Virtualization

Based on materials from:

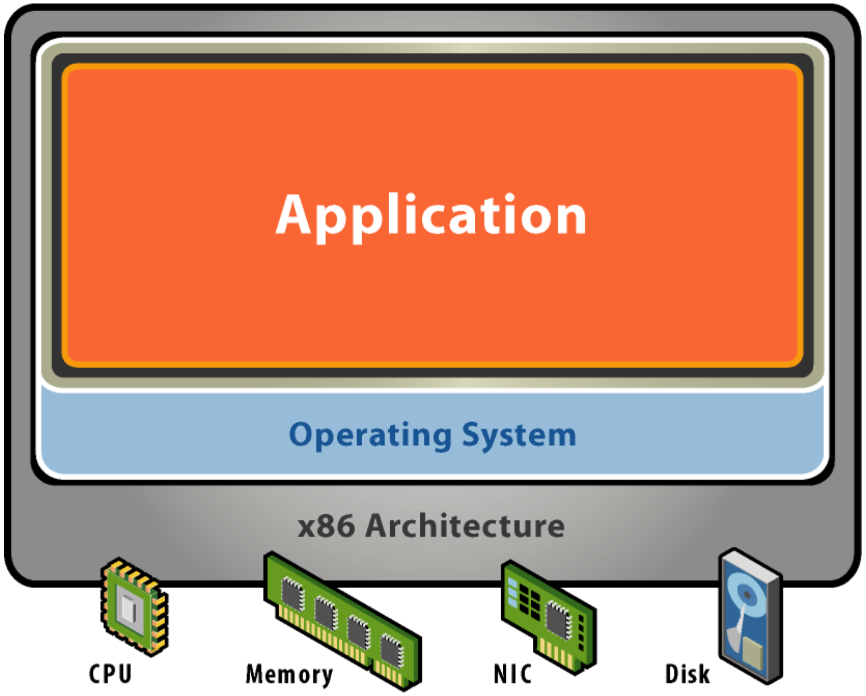
Introduction to Virtual Machines by Carl Waldspurger

Understanding Intel® Virtualization Technology (VT) by N. B. Sahgal and D. Rodgers

Intel Virtualization Technology Roadmap and VT-d Support in Xen by Jun Nakajima

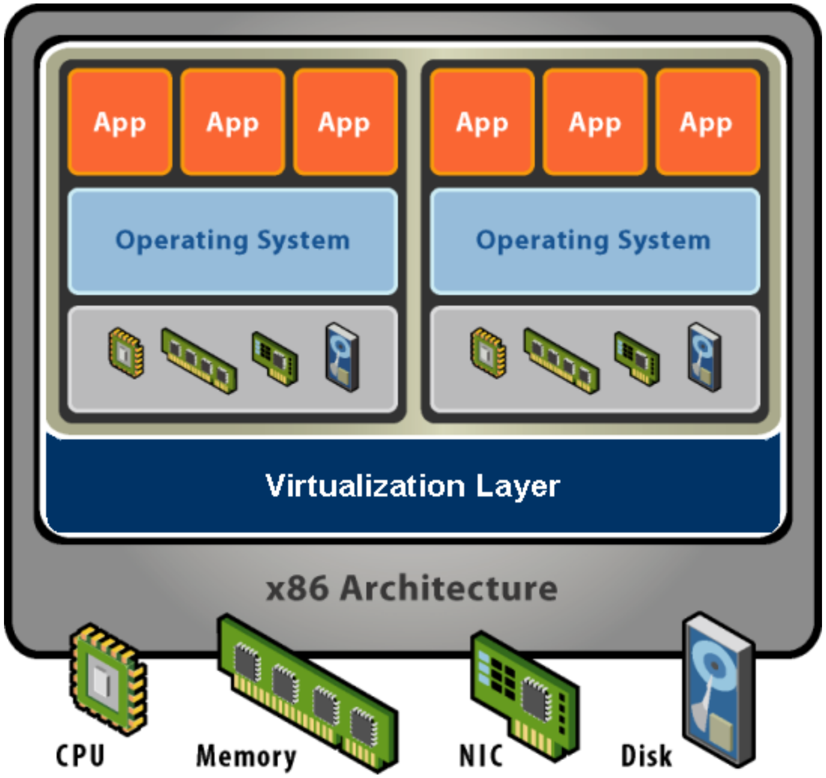
A Performance Comparison of Container-based Virtualization Systems for MapReduce Clusters by M. G. Xavier, M. V. Neves, and C.A.F. De Rose

Starting Point: A Physical Machine



- **Physical Hardware**
  - Processors, memory, chipset, I/O devices, etc.
  - Resources often grossly underutilized
- **Software**
  - Tightly coupled to physical hardware
  - Single active OS instance
  - OS controls hardware

What is a Virtual Machine?



- **Software Abstraction**
  - Behaves like hardware
  - Encapsulates all OS and application state
- **Virtualization Layer**
  - Extra level of indirection
  - Decouples hardware, OS
  - Enforces isolation
  - Multiplexes physical hardware across VMs

Virtualization Properties

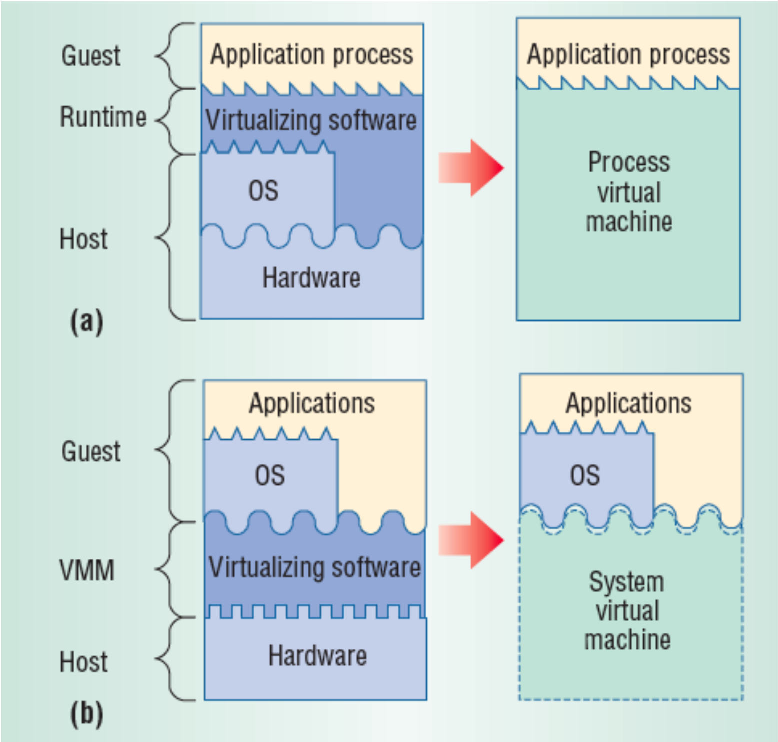
- **Isolation**
  - Fault isolation
  - Performance isolation
- **Encapsulation**
  - Cleanly capture all VM state
  - Enables VM snapshots, clones
- **Portability**
  - Independent of physical hardware
  - Enables migration of live, running VMs
- **Interposition**
  - Transformations on instructions, memory, I/O
  - Enables transparent resource overcommitment, encryption, compression, replication …

Virtualization Applications

- Server consolidation
- Data center management
- Desktop management
- Development, test and deployment
- Application and OS flexibility
- Fast, automated recovery
- Fault tolerance

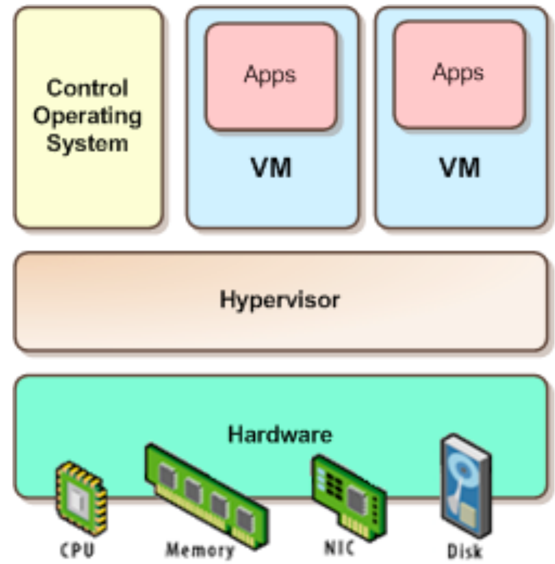
Types of Virtualization

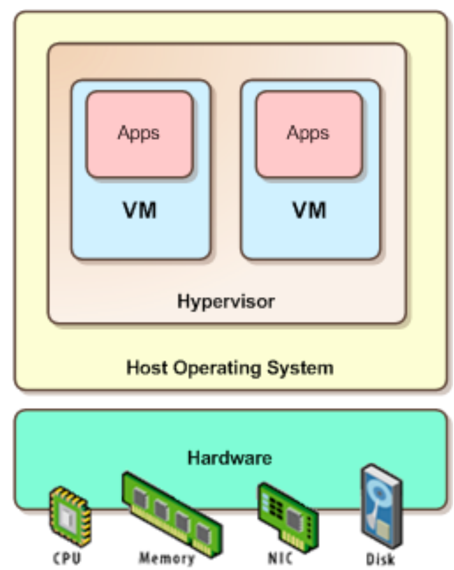
- **Process Virtualization**
  - Language-level   Java, .NET, Smalltalk
  - OS-level processes, Solaris Zones, BSD Jails, Docker Containers
  - Cross-ISA emulation Apple 68K-PPC-x86
- **System Virtualization**
  - VMware Workstation, Microsoft VPC, Parallels
  - VMware ESX, Xen, Microsoft Hyper-V



Types of Virtualization

- **Native/Bare metal (Type 1)**
  - Higher performance
  - ESX, Xen, HyperV, KVM
- **Hosted (Type 2)**
  - Easier to install
  - Leverage host’s device drivers
  - VMware Workstation, Parallels





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What is a Virtual Machine Monitor?

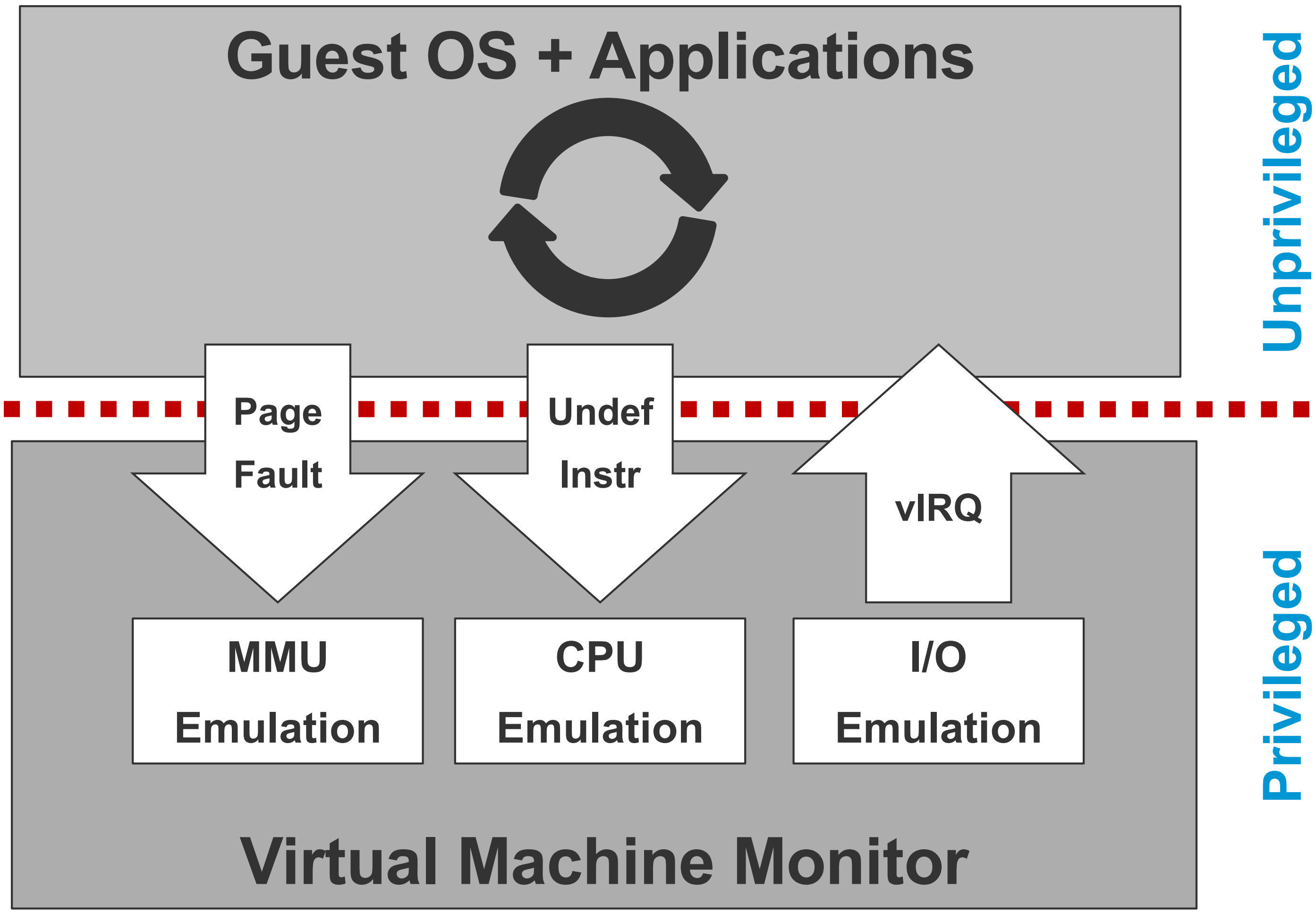
- **Classic Definition (Popek and Goldberg ’74)**

> A virtual machine is taken to be an *efficient, isolated duplicate* of the real machine. We explain these notions through the idea of a *virtual machine monitor* (VMM). See Figure 1. As a piece of software a VMM has three essential characteristics. First, the VMM provides an environment for programs which is essentially identical with the original machine; second, programs run in this environment show at worst only minor decreases in speed; and last, the VMM is in complete control of system resources.

- **VMM Properties**
  - Equivalent execution: Programs running in the virtualized environment run identically to running natively.
  - Performance: A statistically dominant subset of the instructions must be executed directly on the CPU.
  - Safety and isolation: A VMM most completely control system resources.

What Needs to Virtualized Virtualized?

- Processor
- Memory
- IO



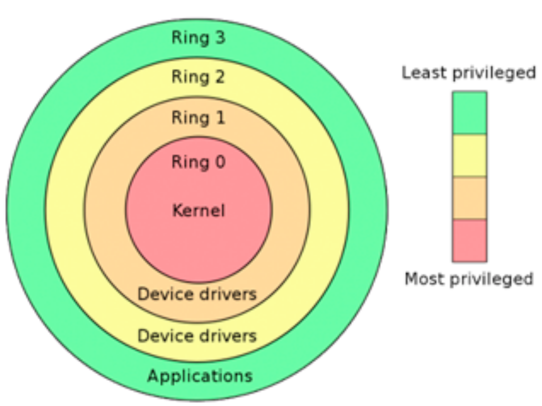
Processor Virtualization

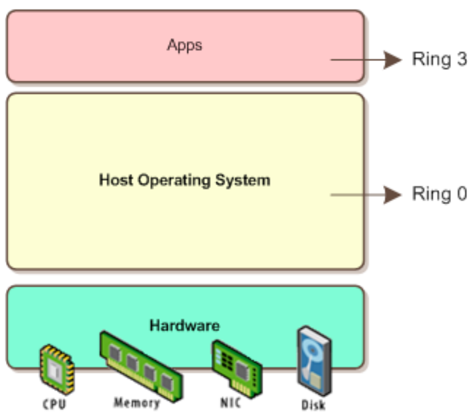
An architecture is classically/strictly virtualizable if all its sensitive instructions (those that violate safety and encapsulation) are a subset of the privileged instructions.

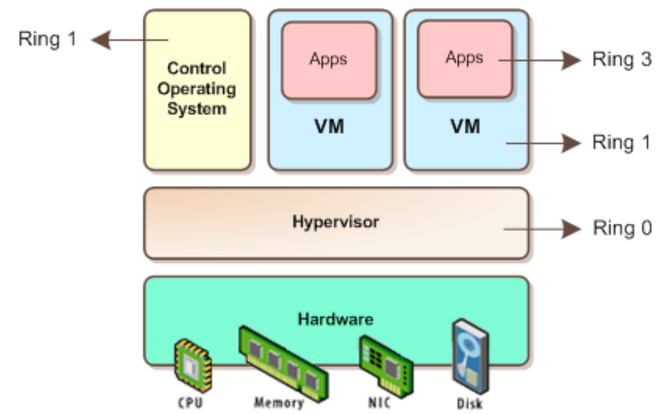
- **all instructions either trap or execute identically**
- **instructions that access privileged state trap**

Trap and Emulate

- Run guest operating system deprivileged
- All privileged instructions trap into VMM
- VMM emulates instructions against virtual state
  e.g. disable virtual interrupts, not physical interrupts
- Resume direct execution from next guest instruction







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x86 Virtualization Challenges

- **Not Classically Virtualizable**
  - x86 ISA includes instructions that read or modify privileged state
  - But which don’t trap in unprivileged mode
- **Example: POPF instruction**
  - Pop top-of-stack into EFLAGS register
  - EFLAGS.IF bit privileged (interrupt enable flag)
  - POPF silently ignores attempts to alter EFLAGS.IF in unprivileged mode!
  - So no trap to return control to VMM
- **Deprivileging not possible with x86!**

x86 Virtualization Approaches

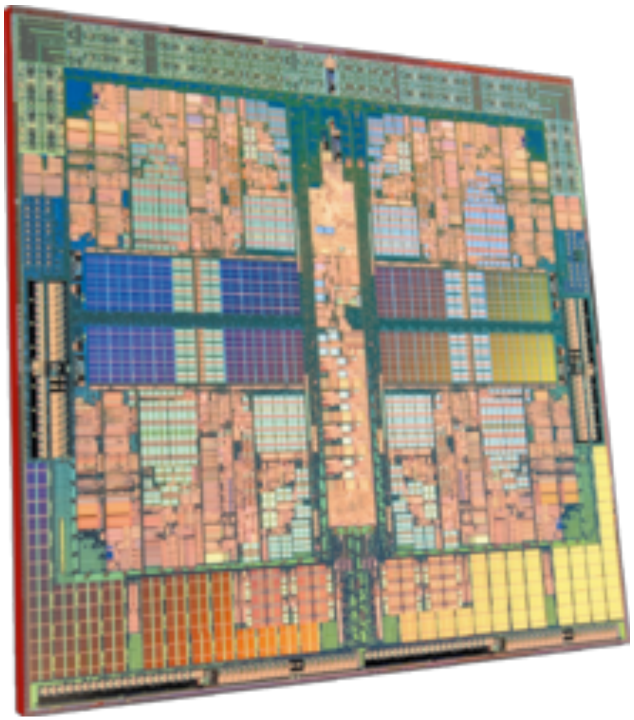
- Binary translation
- Para virtualization
- HW support

Processor Paravirtualization

- **Make OS aware of virtualization**
- **Present to OS software interface that is similar, but not identical to underlying hardware**
- **Replace dangerous system calls with calls to VMM**
  - Page table updates
- **Advantages: High performance**
- **Disadvantages: Requires porting OS**
- **Examples: Xen**

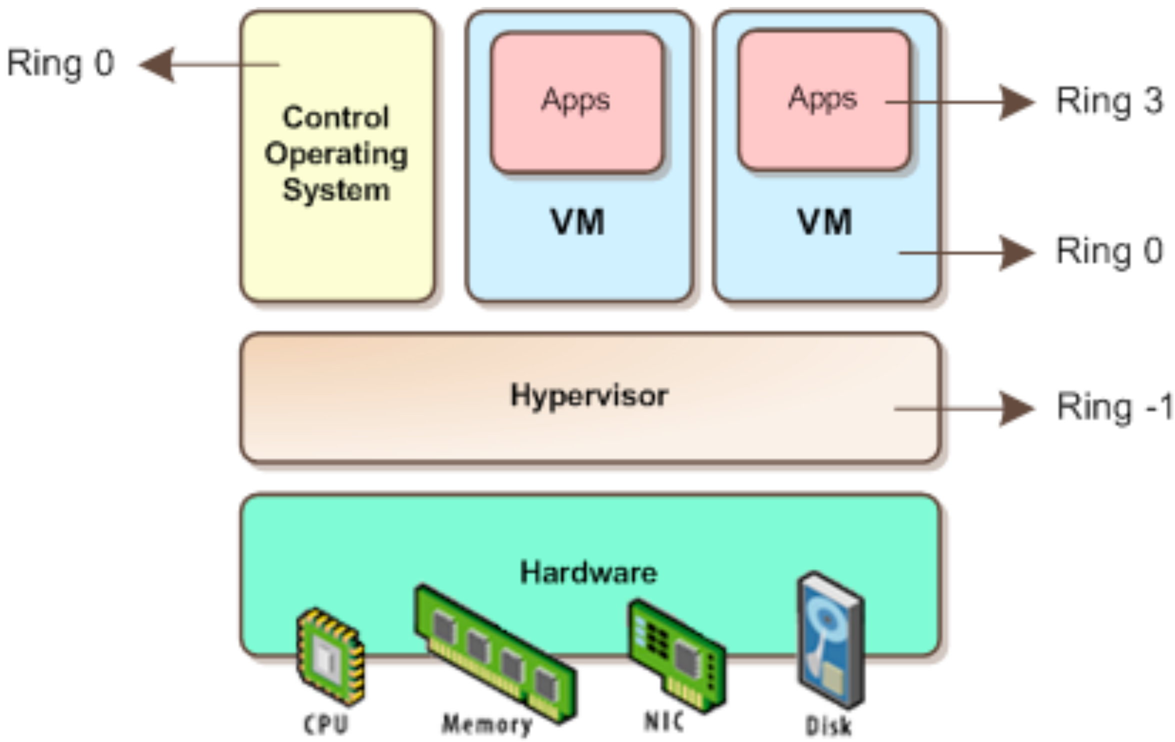
HW Support

- **Intel VT-x**
  - Codenamed "Vanderpool"
  - Available since Itanium 2 (2005), Xeon and Centrino (2006)
- **AMD-V**
  - Codename “Pacifica”
  - Available since Athlon 64 (2006)



Intel VT-x

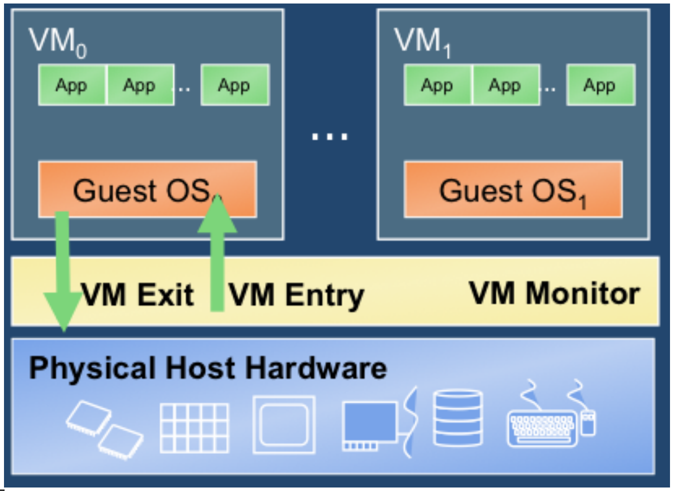
- **VT extends the original x86 architecture to eliminate holes that make virtualization hard.**



Operating Modes

- **VMX root operation:**
  - Fully privileged, intended for VM monitor
- **VMX non-root operation:**
  - Not fully privileged, intended for guest software
  - Reduces Guest SW privilege w/o relying on rings
  - Solution to Ring Aliasing and Ring Compression

VM Entry and VM Exit



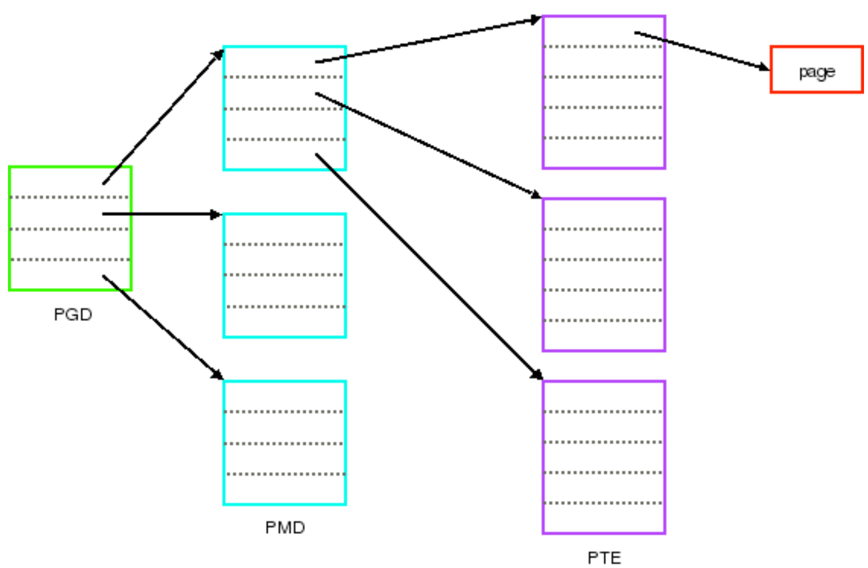
- **VM Entry**
  - Transition from VMM to Guest
  - Enters VMX non-root operation
    Loads Guest state and Exit criteria from VMCS
  - VMLAUNCH instruction used on initial entry
    VMRESUME instruction used on subsequent entries
- **VM Exit**
  - VMEXIT instruction used on transition from Guest to VMM
  - Enters VMX root operation
  - Saves Guest state in VMCS
  - Loads VMM state from VMCS
- **VMM can control which instructions cause VM exists**
  - CR3 accesses, INVLPG

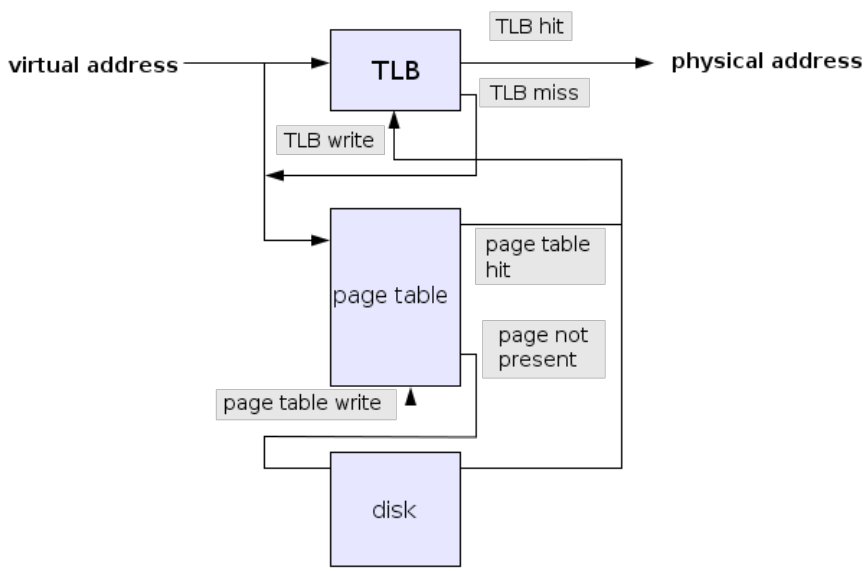
Benefits: VT Helps Improve VMMs

- **VT Reduces guest OS dependency**
  - Eliminates need for binary patching / translation
  - Facilitates support for Legacy OS
- **VT improves robustness**
  - Eliminates need for complex SW techniques
  - Simpler and smaller VMMs
  - Smaller trusted-computing base
- **VT improves performance**
  - Fewer unwanted Guest ⇔ VMM transitions

x86 Memory Management Primer

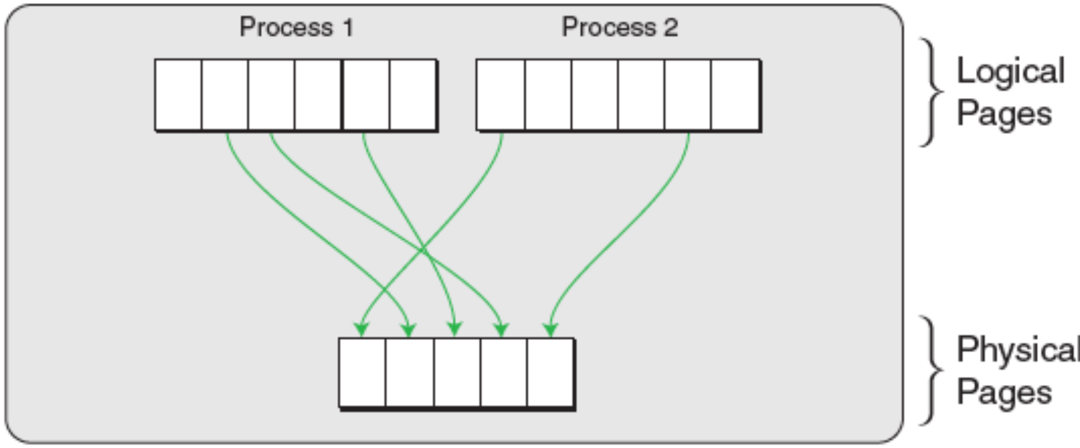
- **The processor operates with virtual addresses**
- **Physical memory operates with physical addresses**
- **x86 includes a hardware translation lookaside buffer (TLB)**
  - Maps virtual to physical page addresses
- **x86 handles TLB misses in HW**
  - CR3 points to page table root
  - HW walks the page tables
  - Inserts virtual to physical mapping



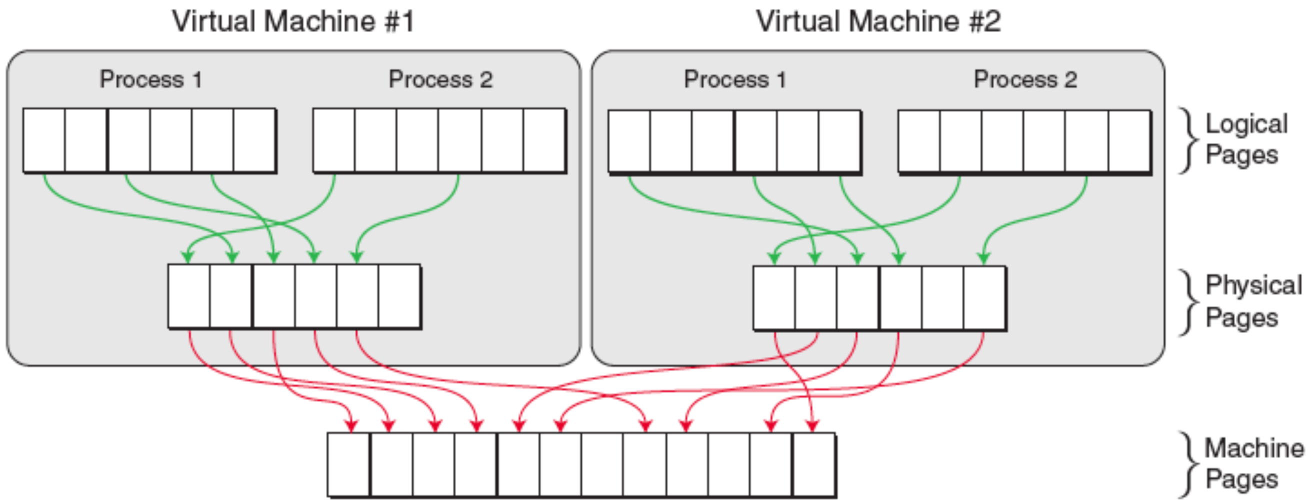


Memory Virtualization

- **Native**



- **Virtualized**

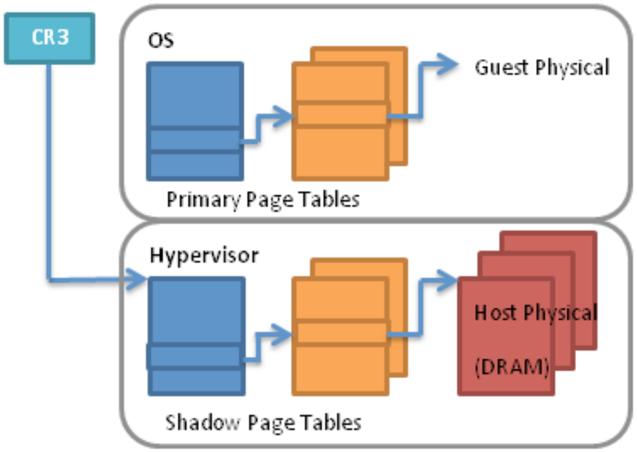


Memory Virtualization Techniques

- Shadow page tables
- Paravirtualization
- HW supported nested page tables

Shadow Page Tables

- Keep a second set of page tables hidden from guest
- Map between guest virtual and machine pages
- Detect when guest changes page tables
  - TLB invalidation requests, page table creation, write to existing page tables
- Update shadow page accordingly
- On context switch, install shadow page instead of guest page
- Advantages: Can support unmodified guest
- Disadvantages: Significant overhead to maintain consistency
- Examples: VMware and Xen HVM

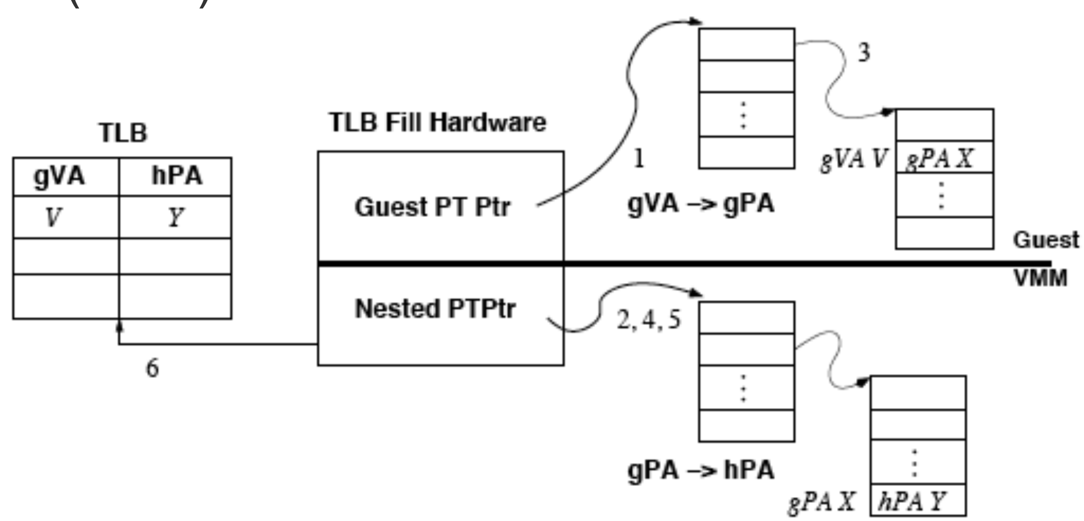


Memory Paravirtualization

- **Page table maps between virtual and machine addresses**
- **OS and VMM share page tables**
- **OS can only read**
- **Changes to page table require hyper call**
  - VMM validates that guest owns machine address
- **Advantages: Higher performance can be achieved by batching updates**
- **Disadvantages: Requires changes to the OS**
- **Examples: Xen**

Hardware Support

- **Nested page tables**
- **HW keeps a second set of page tables that map from physical to machine addresses.**
- **On a TLB miss, first find physical address from guest page tables, then map to machine address**
- **Intel EPT (Extended Page Table)**
  - Since Corei7 (2008)
- **AMD RVI (Rapid Virtualization Indexing)**
  - Since Opteron and Phenom II (2007)



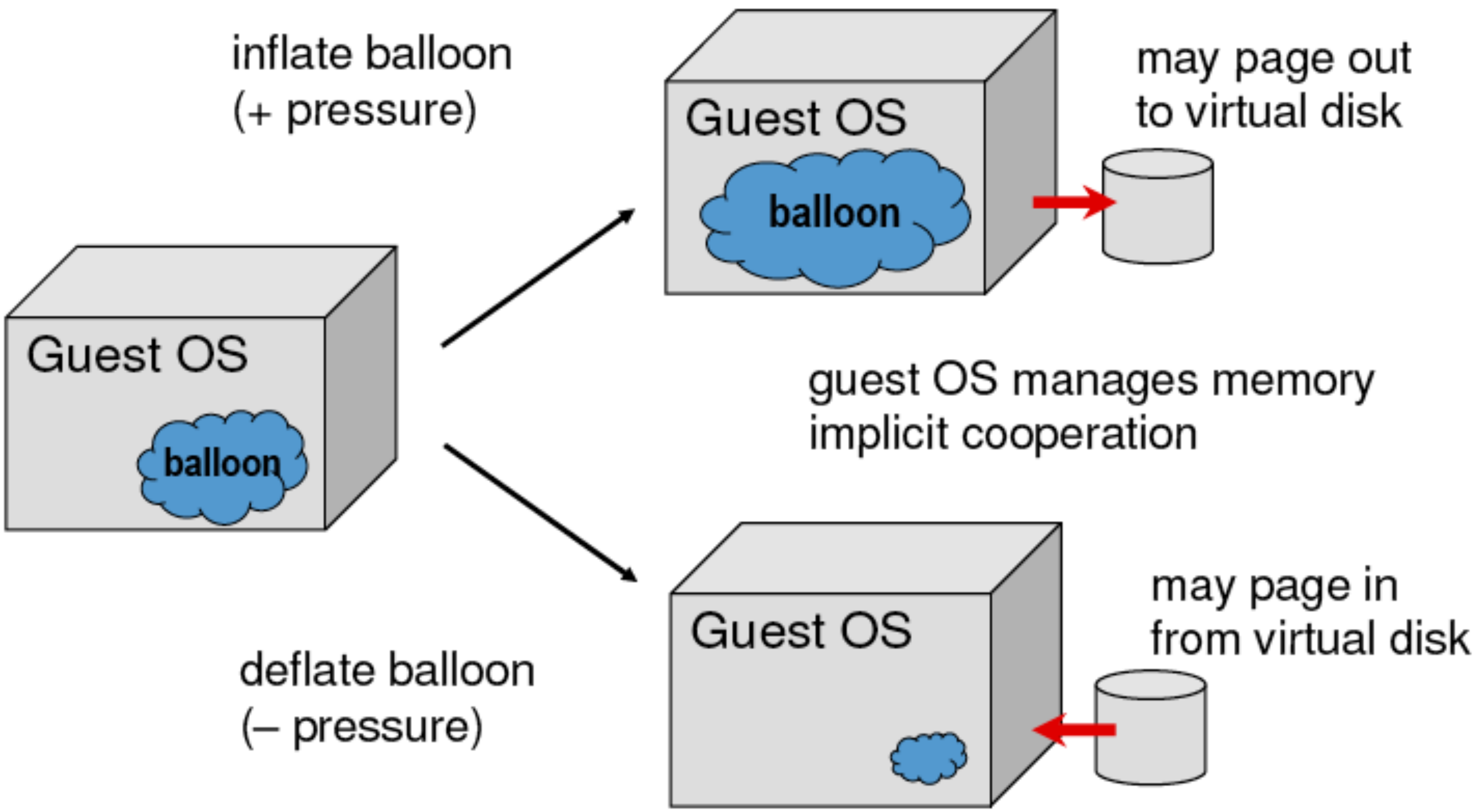
Issues with Nested Page Tables

- **Positives**
  - Simplifies monitor design
  - No need for page protection calculus
- **Negatives**
  - Guest page table is in physical address space
  - Need to walk PhysMap multiple times
    - Need physical-to-machine mapping to walk guest page table
    - Need physical-to-machine mapping for original virtual address

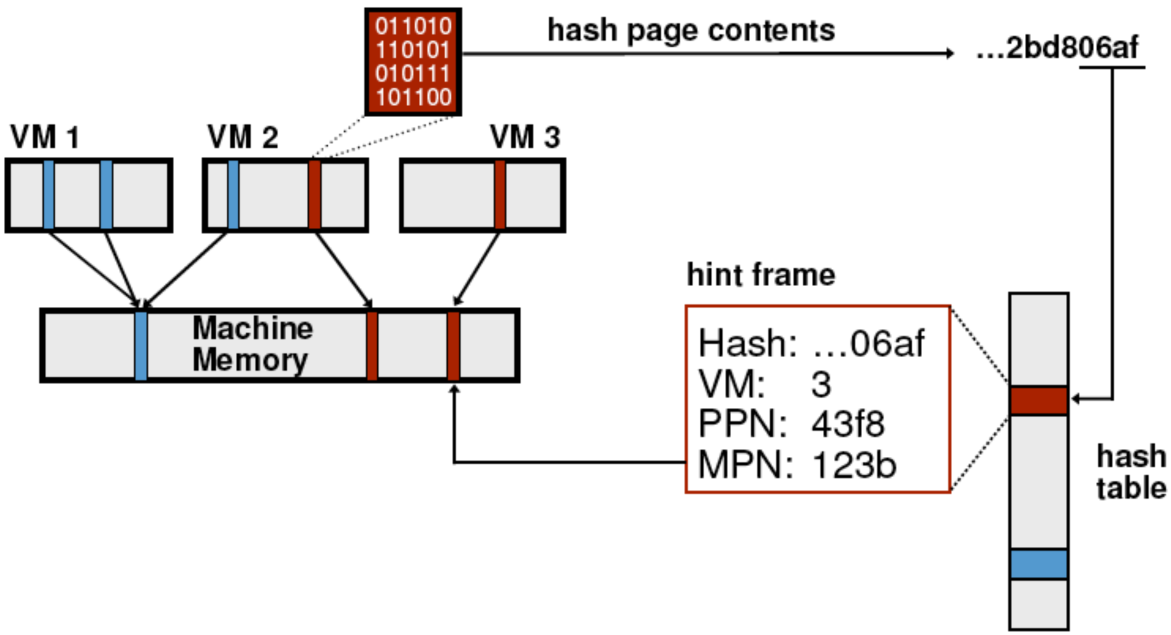
Memory Reclamation

- Balloning: guest driver allocates pinned PPNs, hypervisor deallocates backing MPNs
- Swapping: hypervisor transparently pages out PPNs, paged in on demand
- Page sharing: hypervisor identifies identical PPNs based on content, maps to same MPN copy-on-write

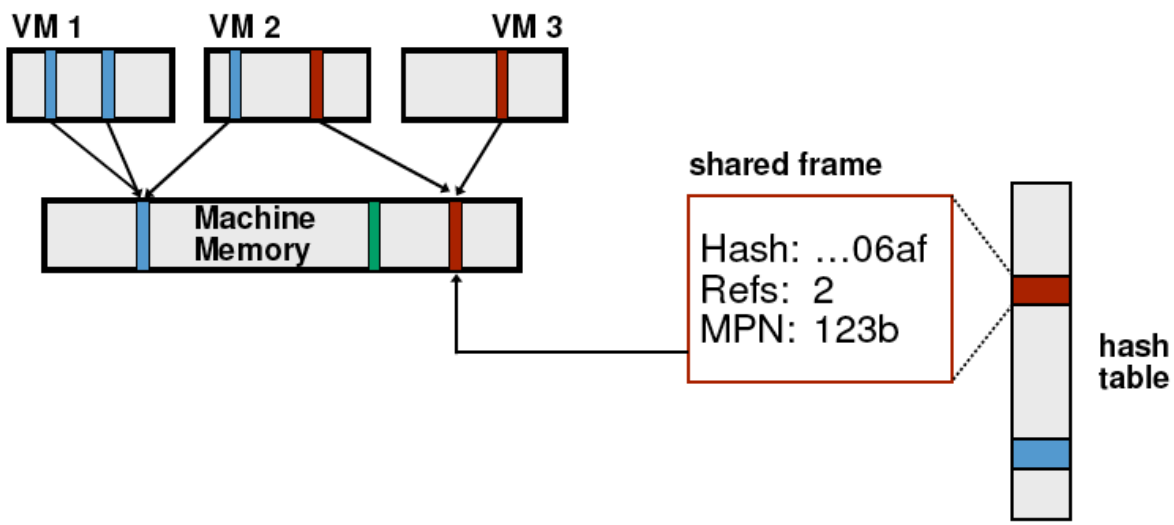
Ballooning


inflate balloon
(+ pressure)
Guest OS
balloon
may page out
to virtual disk
Guest OS
balloon
guest OS manages memory
implicit cooperation
Guest OS
may page in
from virtual disk
deflate balloon
(– pressure)

Page Sharing



Page Sharing

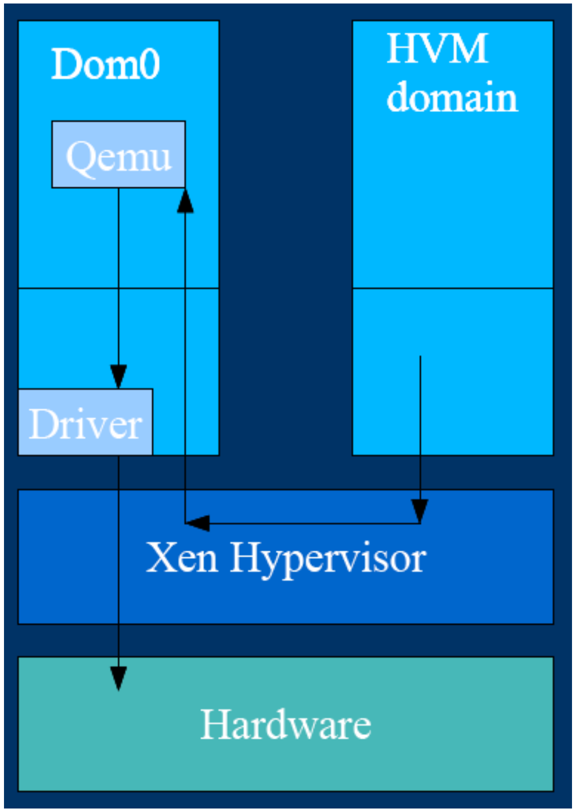


I/O Virtualization

- **Emulation**
- **Paravirtualization (split driver)**
- **Direct mapped/PCI passthrough**
- **Hardware support**

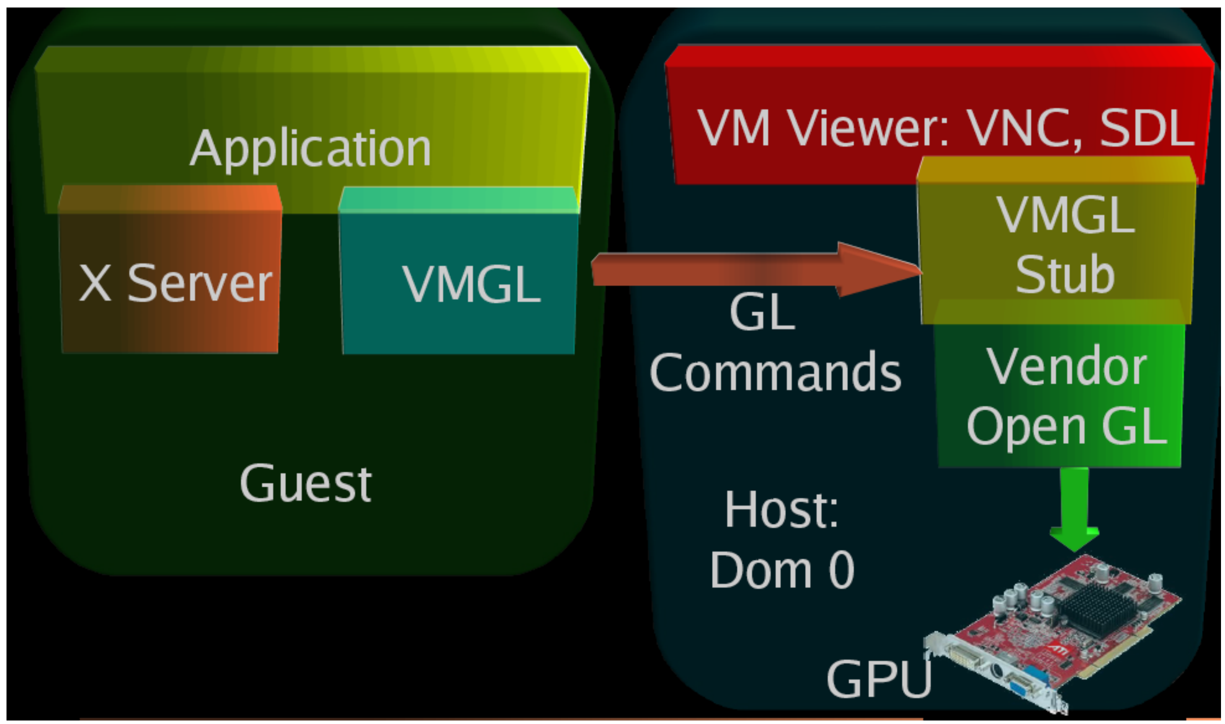
Emulation

- Guest runs original driver
- VMM emulates HW in SW
- Advantages: Can run unmodified guest
- Disadvantages: Slow



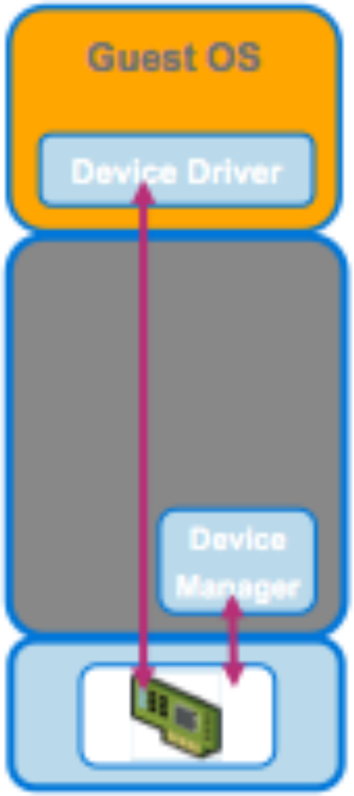
IO Paravirtualization

- Slip driver approach
- Privileged domain interact with IO devices, exports high level interface as back-end drive
- Guest domain implements front end driver
- Front and back end drivers



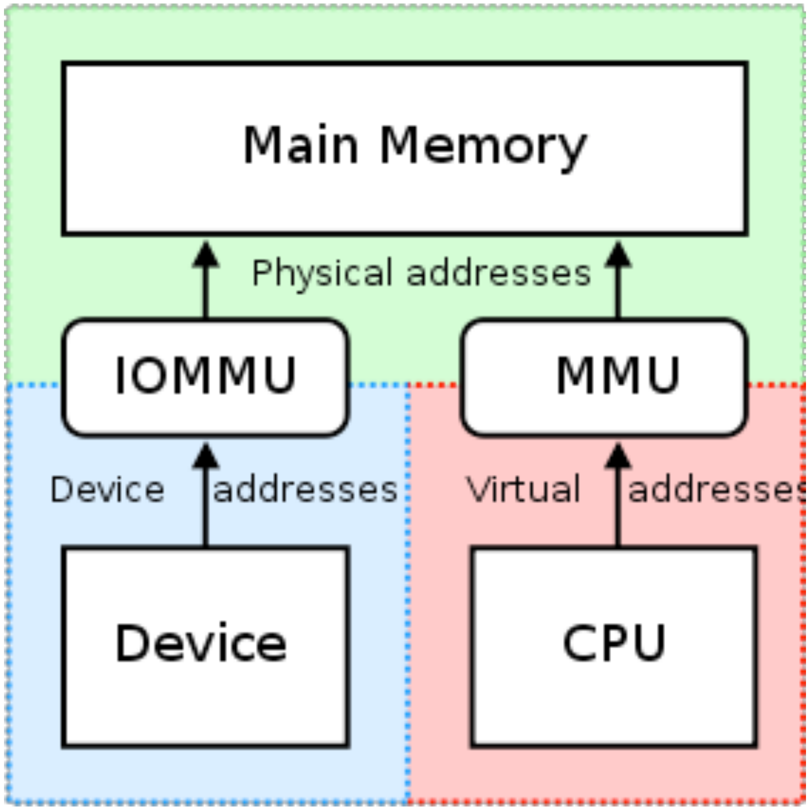
Direct Mapped/PCI Passthrough

- Allocate a physical device to a specific domain
- Driver runs of guest domain
- Cannot use DMA
  - DMA uses physical addresses.
  - Breaks isolation



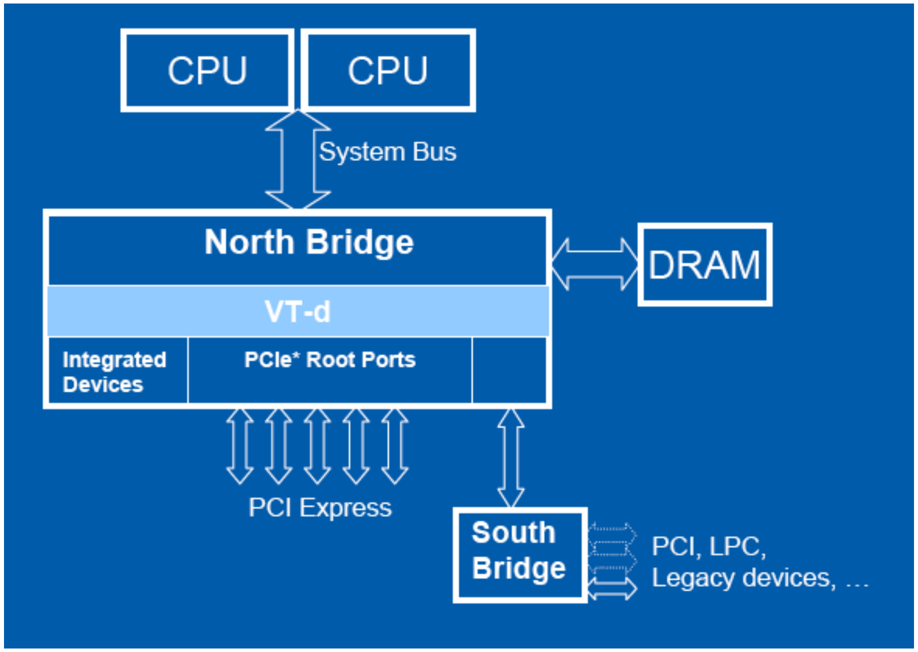
Hardware Support

- IOMMU (IO Memory Management Unit)
- Translates memory addresses from “IO space” to “physical space”
- Provides isolation. Limits device’s ability to access machine memory.
- Intel VT-d
  - Core 2 (2008)
- AMD-Vi
  - Six Core Opteron (2010)



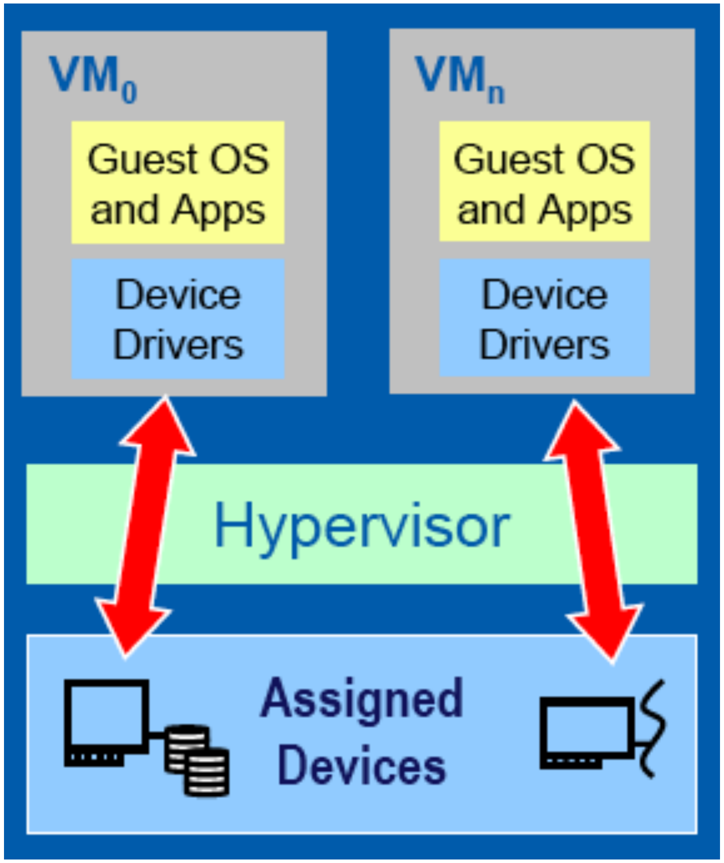
Intel VT-d

- Provides infrastructure for I/O virtualization
- DMA and interrupt remapping



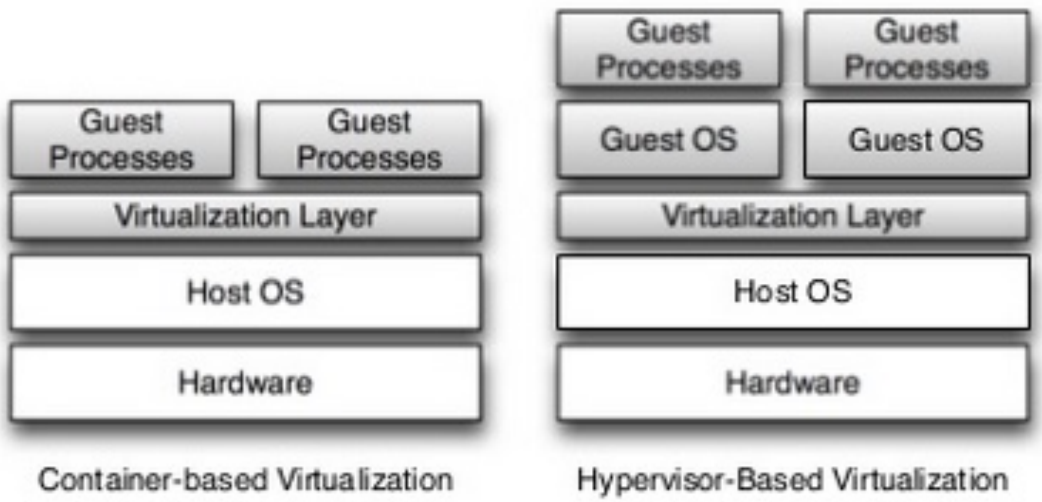
VT-d Applied to Pass-through Model

- Direct Device Assignment to Guest OS
  - Guest OS directly programs physical device
  - VMM sets up guest- to host-physical DMA mapping
- PCI-SIG I/O Virtualization Working Group
  - Activity towards standardizing natively sharable I/O devices
  - IOV devices provide virtual interfaces, each independently assignable to VMs
- Advantages: High performance and simple VMM
- Disadvantages: Limits VM migration



Operating System Level Virtualization

- aka Container-based Virtualization
- Shared operating system
- A group of OS processes in an insolated environment
- Lightweight virtualization layer



Operating System-Level Virtualization

- Each container has:
  - Own virtual network interface (and IP Address)
  - Own filesystem
  - Isolation
    - Processes in different containers can not see each other
    - Allocation of RAM, CPU, I/O
- Examples
  - Linux Vserver, OpenVZ, LXC

Hypervisor vs. System-Level Virtualization

Hypervisor	OS-Level/Container
Different Kernel OS	Single Kernel
Device Emulation	Syscall
Limits per machine	Limits per process
Higher overhead	Lower overhead
More secure	Less secure