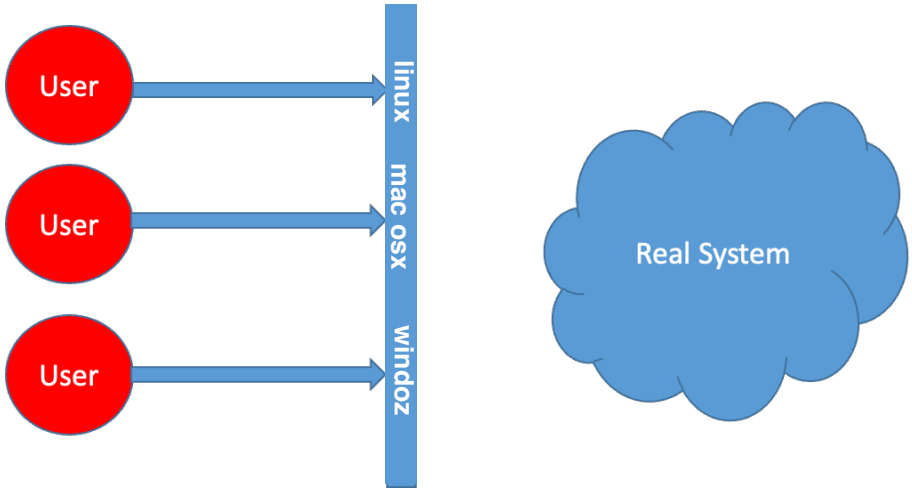
Virtual Machines

Virtual Machines

- Overview
- History
- Benefits / Features
- Building Blocks
- Implementations
- Virtualization and Operating System Components
- Examples

Key Ideas

- User only knows and uses what the interface allows
- System may support different users, with different interfaces



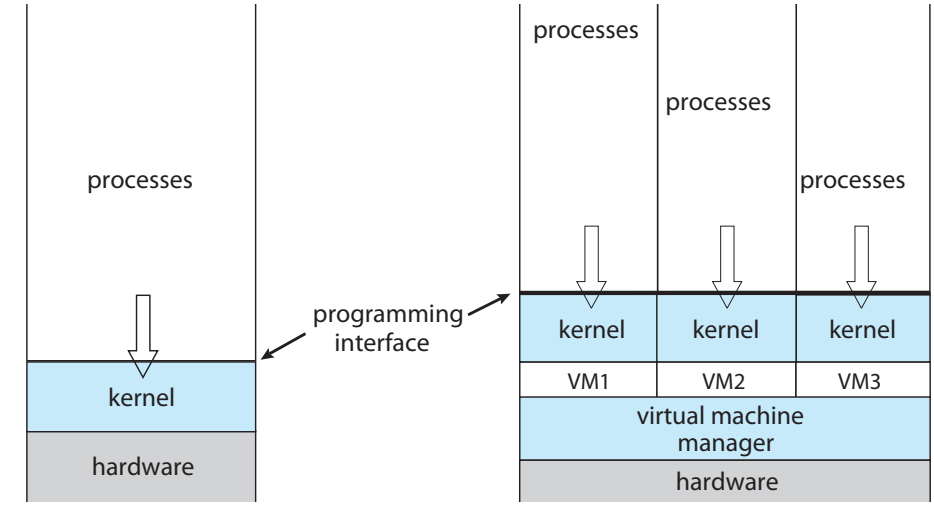
Overview

- Fundamental idea

"abstract hardware for different execution environments"

- Several components
  - Host – underlying hardware system
  - Virtual machine manager (VMM) or hypervisor – creates and runs virtual machines by *providing interface that is identical to the host*
    - Except for paravirtualization
  - Guest – process provided with virtual copy of the host
    - Usually, an operating system
- Single physical machine can run multiple operating systems concurrently, each in its own virtual machine

System Model



Non-virtual machine

Virtual machine

VMM Implementation

- Vary greatly, with options including:
  - Type 0 hypervisors
    - all hardware via firmware
    - could provide dedicated CPUS, memory, I/O for each
    - IBM LPARs and Oracle LDOMs are examples
  - Type 1 hypervisors
    - runs on bare metal
    - OS-like software built to provide virtualization
    - VMware ESX, Joyent SmartOS, and Citrix XenServer
    - includes general-purpose operating systems that provide standard functions as well as VMM functions
      - Microsoft Windows Server / HyperV, RedHat Linux with KVM
  - Type 2 hypervisors
    - Applications that run *on* standard operating systems but provide VMM features to guest operating systems
    - VMware Workstation and Fusion, Parallels Desktop, Oracle VirtualBox, *QEMU*

VMM Implementation *cont…*

- Other variations include:
  - Paravirtualization - Guest operating system is modified to work *in cooperation* with the VMM to optimize performance
  - Programming-environment virtualization - VMMs do not virtualize real hardware but instead create an optimized virtual system
    - Used by Oracle Java and Microsoft.Net
  - Emulators – Allow applications written for one hardware environment to run on a very different hardware environment, such as a different type of CPU
  - Application containment - Not virtualization at all but rather provides virtualization-like features by segregating applications from the operating system, making them more secure, manageable
    - Including Oracle Solaris Zones, BSD Jails, and IBM AIX WPARs
- Much variation due to breadth, depth and importance of virtualization in modern computing

Benefits

- Host protected from VMs, VMs protected from each other
  - viruses less likely to spread
  - sharing is provided via shared file system volume, network
- Freeze, suspend, running VM
  - Move, copy somewhere else and resume
  - Snapshot and restore back to that state
  - Clone by creating copy and running both original and copy
- Great for OS research
  - better system development efficiency
- Run multiple, different OSes on a single machine
  - Consolidation, app dev, …

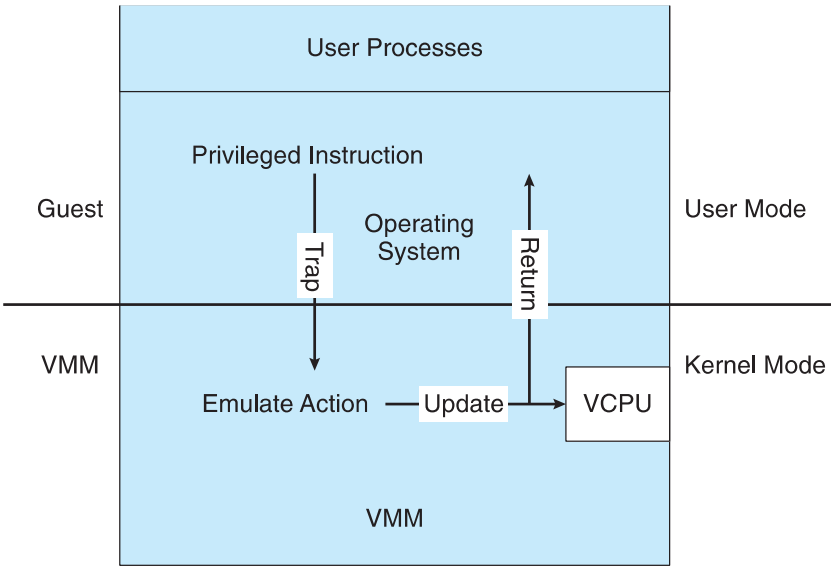
Benefits *cont…*

- Templating
  - create an OS + application VM, provide it to customers, use it to create multiple instances of that combination
- Live migration –
  - move a running VM from one host to another!
  - no interruption of user access
- All those features taken together $\Longrightarrow$ cloud computing
  - Using APIs, programs tell cloud infrastructure (servers, networking, storage) to create new guests, VMs, virtual desktops

Building Block - Trap and Emulate

- Dual mode CPU means guest executes in user mode
  - Kernel runs in kernel mode
  - Not safe to let guest kernel run in kernel mode
  - VM needs two modes:
    - virtual user mode
    - virtual kernel mode
    - both run in real user mode
- How does switch from virtual user mode to virtual kernel mode occur?
  - Attempting a privileged instruction in user mode causes an error -> trap
  - VMM gains control, analyzes error, *executes operation as attempted by guest*
  - Returns control to guest in user mode
  - Known as *trap-and-emulate*
- Guest user mode code in runs at same speed
  - kernel mode privileged code runs slower
  - especially a problem with multiple guests
- CPUs adding hardware support mode
  - more modes improves virtualization performance

Trap-and-Emulate *implementation*



Building Block *need for binary Translation*

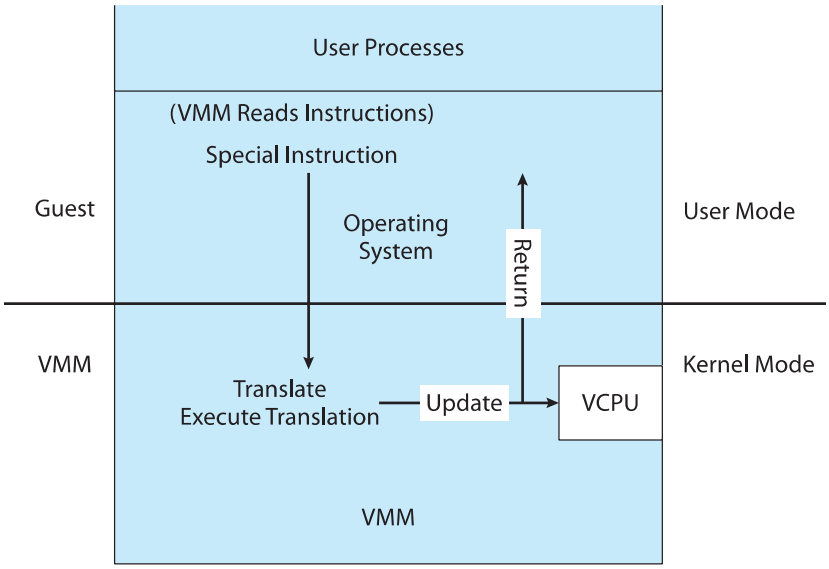
- Some CPUs blur line between privileged and non-privileged
  - Earlier Intel x86 CPUs are among them
    - Earliest Intel CPU designed for a *calculator*
  - Backward compatibility means difficult to improve
  - Consider Intel x86 `popf` instruction
    - Loads CPU flags register from contents of the stack
    - CPU in privileged mode ⇒ all flags replaced
    - CPU in user mode ⇒ only some flags replaced
      - No trap generated
  - Other special instructions as well

Binary translation…

Binary translation *to the rescue*

- Binary translation
  - Basics are simple, but implementation complex
  - If guest VCPU is in user mode, guest runs instructions natively
  - If guest VCPU in kernel mode
    - VMM examines every instruction guest is about to execute by reading a few instructions ahead of program counter
    - Non-special-instructions run natively
    - Special instructions translated into new set of instructions that perform equivalent task (for example changing the flags in the VCPU)
- Implemented by translation of code within VMM
  - Code reads native instructions dynamically from guest, on demand, generates native binary code that executes in place of original code
- Performance of this method would be poor without optimizations
  - Products like VMware use caching:
    - Translate once, cache, and reuse when guest executes code again
    - Testing showed booting Windows XP as guest caused 950,000 translations, at 3 microseconds each, or 3 second (5 %) slowdown over native (obviously an old data point)

Binary Translation *implementation*



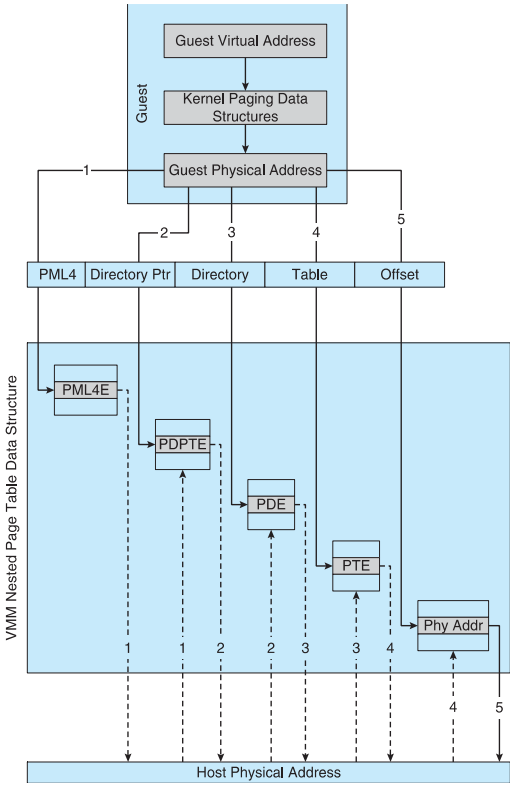
Nested Page Tables *NPTs*

- How can VMM keep page-table state for guests?
  - Each guest maintains page tables to translate virtual to physical addresses
  - VMM maintains per-guest NPTs
  - When guest OS tries to change page tables:
    - VMM makes equivalent change to NPTs and its own page tables
  - Can cause many more TLB misses
    - potentially large performance impact

Hardware Assistance

- All virtualization needs some HW support
  - More support ⇒ more features, stability, performance
- Intel added VT-x instructions in 2005 and AMD the AMD-V instructions in 2006
  - CPUs with these instructions remove need for binary translation
  - define more CPU modes – “guest” and “host”
  - VMM can enable host mode, define characteristics of each guest VM, switch to guest mode and guest(s) on CPU(s)
  - In guest mode, guest OS thinks it is running natively, sees devices (as defined by VMM for that guest)
    - Access to virtualized device, priv instructions cause trap to VMM
    - CPU maintains VCPU, context switches it as needed
- HW continues to improve
  - support for Nested Page Tables
  - DMA
  - interrupts

Nested Page Tables

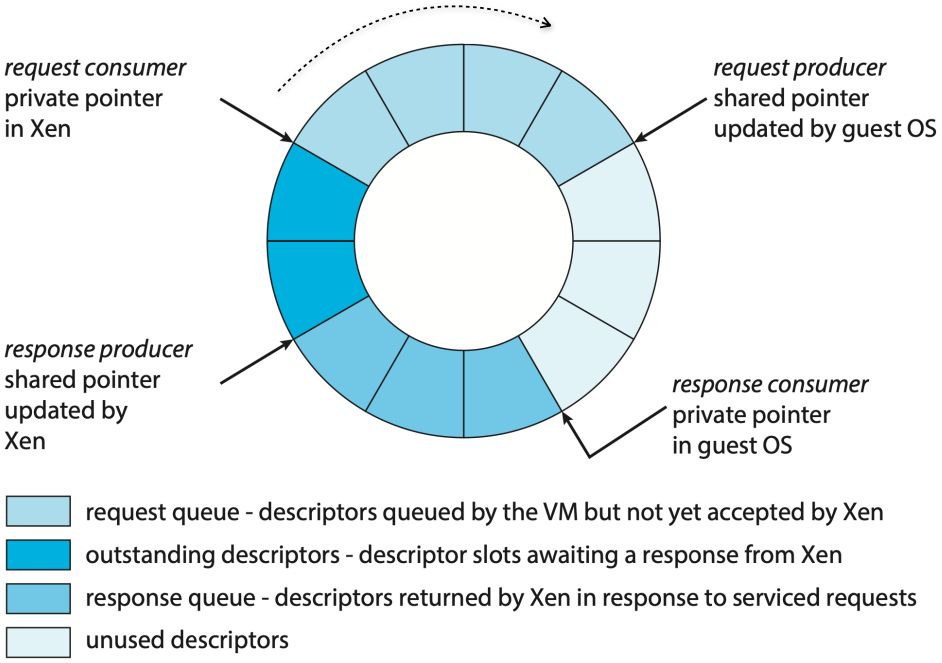


*Similar acronym: page modification logging (**PML**) is a hardware feature that tracks modified memory pages of VMs*

Paravirtualization *guest OS knows the matrix is real*

- Not really virtualization
  - VMM provides an *abstraction* of hardware
  - *Guest is modified* to account for the virtualization layers
    - increased performance
    - less need for hardware support
- Xen techniques:
  - Clean and simple device abstractions, leads to:
    - Efficient I/O
    - Good communication between guest and VMM for I/O
    - Each device has circular buffer shared by guests and VMM via shared memory

Paravirtualization *not exact duplicate of hardware*



Xen I/O via shared circular buffer

Xen cont.

- More Xen techniques:
  - Memory management does not include nested page tables
    - Each guest has own read-only tables
    - Guest uses *hypercall* (call to hypervisor) when page-table changes are needed
- Paravirtualization allowed virtualization of older x86 CPUs (and others) without binary translation
  - Guest had to be modified to run on paravirtualized VMM
- On modern CPUs Xen doesn't require guest modification
  - not paravirtualization any more

Types of VMs application containment

- Some goals of virtualization are:
  - segregation of apps
  - performance and resource management
  - easy start, stop, move
  - management
- Can do those things without full-fledged virtualization
  - If applications compiled for the host operating system, don't need full virtualization to meet these goals
- Docker *containers* create virtual layer between OS and apps
  - only one kernel running – host OS
  - container only has application layer of OS
  - OS and devices are virtualized
  - Container have their own:
    - applications
    - networking stack, addresses, and ports
    - runtime systems
    - user accounts, etc.

Much research ongoing *both industry and academia*

- basic tech used by cloud providers