Platform Virtualization

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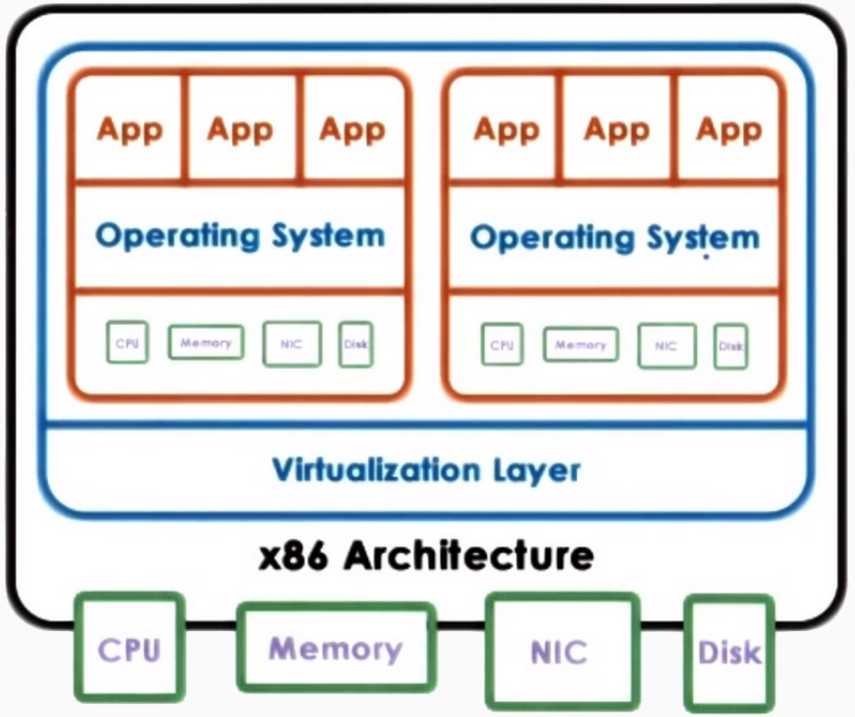
*Many thanks to Prof. Ada Gavrilovska for letting me use some of the contents of her course "Introduction to Operating Systems" thought at Georgia Institute of Technology

What is Platform virtualization?

- Virtualization of a **whole platform** $\rightarrow$ allows concurrent execution of multiple OSes on the same physical machine
- **Virtual machine (VM)** or guest domain = efficient, isolated duplicate of the real physical machine
- A VM is supported by a virtualization layer = **virtual machine monitor (VMM)** or **hypervisor**



Popek and Goldberg requirements for a VMM

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1. **Fidelity**: provide an environment essentially identical to the original machine; software on the VMM executes nearly identically to how it would on real hardware

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3. **Safety & isolation**: VMM is in complete control of system resources (hardware)

Quiz: virtualization technology

Based on the classical definition of virtualization by Popek & Goldberg, which of the following are virtualization technologies?

- Java Virtual Machine (JVM)
- Virtual GameBoy
- Oracle VirtualBox

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How to virtualize the machine?

- VMM must transparently virtualize the machine:
  - CPU
  - Memory
  - devices (Input/Output – I/O)
- Techniques to implement platform (hardware) virtualization:
  - **Full virtualization**
    - Trap-and-Emulate
    - Dynamic Binary Translation
    - Hardware-assisted
- **Paravirtualization**

Platform virtualization: Full virtualization

- Guest OS completely **abstracted** from underlying hardware by the virtualization layer
- Guest OS **unaware** it's running on top of a hypervisor
  $\rightarrow$ Guest OS is **unmodified**
- Hypervisor translate all OS calls (syscalls) on-the-fly

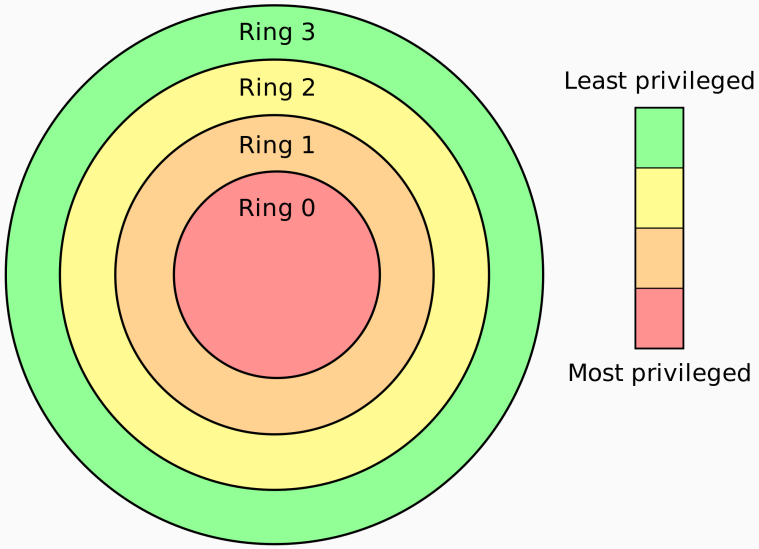
Platform virtualization: Paravirtualization

- By opposition to full virtualization, paravirtualization requires **modification** of the guest OS!
- **Better performance** by avoiding overhead/complexity required to support unmodified OSes
- Guest OS is **slightly modified**
- Guest OS **knows** it's running on top of a hypervisor
- For privilege operations, guest OS makes explicit calls to hypervisor $\rightarrow$ **hypercalls**

Platform virtualization: CPU virtualization

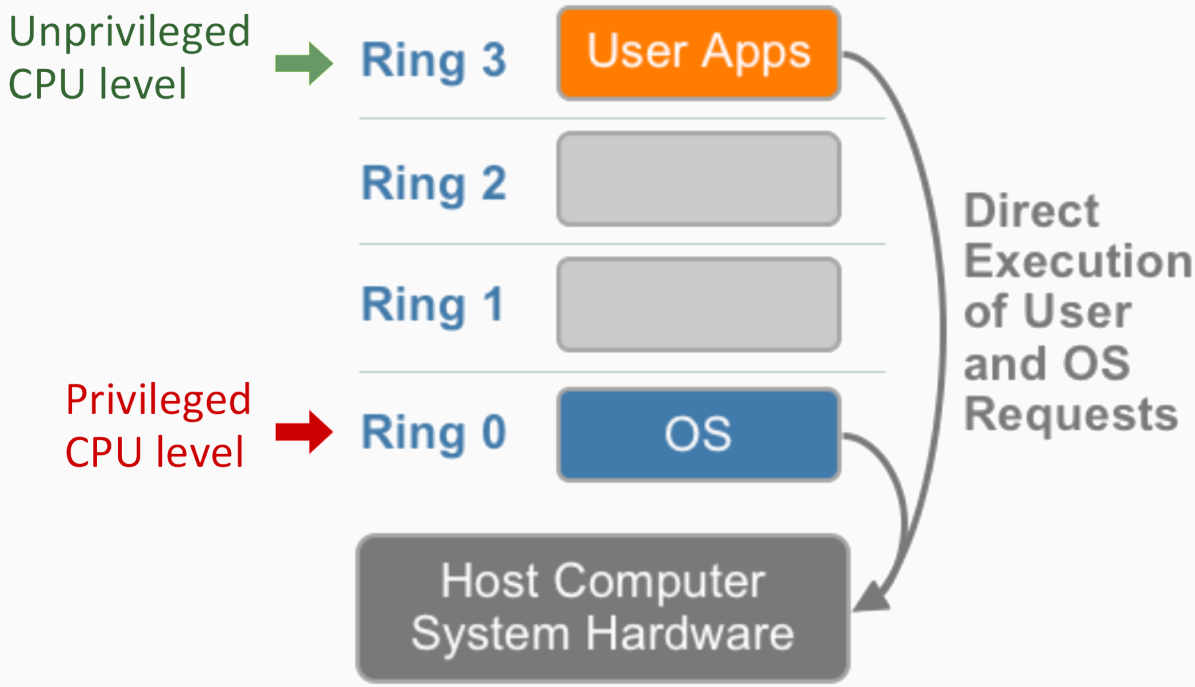
Hardware protection levels

- Commodity hardware has more than two **protection levels**
- For example, the original Intel 32-bit architecture has **four protection levels**, called rings
- **OS (kernel)** runs in **ring 0**
- **Applications** runs in **ring 3**



Direct execution without virtualization

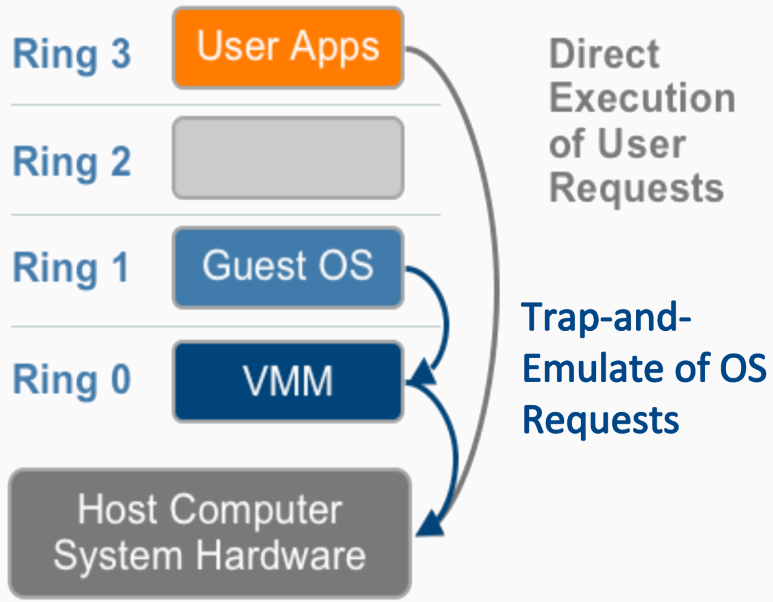
Application execution when executed on top of an OS (x86) without any virtualization:



Full virtualization: Trap-and-Emulate

Guest instructions are executed **directly** by the hardware:

- VMM does not interfere with every instruction/memory access issued by guest OS or applications
- For non-privileged operations → runs at hardware speed = **efficient**
- For privileged operations: **trap** to VMM
- If illegal operation: **terminate** VM
- If legal operation: **emulate** the behavior the guest OS was expecting from the hardware



Full virtualization: issue with Trap-and-Emulate

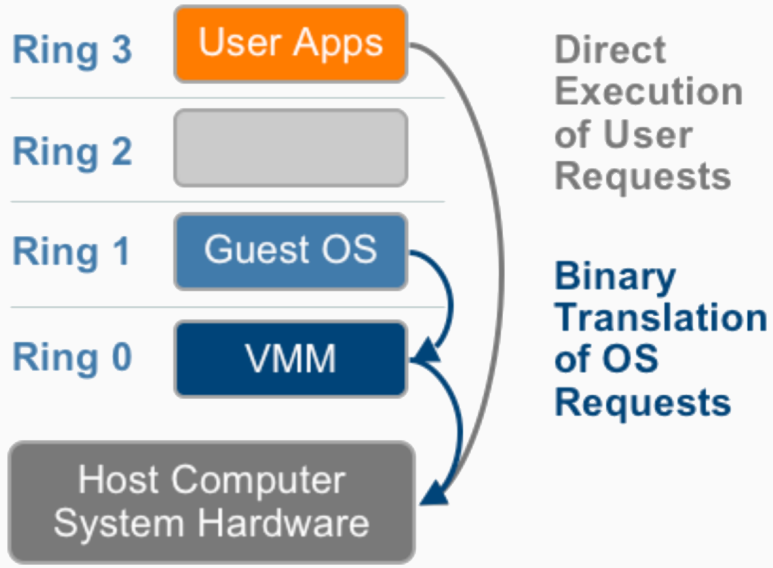
- Trap-and-Emulate worked well on mainframes because their CPUs were designed to support virtualization
- In the 90s, when the need to apply virtualization to x86 architecture arose $\rightarrow$ Trap-and-Emulate model did NOT work!
- x86 pre-2005:
  - 17 privileged instructions do not trap $\rightarrow$ **fail silently!** (doesn't pass control back to hypervisor)
  - E.g. interrupt enable/disable bit in privilege register; `pushf`/`popf` instructions that access it from ring1 fail silently
    - Hypervisor doesn't know, so doesn't try to change settings
    - Guest OS doesn't know, so assume change was successful!

Full virtualization: Binary Translation

- Main idea: modify the guest VM binary at runtime to never use those 17 instructions
- Pioneered by Mendel Rosenblum's group at Stanford, commercialized as VMWare in 1998
- Goal: to **not modify** the guest OS!

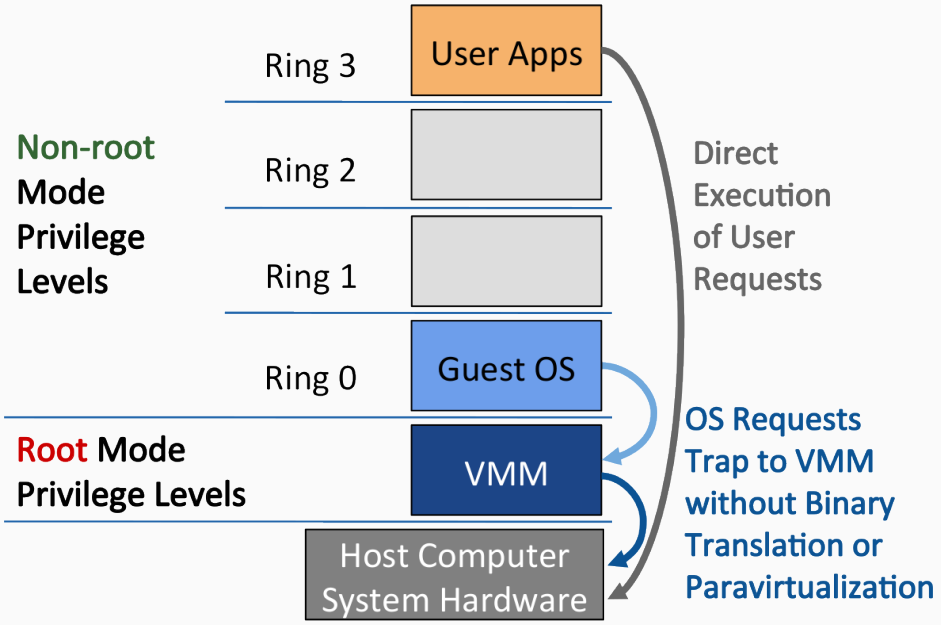
Full virtualization: Dynamic Binary Translation

- Dynamic because a sequence may depend on the runtime state
- Input dependent $\rightarrow$ can't be done statically
- Dynamically capture code blocks
- Inspect code blocks to be executed for the 17 instructions
- If needed, translate to alternate instructions sequence (to emulate desired behavior and avoid traps)
- Otherwise $\rightarrow$ run at hardware speed
- Cache translated blocks to amortize translation costs



Full virtualization: Hardware-assisted

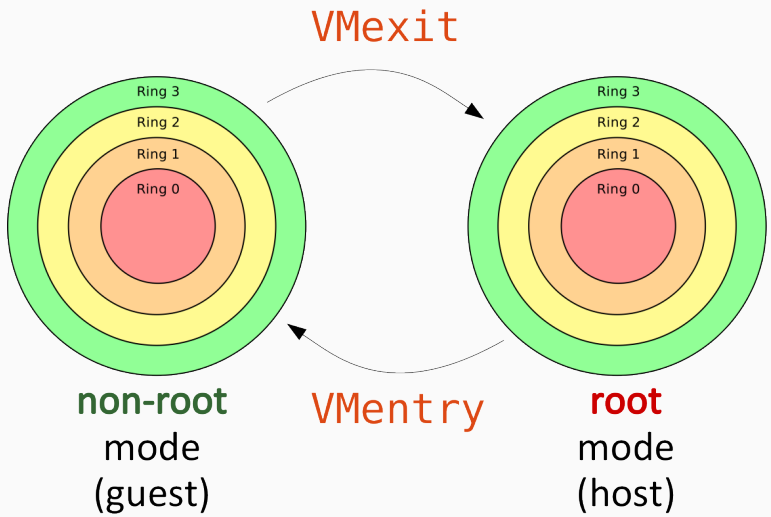
- Also called "Accelerated Virtualization" and "Hardware Virtual Machine" (HVM)
- Exists since the release of Intel VT-x & AMD-V Pacifica (2005):
  - Close "holes" in x86 ISA (Instruction Set Architecture)
  - Adds new modes: root*/non-root = hypervisor/guest



*Completely unrelated to root user in Linux/UNIX!

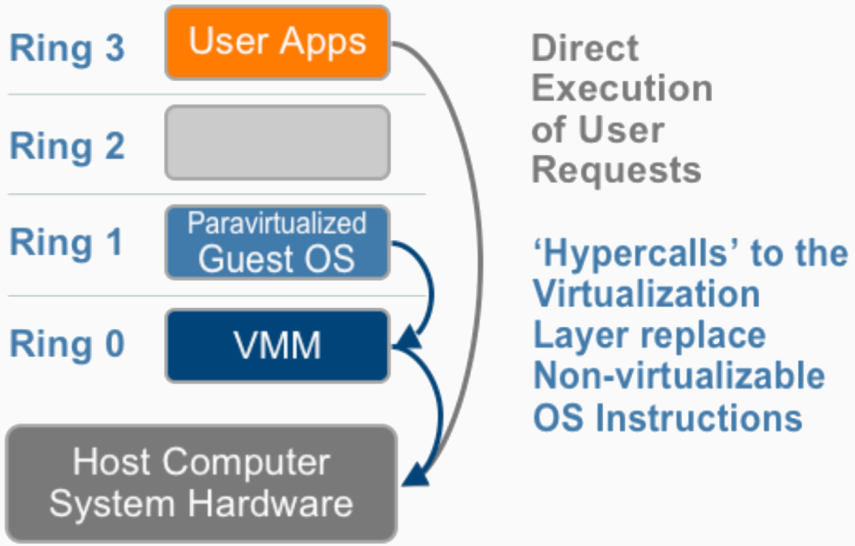
Hardware-assisted, root/non-root modes

- In non-root mode, certain not permitted operations cause traps (`VMexits`) → trigger switch to root mode (hypervisor)
- An hypervisor could use the following:
  - Non-root (guest): VMs
    - Ring 3: applications
    - Ring 0: OS
  - Root (host):
    - Ring 0: hypervisor



Paravirtualization

- Goal: **better performance** by avoiding overhead/complexity required to support unmodified OSes:
  - Guest OS is slightly modified
  - Guest OS knows it's running on top of a hypervisor
  - For privilege operations, guest OS makes explicit calls to hypervisor through hypercalls
  - Hypercalls from guest OS to hypervisor $\approx$ system calls from application to OS
- Paravirtualization popularized by Xen hypervisor from Citrix



Hypervisor models

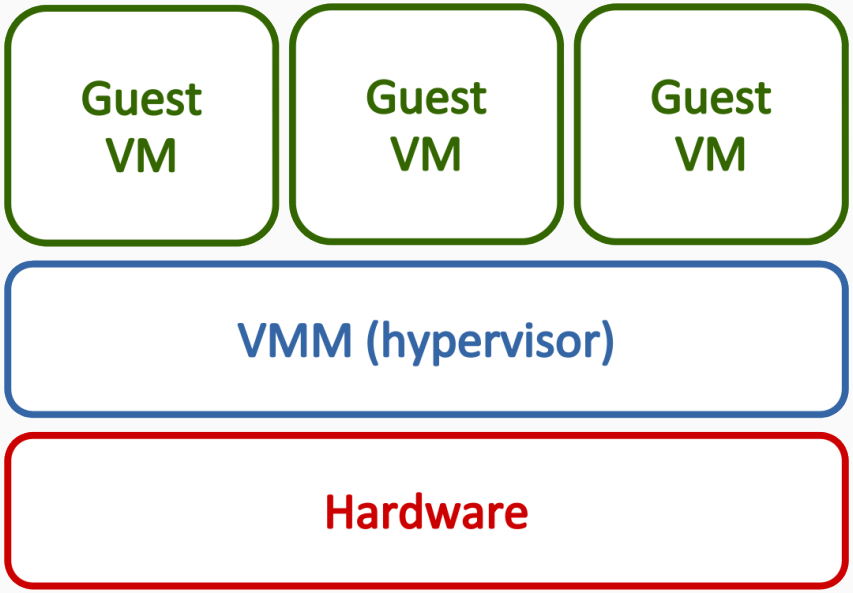
Two hypervisor models:

- **Bare-metal** (type 1)
- **Hosted** (type 2)

Bare-metal (type 1) virtualization model

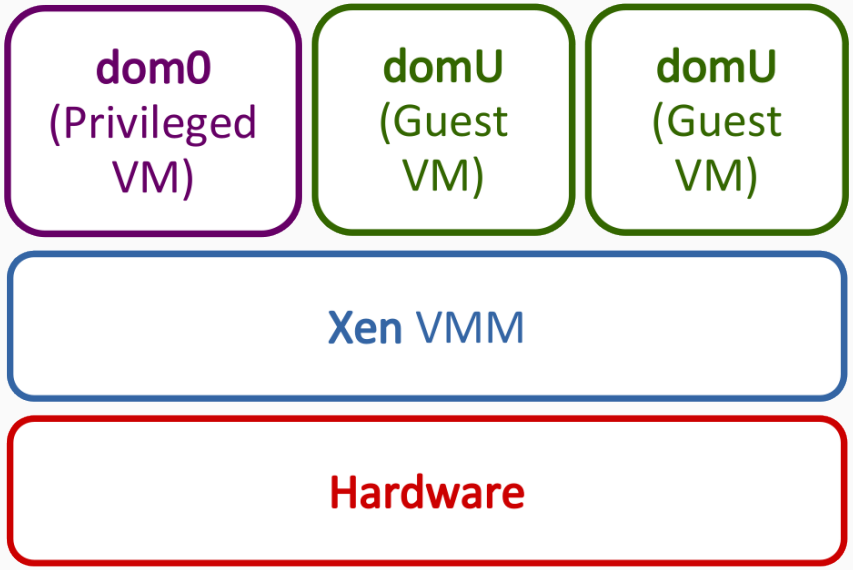
Bare-metal = hypervisor runs above hardware (metal)

- VMM manages all hardware resources and supports execution of VMs → hypervisor must manage all possible devices (drivers)



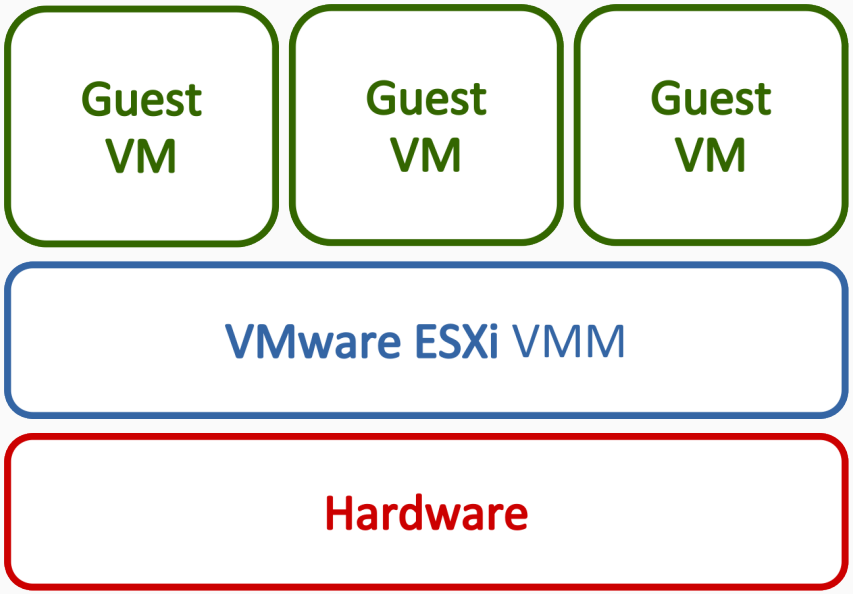
Bare-metal model, variant 1: Xen

- VMM manages all hardware resources and supports execution of VMs
- Integrates a privileged, service VM, that runs a standard OS (Linux) with full hardware privileges
  - Run all device drivers
  - Configuration and management task (how VMM share resources across VMs)



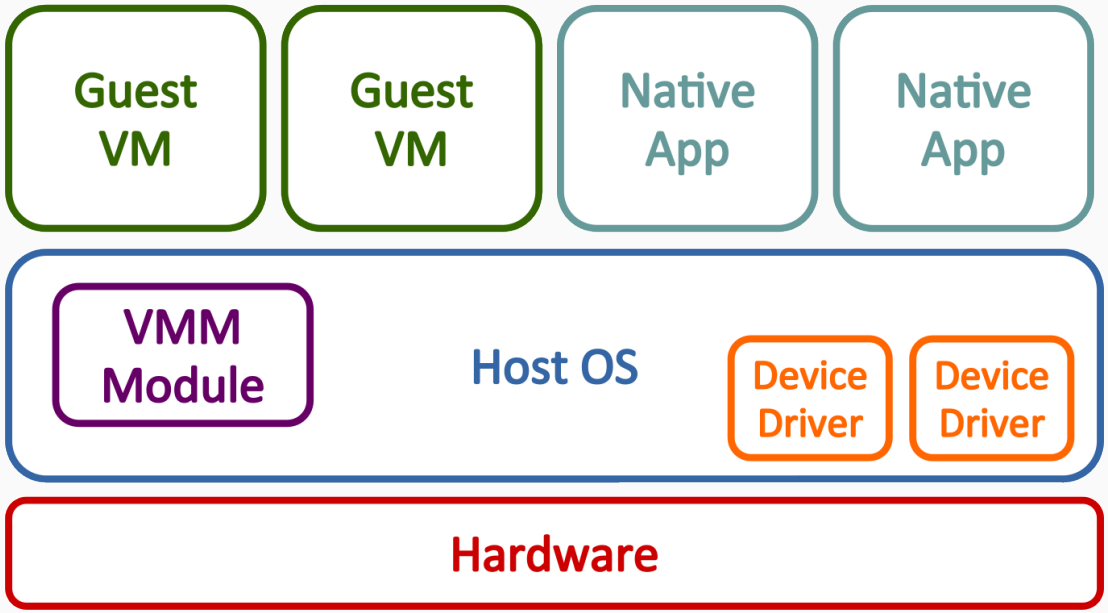
Bare-metal model, variant 2: VMware ESXi

- VMM manages all hardware resources and supports execution of VMs
- Device manufacturers provide device drivers for the hypervisor
- **Limited** hardware support
  $\rightarrow$ ESXi only available for dedicated servers



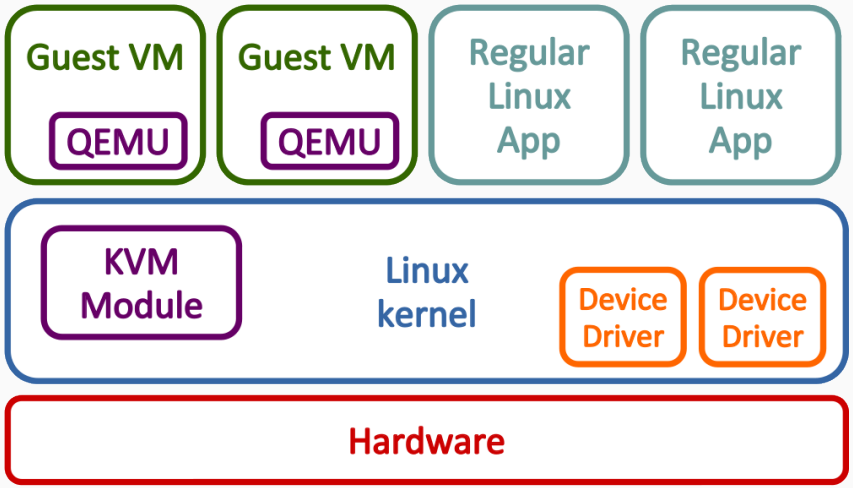
Hosted (type 2) virtualization model

- Host OS owns all hardware
- Special VMM module provides hardware interfaces to VMs and deals with VM context switching



Hosted virtualization example: KVM

- KVM (Kernel Virtual Machine) = Linux kernel module
- Linux host → provides hardware management + runs regular Linux applications
- Guest VMs support through KVM + QEMU (platform emulator + virtualizer) for hardware virtualization
- Massive Linux kernel re-use
- Leverages advances in Linux open-source community



Quiz: bare-metal or hosted

Among the following virtualization products, which ones are **bare-metal** (type-1) hypervisors and which ones are **hosted** (type-2)?

- Linux/KVM
- VMWare Fusion
- VirtualBox
- VMWare Player
- VMWare ESXi
- Citrix XenServer
- Microsoft Hyper-V
- Amazon Web Services

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Platform virtualization: Device virtualization

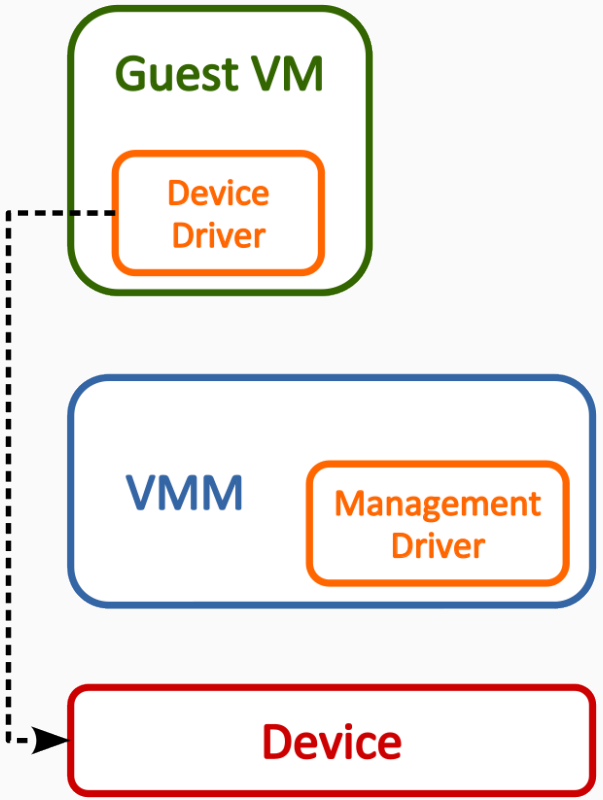
Device virtualization

- For CPU and memory → little diversity
  - ISA[1]-level interface standardization
- For devices → great diversity
  - Lack of standardization
  - Specific device interface
  - Specific device behavior (semantic)
- Three key models for device virtualization (pre VT-d hardware)
  1. Passthrough
  2. Emulated (also called "hypervisor - direct")
  3. Paravirtualized (also called "split - device")

[1] Instruction Set Architecture

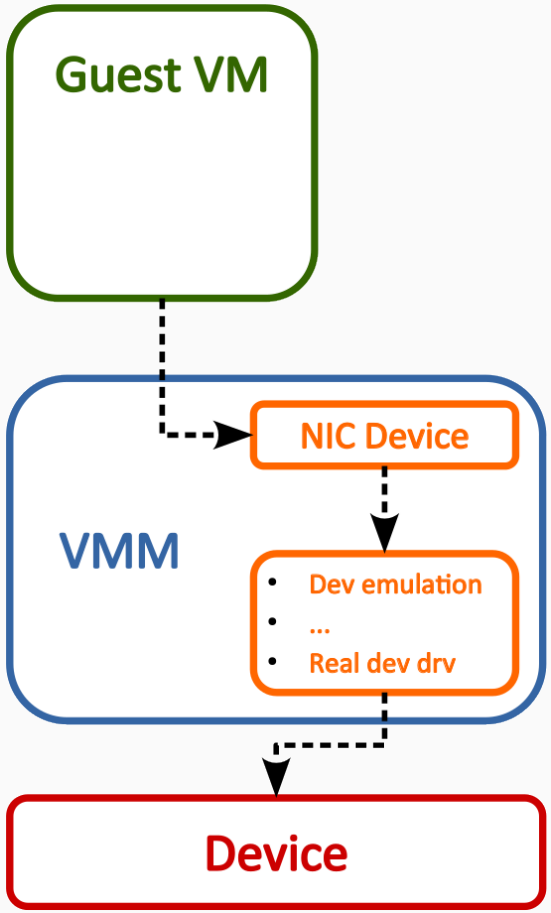
Device virtualization: Passthrough model

- VMM-level driver (management) configures device access permissions
- **Pros**
  - VM provided with exclusive access to the device
  - VM can directly access the device (VMM bypass)
- **Cons**
  - Device sharing is difficult
  - VMM must have exact type of device as what VM expects
  - VM migration difficult



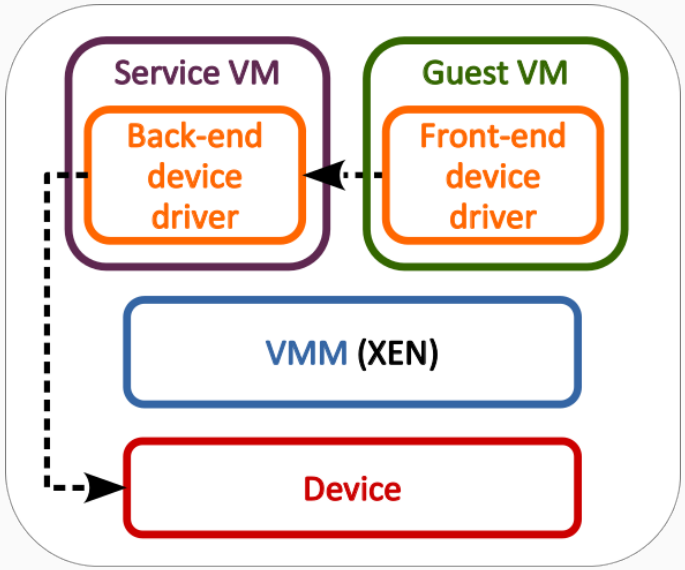
Device virtualization: Emulated

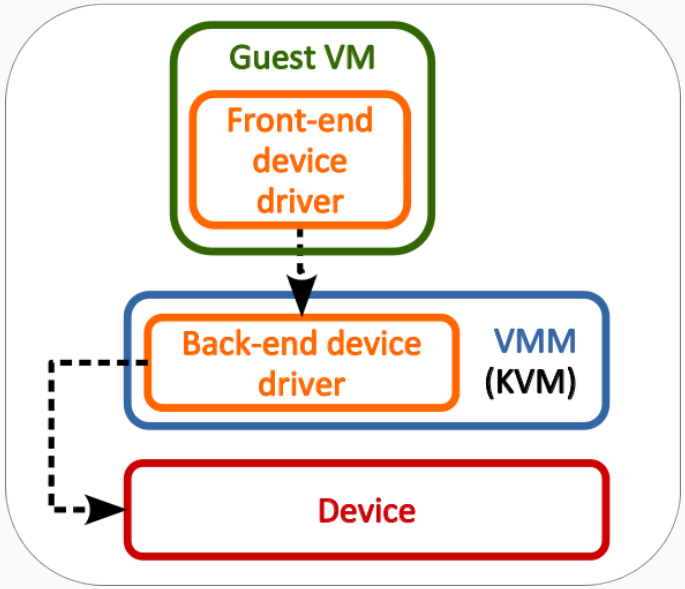
- VMM **intercepts** all device accesses
- **Emulate** device operation:
  - translate to generic I/O operations
  - traverse VMM-resident I/O stack
  - invoke VMM-resident driver
- **Pros**
  - VM decoupled from physical device
  - Sharing, migration, dealing with device specifics
- **Cons**
  - Latency
  - Device driver complexities in VMM



Device virtualization: Paravirtualized

- Also called "Split device driver model"
- Device access control **split** between:
  - **Front-end** driver in guest VM
  - **Back-end** driver in
    - service VM (e.g. XEN)
    - VMM (e.g. KVM)
  - Modified guest drivers
- **Pros**
  - Eliminate emulation overhead
  - Better management of shared devices
- **Cons**
  - Requires drivers on the Guest OS

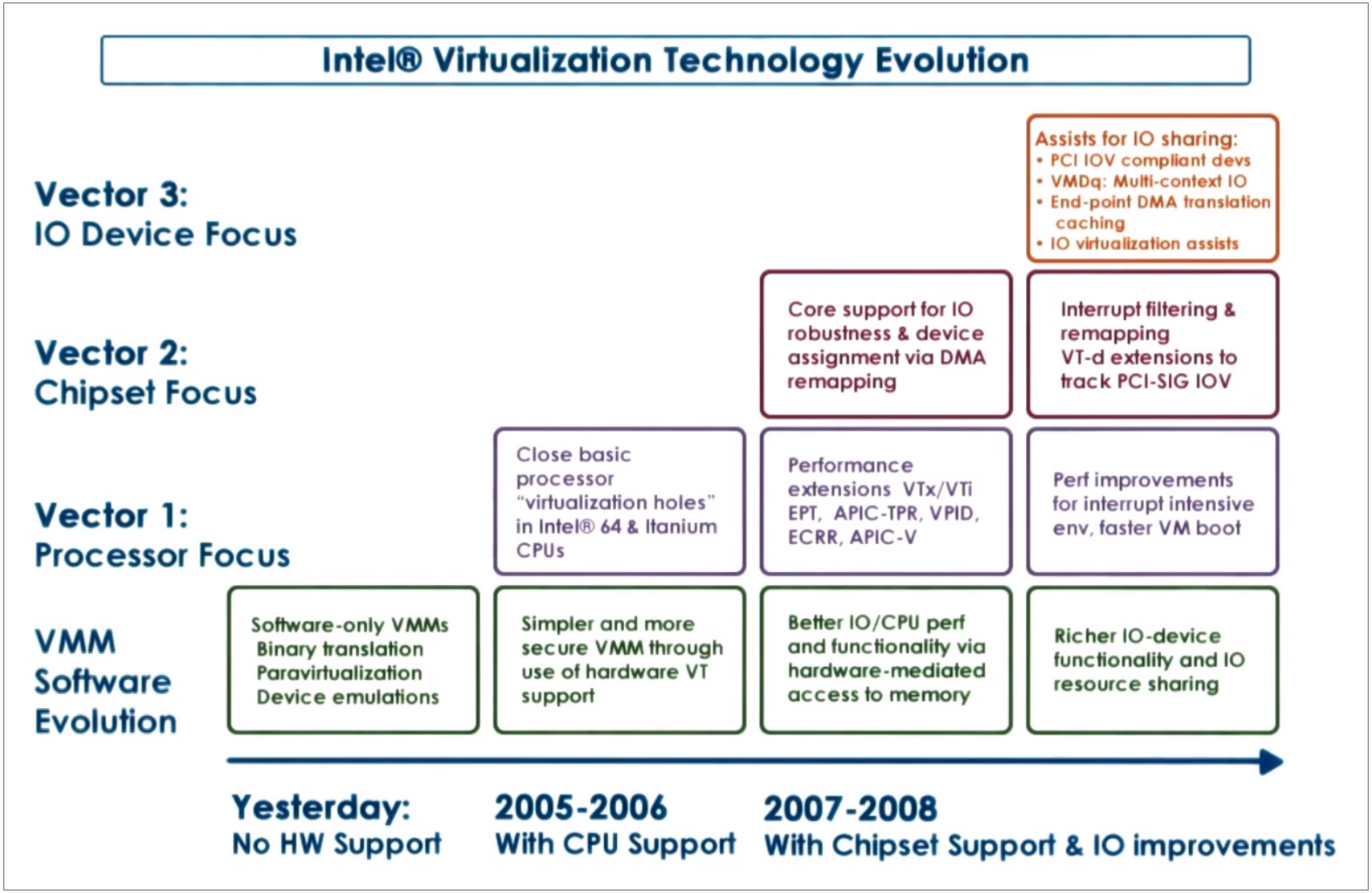




Hardware accelerated device virtualization

- Intel VT-d and AMD-V hardware expose a new feature for virtualizing I/O: IOMMU
- IOMMU creates a virtual address space for devices and sets limits on a device's range of addressable memory
  - allow hypervisor to manage and regulate DMA from devices
  - hypervisor can assign devices to guests and restrict devices' memory access to specific pages
- PCI-Passthrough uses IOMMU isolation for protection
- IOMMU similar to MMU in CPUs but for devices
  - generates exceptions which hypervisor must handle

x86 Intel-VT revolution



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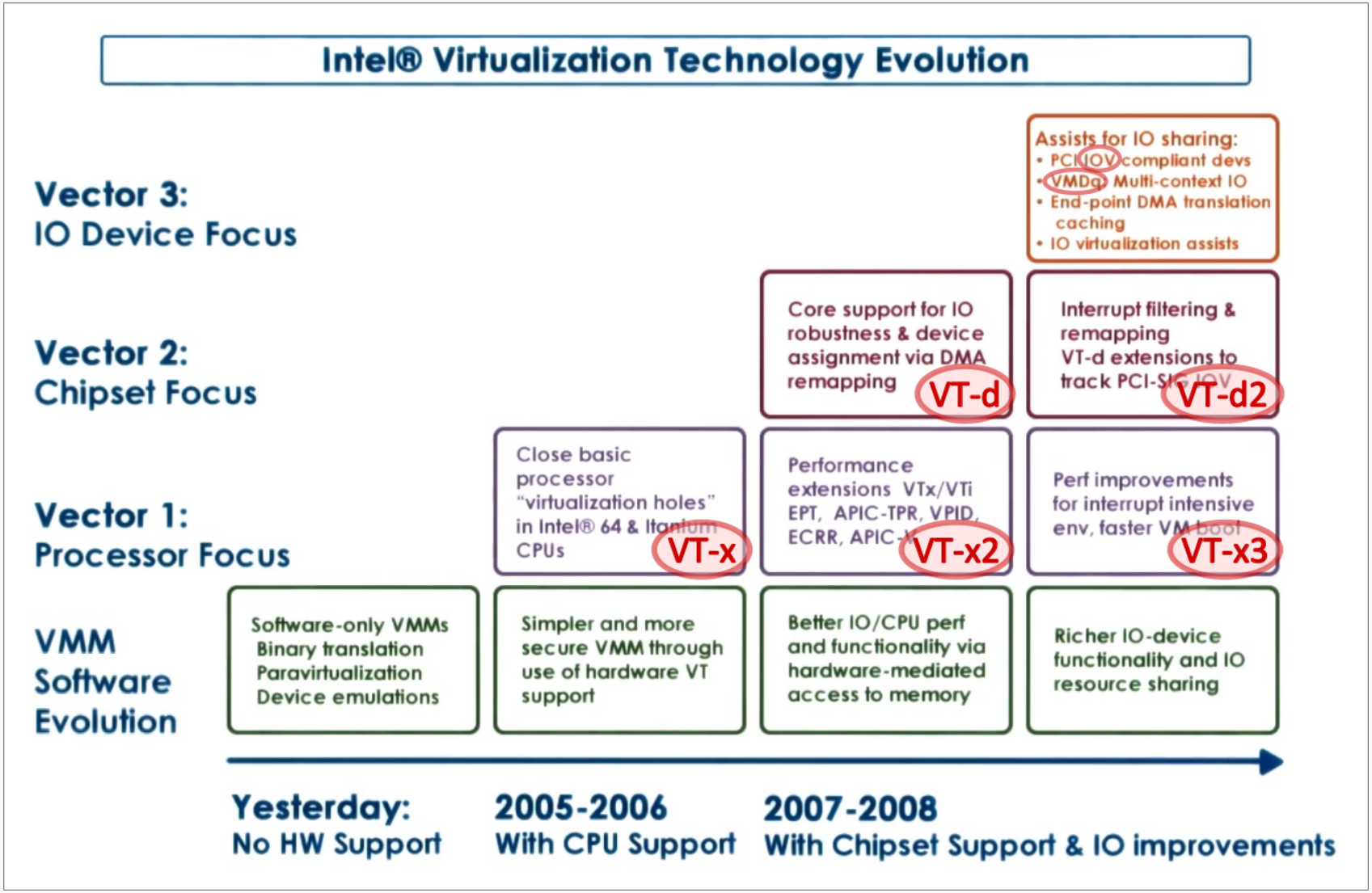


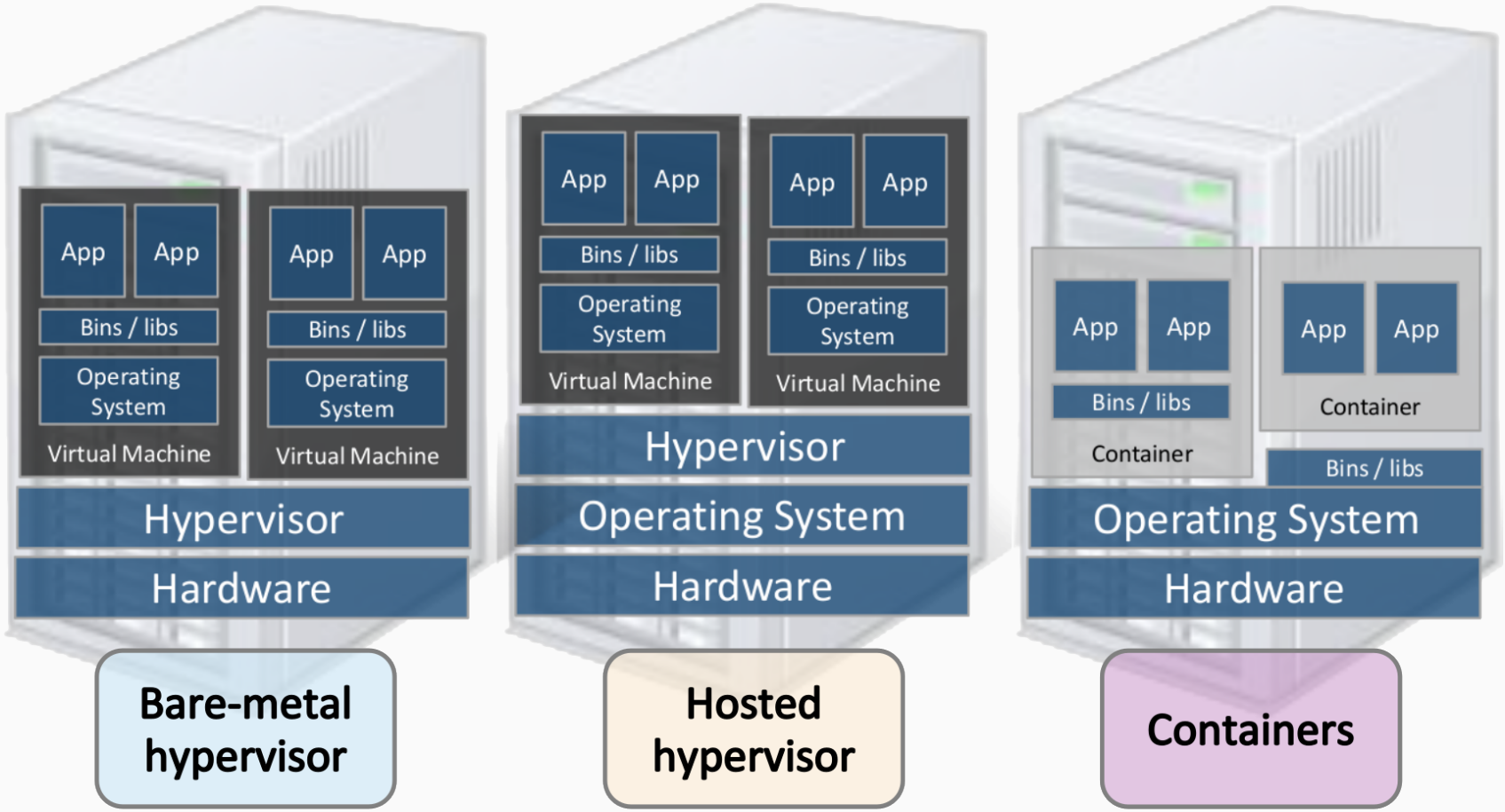
What's used out there?

- Most public hosted services are powered by Linux/KVM
  - Amazon AWS & EC2 $\rightarrow$ Xen $\rightarrow$ minimalistic modified Linux/KVM (Nitro)
  - Google Cloud Platform $\rightarrow$ Linux/KVM
  - Microsoft Azure $\rightarrow$ Microsoft Hyper-V
  - DigitalOcean $\rightarrow$ Linux/KVM
- Everything OpenStack $\rightarrow$ mostly powered by Linux/KVM
- VMware leader in solutions for business/private environments

Operating system virtualization

- OS-level virtualization = containerization
  - OS feature where kernel allows existence of multiple **isolated user-space instances** called containers, partitions, or jails
- Processes inside a container can **only** see the container's contents and devices assigned to the container → isolation
- Kernel provides **resource-management** features to limit impact of one container's activities on other containers
  - Example (Linux kernel): cgroups, namespaces, chroot
- Examples: Linux Containers (LXC), Docker, BSD jails, Solaris Zones, Linux OpenVZ

Platform virtualization vs OS virtualization

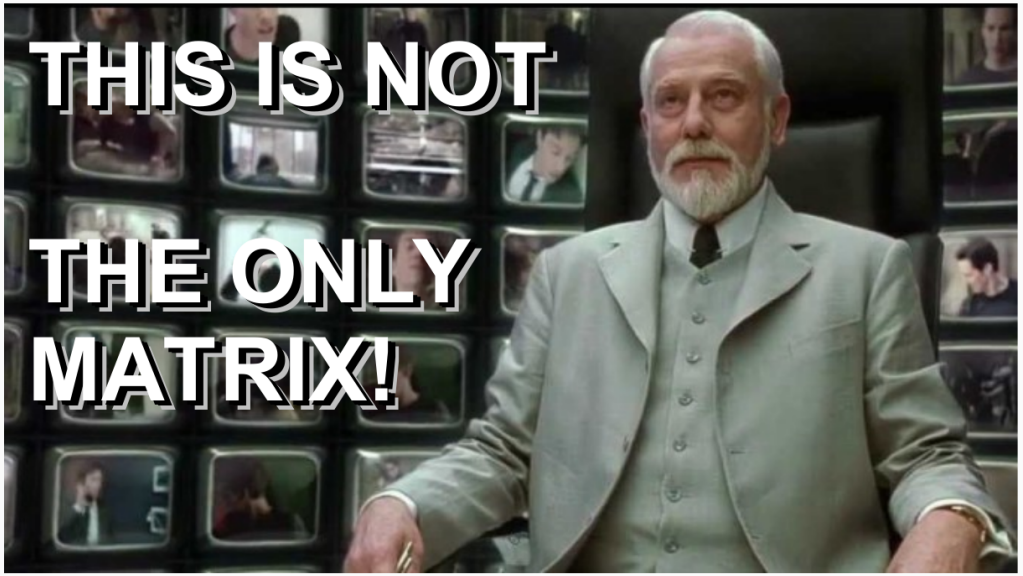


Unikernels

- Single-purpose appliances
  - Trend towards each VM = single application (instead of full OS)
- Unikernel = virtual library OS → **stripped OS to run a single specialized application**
  - No kernel mode/user mode → **single address space** app
    - only a minimal kernel (library) to run the app
  - Create a specialized VM for a specific application
  - Reduce memory footprint
  - Increase security by dramatically reducing the attack surface
- Frameworks to build unikernels:
  - https://unikraft.org/
  - https://mirage.io/

Future trends

- Rise of containers but at the cost of security
- Hybrid solutions:
  - containers inside hypervisors!
- Unikernels?



Resources

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