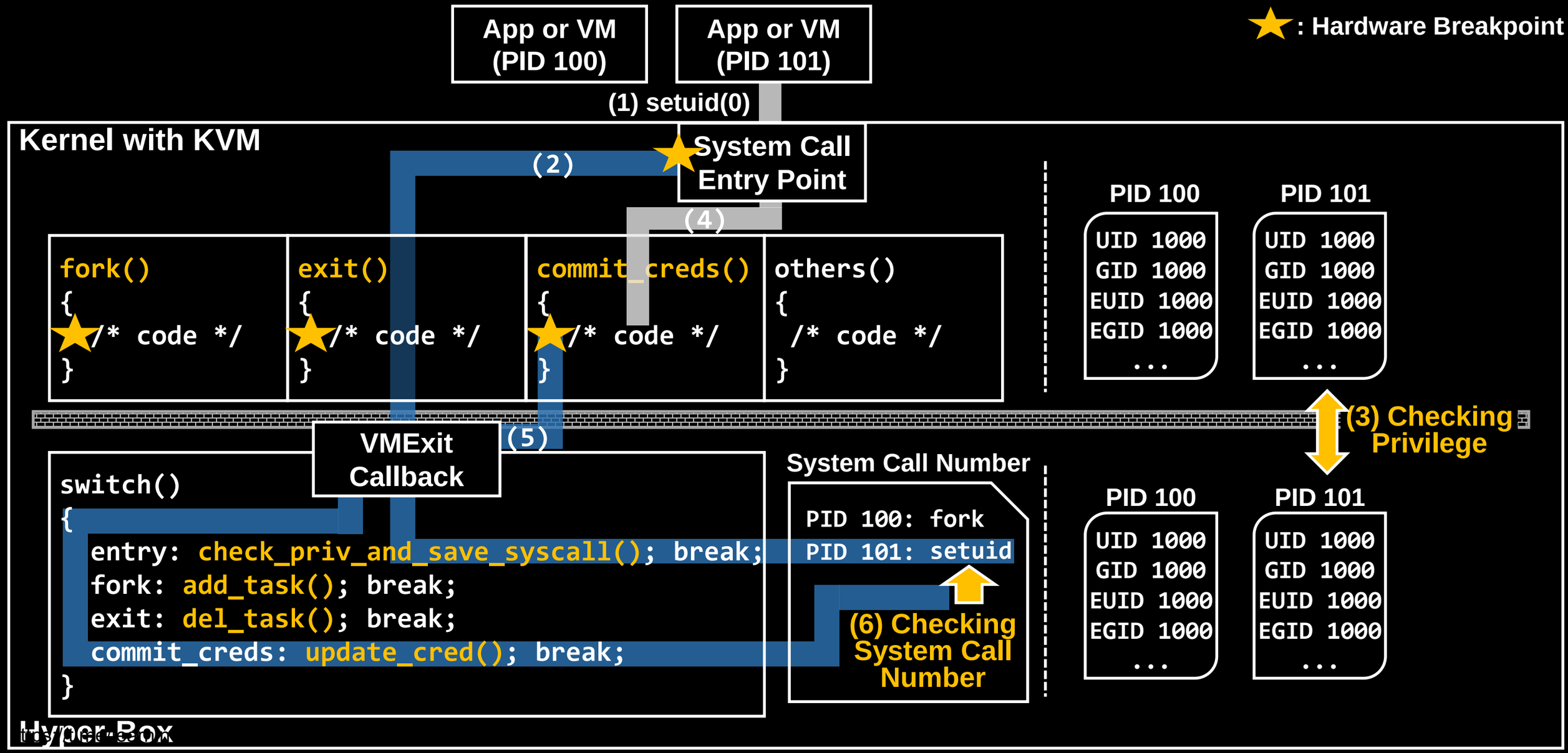
Hyper-Box Design

Preventing Unauthorized Privilege Escalation (1)



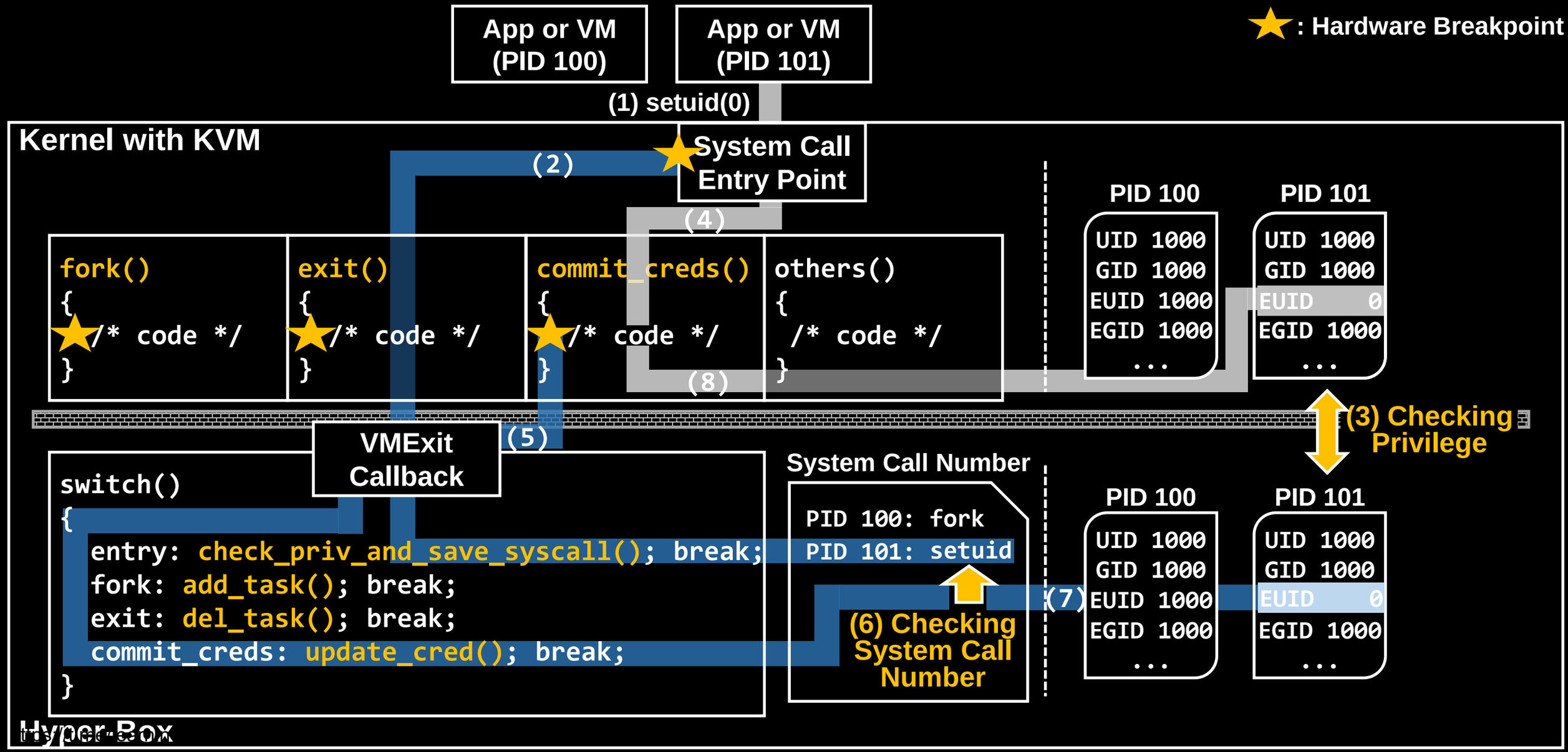
Hyper-Box Design

Preventing Unauthorized Privilege Escalation (1)



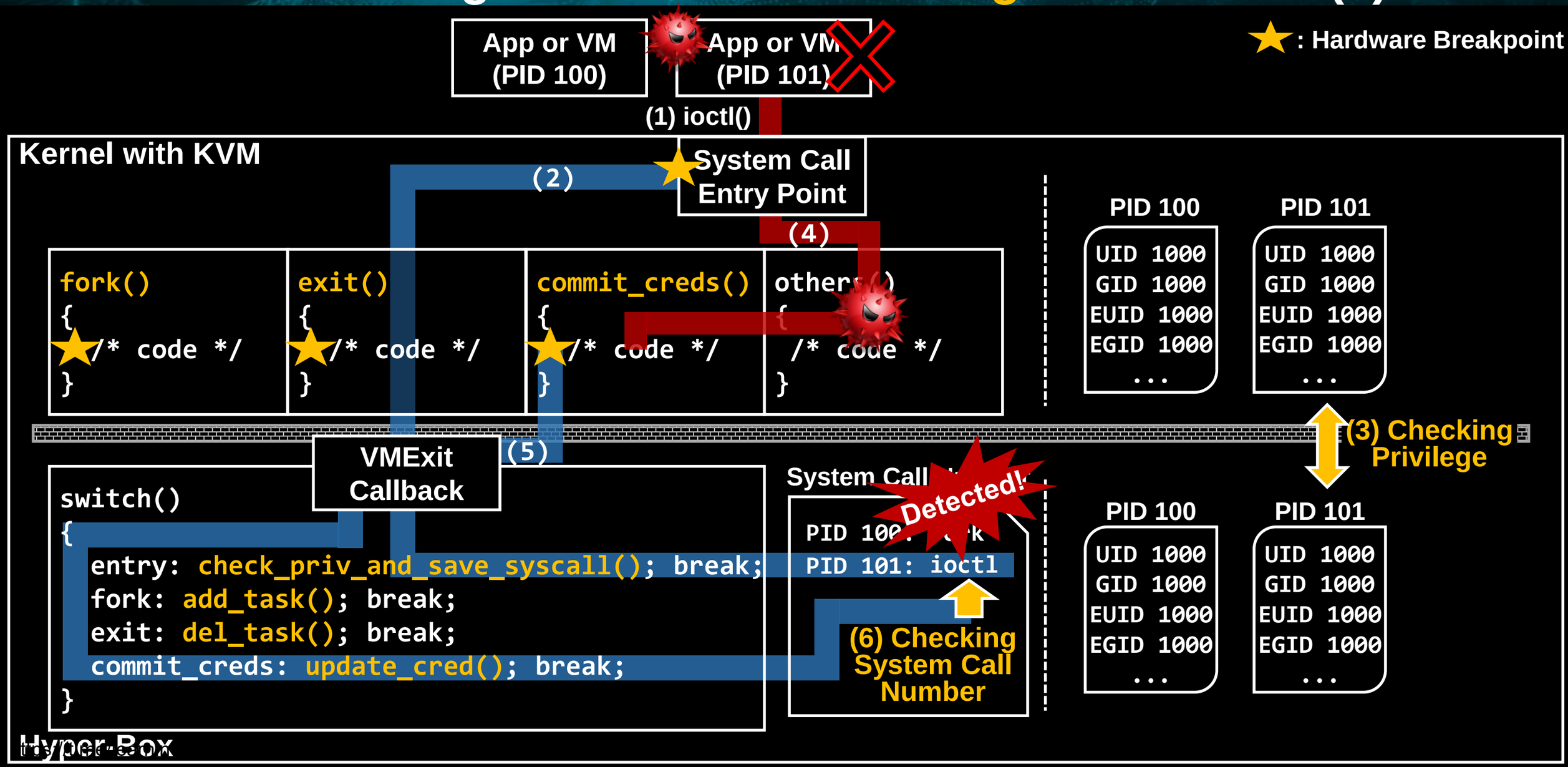
Hyper-Box Design

Preventing Unauthorized Privilege Escalation (1)



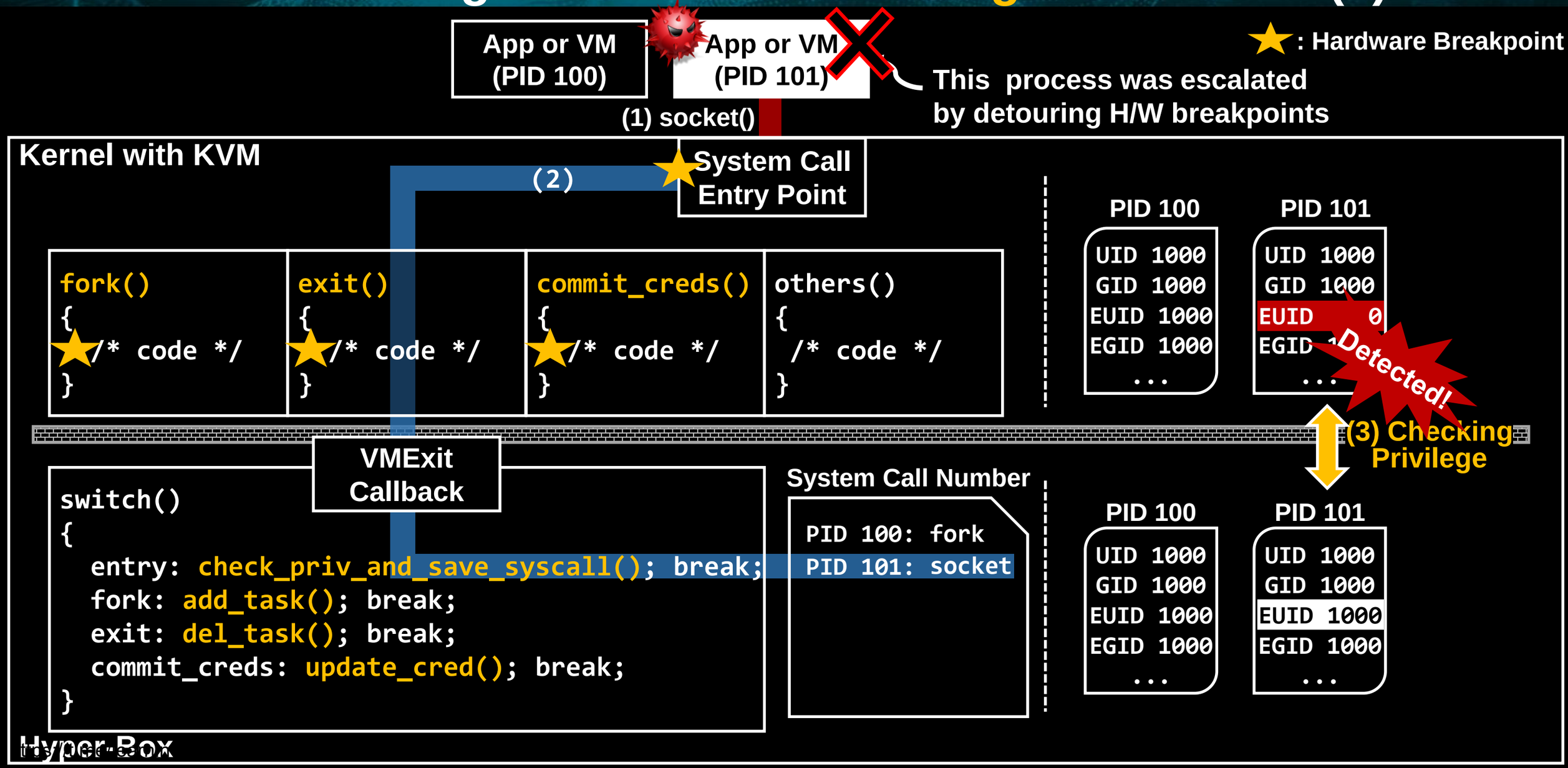
Hyper-Box Design

Preventing Unauthorized Privilege Escalation (2)



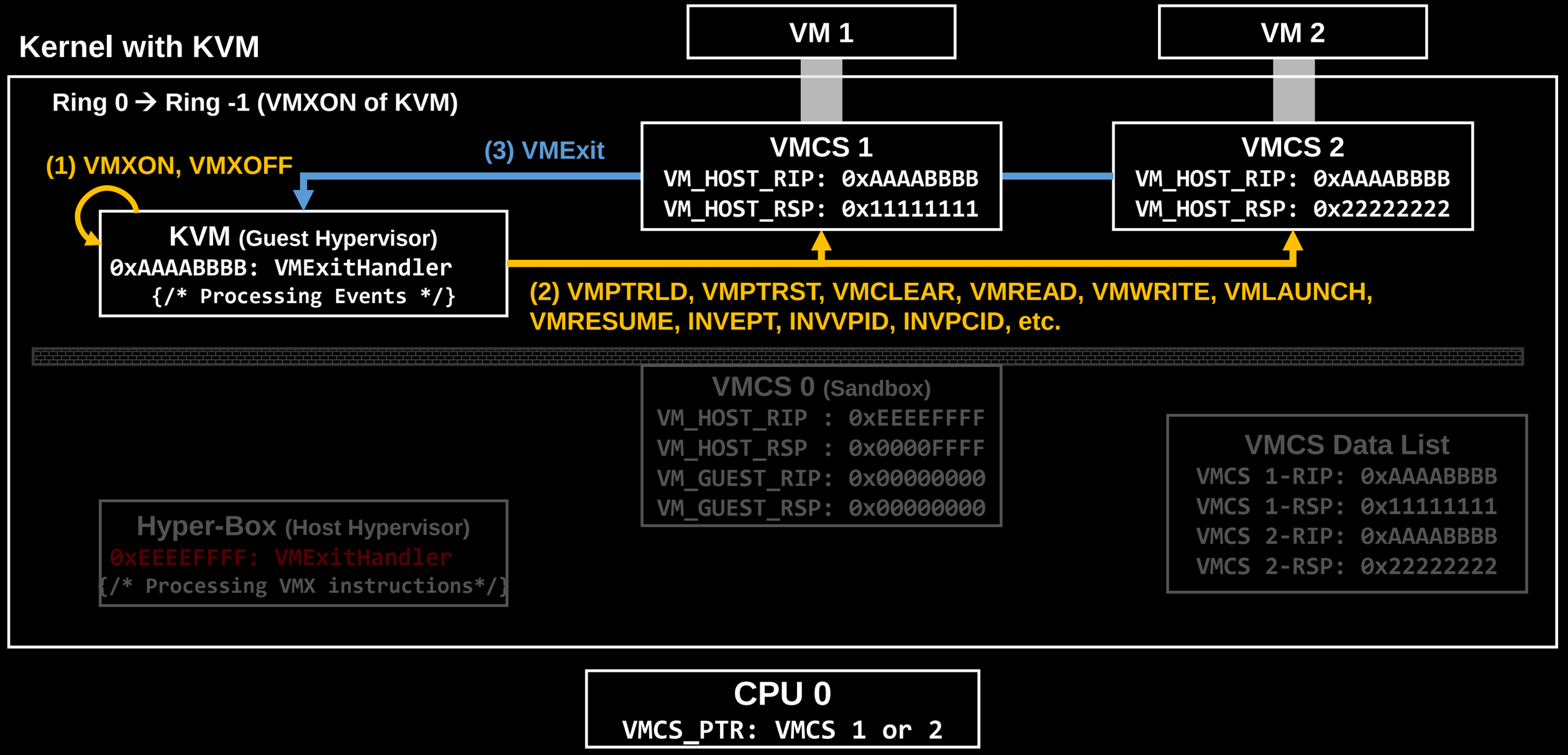
Hyper-Box Design

Preventing Unauthorized Privilege Escalation (3)



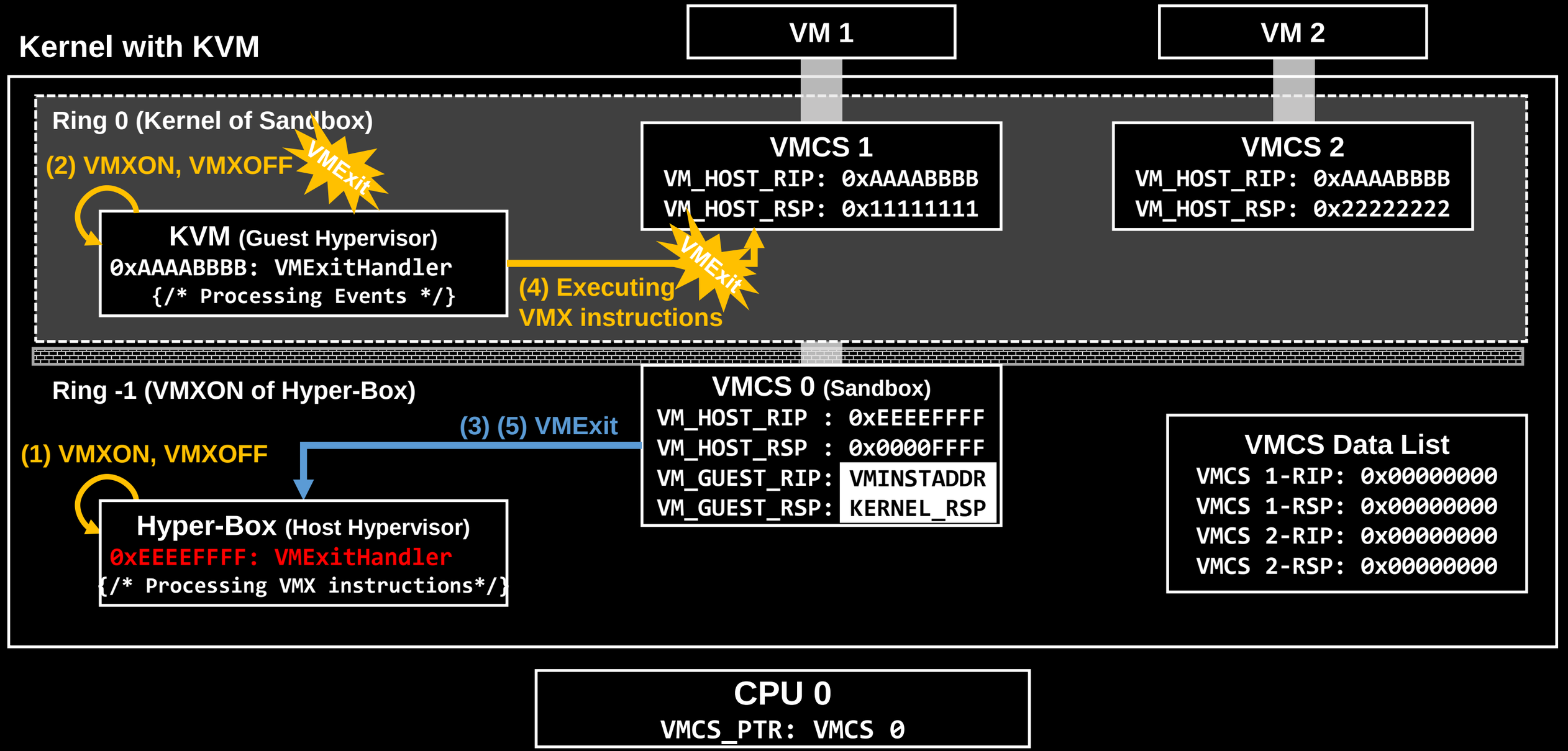
Hyper-Box Design

Emulating VMX instructions – Only KVM



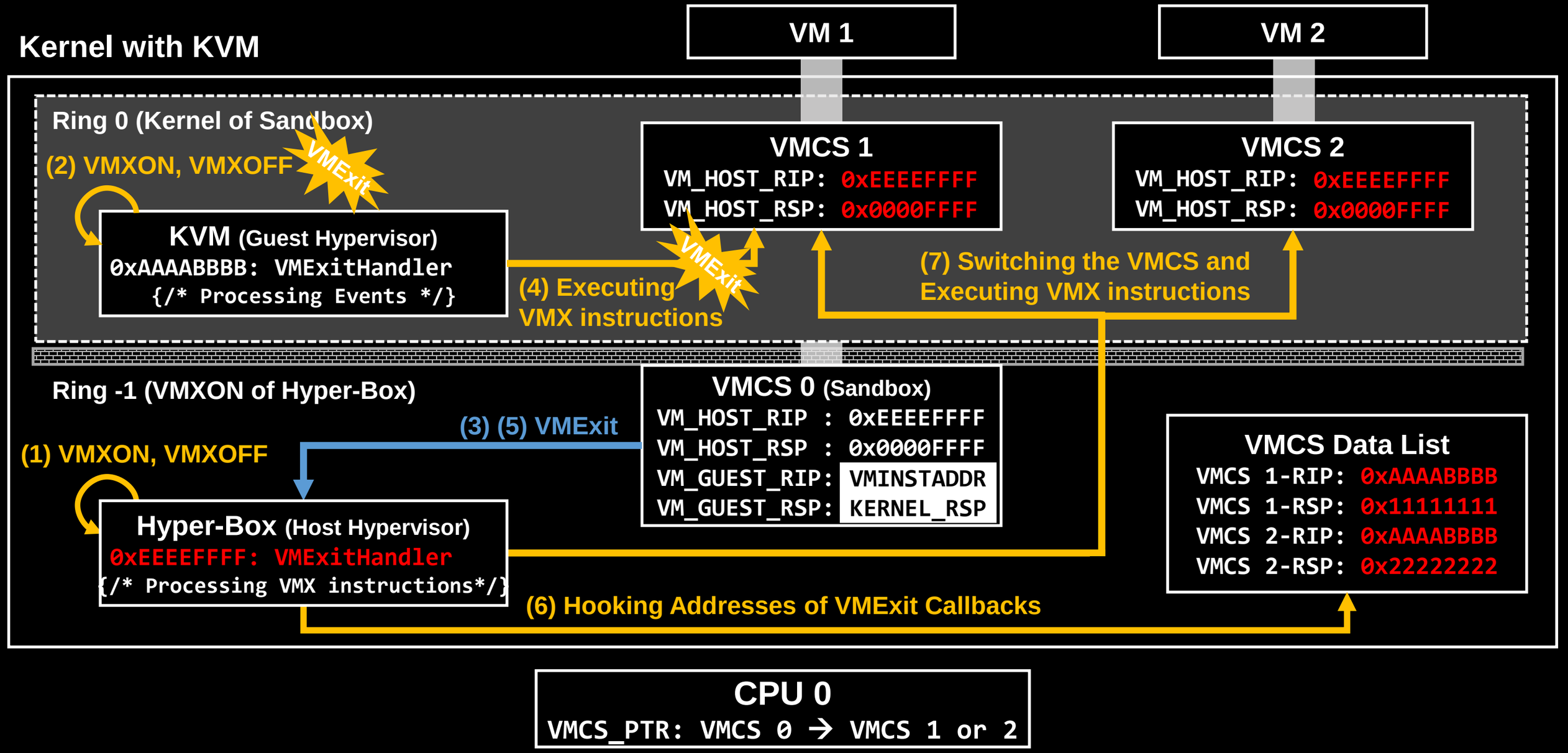
Hyper-Box Design

Emulating VMX instructions – Executing Instructions (1)



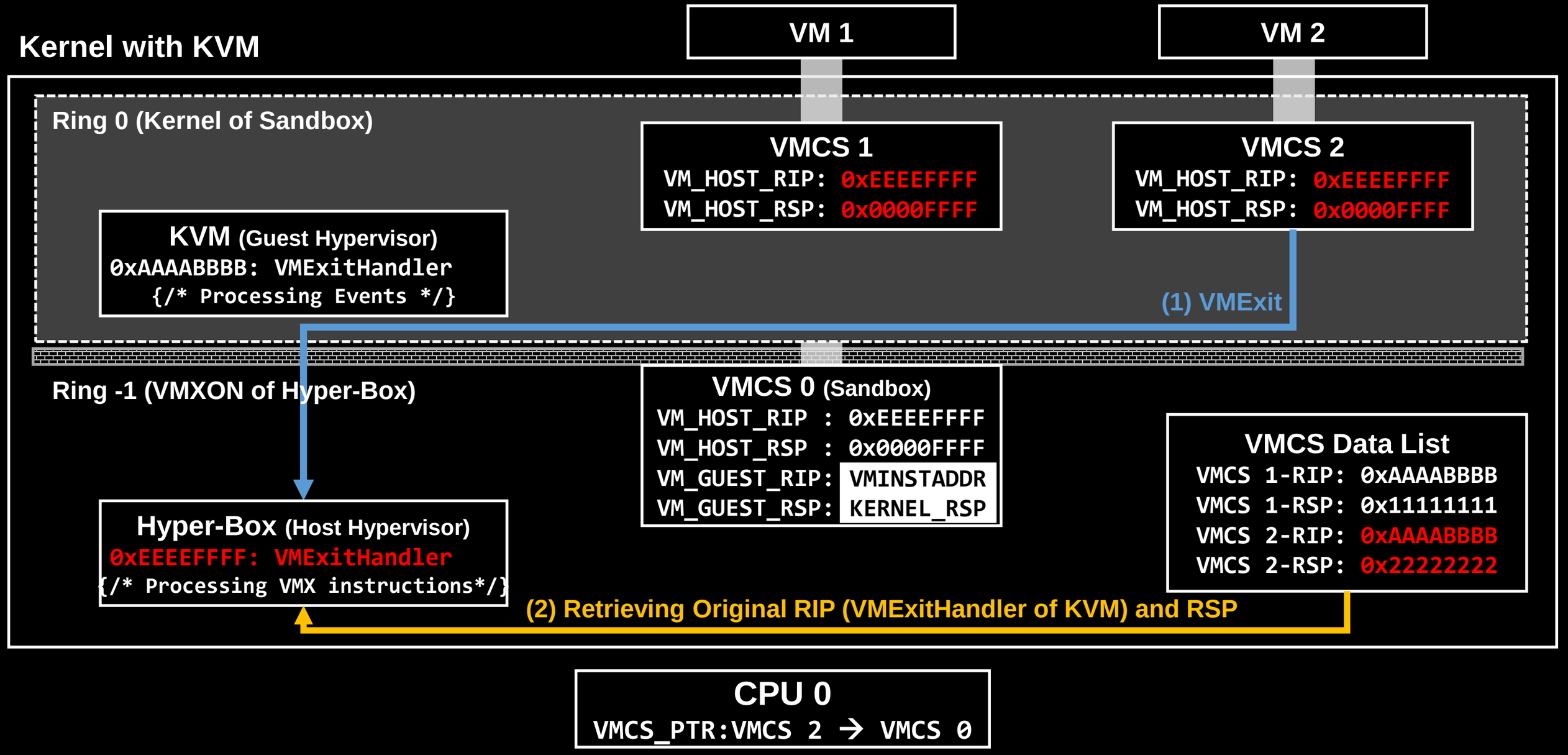
Hyper-Box Design

Emulating VMX instructions – Executing Instructions (2)



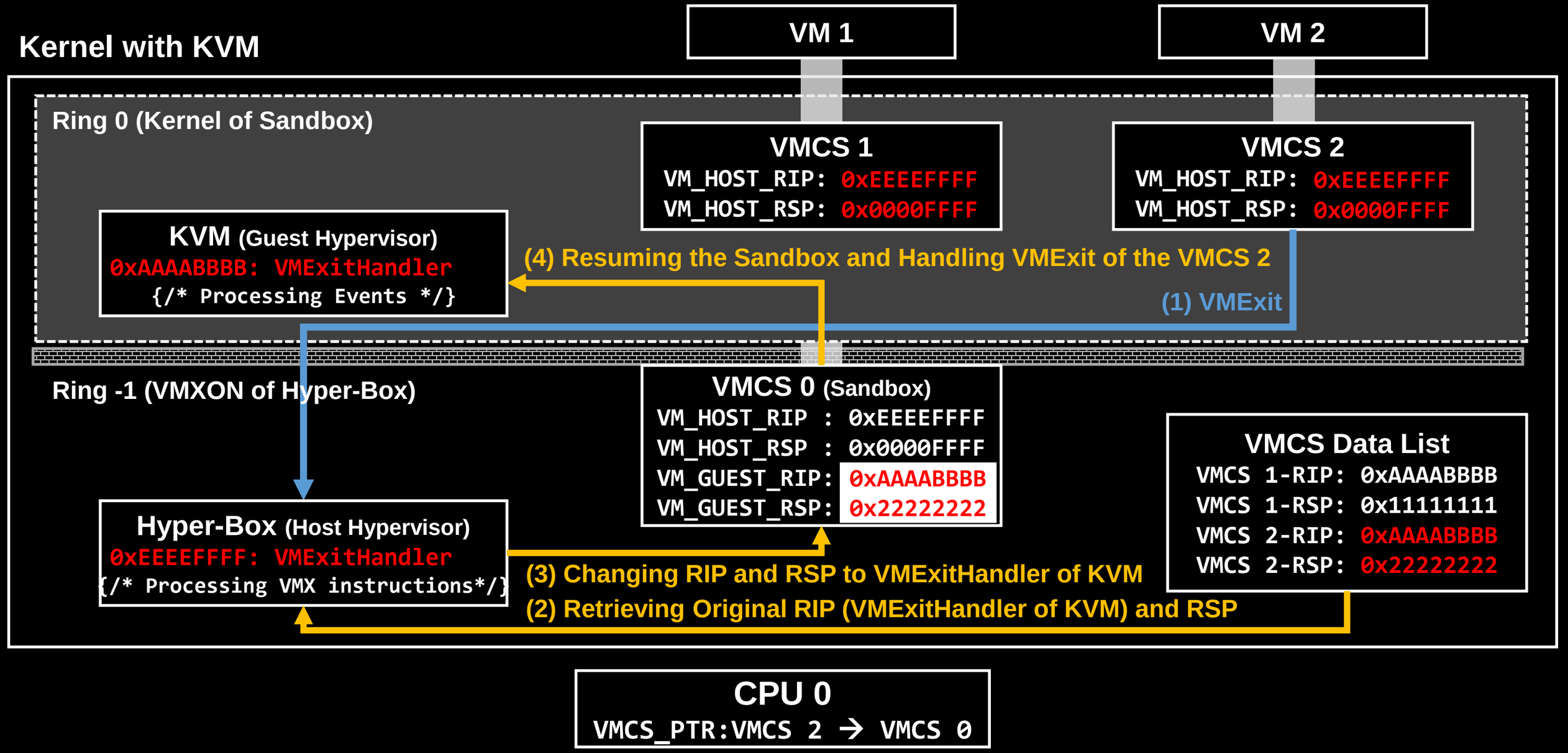
Hyper-Box Design

Emulating VMX instructions – Handling VMExits (1)



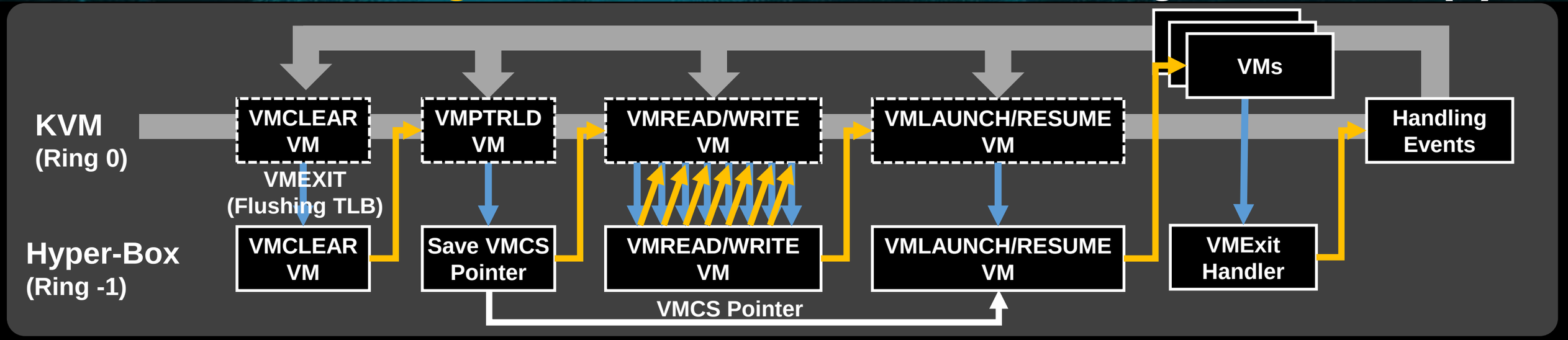
Hyper-Box Design

Emulating VMX instructions – Handling VMExits (2)



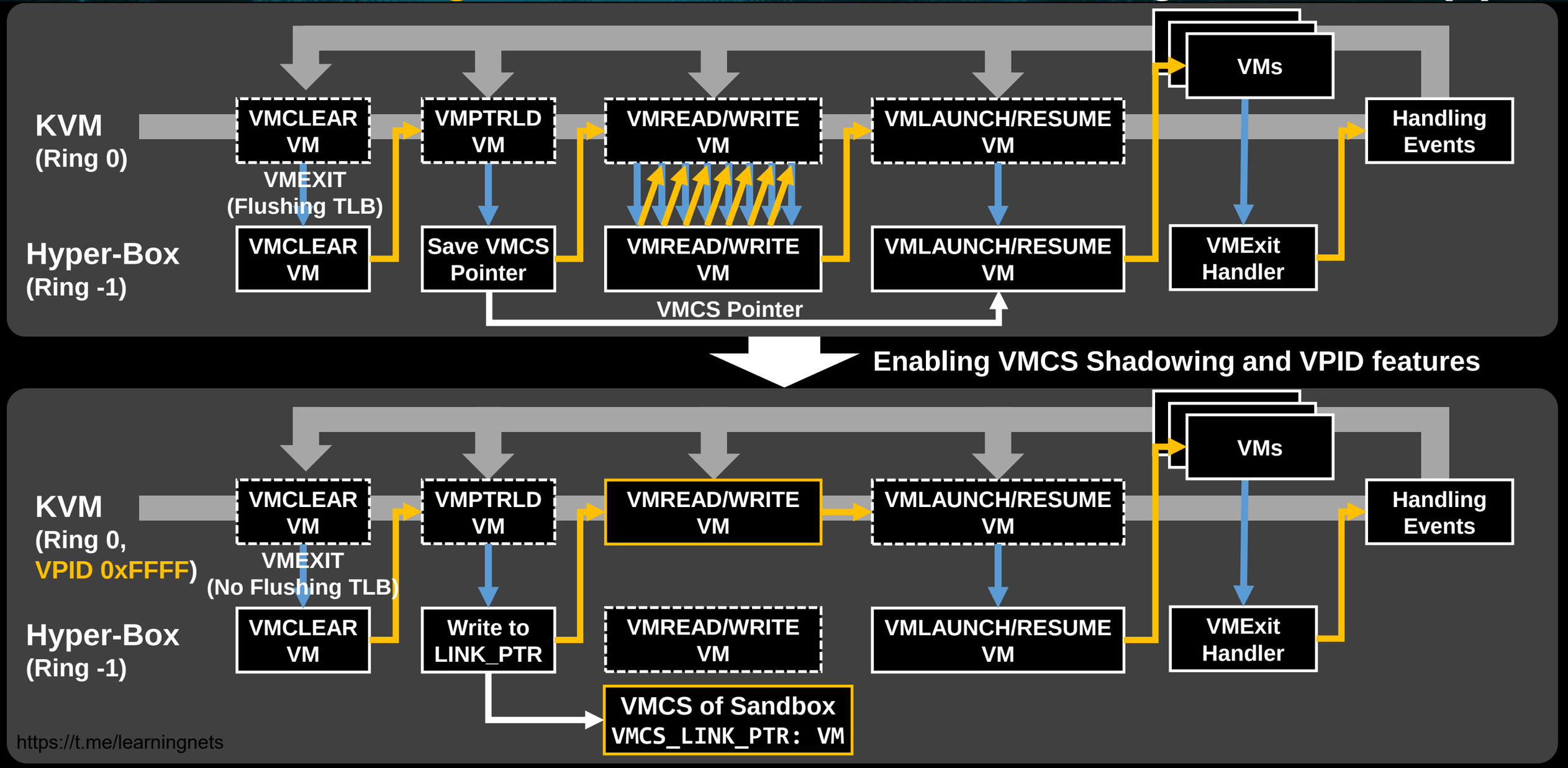
Hyper-Box Design

Emulating VMX instructions – Reducing Overhead (1)



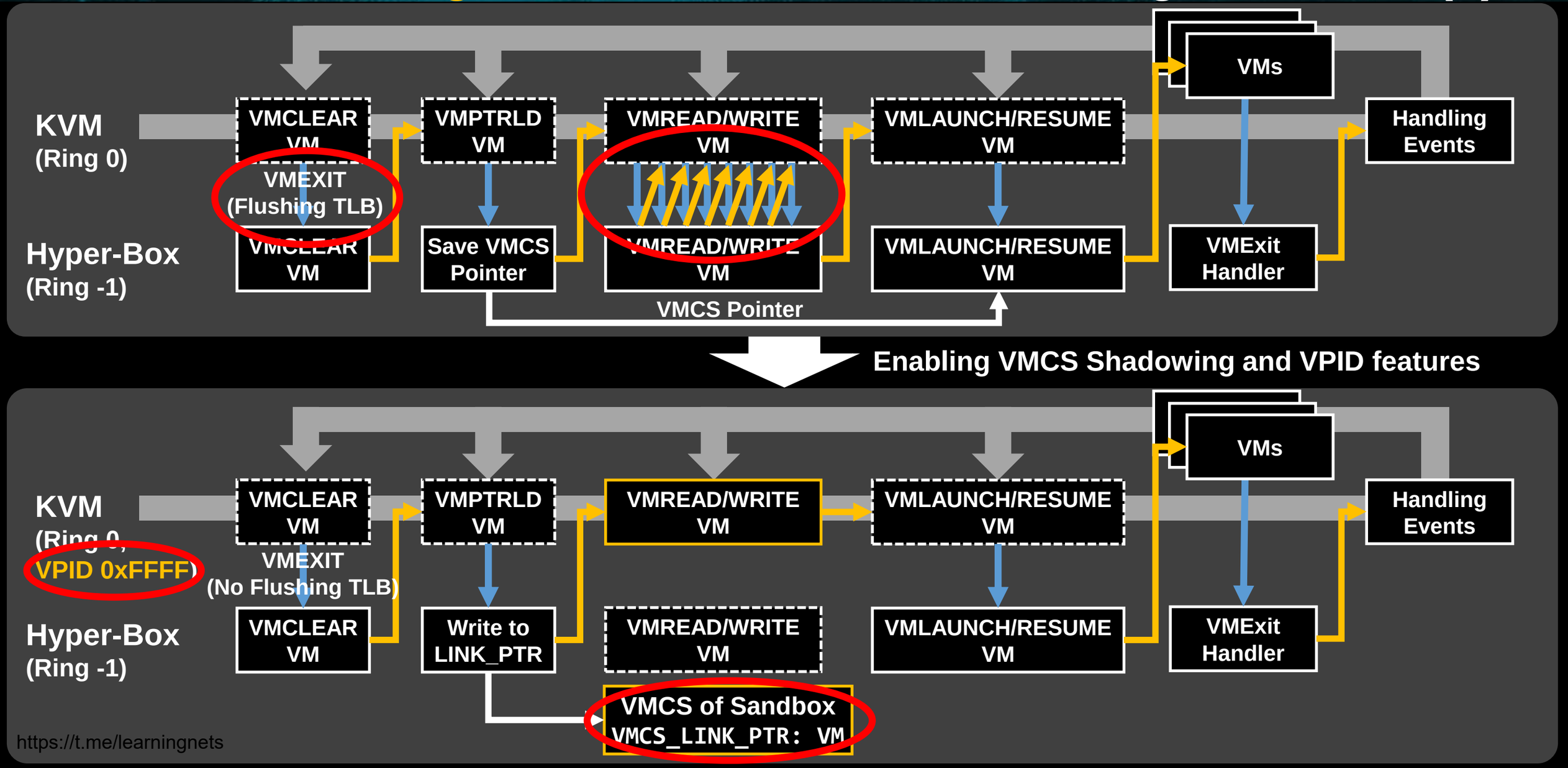
Hyper-Box Design

Emulating VMX instructions – Reducing Overhead (2)



Hyper-Box Design

Emulating VMX instructions – Reducing Overhead (3)



Implementation of Alcatraz

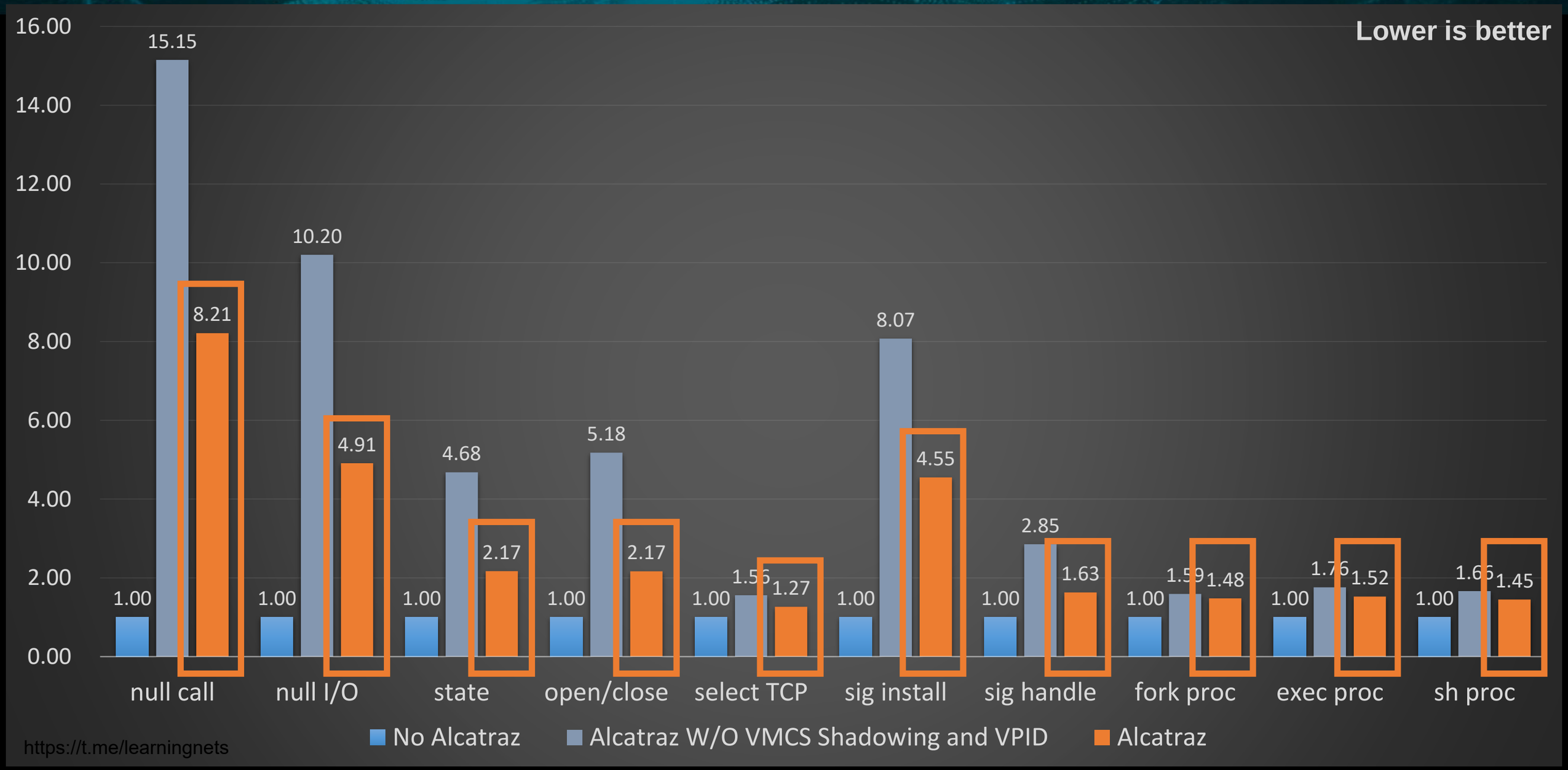
- **Hyper-box is a loadable kernel module**
  - So, It can be loaded any time BEFORE you start VMs
    - If not, it shows some errors related to the VMXON fail
  - It was made with C and assembly code
- **Tailored Linux kernel is just recompiled version**
  - Some options of a kernel config file were REMOVED
    - CONFIG_IA32_EMULATION, CONFIG_COMPAT, CONFIG_COMPAT_32, CONFIG_X86_X32 ➔ System call interfaces
    - CONFIG_JUMP_LABEL ➔ Runtime code modifications
  - No more system call interface for legacy!

- Background
- Analysis of Critical Paths of Escapes
- Design and Implementation of Alcatraz
- **Evaluation and Demo** 
- Conclusion and Black Hat Sound Bytes

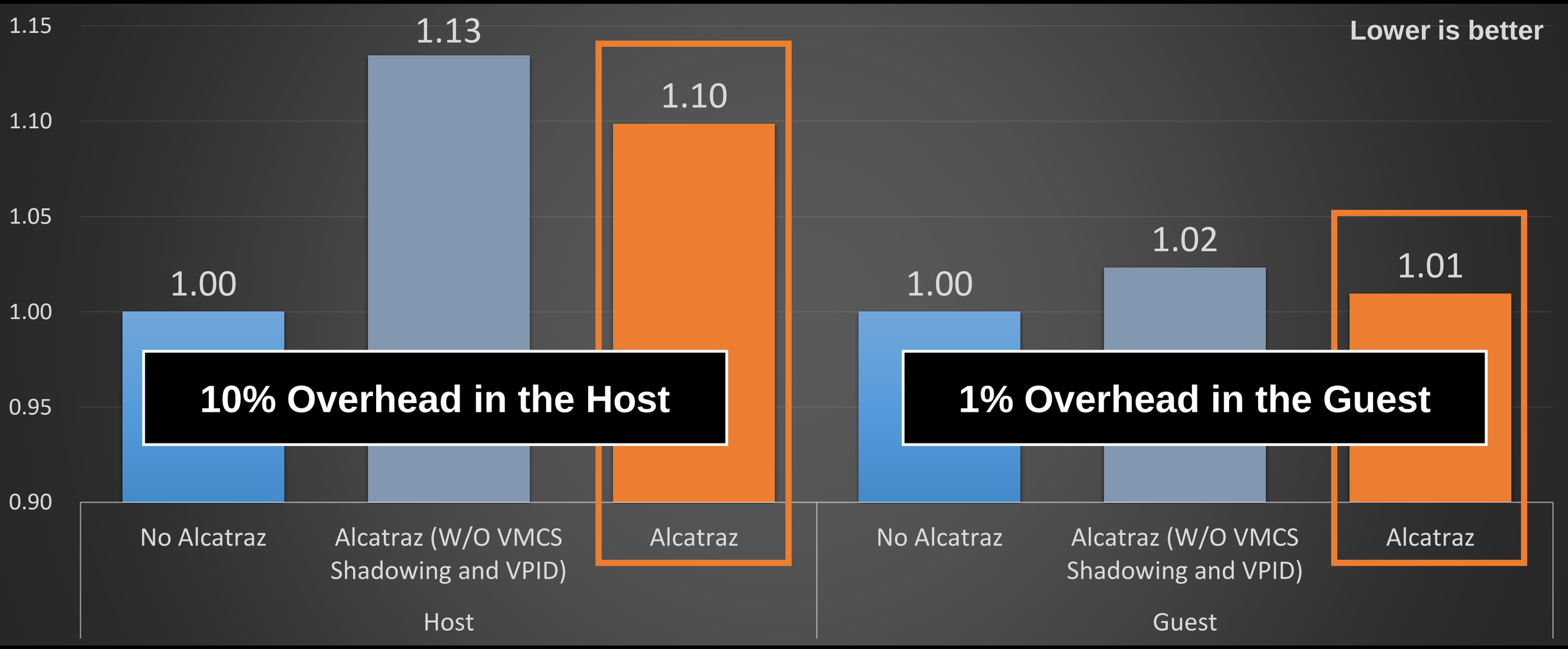
Benchmark Machine

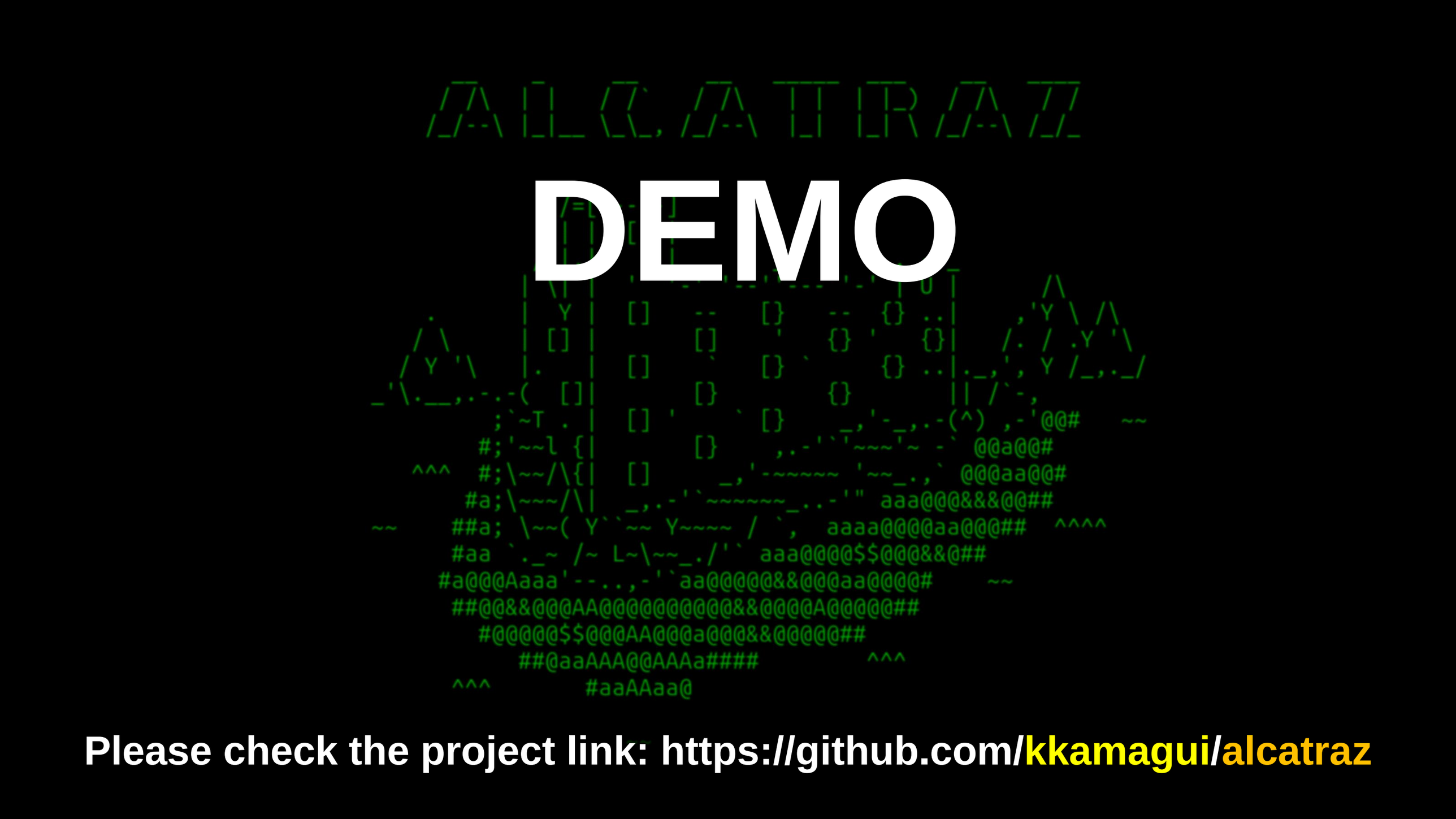
- **Host Machine (Server)**
  - CPU: Intel Xeon Gold 6242R 2 CPU (40 cores, 80 thread)
  - RAM: 512GB
  - HDD: NVME 1TB
  - OS: Ubuntu 20.04.01
  - Kernel: 5.8.0-44-generic Linux kernel
- **Guest Machine (QEMU)**
  - CPU: 4 cores
  - RAM: 16GB
  - HDD: 60GB
  - OS: Ubuntu 20.04.01
  - Kernel: 5.8.0-44-generic Linux kernel

Evaluation – lmbench



Evaluation – Kernel Compilation





DEMO

Please check the project link: https://github.com/kkamagui/alcatraz

Conclusion and Black Hat Sound Bytes

- **Containers, VMs, and microVMs suffer from escapes**
  - The hypervisor can provide strong isolation
  - But, it has excessive privilege and connects with VMs tightly
- **Taking a higher ground is not always the answer**
  - Researchers usually try to solve the problems with the higher privilege
  - The higher privilege we get, the more constraints we have!
- **Alcatraz is a practical hypervisor sandbox to prevent escapes**
  - It downgrades KVM's privilege and makes a sandbox with Intel VT
  - It has approximately 10% overhead in the host and 1% overhead in the guest (kernel compilation benchmark)

Questions?

Project : https://github.com/kkamagui/alcatraz

Contact: hanseunghun@nsr.re.kr, @kkamagui1

Reference

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