第 3 讲：Virtual Machine Monitor

第一节：Overview

陈渝

清华大学计算机系

yuchen@tsinghua.edu.cn

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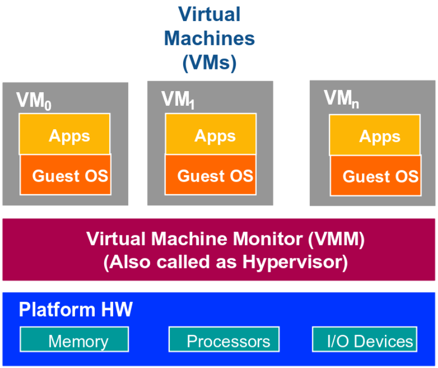
Introduction



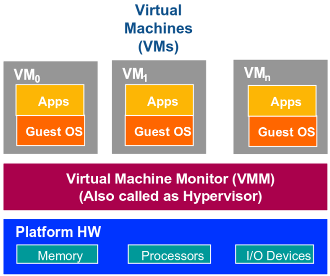
What is Virtualization

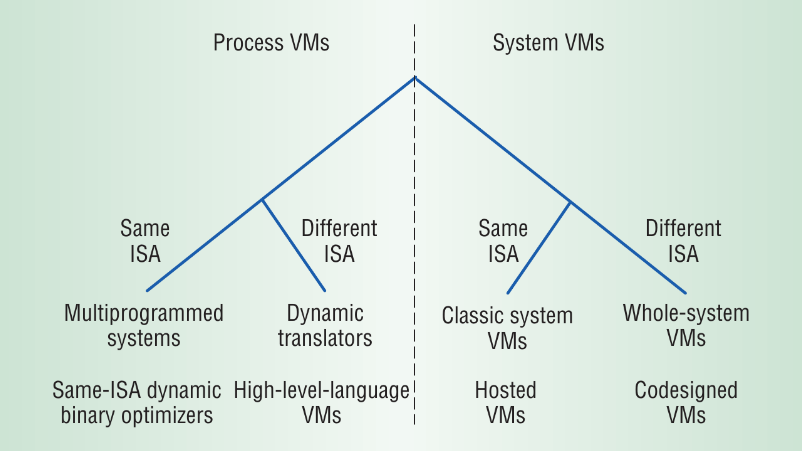
Virtualization is a term that refers to the abstraction of computer resources [wikipedia]

Wisdom

All computer problems can be solved with another layer of redirection [Donald E. Knuth (高德纳), Stanford University]

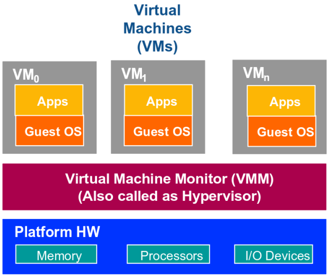
Introduction – taxonomy

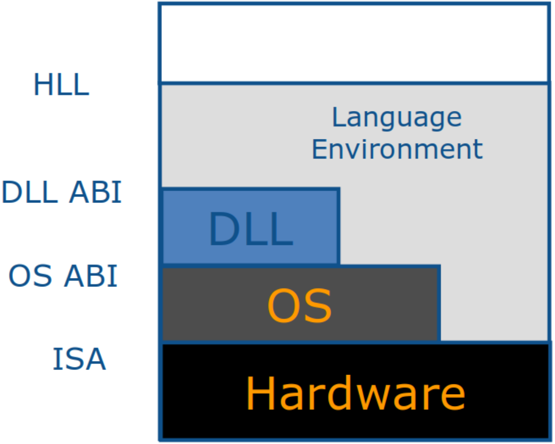




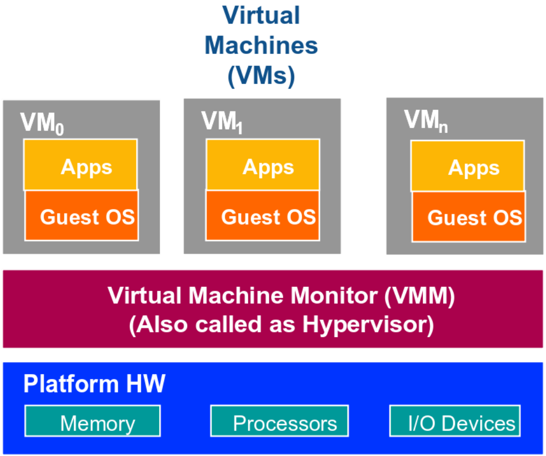
from James E.Smith, IEEE computer Society2005

Introduction – different layer of virtualization





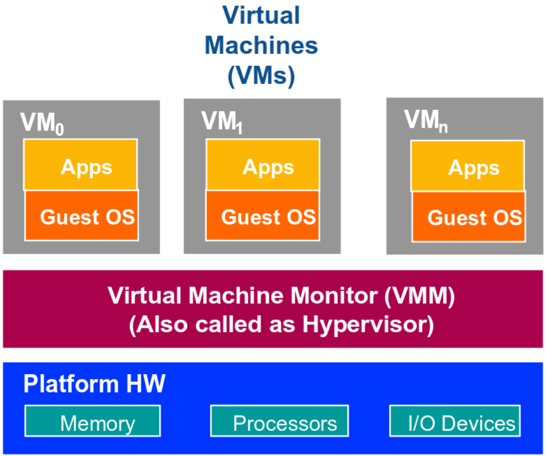
Introduction – VMM



Virtual Machine Monitor, VMM

VMM transforms the single machine interface into the illusion of many. Each of these interfaces (virtual machines) is an efficient replica of the original computer system, complete with all of the processor instructions [Robert P. Goldberg, 1974]

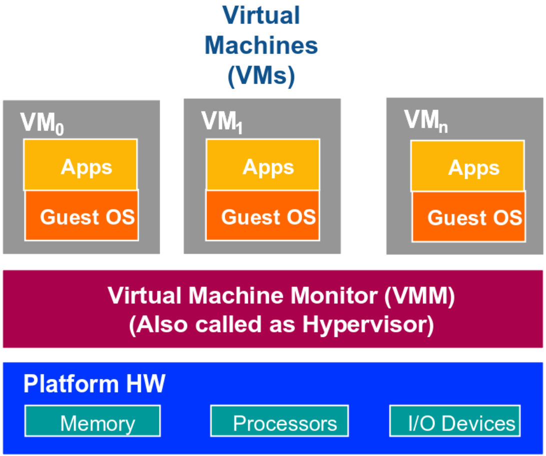
Introduction – VMM



Virtual Machine Monitor, VMM

A virtual machine is implemented by adding software to an execution platform to give it the appearance of a different platform, or for that matter, to give the appearance of multiple platforms. [J.E. Smith, "An Overview of Virtual Machine Architectures"]

Introduction – Why VMM?

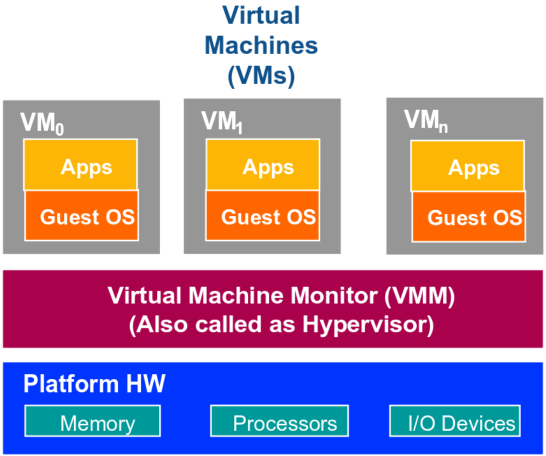


Before there were data centers...

- Many early commercial computers were mainframes
- powerful computation, highly reliable, extensive I/O capabilities
- for computing/data-intensive apps

IBM System/360 hardware and CP/CMS system software: Virtualizable Architecture

Introduction – Why VMM?

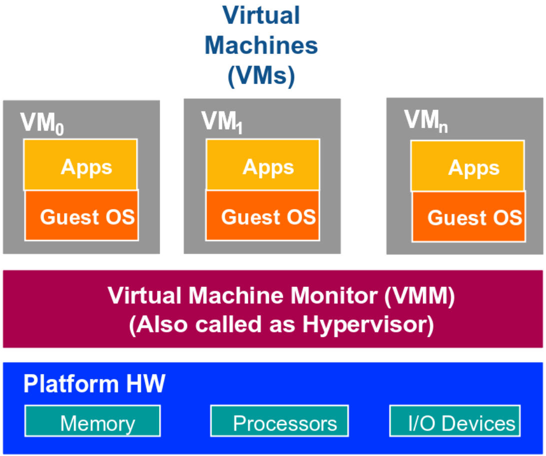


Now there were data centers...

- Many computers were servers connected in the world.
- powerful computation, highly reliable, extensive I/O capabilities
- for computing/data-intensive apps

x86/ARM and Linux/KVM, vmware, xen, etc. system software: Virtualizable Architecture

Introduction – Essential characteristics of VMM



- Equivalence: Essentially identical virtual platform, except
  - Differences caused by the availability of system resources. e.g. memory size
- Isolation, or resource control
  - VMM is in complete control of system resources
- Efficiency
  - At worst only minor decreases in speed
  - speed $>>$ emulators, software interpreters (simulators)

第 3 讲：Virtual Machine Monitor

第二节：How VMM works

陈渝

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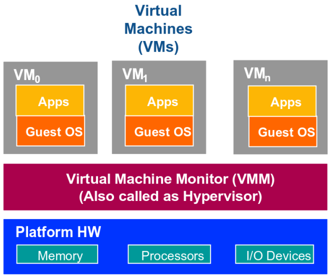
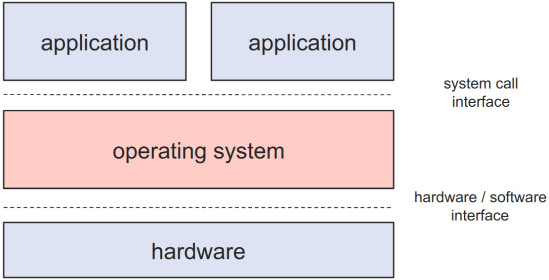
How VMM works

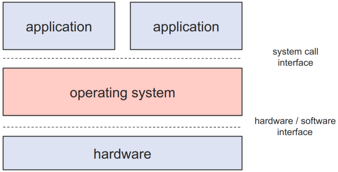


Start with a "simpler" question: how do (regular) machines work?



- What is computer hardware? (CPU, MEM, IO)
- What is an OS?
- What's an application? (relies on the system call interface)

How VMM works

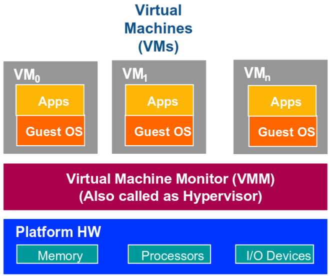


Start with a “simpler” question: how do (regular) machines work?

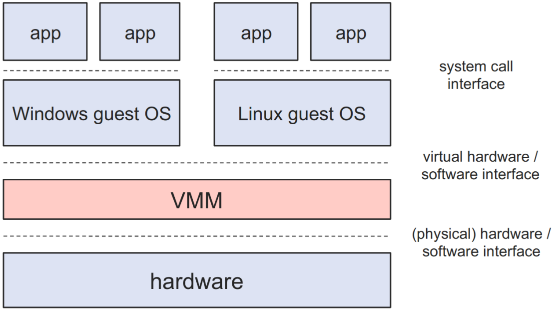
Process	Hardware	Operating System
1. Execute instructions (add, load, etc.)		
2. System call: Trap to OS		
	3. Switch to kernel mode; Jump to trap handler	
		4. In kernel mode; Handle system call; Return from trap
	5. Switch to user mode; Return to user code	
6. Resume execution (@PC after trap)		

Executing a System Call

How VMM works – CPU

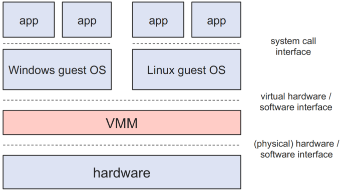


What if we run the Linux/Windows kernel as a user-level program?



- What happens when Linux issues a sensitive instruction?
- What (virtual) hardware devices should Windows see?
- How do you prevent apps running on Linux from hurting Linux?

How VMM works – CPU



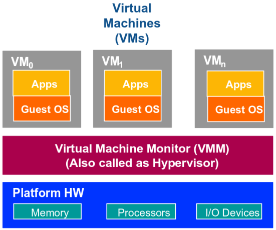
What if we run the Linux/Windows kernel as a user-level program?

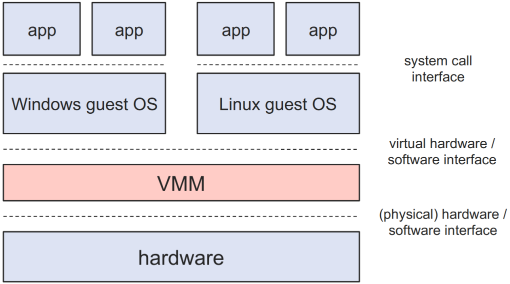
Process	Operating System	VMM
1. System call: Trap to OS		
		2. Process trapped: Call OS trap handler (at reduced privilege)
	3. OS trap handler: Decode trap and execute syscall; When done: issue return-from-trap	
		4. OS tried return from trap: Do real return from trap
5. Resume execution (@PC after trap)		

System Call Flow with Virtualization

How VMM works – CPU

What if we run the Linux/Windows kernel as a user-level program?

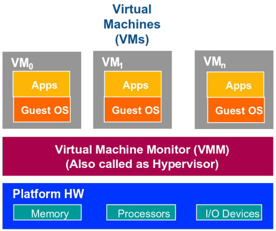




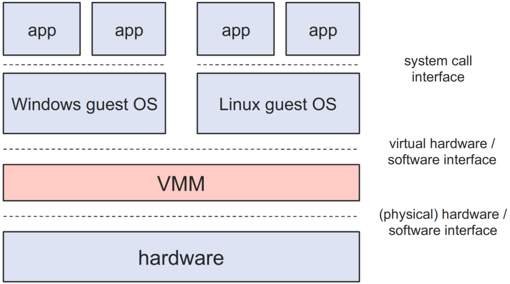
Answer: rely on CPU to trap sensitive instructions and hand off to VMM

- VMM emulates the effect of sensitive instruction on the virtual hardware that it provides to its guest OSs

How VMM works – CPU



What if we run the Linux/Windows kernel as a user-level program?

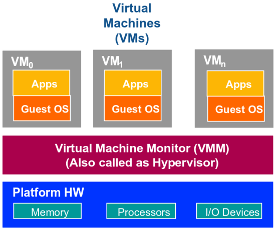


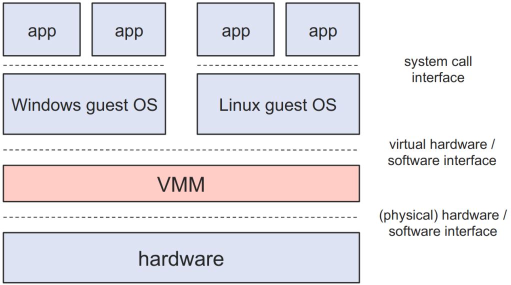
Goldberg (1974): two classes of instructions

- privileged instructions: those that trap when CPU is in user-mode
- sensitive instructions: those that modify hardware

How VMM works – CPU

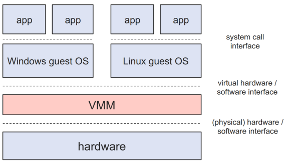
What if we run the Linux/Windows kernel as a user-level program?



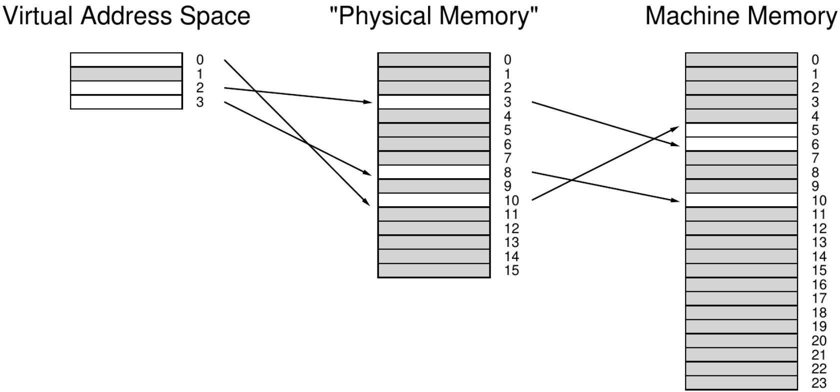


A VMM can be constructed efficiently and safely if the set of sensitive instructions is a subset of the set of privileged instructions.

How VMM works – memory

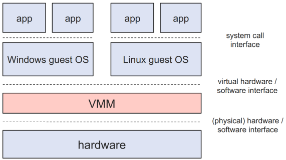


OS Page Table	VMM Page Table
VPN 0 to PFN 10	PFN 03 to MFN 06
VPN 2 to PFN 03	PFN 08 to MFN 10
VPN 3 to PFN 08	PFN 10 to MFN 05



VMM Memory Virtualization

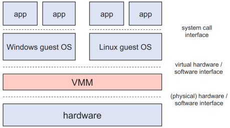
How VMM works – memory



Process	Operating System
1. Load from memory: TLB miss: Trap	
	2. OS TLB miss handler: Extract VPN from VA; Do page table lookup; If present and valid: get PFN, update TLB; Return from trap
3. Resume execution (@PC of trapping instruction); Instruction is retried; Results in TLB hit	

TLB Miss Flow without Virtualization

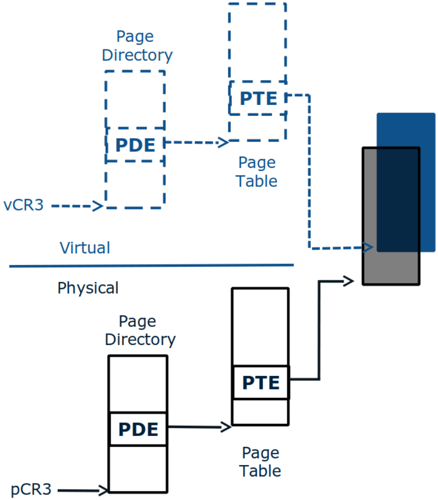
How VMM works – memory

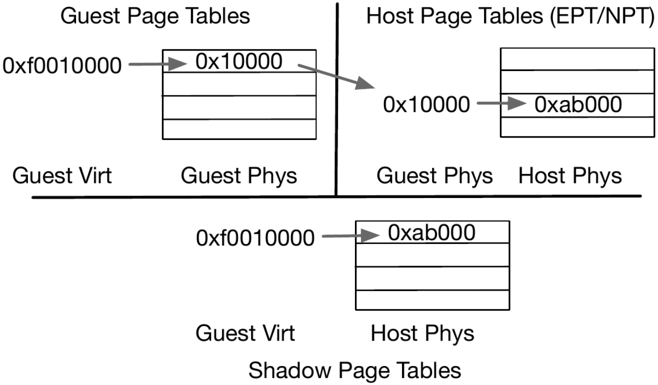


Process	Operating System	Virtual Machine Monitor
1. Load from mem TLB miss: Trap		
		2. VMM TLB miss handler: Call into OS TLB handler (reducing privilege)
	3. OS TLB miss handler: Extract VPN from VA; Do page table lookup; If present and valid, get PFN, update TLB	
		4. Trap handler: Unprivileged code trying to update the TLB; OS is trying to install VPN-to-PFN mapping; Update TLB instead with VPN-to-MFN (privileged); Jump back to OS (reducing privilege)
	5. Return from trap	
		6. Trap handler: Unprivileged code trying to return from a trap; Return from trap
7. Resume execution (@PC of instruction); Instruction is retried; Results in TLB hit		

TLB Miss Flow with Virtualization

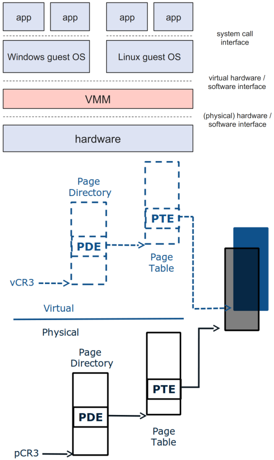
How VMM works – memory





How does the virtual machine monitor get involved with a hardware-managed TLB?

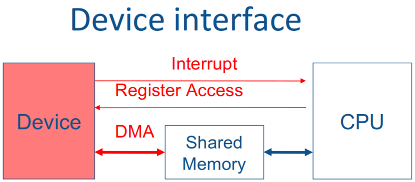
How VMM works – memory



How does the virtual machine monitor get involved with a hardware-managed TLB?

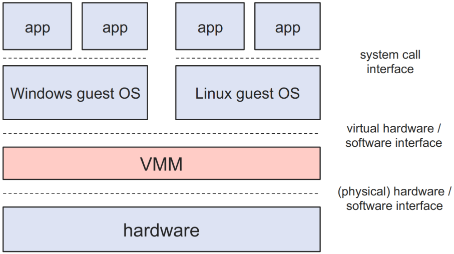
- VMM doesn't have a chance to run on each TLB miss to sneak its translation into the system.
- VMM must closely monitor changes the OS makes to each page table
- VMM must keep a **shadow page table** that maps the virtual addresses of each process to the VMM's desired machine pages
- VMM installs a process's **shadow page table** whenever the OS tries to install the process's OS-level page table

How VMM works – IO

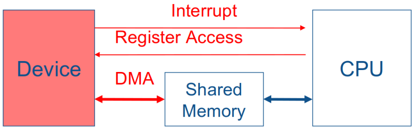


- Interaction between device and driver:
  - Driver programs device through register access
  - Device notifies driver through interrupt
  - Device could DMA for massive data movement

How VMM works – IO

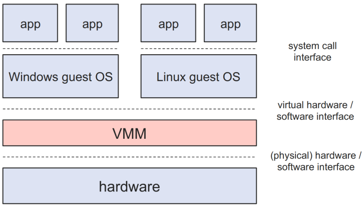


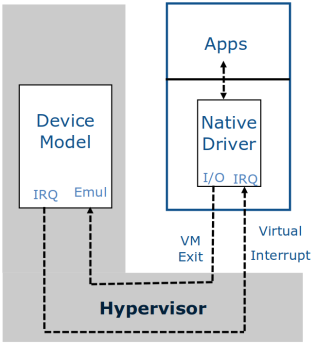
Device interface



- I/O Virtualization requires the hypervisor to present guest a complete device interface
  - Presenting an existing interface: Software Emulation
  - Presenting an existing interface: Direct assignment
- Presenting a brand new interface
  - Paravirtualization

How VMM works – IO

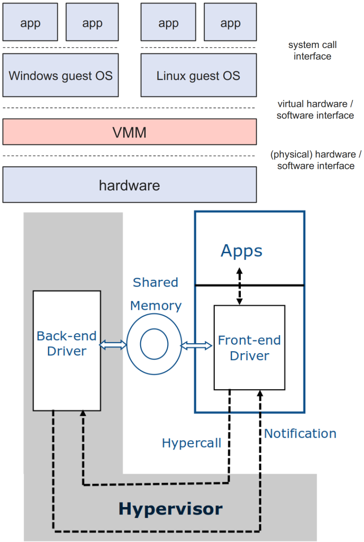




Software Emulation

- Guest runs native device driver, e.g. NE2000
  - I/O access is trap-and-emulated by device model in hypervisor
  - Translation for MMIO is zapped
  - Virtual Interrupt is signaled by device model per semantics
- Excessive trap and emulation

How VMM works – IO



Paravirtualization

- A new front-end driver (FE driver) is run in guest
  - Optimized request through hypercall
- Hypervisor runs a back-end driver (BE driver) to service request from FE driver
  - Notify guest for processing
- Shared memory is used for massive data communication
  - To reduce guest/hypervisor boundary crossin
  - e.g. Xen VNIF, KVM Virtio-Net