Kernel Protection Using Hardware-Based Virtualization

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Agenda

• Hardware-Based Virtualization
• Monitoring/Protecting the Kernel in Virtualization
• Policy and Incident Handling
• Architecture and Implementation
• VM and Bare Metal
• Beyond Kernel Protection
Hardware Virtual Machines (VMs)

Without VMs: Single OS owns all hardware resources

With VMs: Multiple OSes share hardware resources

A new layer of software...
Virtual Machine Monitor (VMM)

Virtual Machines (VMs)

VM0
- Apps
- OS

VM1
- Apps
- OS

VM2
- Apps
- OS

VMn
- Apps
- OS

Virtualization Non-Root Mode (Guest)

Higher-level VMM Functions:
- Resource Discovery / Provisioning / Scheduling / User Interface

Processor Virtualization
- State Control
- Context Switching

Memory Virtualization
- PMEM Translation
- I/O DMA Remapping

I/O Device Virtualization
- Interrupt Remapping
- I/O Device Emulation

VMM (a.k.a., hypervisor)

Linux Host/KVM

Physical Platform Resources

CPU_n

Processes

Memory

I/O Devices

CPU0

Storage

Network
Overview of Kernel Protection

Memory:
• Monitoring
• Write-protection (RO)

Processor (VCPU):
• CPU control monitoring/locking
• Extensions for security

IOMMU:
• Monitoring
• Write-Protection

Higher-level VMM Functions:
Resource Discovery / Provisioning / Scheduling / User Interface

Processor Virtualization
State Control
Context Switching

Memory Virtualization
PMEM Translation
I/O DMA Remapping

I/O Device Virtualization
Interrupt Remapping
I/O Device Emulation

Linux Host/KVM
Benefits of Virtualization-Based Kernel Protection

More monitoring and isolation capabilities in virtualization than in native:
- Monitoring, isolation, and protection – Hypervisor as “Ring -1” or Virtualization Root Mode
- Security feature extensions to the CPUs so that the kernel can harden itself

No or minimal modifications to guest Linux kernel:
- Can be implemented inside the hypervisor (e.g. KVM)
- Hot patches

Applicable to bare metal kernel:
- Bare-metal Linux can de-privilege itself to become Virtualization Non-Root Mode
- Additional protection when running bare-metal containers, HPC without overhead
Kernel Memory Protection

- Kernel can write-protect its own code or data by RO (Read-Only) permission for the page
- But the page can be modified by:
  - Changing the permission, or
  - Establishing different mapping with RW permission
- H/W-based virtualization can add enforcement by:
  - RO permission for GPA* to HPA translation
  - VM exit upon attempt to write the page

*:GPA: Guest Physical Address, HPA: Host Physical Address
Examples of code/data to monitor or protect:
• Kernel code and page tables entries for such mappings
• Syscall table
• IDT (Interrupt Descriptor Table)
• ...
• Various data structures, e.g. kernel data declared as “const ...”
Protecting CPU State Control

Linux kernel does not change the setting for CPU control at runtime:

- Control Registers
  - CR0 – PG, CD, WP, PE,
  - CR4 – UMIP, VMXE, SMXE, SMEP, SMAP, PKE,
- MSRs
  - EFER
  - PAT
  - MISC_ENABLE

![Diagram showing the structure of CPU state control with layers for VM (Guest), Apps, Linux Kernel, VCPUs, and Processors]
Security Feature Extensions to CPUs

- Implement new or future H/W security features in virtualization so that the current or older CPUs can take advantage of them
  - Example: **UMIP (User-Mode Instruction Prevention)** – can be mostly emulated by the exiting H/W virtualization feature
- Para-virtualization
  - Requires modifications to the kernel
Protecting IOMMU State Control

Setup once and never modified:
- Root Table Address
- Invalidation Queue Address
- Interrupt Remapping Table Address

Feature Enabling:
- DMA Translation
- Interrupt Remapping
- Queued Invalidation
Policy and Incident Handling

Monitor and protect **specific** kernel data/code and system resources (assets):

<Which asset to monitor>, <Permission>, <Action upon Permission Violation>

- <Which asset to monitor> := Bits of a control register, MSRs, memory pages, or I/O ports,
- <Permission> := RO (Read-Only), XO (Execution Only), NA (No Access Allowed)
- <Action(s)> := **Omit** the attempt and log, **Allow** the attempt and log,
Architecture Overview (KVM Guests Only)

Extend KVM:
• Kernel Monitoring/Protection
**Extend KVM:**
- Kernel Monitoring/Protection

**Thin Hypervisor for bare metal:**
- Integrated into KVM
- Does not require QEMU
- Activated/deactivated at runtime from user-level

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**Architecture Overview (Host and KVM Guests)**

- User Process
- User Process
- VM<sub>0</sub>
  - Apps
  - OS
- VM<sub>1</sub>
  - Apps
  - OS
- Linux Kernel
- Physical Host Hardware
Bare-Metal Linux in Virtualization Non-Root Mode

Bare-metal Linux can run like the native with Virtualization Non-Root Mode enabled:

• Pass-through
  • I/O devices, interrupt controllers, timers, power management, – No VM exits (Done by “VM Exit Control”)
• Identity mapping (+ protection):
  • EPT (Extended page tables) – EPT(GPA) == HPA
  • Use the bare metal kernel – No additional memory for virtualization (except EPT)
• Platform protection
  • Prevent access to platform resources – Platform-specific MSRs, ports, I/O spaces
Switching from Virt. Non-Root to KVM (Virt. Root)

Go back to Virtualization Root Mode to run guests on top of KVM:
- Avoid nested virtualization

Current Implementation:
1. VM Exit in the kernel (e.g. VMXOFF instruction)
2. VM Exit handler for the bare-metal kernel
3. IRET to the next instruction that caused the VM exit (one after VMXOFF)
Prototype Implementation of “Non-Root Mode Bare-Metal Linux”

- Add new IOCTLs to KVM
  - De-privilege and privilege the current CPU (switch_and_exit)
  - Start running in Virtualization Non-Root Mode from the next instruction in the KVM module
  - Generate a dedicated VM exit to go back to Virtualization Root Mode
- Separate VM exit handler
  - Monitoring and protection
  - EPT is constructed in advance or at runtime (optional)
- Code changes are well contained in KVM module
Comparison of Overhead
Using Imbench (micro benchmark) and kernel build

• Imbench

<table>
<thead>
<tr>
<th>Activity</th>
<th>Bare Metal</th>
<th>Non-Root Bare Metal</th>
<th>KVM Guest</th>
</tr>
</thead>
<tbody>
<tr>
<td>null</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>read</td>
<td></td>
<td></td>
<td></td>
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<td>write</td>
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<td>stat</td>
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<td>fstat</td>
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<td></td>
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<tr>
<td>open</td>
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</tr>
</tbody>
</table>

• Kernel build

1.2% overhead with bare-metal kernel in Virtualization Non-Root Mode

Imbench3 Results

lat_sys_call -P 1 -W 1000000 -N 1000 null
*KVM guest - qemu-system-x86_64 -enable-kvm -cpu host - smp 4 -m 4096 -hda image_file -serial stdio
Beyond Kernel Protection

Debugging:
• Monitor specific behaviors or events for debugging

More operations are available in virtualization (Virtualization Non-Root Mode):
• PML (Page Modification Logging)
  • Can be used to monitor memory activities, which guest physical memory pages are modified frequently
• #VE (Virtualization Exception)
  • Additional exception regarding GPA to HPA translation (access to non-present guest physical memory)

Hot patching and Intercepting exceptions (examples):
• Intercept #DE in the kernel (oftentimes used as DoS) – Patching in the KVM module without modifying the kernel code
Current Status and Next Step

Current Status:
- PoC has been done (< 1000 lines of code changes to KVM module only)
- Adding policies and actions
- Planning to share the patches and findings with the community
- Feedbacks are welcome

Next Step:
- Reflect feedback to the design and patches
- Send out RFC
Q & A
Goals of Kernel Protection

- Monitor and protect the system resources and critical kernel data/code
- Extend the CPU features so that the kernel can harden itself
- Implement the above with no or minimal modifications to the core kernel
- Make it available both to VMs and bare-metal Linux

**System resources (examples):**

- CPU control (determined by the control registers, MSRs, )
- IOMMU
- Platform resources (e.g. system PCIe devices such as memory controllers, BIOS, )