COS 318: Operating Systems

Virtual Machine Monitors

Jaswinder Pal Singh and a Fabulous Course Staff
Computer Science Department
Princeton University

http://www.cs.princeton.edu/courses/archive/fall13/cos318/

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Virtual Machines

- We have seen how the OS virtualizes subsystems
  - CPU, Memory, IO
  - To give applications illusions about owning the system
  - The OS knows all
- What about:
  - Virtualizing the whole system
  - Giving OSes the illusion of a system that isn't real
  - The OS doesn't know all
- Why do this?
  - To enable multiple OSes to run "at the same time" on the same hardware, sharing resources without harming anyone

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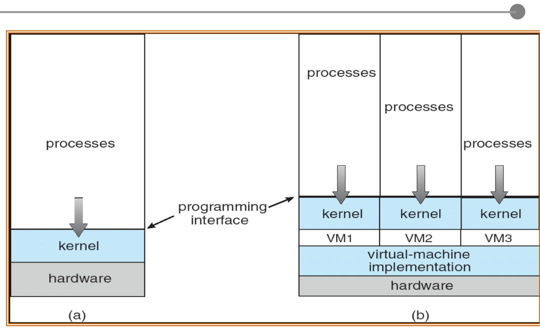
The Idea



Who implements the virtual machine, and knows all, if not OS?

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Virtual Machine Monitor (VMM)

- Sits between multiples OSes and hardware (or a host OS)
- Presents a hardware interface to the OSes above
- Gives the illusion to each OS above that it controls the whole machine
  - Actually, the VMM does, and each OS sees a virtual machine
  - The VMs (and OSes) share the actual hardware resources
- Manages (multiplexes) resources among several virtual machines (VMs)
- Isolates VMs from each other
- Similar to what an OS does: abstraction, resource mgmt
- a.k.a. Hypervisor

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History

- Have been around since 1960's on mainframes
  - Used to run apps on different OSes on same (very expensive) mainframe
  - Good example – VM/370
- Computers became cheaper, people lost interest
- Have resurfaced on commodity platforms
  - Server Consolidation: save space, power; data centers
  - High-Performance Compute Clusters: run different OSes
  - Managed desktop / thin-client
    - Save desktop in a VM and bring it with you on a USB drive
  - Software development / kernel hacking
    - Crash your development kernel but don't disable whole machine

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Goals

- Manageability
  - Creation, maintenance, administration, provisioning, etc.
- Performance
  - Overhead of virtualization should be small
- Isolation, like separate physical machines
  - Activity of one VM should not impact other active VMs
  - Data of one VM is inaccessible by another
- Scalability
  - Minimize cost per VM; run more VMs on hardware
- Reliability

Same goals as for many susbystems

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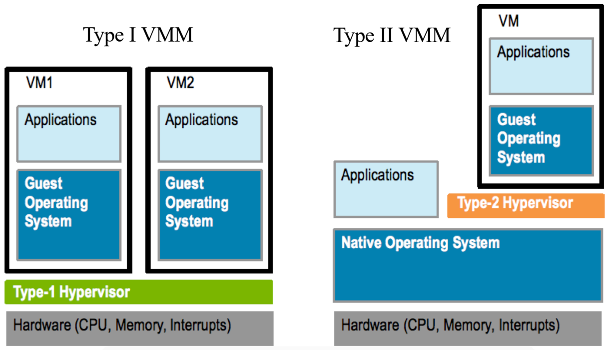
VMM Types



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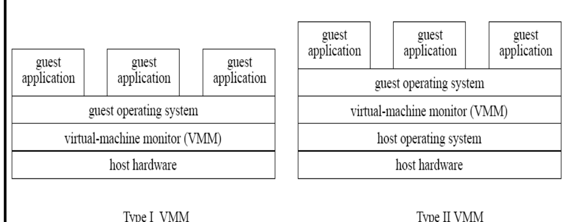
VMM Types



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Virtualization Styles

- Fully virtual*izing* VMM
  - Virtual machine looks exactly like a (some) physical machine
    - Not necessarily exactly like the underlying hardware itself
  - Run guest OS unchanged
  - VMM is transparent to the OS
- Para- virtual*izing* VMM
  - Guest OS is changed to cooperate with VMM
  - Sacrifice transparency for better performance
  - E.g. VMM can provide idealized view of some hardware
  - E.g. VMM can provide “hypervisor API” so guest can perform certain functions, e.g. with optimizations for performance

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VMM Classification

	Type I	Type II
Fully-virtualized	VMware ESX (stand alone, Windows Hyper V (with OS)	VMware Workstation, Fusion. Parallels Desktop VIrtualBox, Virtual PC
Para-virtualized	Xen	User Mode Linux

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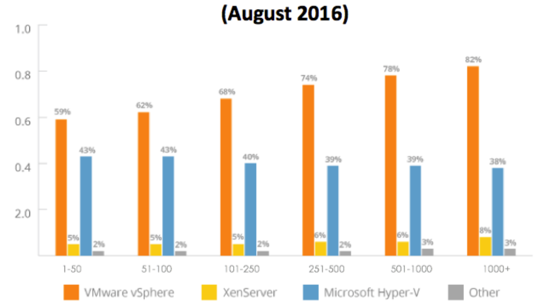
Server Virtualization Usage Across Company Sizes (August 2016)



SPICEWORKS

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VMM Implementation

Should efficiently virtualize the hardware

- Provide illusion of multiple machines
- Retain control of the physical machine

Subsystems

- Processor Virtualization
- I/O virtualization
- Memory Virtualization

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Processor Virtualization

Popek and Goldberg (1974)
- Sensitive instructions: only executed in kernel mode
- Privileged instructions: trap when run in user mode
- CPU architecture is virtualizable only if sensitive instructions are subset of privileged instructions
  - i.e. sensitive instructions will always trap if run in user mode
- When guest OS, which runs in user mode, runs a sensitive instruction, must trap to VMM so it maintains control

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Example: System Call (Type 1 Hypervisor)

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-frrom-trap	
		4. OS tried to return from trap; do real return-from-trap
5. Resume execution (@PC after trap)		

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What if not fully virtualizable?

- x86 architecture was not fully virtual*izable*
  - Certain privileged instructions behave differently when run in unprivileged mode, e.g. do nothing (e.g. POPF)
  - Certain unprivileged instructions can access privileged state (so guest OS would be able to see that it's not running in kernel mode)
- Techniques to address
  - Replace non-virtualizable instructions with easily virtualized ones statically (Paravirtualization)
  - Perform Binary Translation (Full Virtualization)

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I/O Virtualization

- Issue: lots of I/O devices
- Problem: Writing device drivers for all I/O device in the VMM layer is not a feasible option
- Insight: Device driver already written for popular Operating Systems
- One Solution:
  - Present *virtual* I/O devices to *guest* VMs
  - Channel I/O requests to a trusted *host* VM running a popular OS that has the device drivers

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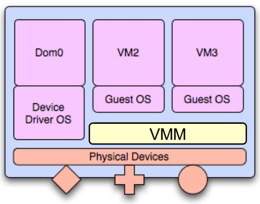
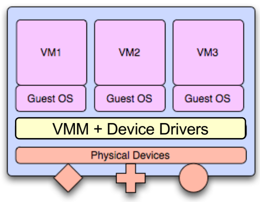
I/O Virtualization



(a) Virtual DD, channel to guest OS
- e.g. Xen



(b) Integrate DD with VMM
- e.g. Vmware ESX (Linux DDs)

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Memory Virtualization

- Traditional way is to have the VMM maintain a shadow of the VM's page table
- The shadow page keeps mapping from virtual pages within a VM to real physical pages
- When VM tries to change MMU to point to a specific page table, this traps to VMM which updates MMU to point to the shadow page table
  - Shadow PT has actual mappings between virtual pages in VM and real physical pages in machine
- Keeping shadow page table in sync with guest PT:
  - When guest OS updates page table, VMM updates shadow
  - E.g. pages of guest OS page table marked read-only

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Case Study: VMware ESX Server

- Type I VMM - Runs on bare hardware
- Full-virtualized – Legacy OS can run unmodified on top of ESX server
- Fully controls hardware resources and provides good performance

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ESX Server – CPU Virtualization

- Most user code executes in Direct Execution mode; near native performance
- For kernel code, uses *runtime* Binary Translation for x86 virtualization
  - Privileged mode code is run under control of a Binary Translator, which emulates problematic instructions
  - Fast compared to other binary translators as source and destination instruction sets are nearly identical

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ESX Server – Memory Virtualization

- Maintains shadow page tables with virtual to machine address mappings.
- Shadow page tables are used by the physical processor
- ESX maintains a “pmap” data structure for each VM, which holds “physical” to machine address mappings
- Shadow page tables are kept consistent with pmap
- With pmap, ESX can easily remap a physical to machine page mapping, without guest VM knowing the difference

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ESX Server – Memory Mgmt

- Page reclamation
  - Problem: VMM does not have as good information on page usage as guest OS, for actual page replacement algorithms
  - Solution: Ballooning technique
    - Reclaims memory from other VMs when memory is overcommitted
- Page sharing
  - Many VMs will use the same pages
  - Solution: – Content based sharing
  - Eliminates redundancy and saves memory pages when VMs use same operating system and applications

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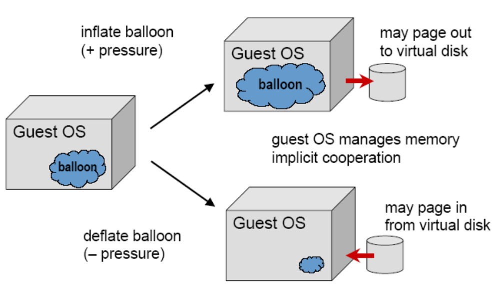
ESX Server- Ballooning



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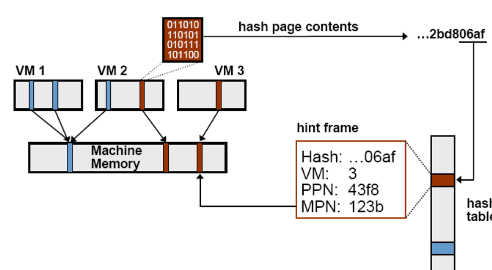
ESX Server – Page Sharing



- Copy-on-write for writing shared pages

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Real World Page Sharing

		Total	Saved	
Workload	Guest Types	MB	MB	%
Corporate IT	10 Windows	2048	673	32.9
Nonprofit Org	9 Linux	1846	345	18.7
VMware	5 Linux	1658	120	7.2

Corporate IT – database, web, development servers (Oracle, Websphere, IIS, Java, etc.)
Nonprofit Org – web, mail, anti-virus, other servers (Apache, Majordomo, MailArmor, etc.)
VMware – web proxy, mail, remote access (Squid, Postfix, RAV, ssh, etc.)

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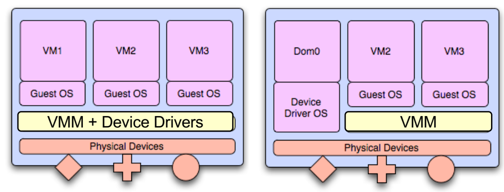
ESX Server – I/O Virtualization

- Has highly optimized storage subsystem for networking and storage devices
  - Directly integrated into the VMM
  - Uses device drivers from Linux kernel to talk directly to device
- Low performance devices are channeled to special "host" VM, which runs a full Linux OS



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VMware Workstation

- Type II VMM - Runs on host operating system
- Full-virtualized – Legacy OS can run unmodified on top of VMware Workstation
- Appears like a process to the Host OS

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Workstation - Virtualization

- CPU Virtualization and Memory Virtualization
  - Uses Similar Techniques as the VMware ESX server
- I/O Virtualization
  - Workstation relies on the Host OS for satisfying I/O requests
  - I/O incurs huge overhead as it has to switch to the Host OS on every IN/OUT instruction.
  - E.g., Virtual disk maps to a file in Host OS

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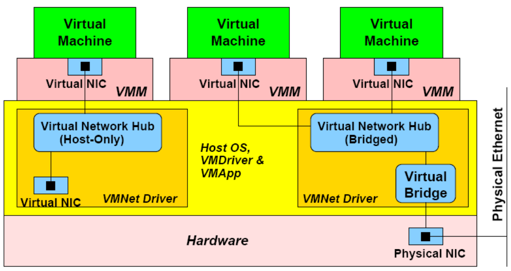
Workstation – Virtualize NIC



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Xen

- Type I VMM
- Para-virtualized
- Open-source
- Designed to run about 100 virtual machines on a single machine

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Xen – CPU Virtualization

- Privileged instructions are para-virtualized by requiring them to be validated and executed with Xen
- Processor Rings
  - Guest applications run in Ring 3
  - Guest OS runs in Ring 1 (not ring 0 as without virtualization)
  - Xen runs in Ring 0
  - So if guest OS executes privileged instruction, it traps to Xen

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Xen – Memory Virtualization(1)

- Initial memory allocation is specified and memory is statically partitioned
- A maximum allowable reservation is also specified.
- Balloon driver technique similar to ESX server used to reclaim pages

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Xen – Memory Virtualization(2)

- Guest OS is responsible for allocating and managing hardware page table
- Xen involvement is limited to ensure safety and isolation
- OS maps Xen VMM into the top 64 MB section of every address space to avoid TLB flushes when entering and leaving the VMM

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Xen – I/O Virtualization

- Xen exposes its own set of clean and simple device abstractions – doesn't emulate existing devices
- I/O data is transferred to and from each domain via Xen, using shared memory, asynchronous buffer descriptor rings
- Xen supports lightweight event delivery mechanism used for sending asynchronous notifications to domains

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Summary

- Classifying Virtual Machine Monitors
  - Type I vs. type II
  - Full vs. para-virtualization
- Processor virtualization
- Memory virtualization
- I/O virtualization

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