KVM

Jin-Soo Kim
(*jinsoo.kim@snu.ac.kr*)

Systems Software &
Architecture Lab.

Seoul National University

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Popek/Goldberg Theorem

For any conventional third-generation computer, a virtual machine monitor may be constructed if the set of sensitive instructions for that computer is a subset of the set of privileged instructions.

-- G. Popek and R. Goldberg, "Formal Requirements for Virtualizable Third-Generation Architectures," CACM, 1974.

- An instruction is control-sensitive if it can update the system state
- An instruction is behavior-sensitive if its semantics depend on the actual values set in the system state
- An instruction is privileged if it can only be executed in supervisor mode and causes a trap when attempted from user mode

$$\{control\text{-}sensitive\} \cup \{behavior\text{-}sensitive\} \subseteq \{privileged\}.$$

Violations in IA-32

- 17 problematic instructions that are sensitive and yet unprivileged

Group	Instructions
Access to interrupt flag	pushf, popf, iret
Visibility into segment descriptors	lar, verr, verw, lsl
Segment manipulation instructions	pop <seg>, push <seg>, mov <seg>
Read-only access to privileged state	sgdt, sldt, sidt, smsw
Interrupt and gate instructions	fcall, longjump, retfar, str, int <n>

Intel Virtualization Technology (VT-x)

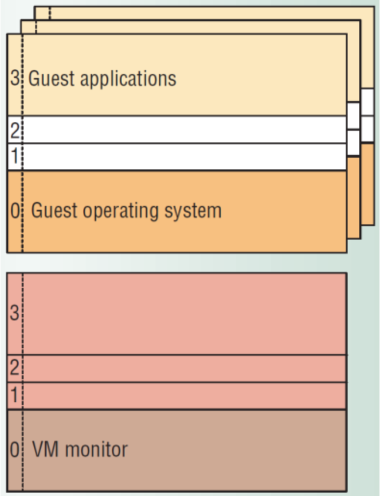
A central design goal for Intel Virtualization Technology is to eliminate the need for CPU paravirtualization and binary translation techniques, and thereby enable the implementation of VMMs that can support a broad range of unmodified guest operating systems while maintaining high levels of performance.

-- R. Uhlig et al., "Intel Virtualization Technology," IEEE Computer, 2005

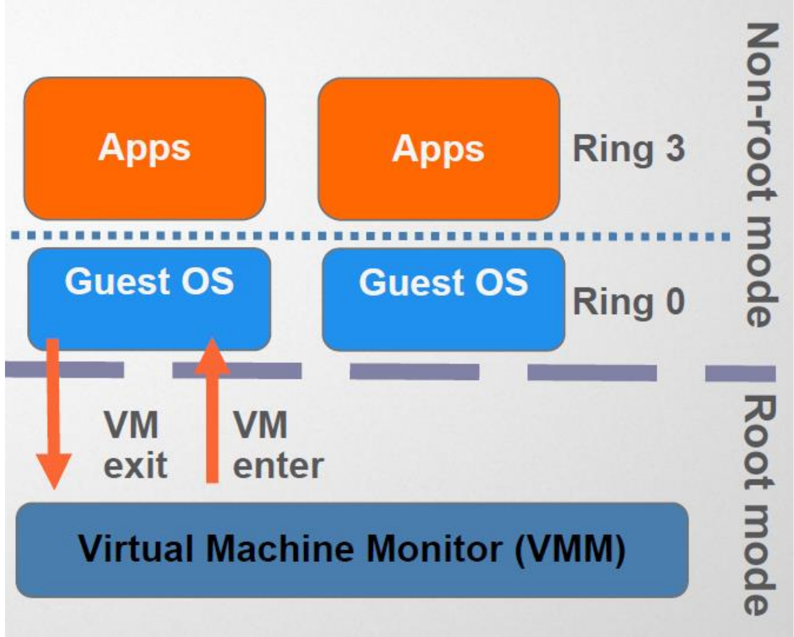
- Virtual machine extensions (VMX) introduced in 2005
- 13 new instructions are added
- Two new VT-x operating modes: VMX non-root and VMX root
- Two new transitions: VM entry and VM exit
- Extended Page Tables (EPT) added in 2008 for memory virtualization

VMX

- VMX root/non-root operations
  - A VMM runs in VMX root operation
  - Guest OSes run in VMX non-root operation
  - Both support all four privilege levels



- Transitions
  - VM entry: VMX root → VMX non-root
  - VM exit: VMX non-root → VMX root

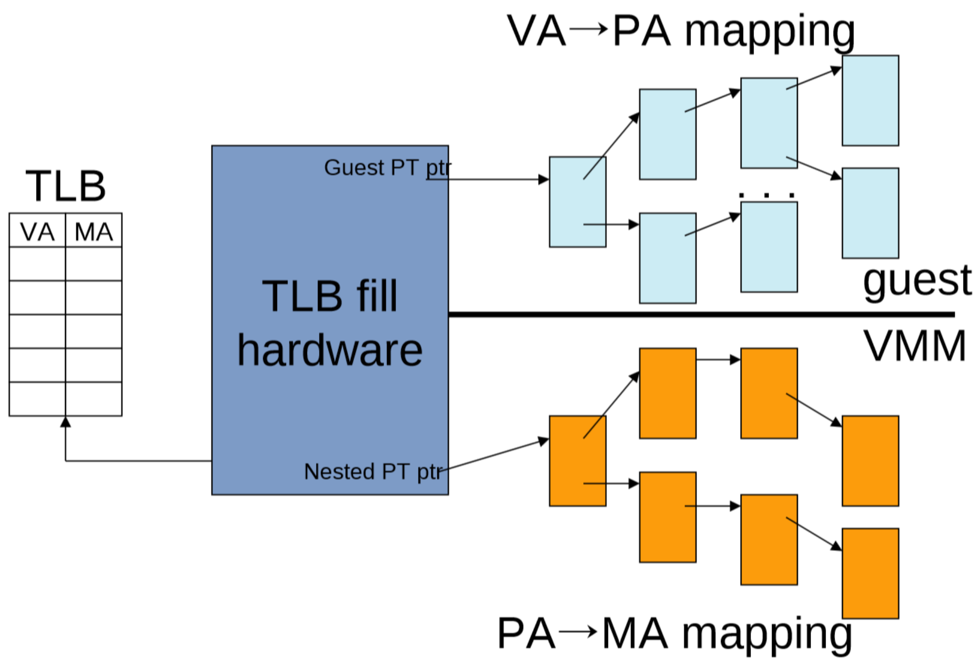


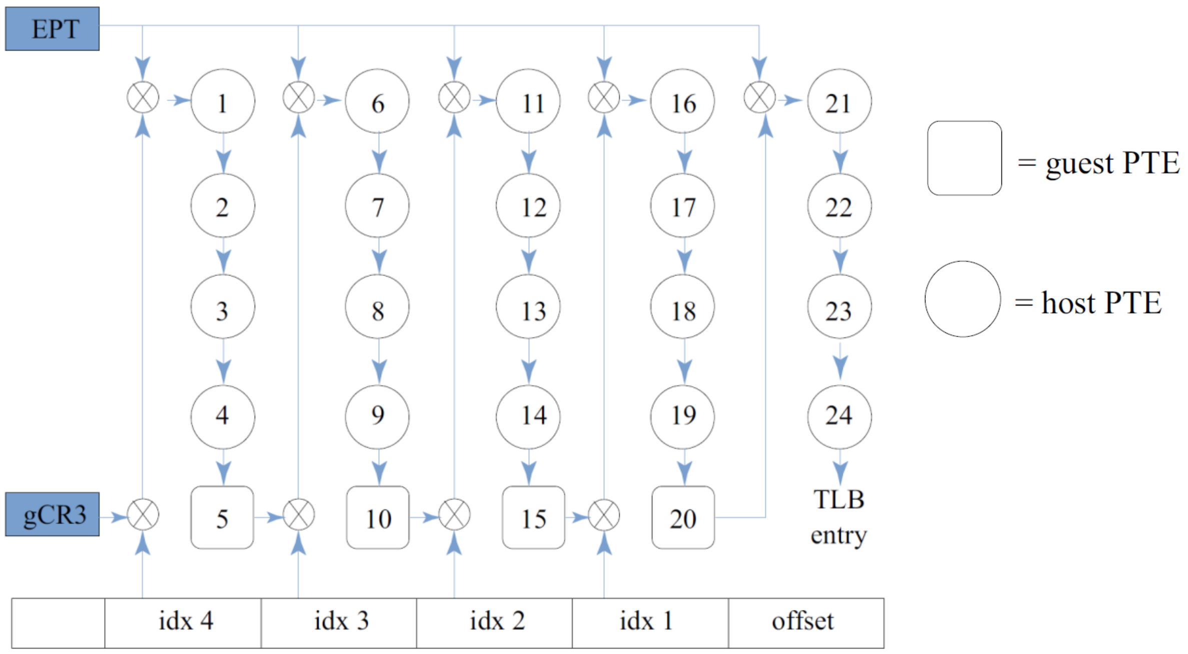
VMCS

- Virtual-Machine Control Structure
  - A new data structure that manages VM entries and VM exist and processor behavior in VMX non-root operations
  - Guest-state area vs. host-state area
  - VM entries load processor state from the guest-state area
  - VM exits save processor state to the guest-state area and then load processor state from the host-state area
- Processor behavior changes in VMX non-root operation
  - Some instructions cannot be executed in VMX non-root operation because they cause VM exists unconditionally
  - Other instructions, interrupts and exceptions can be configured to cause VM exists conditionally (using VM-execution control fields in VMCS)

Extended Page Tables (EPT)

- VMM maintains PPN→MPN mappings in "nested page tables"
  - For every PPN (guest-physical) accessed during guest page table walk, the hardware also walks nested page tables to determine the corresponding MPN (host-physical)
  - TLB still maps guest-virtual pages to host-physical pages



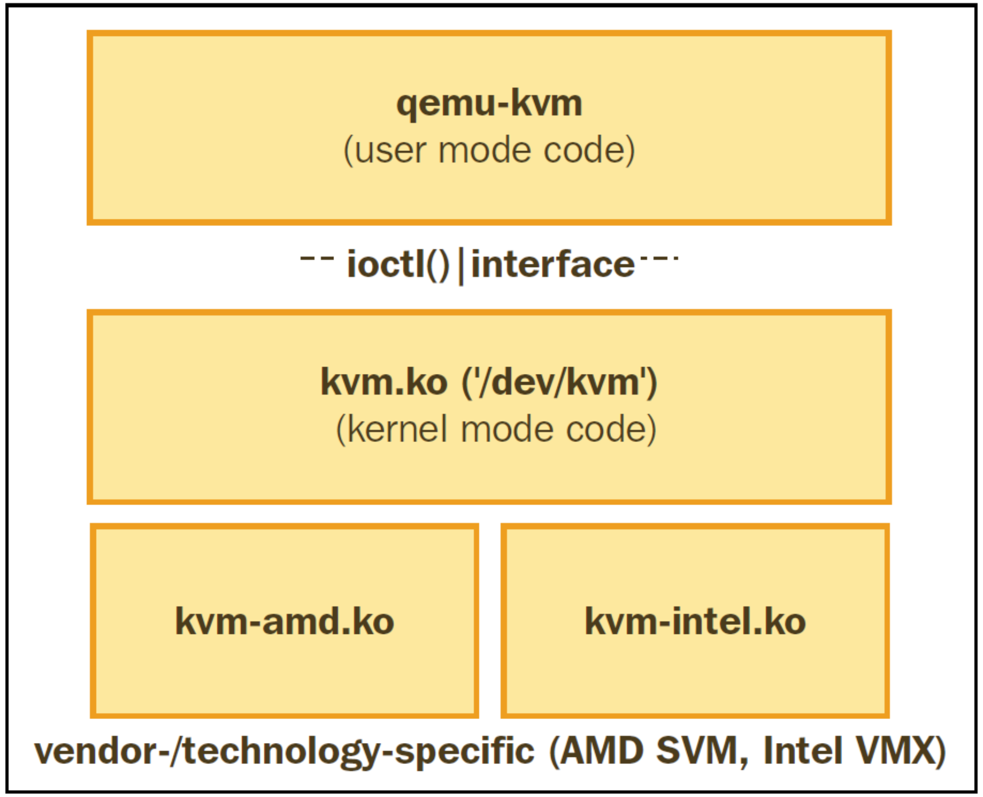


Source: *E. Bugnion et al., Hardware and Software Support for Virtualization, 2017.*

KVM

- Developed by Qumranet
  - Has been part of the Linux kernel since v2.6.20
  - Later Qumranet was acquired by Red Hat
  - Officially supported hypervisor of major commercial Linux distributions

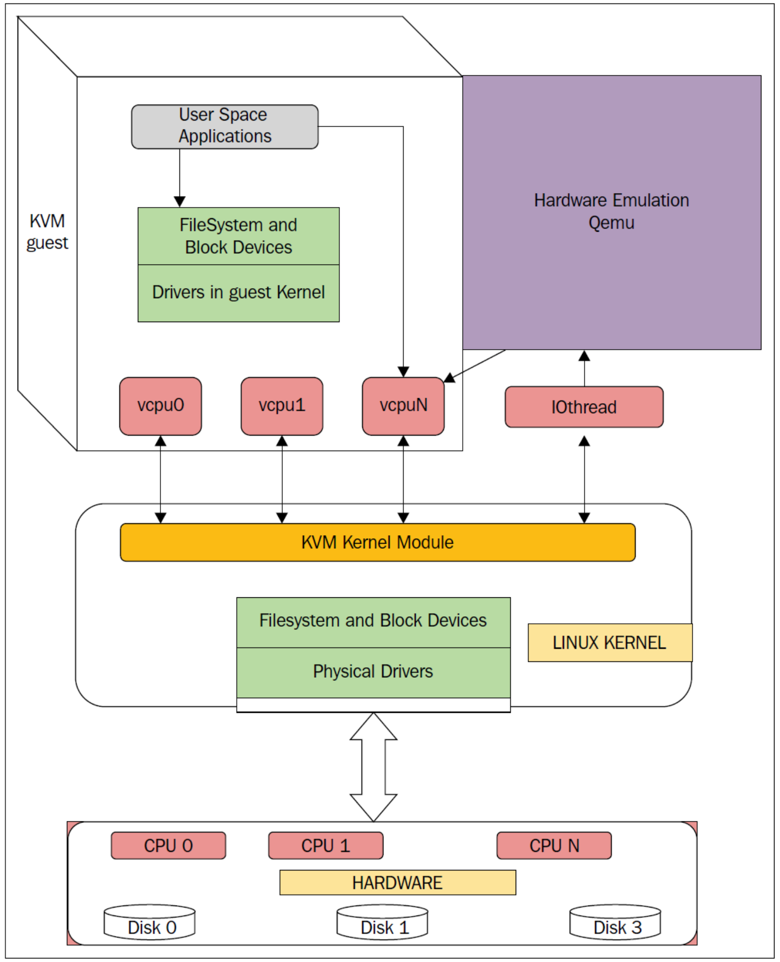
  - Requires hardware virtualization capable processors to operate
  - KVM turns the standard Linux kernel into a hypervisor



Source: H. D. Chirammal et al., Mastering KVM Virtualization, 2016

QEMU

- Open source machine emulator and virtualizer
  - Developed by Fabrice Bellard
  - Runs OSes and programs for another CPU ISA using dynamic binary translation or direct execution
  - Emulates a set of devices: disks, networks, VGA, PCIe, serial & parallel ports, USB, …
  - Runs other management tasks: creating and initializing a virtual machine, BIOS, VM management, etc.



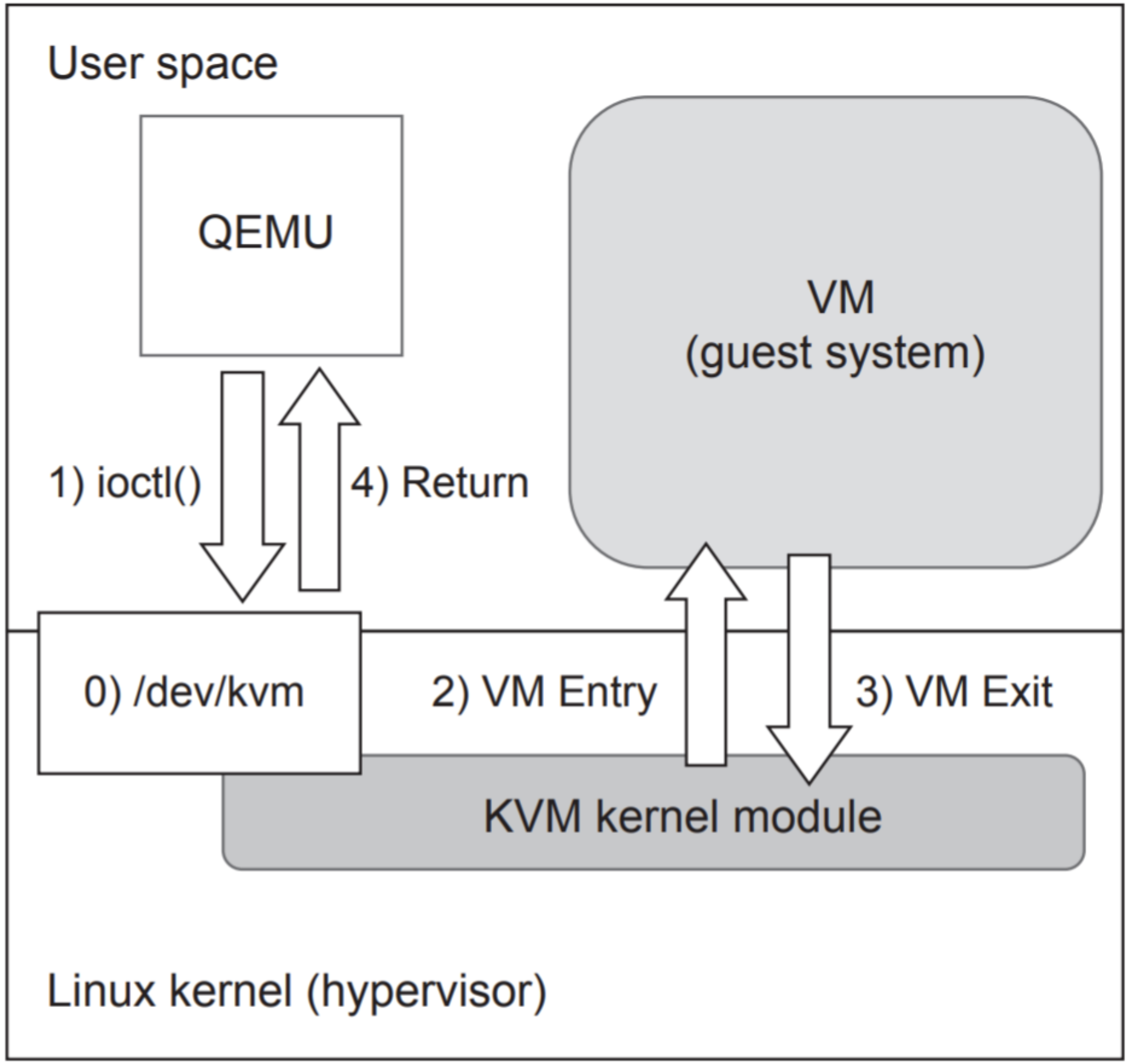
Source: *H. D. Chirammal et al., Mastering KVM Virtualization, 2016*

KVM Architecture

- KVM kernel module (kvm.ko)
  - Handles the basic CPU platform emulation issues
  - CPU / memory / interrupt virtualization
  - Some chipset emulation (APIC, IOAPIC, etc.)

- QEMU-KVM
  - For each and every VM, there is a QEMU process running in the host system
  - Virtual CPUs are executed in the host kernel as POSIX threads
  - Guest RAM is assigned inside the QEMU process's virtual address space
  - Worker threads (iothreads) for virtual network and disk devices
  - QEMU talks to the KVM kernel module using ioctls on /dev/kvm

Execution Flow



Source: Y. Goto, "Kernel-based Virtual Machine Technology", Fujitsu Sci. Tech. J., 2011