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بسم الله الرحمن الرحیم

سیستم عامل

جلسه بیست و ششم – مجازی‌سازی و کانتینرسازی

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جلسه‌ی گذشته

- Security
- Cryptography – hash functions
- User Authentication
- Protection Domains
- Attacks

جلسه‌ی جدید

مجازی‌سازی

What is Virtualization?

- Abstracting hardware to run multiple OSs
- Guest OS believes it has dedicated hardware
- Layer called Hypervisor/Virtual Machine Manager

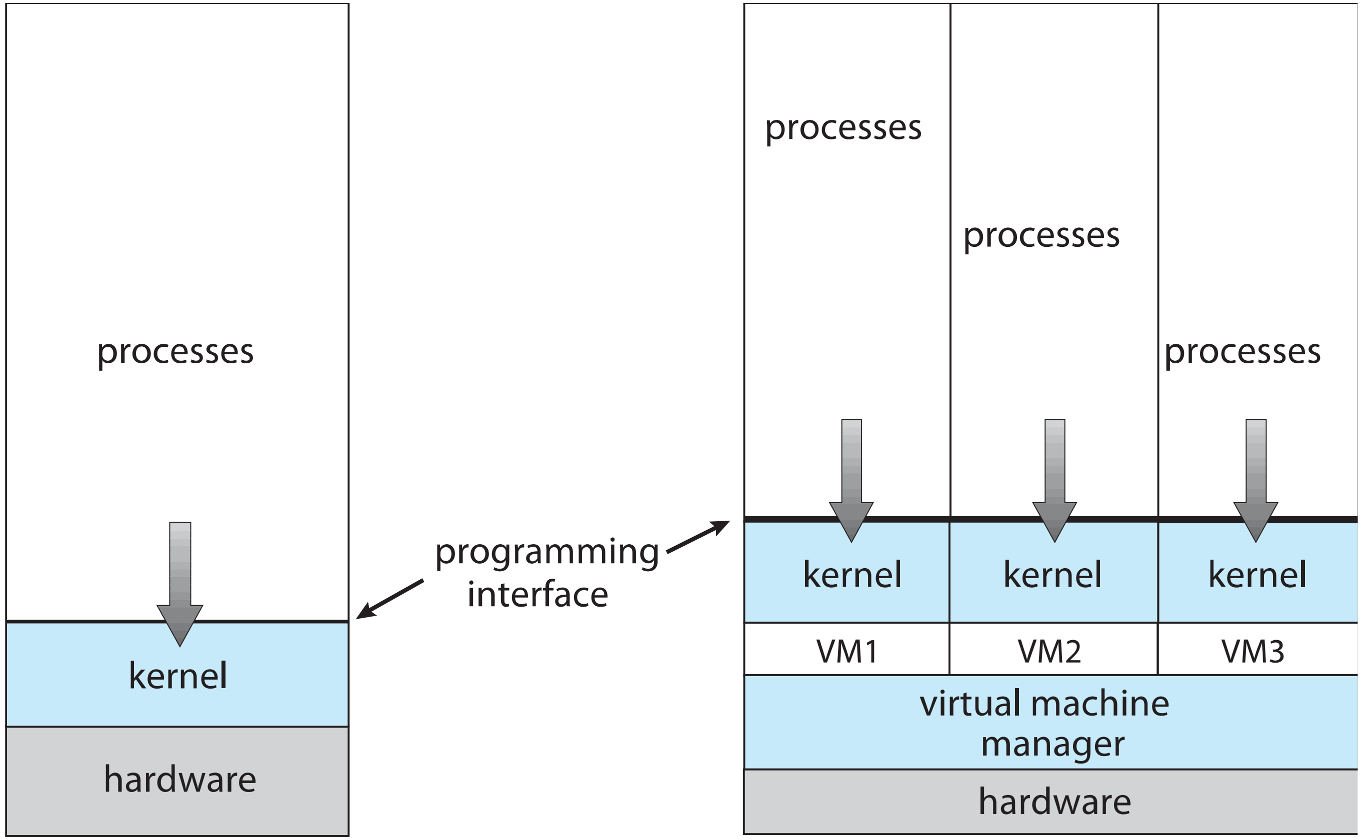
Overview

- Fundamental idea – abstract hardware of a single computer into several different execution environments
  - *Similar to layered approach*
  - *But layer creates virtual system (**virtual machine**, or **VM**) on which operation systems or applications can run*

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 in the case of paravirtualization)*
- **Guest** – process provided with virtual copy of the host
  - *Usually an operating system*

System Models



(a)

(b)

Non-virtual machine

Virtual machine

WHY VIRTUALIZATION?

Protection

- Host system protected from VMs, VMs protected from each other
  - *i.e., A virus less likely to spread*
  - *Sharing is provided though via shared file system volume, network communication*

Suspend/Resume/Clone!

- Freeze, **suspend**, running VM
  - *Then can move or copy somewhere else and **resume***
  - *Snapshot of a given state, able to restore back to that state*
    - Some VMMs allow multiple snapshots per VM
  - ***Clone** by creating copy and running both original and copy*

Developing OS Itself!

- Great for OS research, better system development efficiency

Resource consolidation

- Assume we need to run and protect 2000 small applications
- Are we need to set-up 2000 computers?
- Run multiple, different OSes on a single machine
  - ***Consolidation***, *app dev, …*

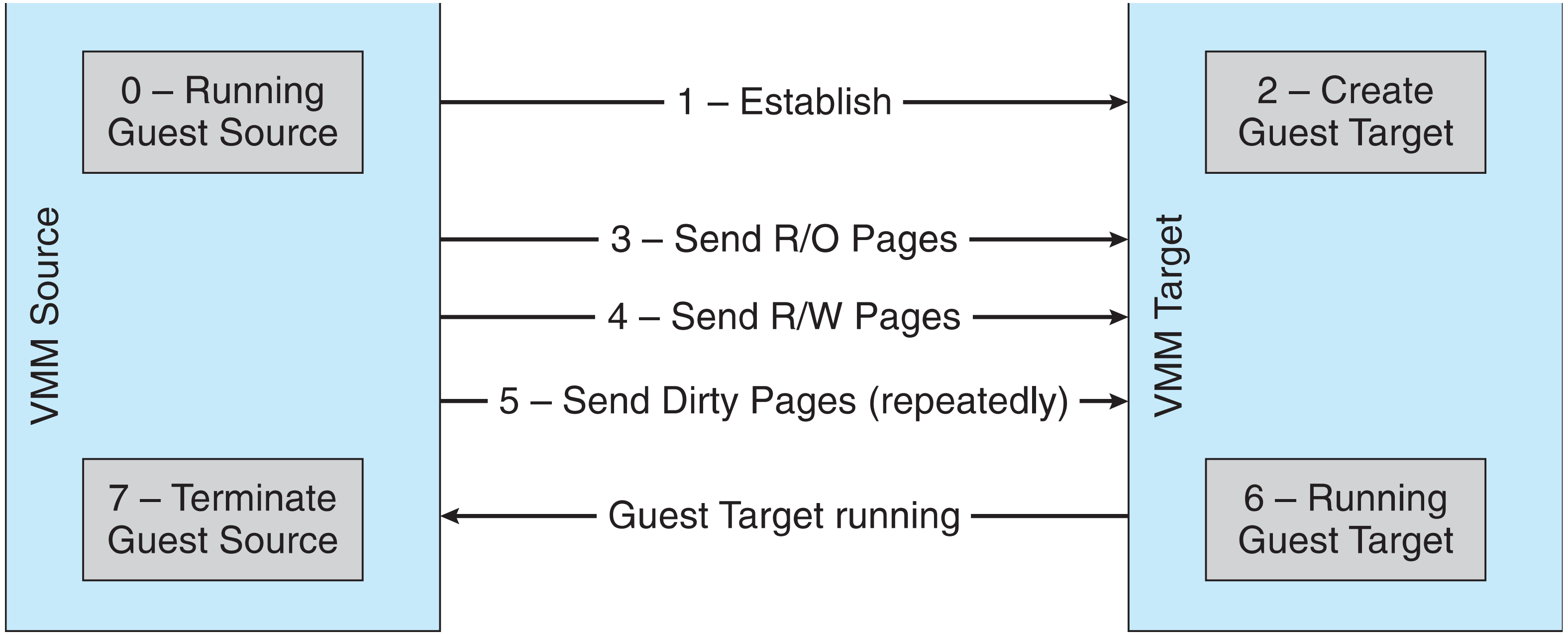
Templating

- create an OS + application VM, provide it to customers, use it to create multiple instances of that combination

Availability

- Assume that we need to change some hardware or we need to power off the hardware…
- Are we need to stop our OS?
- With Virtualization – No!
- move a running VM from one host to another!
  - *No interruption of user access*

Live Migration



Cloud Computing

- All Features together
- Using APIs, programs tell cloud infrastructure (servers, networking, storage) to create new guests, VMs, virtual desktops

BUILDING BLOCKS

Building Blocks

- Generally difficult to provide an ***exact*** duplicate of underlying machine
  - *Especially if only dual-mode operation available on CPU*
  - *But getting easier over time as CPU features and support for VMM improves*
  - *Most VMMs implement* ***virtual CPU*** *(****VCPU****) to represent state of CPU per guest as guest believes it to be*
    - When guest context switched onto CPU by VMM, information from VCPU loaded and stored
  - *Several techniques, as described in next slides*

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 too*
  - *So VM needs two modes – virtual user mode and virtual kernel mode*
    - Both of which run in real user mode
  - *Actions in guest that usually cause switch to kernel mode must cause switch to virtual kernel mode*

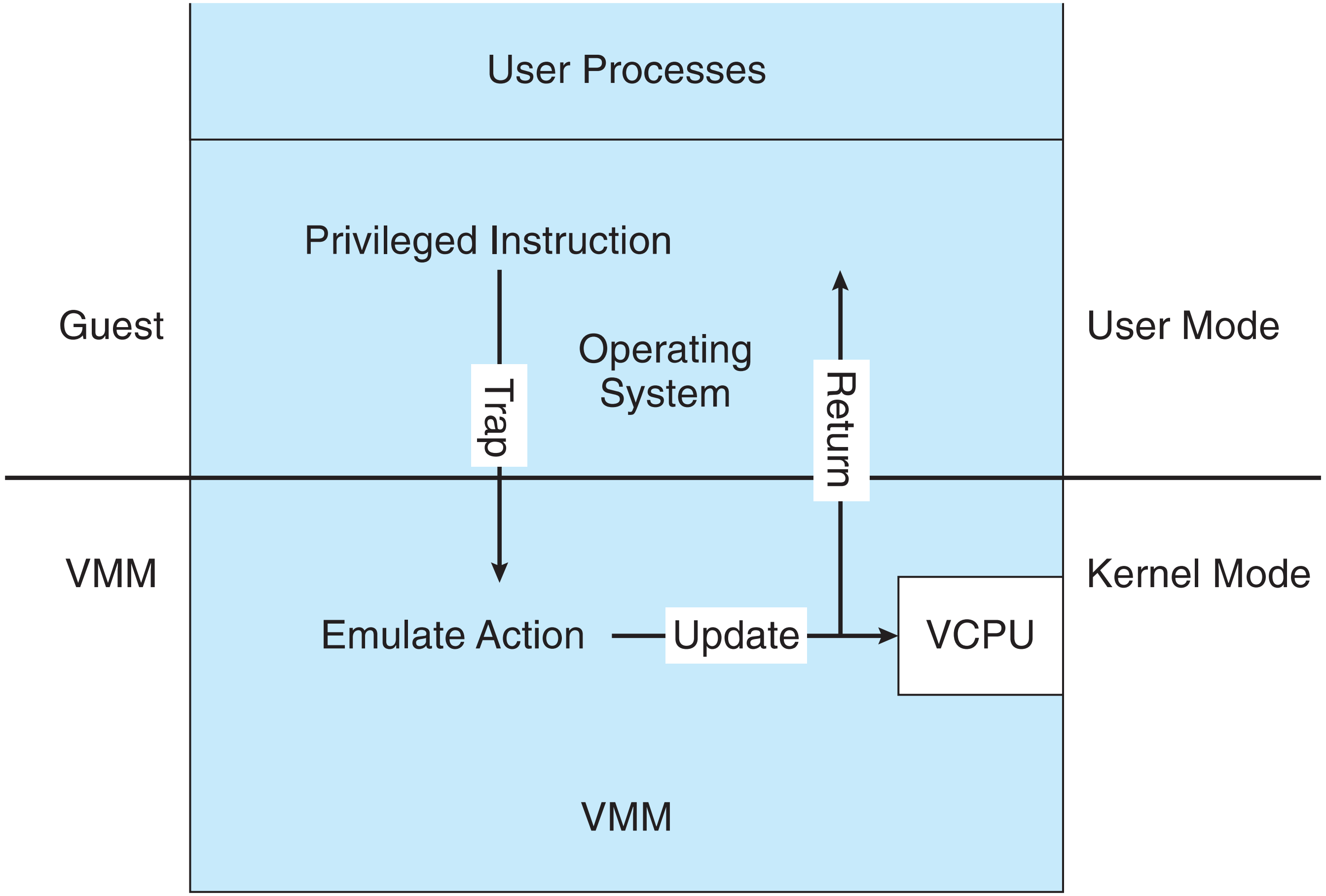
Trap-and-Emulate (Cont.)

- 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***
  - *Most virtualization products use this at least in part*

Trap-and-Emulate (Cont.)

- User mode code in guest runs at same speed as if not a guest
- But kernel mode privilege mode code runs slower due to trap-and-emulate
  - *Especially a problem when multiple guests running, each needing trap-and-emulate*
- CPUs adding hardware support, mode CPU modes to improve virtualization performance

Trap-and-Emulate Virtualization Implementation



Building Block – Binary Translation

- Some CPUs don't have clean separation between privileged and nonprivileged instructions
  - *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
    - If CPU in privileged mode -> all flags replaced
    - If CPU in user mode -> only some flags replaced
      - *No trap is generated*

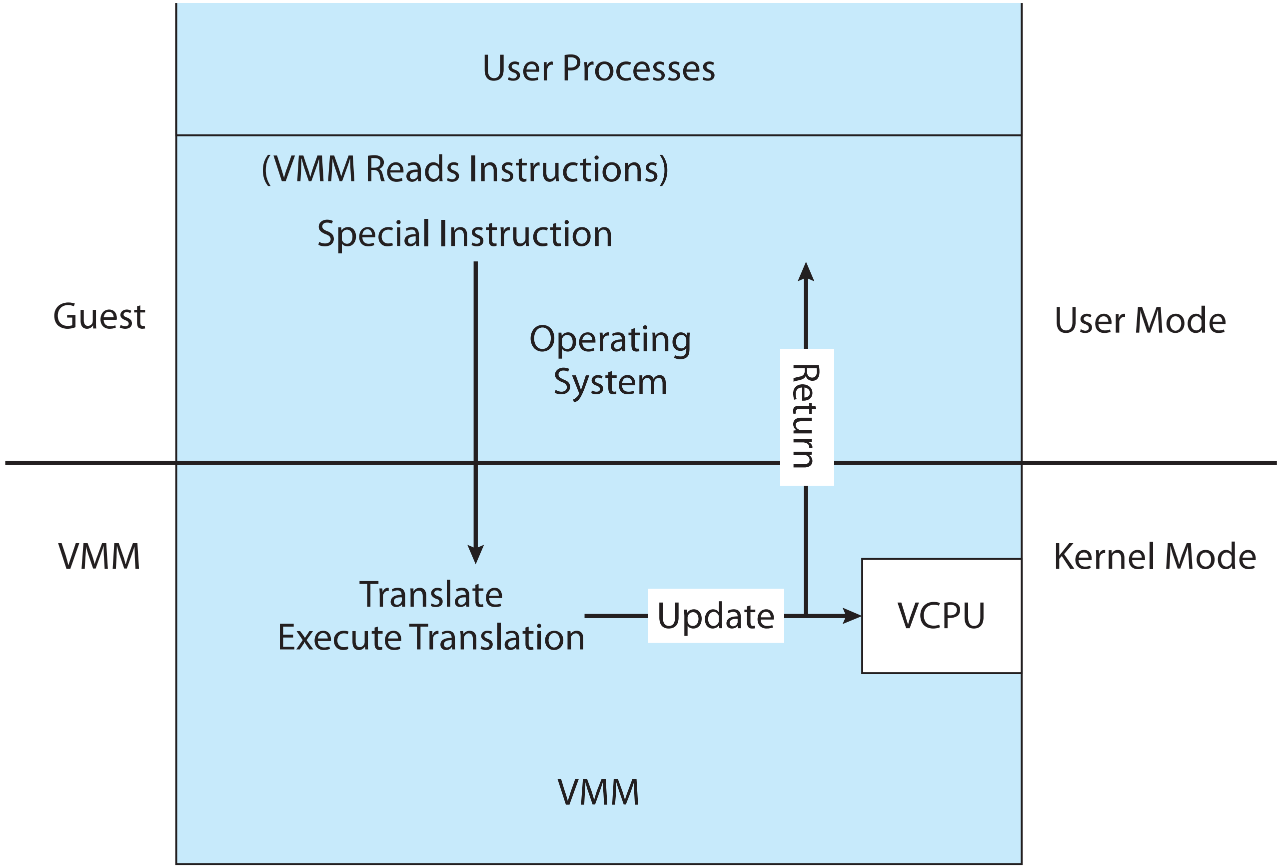
Binary Translation (Cont.)

- Other similar problem instructions we will call ***special instructions***
  - *Caused trap-and-emulate method considered impossible until 1998*
- Binary translation solves the problem
  1. *Basics are simple, but implementation very complex*
  2. *If guest VCPU is in user mode, guest can run instructions natively*
  3. *If guest VCPU in kernel mode (guest believes it is in kernel mode)*
     a) VMM examines every instruction guest is about to execute by reading a few instructions ahead of program counter
     b) Non-special-instructions run natively
     c) Special instructions translated into new set of instructions that perform equivalent task (for example changing the flags in the VCPU)

Binary Translation (Cont.)

- 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, and when guest executes code containing special instruction cached translation used instead of translating again
    - Testing showed booting Windows XP as guest caused 950,000 translations, at 3 microseconds each, or 3 second (5 %) slowdown over native

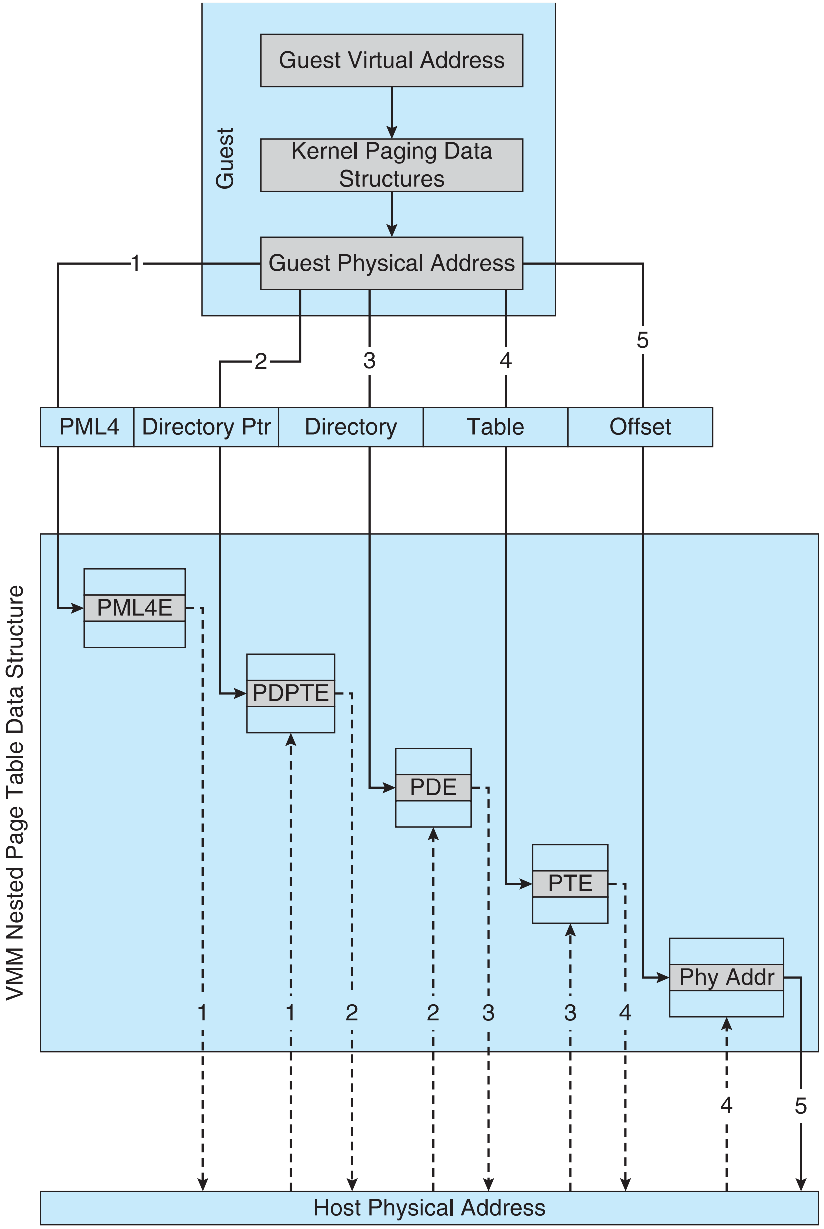
Binary Translation Virtualization Implementation



Nested Page Tables

- Memory management another general challenge to VMM implementations
- How can VMM keep page-table state for both guests believing they control the page tables and VMM that does control the tables?
- Common method (for trap-and-emulate and binary translation) is **nested page tables** (**NPTs**)
  - *Each guest maintains page tables to translate virtual to physical addresses*
  - *VMM maintains per guest NPTs to represent guest's page-table state*
    - Just as VCPU stores guest CPU state
  - *When guest on CPU -> VMM makes that guest's NPTs the active system page tables*
  - *Guest tries to change page table -> VMM makes equivalent change to NPTs and its own page tables*
  - *Can cause many more TLB misses -> much slower performance*

Nested Page Tables



Building Blocks – Hardware Assistance

- All virtualization needs some HW support
- More support -> more feature rich, stable, better performance of guests
- Intel added new **VT-x** instructions in 2005 and AMD the **AMD-V** instructions in 2006
  - *CPUs with these instructions remove need for binary translation*
  - *Generally 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 support for Nested Page Tables, DMA, interrupts as well over time

TYPES OF VMS

Implementation of VMMs

- **Type 0 hypervisors -** Hardware-based solutions that provide support for virtual machine creation and management via firmware
  - *IBM LPARs and Oracle LDOMs are examples*
- **Type 1 hypervisors -** Operating-system-like software built to provide virtualization
  - *Including VMware ESX, Joyent SmartOS, and Citrix XenServer*
- **Type 1 hypervisors –** Also includes general-purpose operating systems that provide standard functions as well as VMM functions
  - *Including Microsoft Windows Server with HyperV and RedHat Linux with KVM*
- **Type 2 hypervisors -** Applications that run on standard operating systems but provide VMM features to guest operating systems
  - ***Including** VMware Workstation and Fusion, Parallels Desktop, and Oracle VirtualBox*

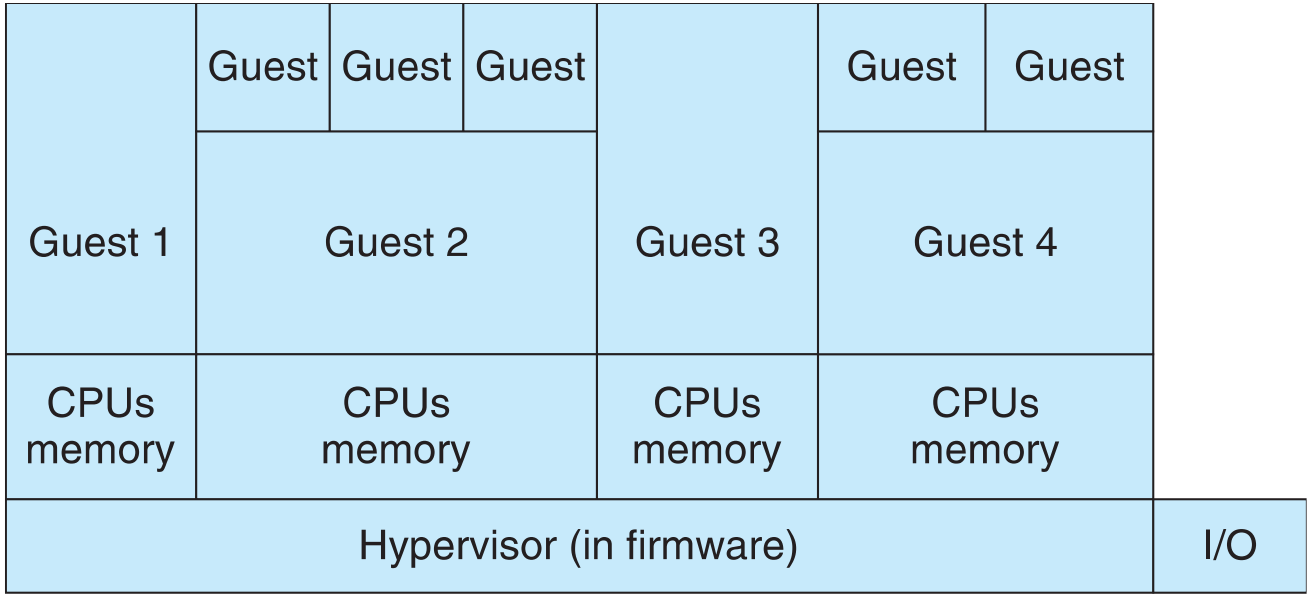
Types of Virtual Machines and Implementations

- Many variations as well as HW details
  - *Assume VMMs take advantage of HW features*
    - HW features can simplify implementation, improve performance
- Whatever the type, a VM has a lifecycle
  - *Created by VMM*
  - *Resources assigned to it (number of cores, amount of memory, networking details, storage details)*
  - *In type 0 hypervisor, resources usually dedicated*
  - *Other types dedicate or share resources, or a mix*
  - *When no longer needed, VM can be deleted, freeing resources*
- Steps simpler, faster than with a physical machine install
  - *Can lead to **virtual machine sprawl** with lots of VMs, history and state difficult to track*

Types of VMs – Type 0 Hypervisor

- Old idea, under many names by HW manufacturers
  - *“partitions”, “domains”*
  - *A HW feature implemented by firmware*
  - *OS need to nothing special, VMM is in firmware*
  - *Smaller feature set than other types*
  - *Each guest has dedicated HW*
- I/O a challenge as difficult to have enough devices, controllers to dedicate to each guest
- Sometimes VMM implements a **control partition** running daemons that other guests communicate with for shared I/O
- Can provide virtualization-within-virtualization (guest itself can be a VMM with guests
  - *Other types have difficulty doing this*

Type 0 Hypervisor



Types of VMs – Type 1 Hypervisor

- Commonly found in company datacenters
  - *In a sense becoming "datacenter operating systems"*
    - Datacenter managers control and manage OSes in new, sophisticated ways by controlling the Type 1 hypervisor
    - Consolidation of multiple OSes and apps onto less HW
    - Move guests between systems to balance performance
    - Snapshots and cloning

Types of VMs – Type 1 Hypervisor (Cont.)

- Special purpose operating systems that run natively on HW
  - *Rather than providing system call interface, create run and manage guest OSes*
  - *Can run on Type 0 hypervisors but not on other Type 1s*
  - *Run in kernel mode*
  - *Guests generally don't know they are running in a VM*
  - *Implement device drivers for host HW because no other component can*
  - *Also provide other traditional OS services like CPU and memory management*

Types of VMs – Type 1 Hypervisor (Cont.)

- Another variation is a general purpose OS that also provides VMM functionality
  - *RedHat Enterprise Linux with KVM, Windows with Hyper-V, Oracle Solaris*
  - *Perform normal duties as well as VMM duties*
  - *Typically less feature rich than dedicated Type 1 hypervisors*
- In many ways, treat guests OSes as just another process
  - *Albeit with special handling when guest tries to execute special instructions*

Types of VMs – Type 2 Hypervisor

- Less interesting from an OS perspective
  - *Very little OS involvement in virtualization*
  - *VMM is simply another process, run and managed by host*
    - Even the host doesn't know they are a VMM running guests
  - *Tend to have poorer overall performance because can't take advantage of some HW features*
  - *But also a benefit because require no changes to host OS*
    - Student could have Type 2 hypervisor on native host, run multiple guests, all on standard host OS such as Windows, Linux, MacOS

Types of VMs – Paravirtualization

- Does not fit the definition of virtualization – VMM not presenting an exact duplication of underlying hardware
  - *But still useful!*
  - *VMM provides services that guest must be modified to use*
  - *Leads to increased performance*
  - *Less needed as hardware support for VMs grows*
- Xen, leader in paravirtualized space, adds several techniques
  - *For example, clean and simple device abstractions*
    - Efficient I/O
    - Good communication between guest and VMM about device I/O
    - Each device has circular buffer shared by guest and VMM via shared memory

Types of VMs –
Programming Environment Virtualization

- Also not-really-virtualization but using same techniques, providing similar features
- Programming language is designed to run within custom-built virtualized environment
  - *For example Oracle Java has many features that depend on running in **Java Virtual Machine** (**JVM**)*
- In this case virtualization is defined as providing APIs that define a set of features made available to a language and programs written in that language to provide an improved execution environment
- JVM compiled to run on many systems (including some smart phones even)
- Programs written in Java run in the JVM no matter the underlying system
- Similar to **interpreted languages**

Types of VMs – Emulation

- Another (older) way for running one operating system on a different operating system
  - *Virtualization requires underlying CPU to be same as guest was compiled for*
  - *Emulation allows guest to run on different CPU*
- Necessary to translate all guest instructions from guest CPU to native CPU
  - *Emulation, not virtualization*
- Useful when host system has one architecture, guest compiled for other architecture
  - *Company replacing outdated servers with new servers containing different CPU architecture, but still want to run old applications*
- Performance challenge – order of magnitude slower than native code
  - *New machines faster than older machines so can reduce slowdown*
- Very popular – especially in gaming where old consoles emulated on new

OS COMPONENTS

Virtualization and Operating-System Components

- Now look at operating system aspects of virtualization
  - *CPU scheduling, memory management, I/O, storage, and unique VM migration feature*
    - How do VMMs schedule CPU use when guests believe they have dedicated CPUs?
    - How can memory management work when many guests require large amounts of memory?

OS Component – CPU Scheduling

- Even single-CPU systems act like multiprocessor ones when virtualized
  - *One or more virtual CPUs per guest*
- Generally VMM has one or more physical CPUs and number of threads to run on them
  - *Guests configured with certain number of VCPUs*
    - Can be adjusted throughout life of VM
  - *When enough CPUs for all guests -> VMM can allocate dedicated CPUs, each guest much like native operating system managing its CPUs*
  - *Usually not enough CPUs -> CPU* ***overcommitment***
    - VMM can use standard scheduling algorithms to put threads on CPUs
    - Some add fairness aspect

OS Component –
CPU Scheduling (Cont.)

- Cycle stealing by VMM and oversubscription of CPUs means guests don't get CPU cycles they expect
  - *Consider timesharing scheduler in a guest trying to schedule 100ms time slices -> each may take 100ms, 1 second, or longer*
    - Poor response times for users of guest
    - Time-of-day clocks incorrect
  - *Some VMMs provide application to run in each guest to fix time-of-day and provide other integration features*

OS Component – Memory Management

- Also suffers from oversubscription -> requires extra management efficiency from VMM
- For example, VMware ESX guests have a configured amount of physical memory, then ESX uses 3 methods of memory management
  1. *Double-paging, in which the guest page table indicates a page is in a physical frame but the VMM moves some of those pages to backing store*
  2. *Install a **pseudo-device driver** in each guest (it looks like a device driver to the guest kernel but really just adds kernel-mode code to the guest)*
     - **Balloon** memory manager communicates with VMM and is told to allocate or de-allocate memory to decrease or increase physical memory use of guest, causing guest OS to free or have more memory available
  3. *De-duplication by VMM determining if same page loaded more than once, memory mapping the same page into multiple guests*

OS Component – I/O

- Easier for VMMs to integrate with guests because I/O has lots of variation
  - *Already somewhat segregated / flexible via device drivers*
  - *VMM can provide new devices and device drivers*
- But overall I/O is complicated for VMMs
  - *Many short paths for I/O in standard OSes for improved performance*
  - *Less hypervisor needs to do for I/O for guests, the better*
  - *Possibilities include direct device access, DMA pass-through, direct interrupt delivery*
    - Again, HW support needed for these

OS Component – I/O

- Networking also complex as VMM and guests all need network access
  - *VMM can **bridge** guest to network (allowing direct access)*
  - *And / or provide **network address translation** (**NAT**)*
    - NAT address local to machine on which guest is running, VMM provides address translation to guest to hide its address

OS Component – Storage Management

- Both boot disk and general data access need be provided by VMM
- Need to support potentially dozens of guests per VMM (so standard disk partitioning not sufficient)
- Type 1 – storage guest root disks and config information within file system provided by VMM as a **disk image**
- Type 2 – store as files in file system provided by host OS

OS Component – Storage Management

- Duplicate file -> create new guest
- Move file to another system -> move guest
- **Physical-to-virtual** (**P-to-V**) convert native disk blocks into VMM format
- **Virtual-to-physical** (**V-to-P**) convert from virtual format to native or disk format
- VMM also needs to provide access to network attached storage (just networking) and other disk images, disk partitions, disks, etc.

CONTAINERS

Application Containment

- Some goals of virtualization are segregation of apps, performance and resource management, easy start, stop, move, and management of them
- 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*

Application Containment

- Oracle **containers** / **zones** for example create virtual layer between OS and apps
  - *Only one kernel running – host OS*
  - *OS and devices are virtualized, providing resources within zone with impression that they are only processes on system*
  - *Each zone has its own applications; networking stack, addresses, and ports; user accounts, etc*
  - *CPU and memory resources divided between zones*
    - Zone can have its own scheduler to use those resources

Solaris 10 with Two Zones