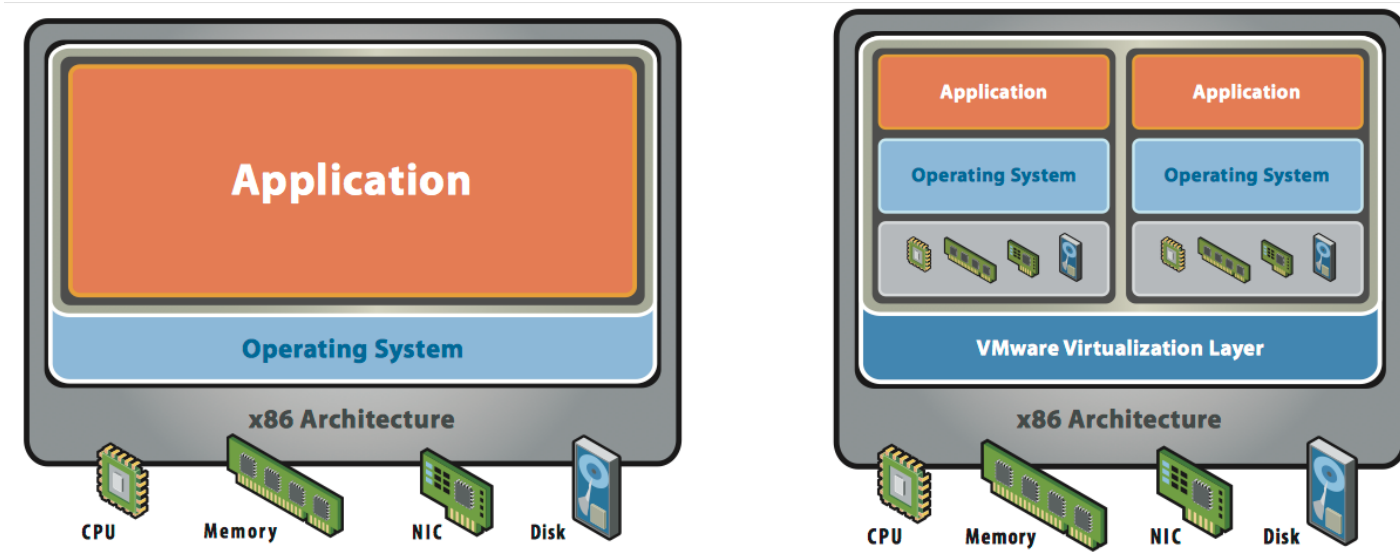
CS 5450

Virtualization

Vitaly Shmatikov

Virtualization



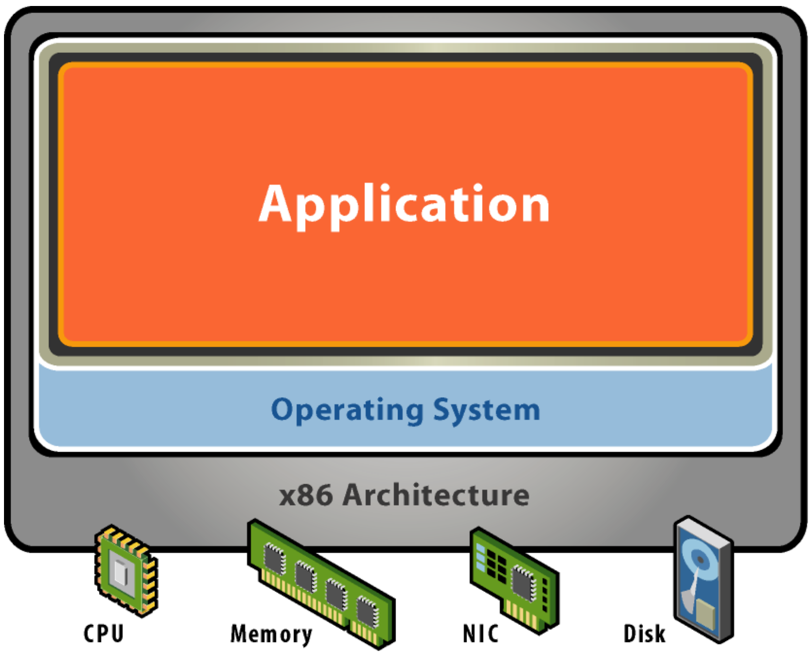
Before Virtualization:

- Single OS image per machine
- Software and hardware tightly coupled
- Running multiple applications on same machine often creates conflict
- Underutilized resources
- Inflexible and costly infrastructure

After Virtualization:

- Hardware-independence of operating system and applications
- Virtual machines can be provisioned to any system
- Can manage OS and application as a single unit by encapsulating them into virtual machines

Physical Machine

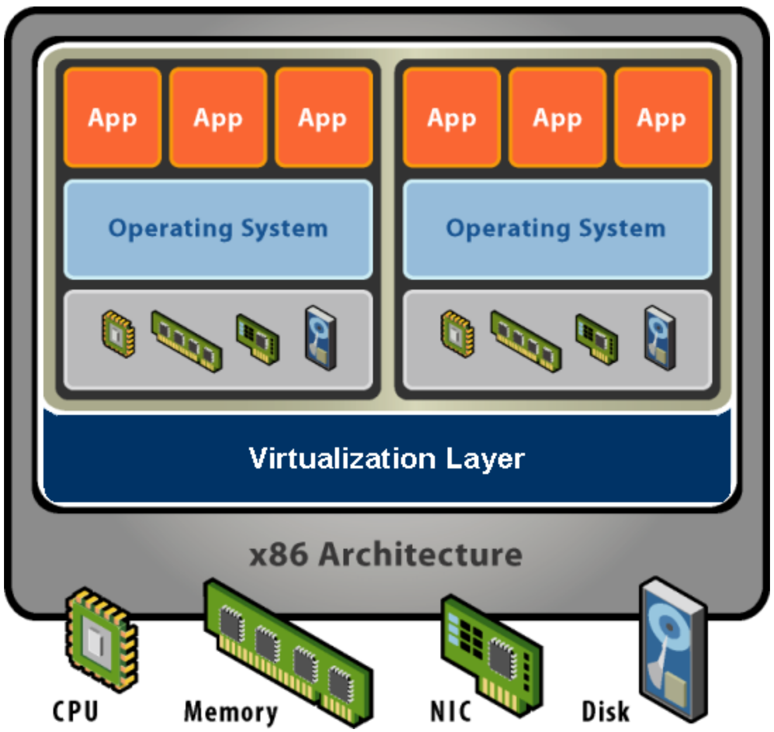


- Physical hardware
  - Processors, memory, chipset, I/O devices, etc.
  - Resources often grossly underutilized
- Software
  - Tightly coupled to physical hardware
  - Single active OS instance
  - OS controls hardware

OS Limitations

- OSes provide a way of virtualizing hardware resources among processes
- Helps isolate processes from one another, but does <u>not</u> provide a virtual machine to a user who may wish to run a different OS
- Having hardware resources managed by a single OS limits the flexibility of the system in terms of available software, security, and failure isolation

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

Types of Virtualization

- Process virtualization
  - Language-level Java, .NET, Smalltalk
  - OS-level processes, Solaris Zones, BSD Jails, Virtuozzo
  - Cross-ISA emulation Apple 68K-PPC-x86, Digital FX!32
- Device virtualization
  - Logical vs. physical VLAN, VPN, NPIV, LUN, RAID
- System virtualization
  - "Hosted" VMware Workstation, Microsoft VPC, Parallels
  - "Bare metal" VMware ESX, Xen, Microsoft Hyper-V

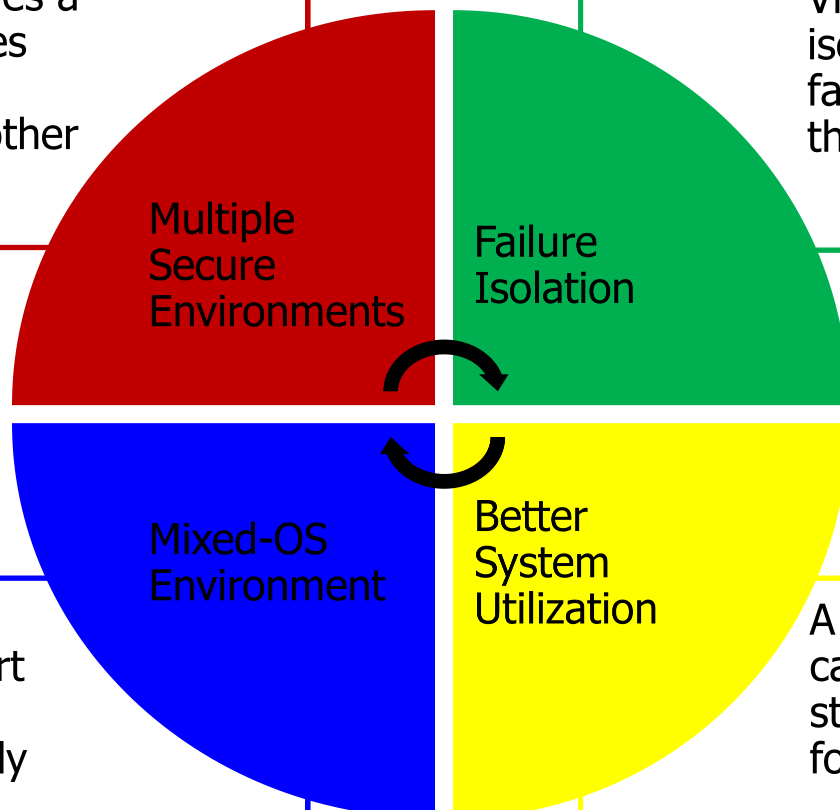
Virtualization Properties

- Isolation of faults and performance
- Encapsulation of entire VM state
  - Enables snapshots and cloning of VMs
- 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 …

Benefits of Virtualization

A system VM provides a sandbox that isolates one system environment from other environments

Virtualization helps isolate the effects of a failure to the VM where the failure occurred



A single hardware platform can support multiple operating systems concurrently

A virtualized system can be (dynamically or statically) re-configured for changing needs

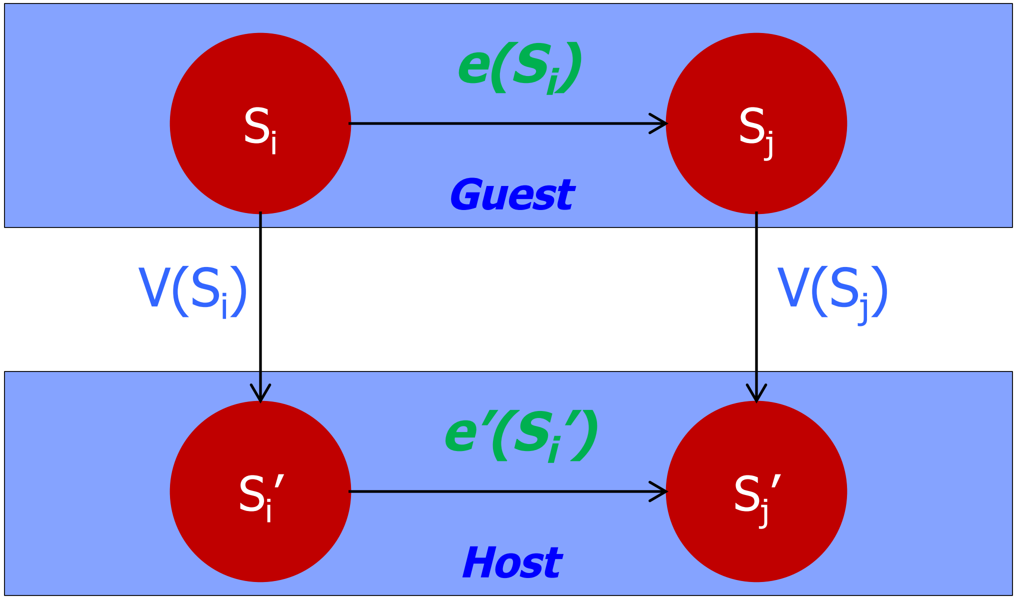
What Is Virtualization?

Informally, a virtualized system (or subsystem) is a <u>mapping</u> of its interface, and all resources visible through that interface, to the interface and resources of a real system

Formally, virtualization involves the construction of an isomorphism that <u>maps</u> a virtual guest system to a real host system (Popek and Goldberg 1974)

Function V maps the guest state to the host state

For a sequence of operations, ***e***, that modifies a guest state, there is a corresponding ***e′*** in the host that performs an equivalent Modification



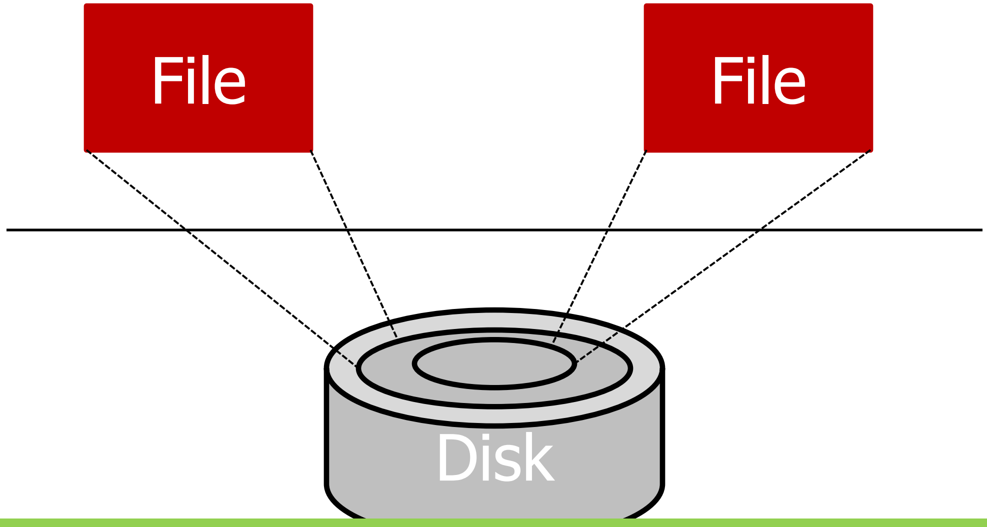
Virtual Machine Monitor

[Popek and Goldberg 1974]

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.

Abstraction

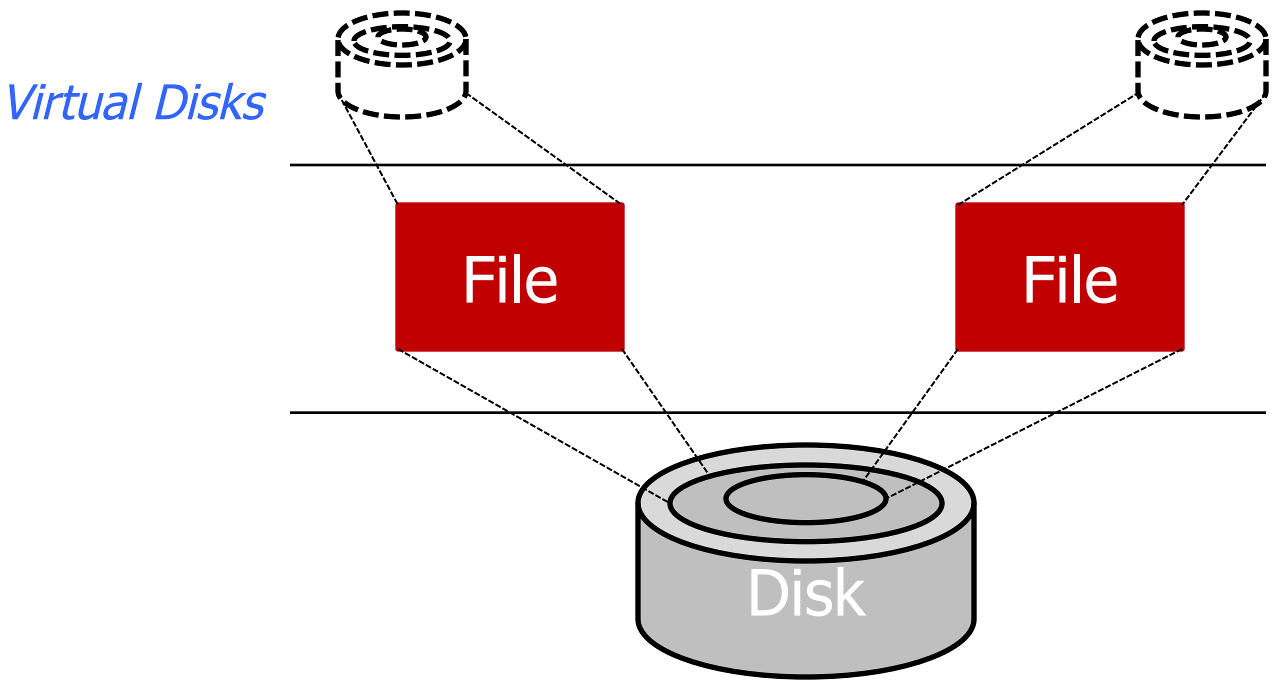
- The key to managing complexity in computer systems is their division into levels of abstraction separated by well-defined interfaces



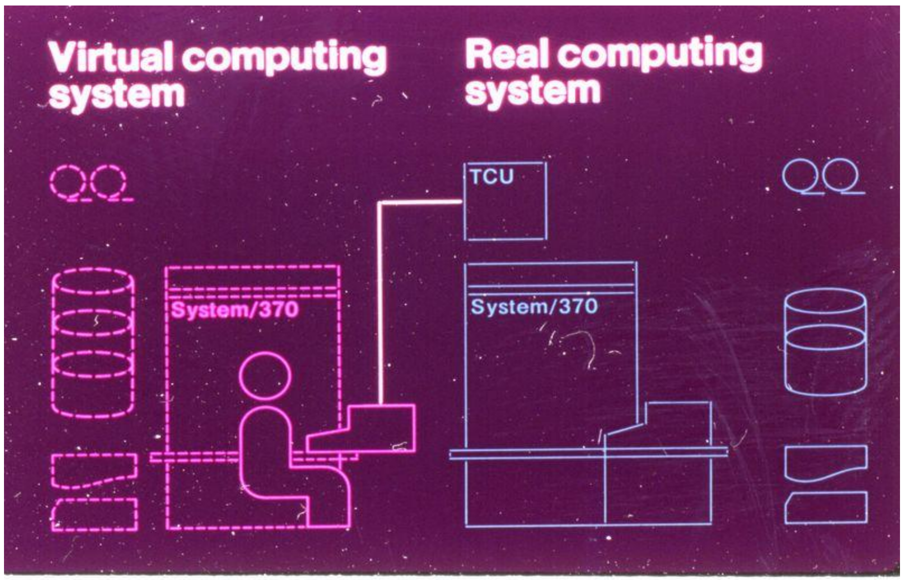
- Files are an abstraction of a disk
- A level of abstraction provides a simplified interface to underlying resources

Virtualization and Abstraction

- Virtualization uses abstraction but the level of detail is often the same as in underlying system



"Classic" Virtualization

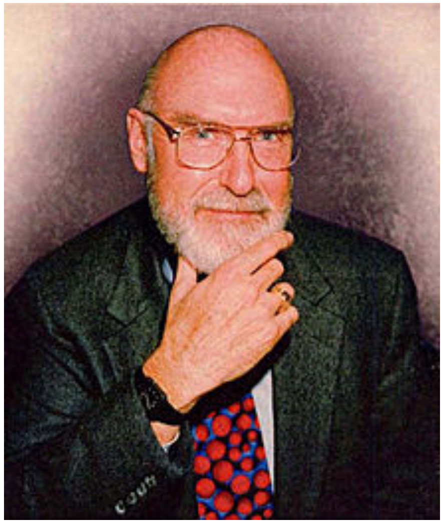


From IBM VM/370 product announcement, *ca*. 1972

- Classical VMM
  - IBM mainframes: IBM S/360, IBM VM/370
  - Co-designed proprietary hardware, OS, VMM
  - "Trap and emulate" model
- Applications
  - Timeshare several single-user OS instances on expensive hardware
  - Compatibility

IBM VM/370

- Robert Jay Creasy (1939-2005)
  - Project leader of the first full virtualization hypervisor: IBM CP-40, a core component in the VM system
- First VM system: VM/370



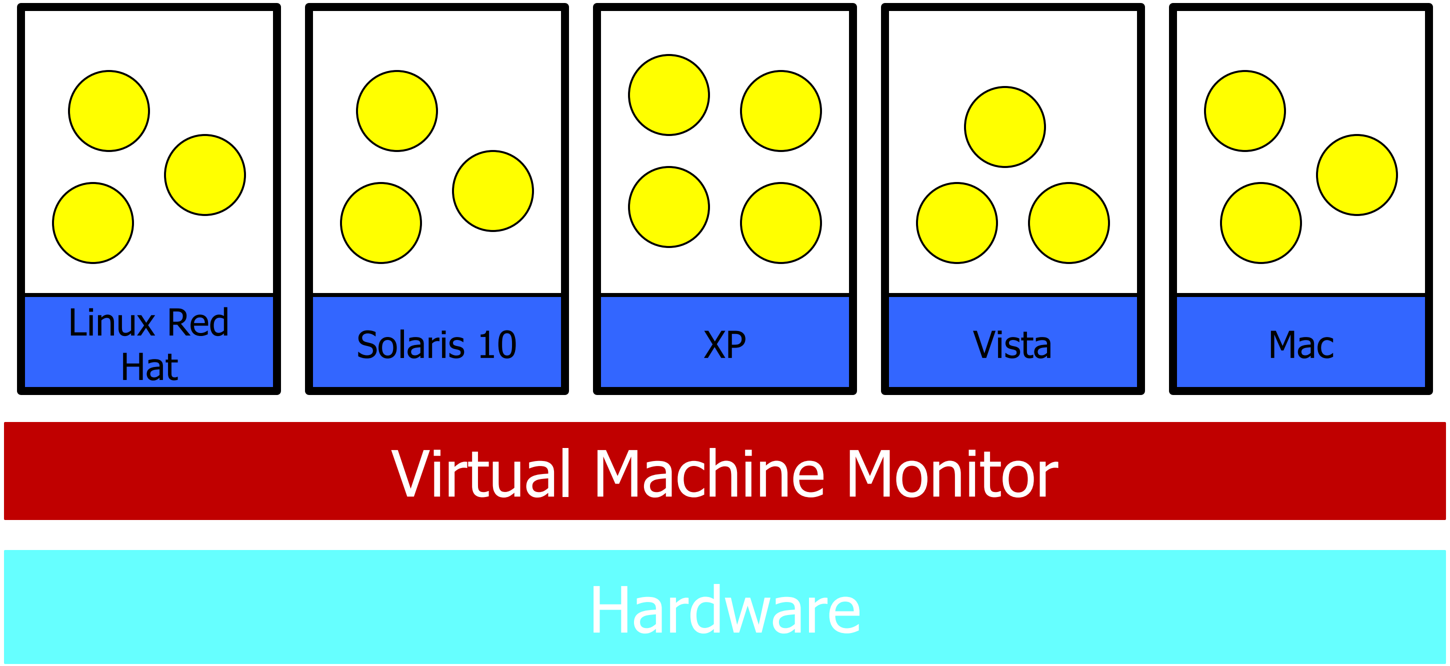
Virtualization Renaissance

- Recent proliferation of VMs
  - Considered exotic mainframe technology in 1990s
  - Now pervasive in datacenters and clouds
  - Huge commercial success
- Why?
  - Introduction on commodity x86 hardware
  - Ability to “do more with less” saves $$$
  - Innovative new capabilities
  - Extremely versatile technology

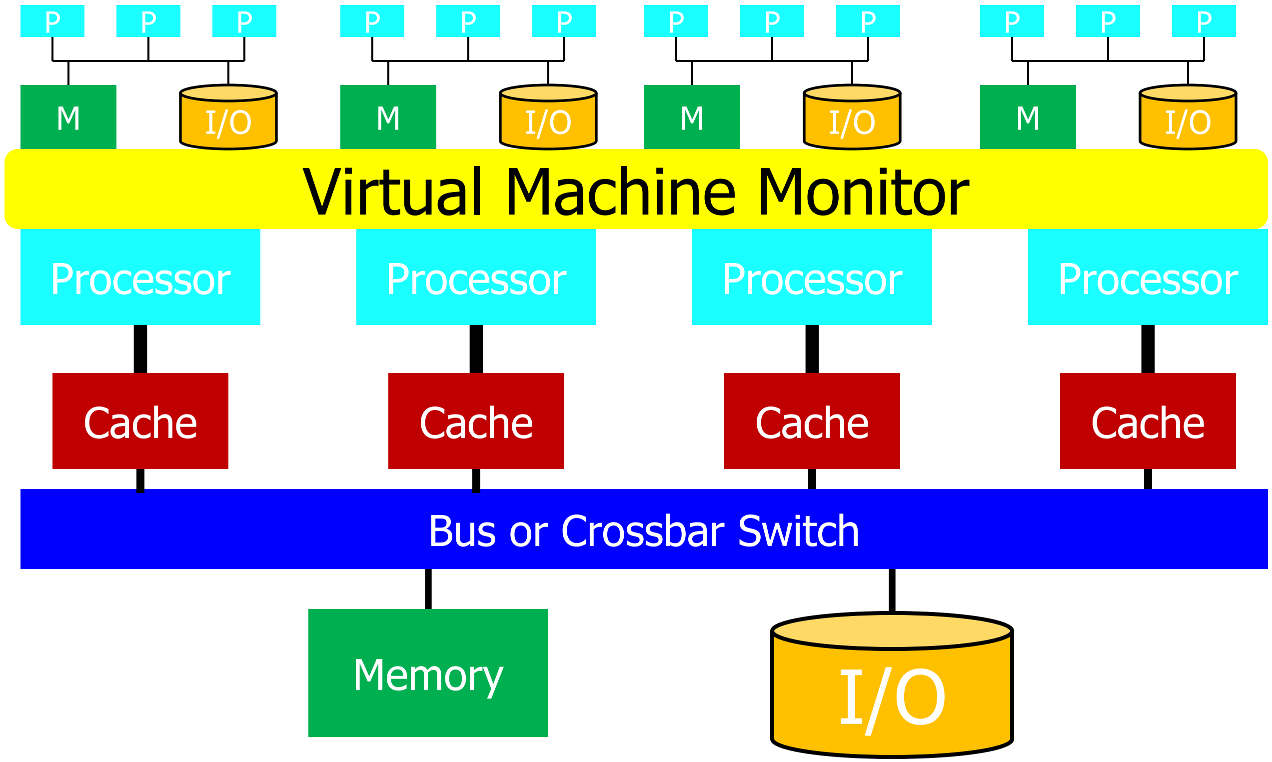
Modern Virtualization Applications

- Server consolidation
  - Convert underutilized servers to VMs
  - Significant cost savings (equipment, space, power)
  - Increasingly used for virtual desktops
- Simplified nanagement
  - Datacenter provisioning and monitoring
  - Dynamic load balancing
- Improved availability
  - Automatic restart, fault tolerance, disaster recovery
- Test and development

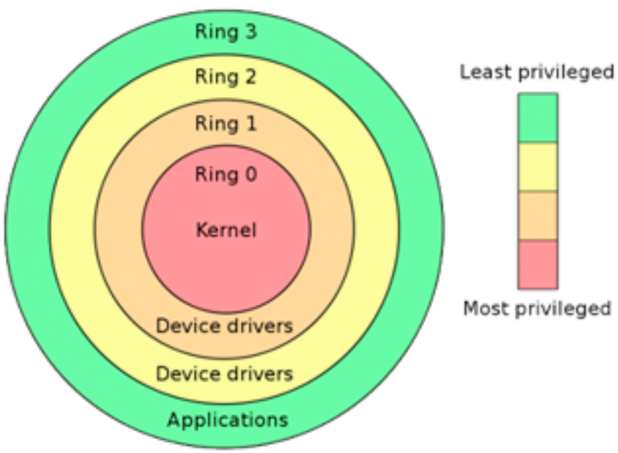
A Mixed OS Environment

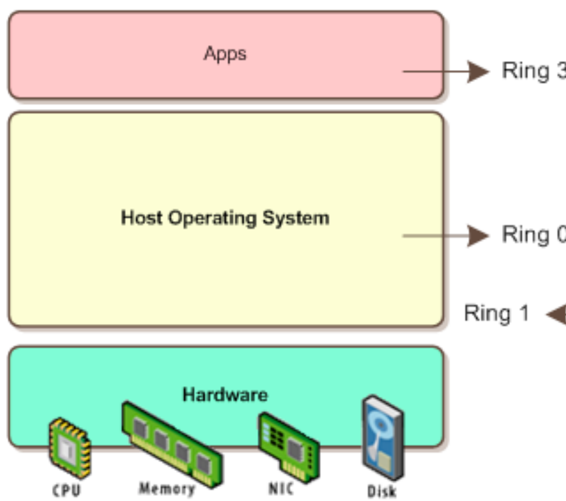


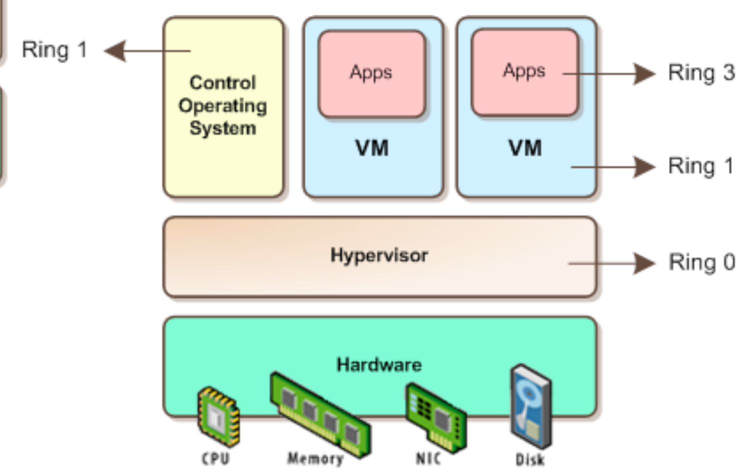
Multiprocessor Virtualization



Virtualizing Processor



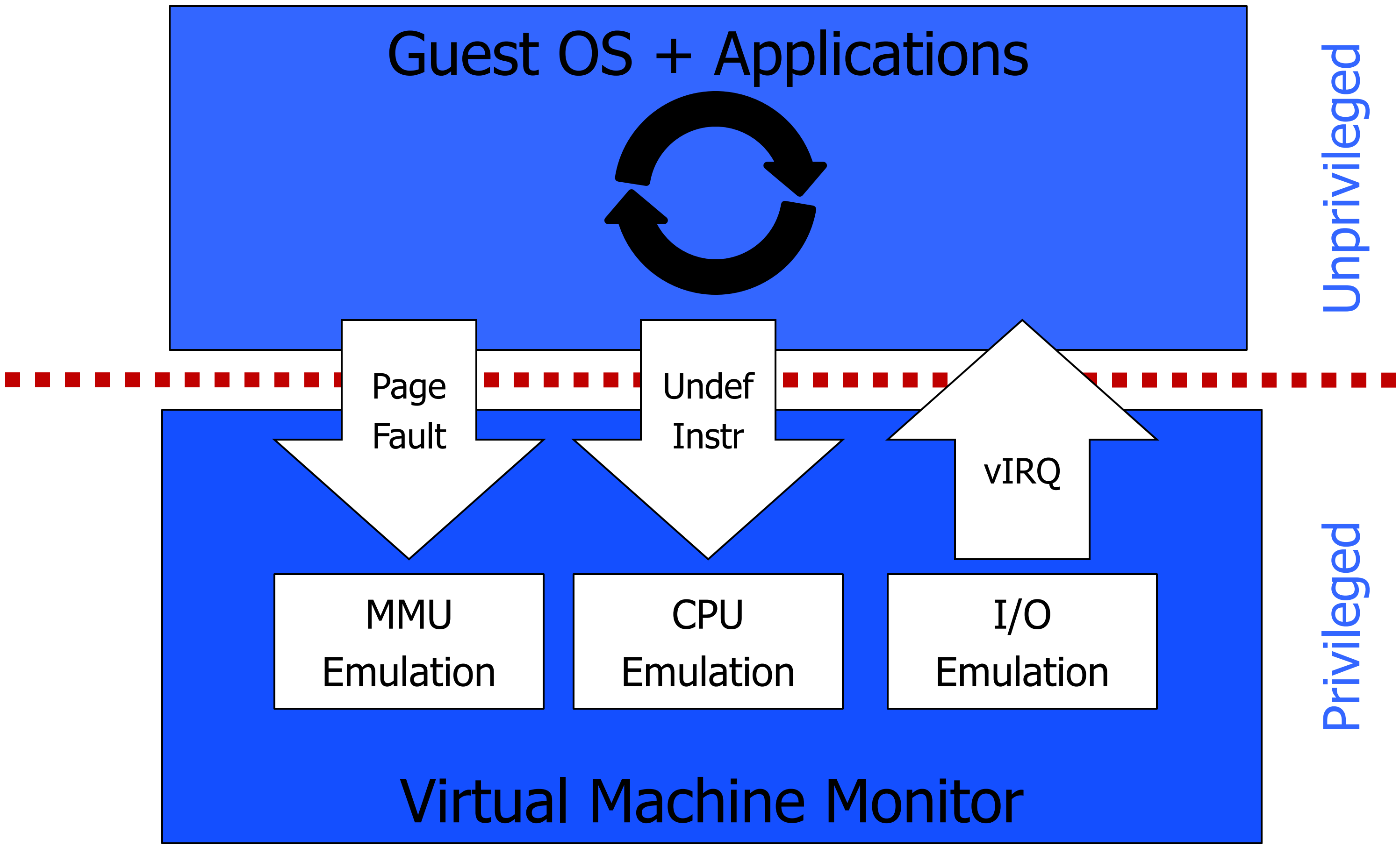




Trap and Emulate

- 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

Trap and Emulate



Pretend to OS it's still running in privileged mode

Issues with Trap-and-Emulate

- Not all architectures support it
- Trap costs may be high
- VMM consumes a privilege level
  - Need to virtualize the protection levels

“Strictly Virtualizable”

A processor or mode of a processor is strictly virtualizable if, when executed in a lesser privileged mode:

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

x86 is Not Strictly Virtualizable

- On x86, popf instruction takes a word off the stack and puts it into the flags register
- At OS level, popf updates interrupt enable flag (IF)
- At user level, updates to IF silently dropped
  - To prevent user-level code from messing up the OS
- When VMM runs the OS at user level, all OS modifications to IF are dropped and VMM doesn't know whether OS wants interrupts enabled or not
- Several other reasons why trap-and-emulate wouldn't work for x86

Binary Translation

Goal: translate potentially dangerous and non-virtualizable instruction sequences one-by-one into safe sequences

- Privileged instructions, control flow, memory accesses

◆ If safe instruction, copy into translation cache

◆ If simple dangerous instruction, "inline" translate into short sequence of emulation code, copy into translation cache

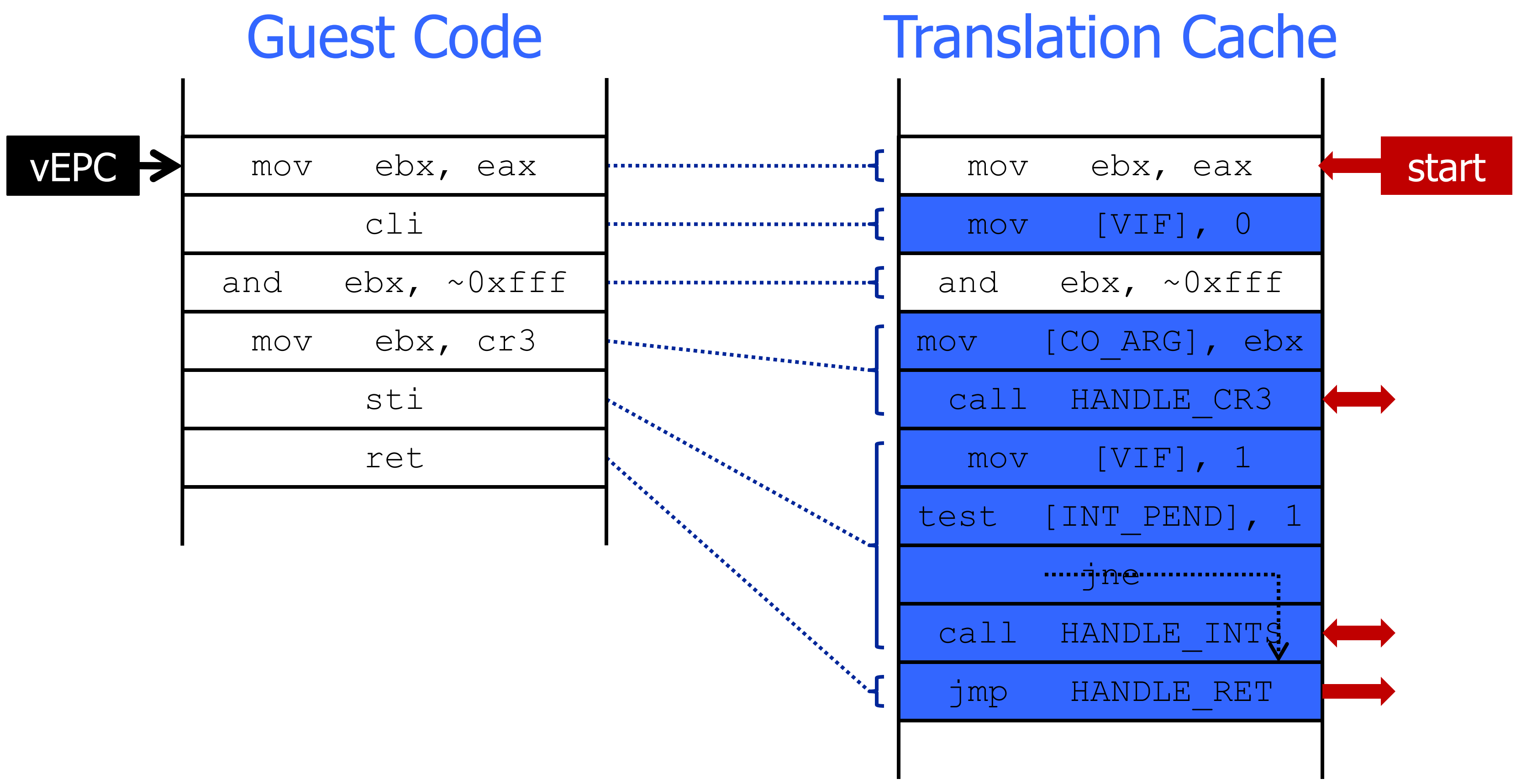
- Example: modification of the Interrupt Enable flag

◆ If another dangerous instructions, execute emulation code in the monitor ("call-out")

- Example: change to the page table base, branch ending basic block

◆ Monitor jumps to the start of the translated basic block with the virtual registers in the hardware registers.

Example of Binary Translation



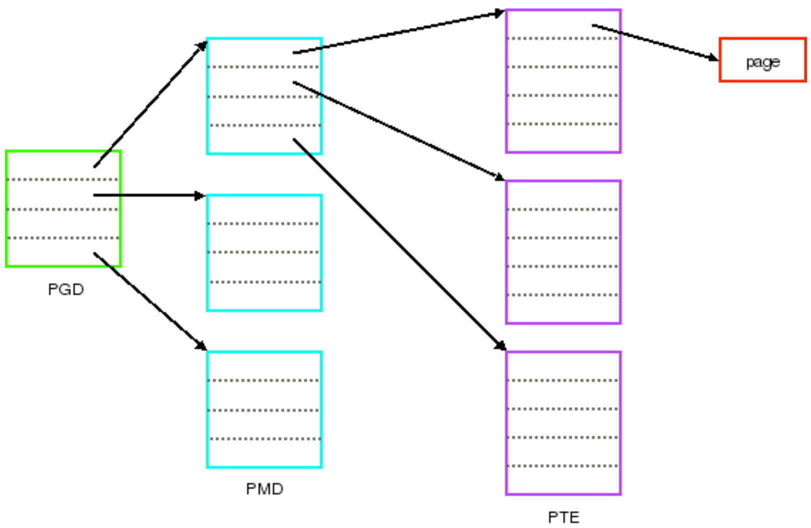
Issues with Binary Translation

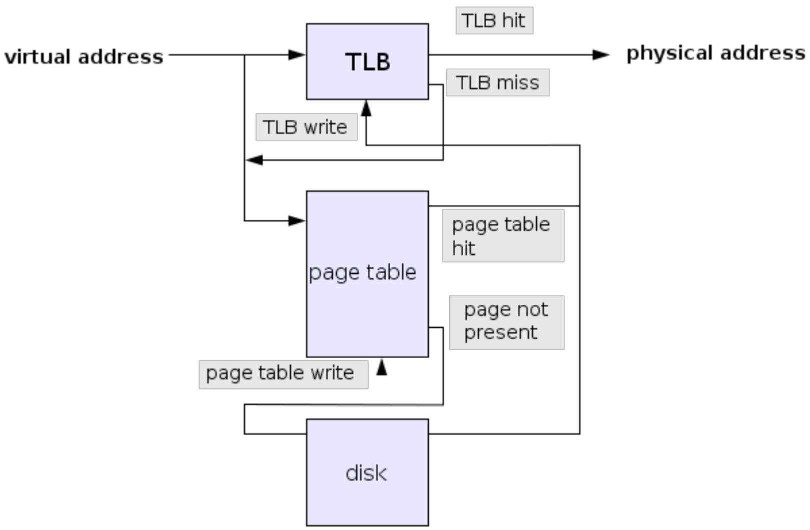
- Translation cache management
- PC synchronization on interrupts
- Self-modifying code
  - Notified on writes to translated guest code
- Protecting VMM from guest

x86 Memory Management

- The processor operates with virtual addresses
- Physical memory operates with physical addresses
- Hardware translation lookaside buffer (TLB) maps virtual to physical page addresses
- TLB misses handled in hardware
  - Hardware walks the page tables and inserts virtual to physical mapping

x86 Memory Management



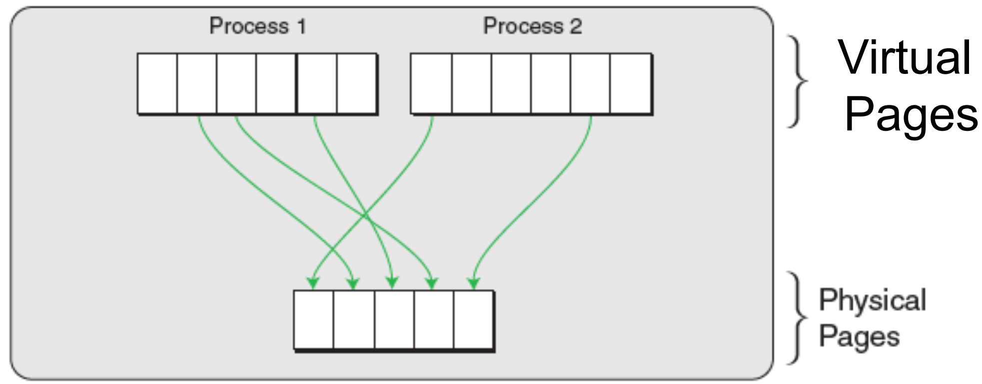


Virtualizing Memory

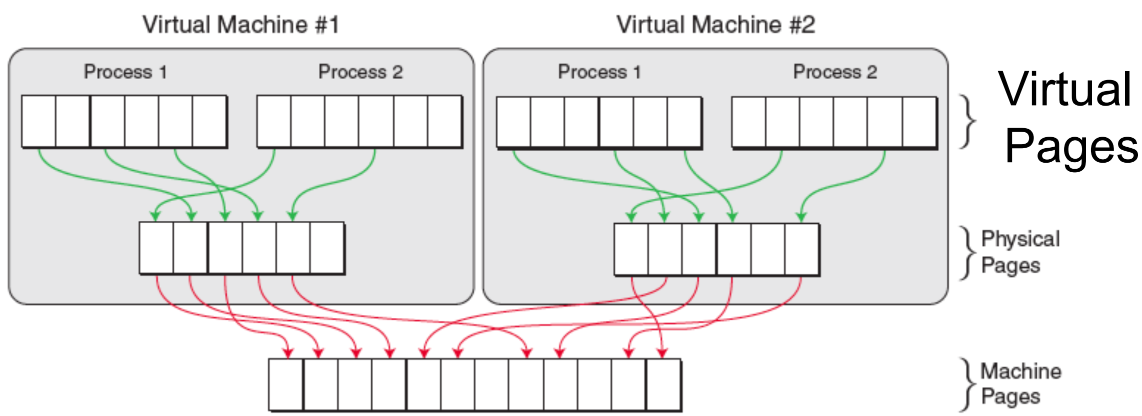
- OS assumes that it has full control over memory
  - Management: assumes it owns it all
  - Mapping: assumes it can map any virtual → physical
- However, VMM partitions memory among VMs
  - VMM needs to assign hardware pages to VMs
  - VMM needs to control mapping for isolation
    - Cannot allow OS to map any virtual → hardware page
- Hardware-managed TLBs make this difficult
  - On TLB misses, hardware walks page tables in memory
  - VMM needs to control access by OS to page tables

Virtualized Memory

Native



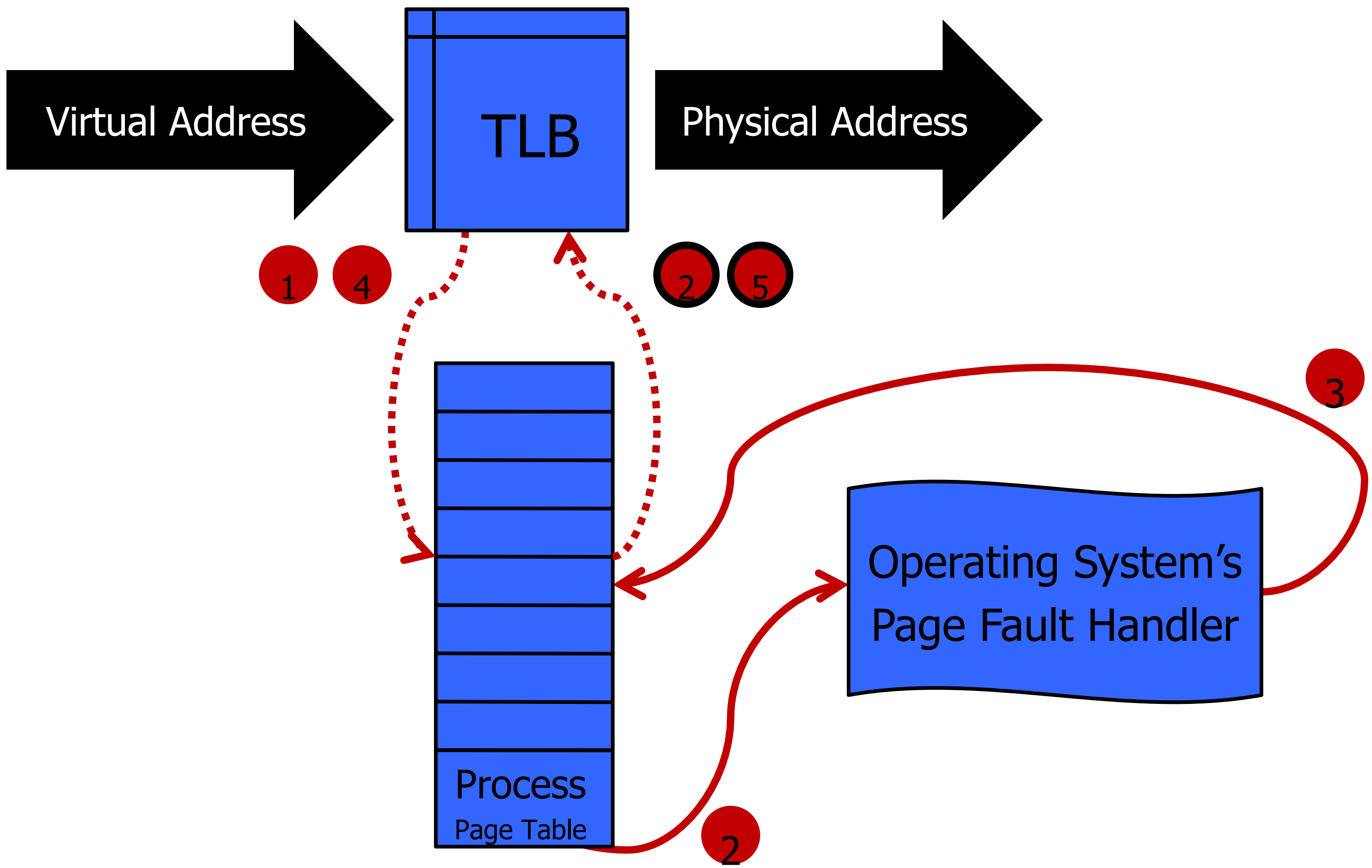
Virtualized



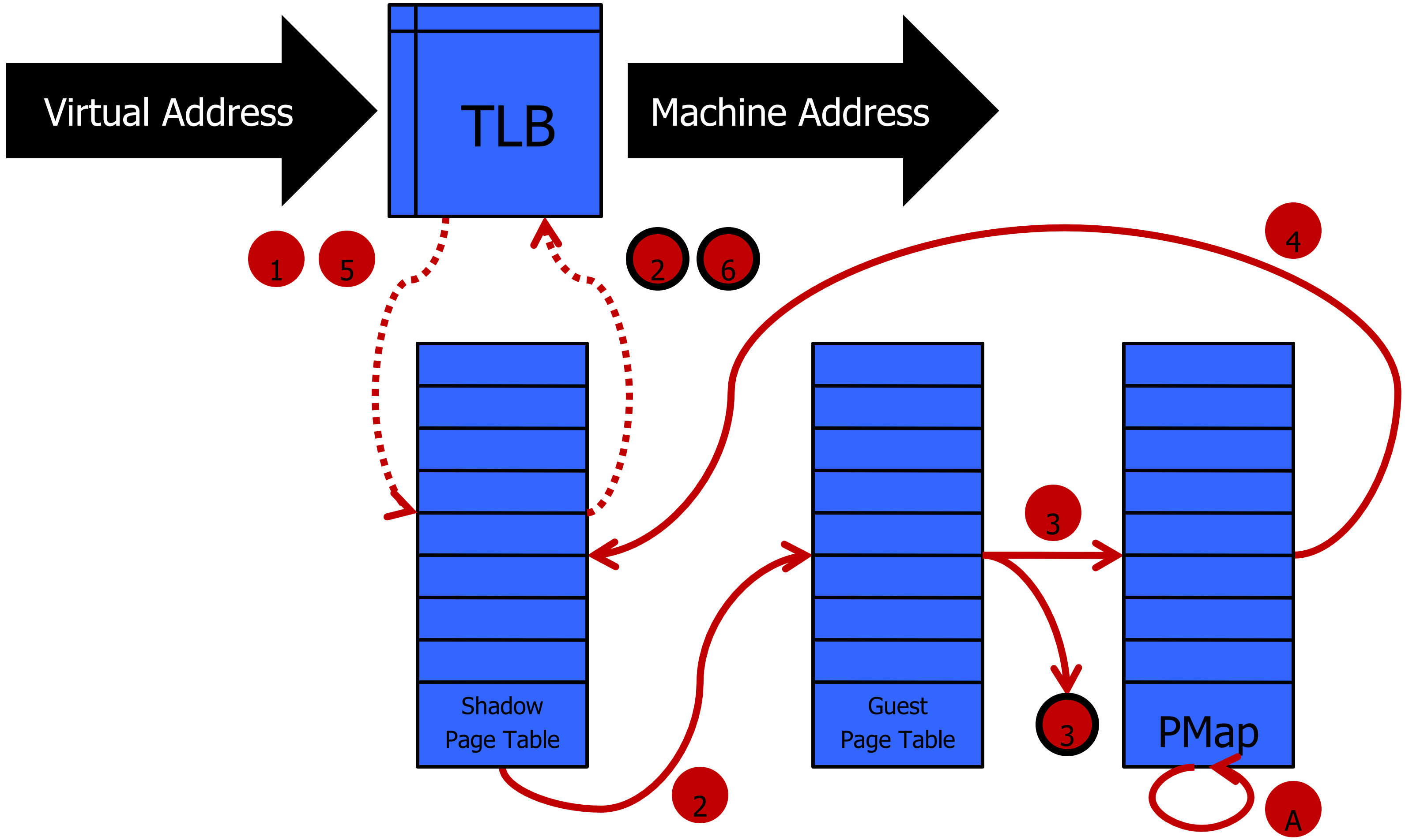
Shadow Page Tables

- Three abstractions of memory
  - Machine: actual hardware memory (e.g. 2GB of DRAM)
  - Physical: abstraction of hardware memory, OS managed
    - E.g. VMM allocates 512 MB to a VM, the OS thinks the computer has 512 MB of contiguous physical memory (underlying machine memory may be discontiguous)
  - Virtual: virtual address space
    - Standard 2^32 address space
- In each VM, OS creates and manages page tables for its virtual address spaces without modification
  - But these page tables are not used by the MMU

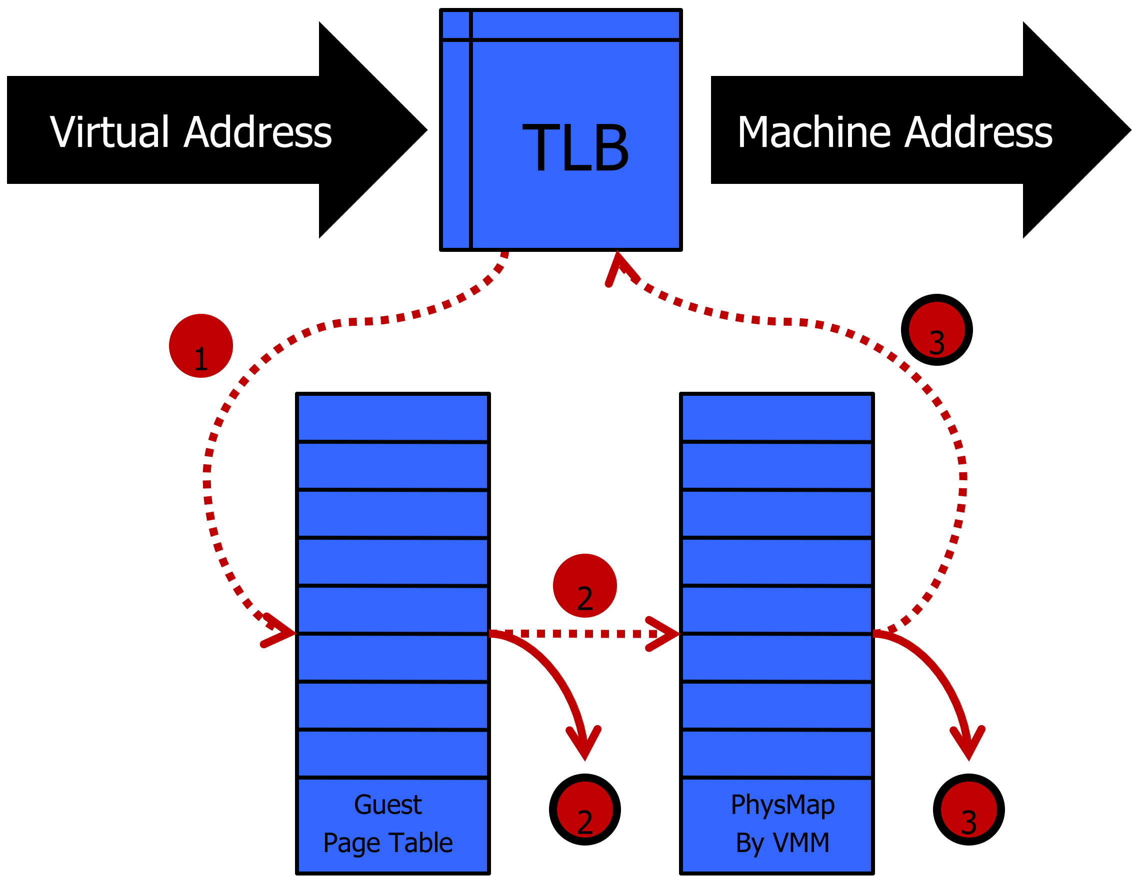
Traditional Address Translation



Using Shadow Page Tables

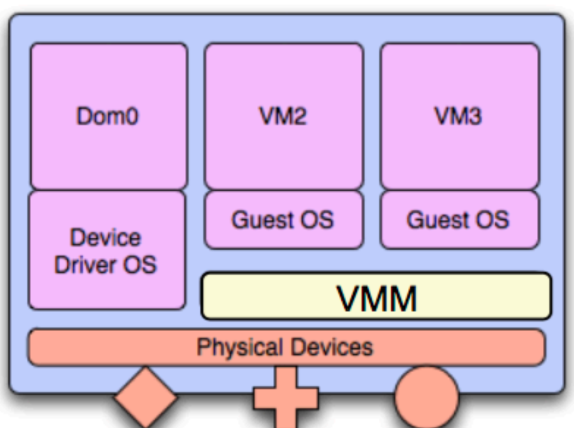


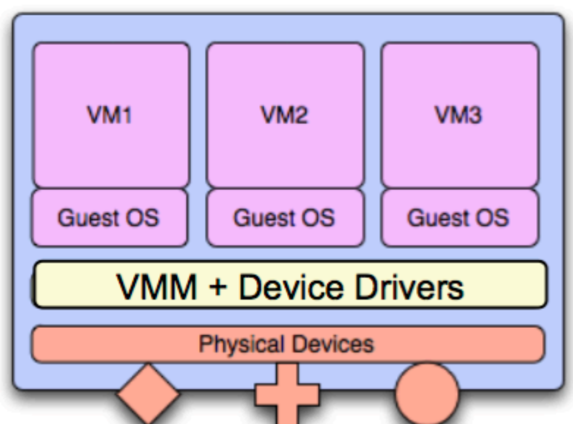
Using Nested Page Tables



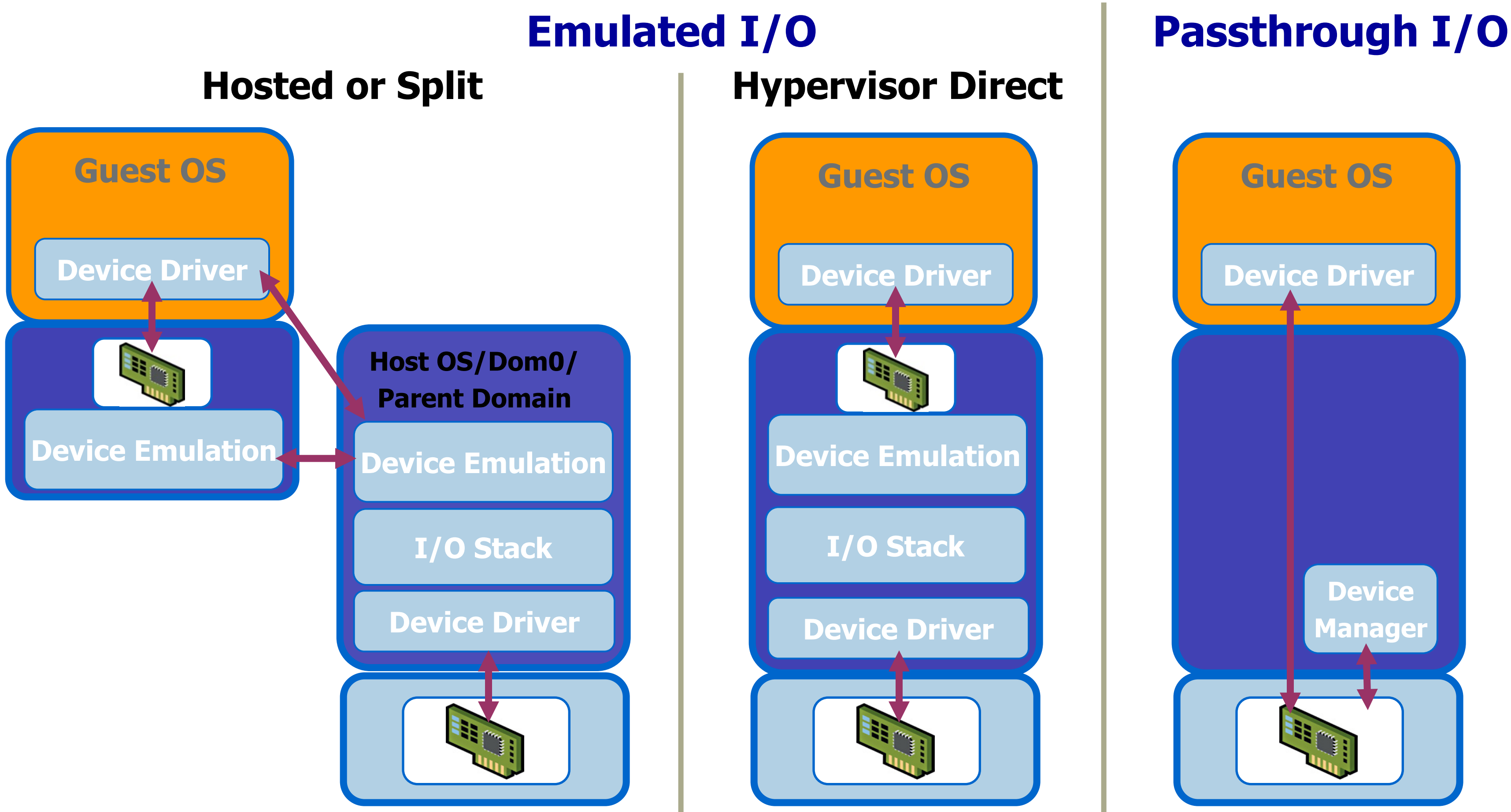
Virtualizing I/O

- Challenge: Lots of I/O devices… writing device drivers for all of them in the VMM layer is not a feasible option
- Insight: Device drivers already written for popular operating systems
- Solution: Present virtual I/O devices to guest VMs and channel I/O requests to a trusted host VM (popular OS)





I/O Virtualization Implementations



VMware Workstation, VMware Server, Xen, Microsoft Hyper-V, Virtual Server

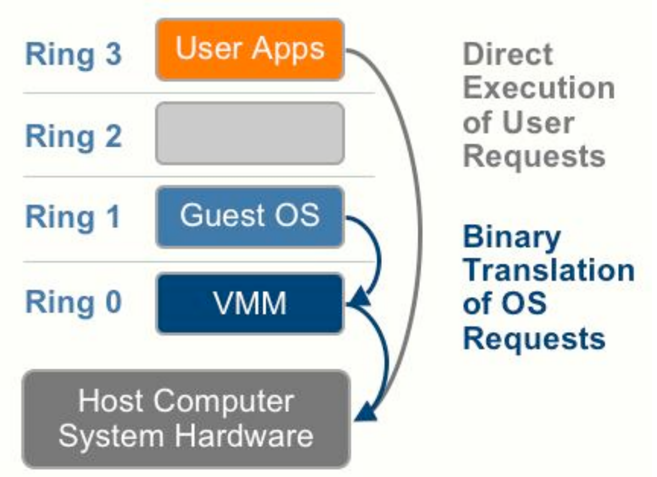
VMware ESX

VMware ESX (FPT)

Full Virtualization

Example: VMware ESX

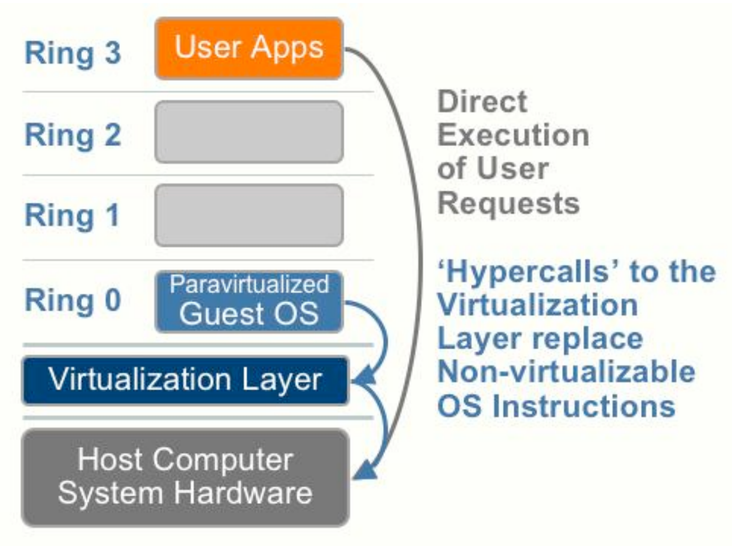
- Functionally identical to underlying physical hardware
- Functionality is exposed to the VMs
- Allows unmodified guest OS to execute on the VMs
  - Transparent to OS: VM looks like the physical machine
  - This might result in some performance degradation



Para-Virtualization

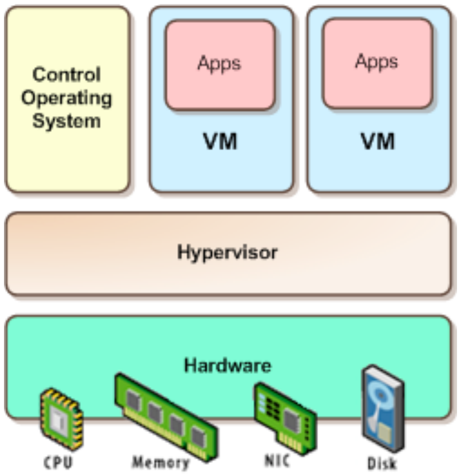
Example: Xen

- Virtual hardware abstraction similar, but not identical to the real hardware
- Guest OS modified to cooperate with the VMM
  - Lower overhead leading to better performance



Type 1 vs. Type 2

- Native/Bare metal (Type 1)
  - Higher performance
  - ESX, Xen, HyperV



- Hosted (Type 2)
  - Easier to install
  - Leverage host's device drivers
  - VMware Workstation, Parallels