COS 318: Operating Systems

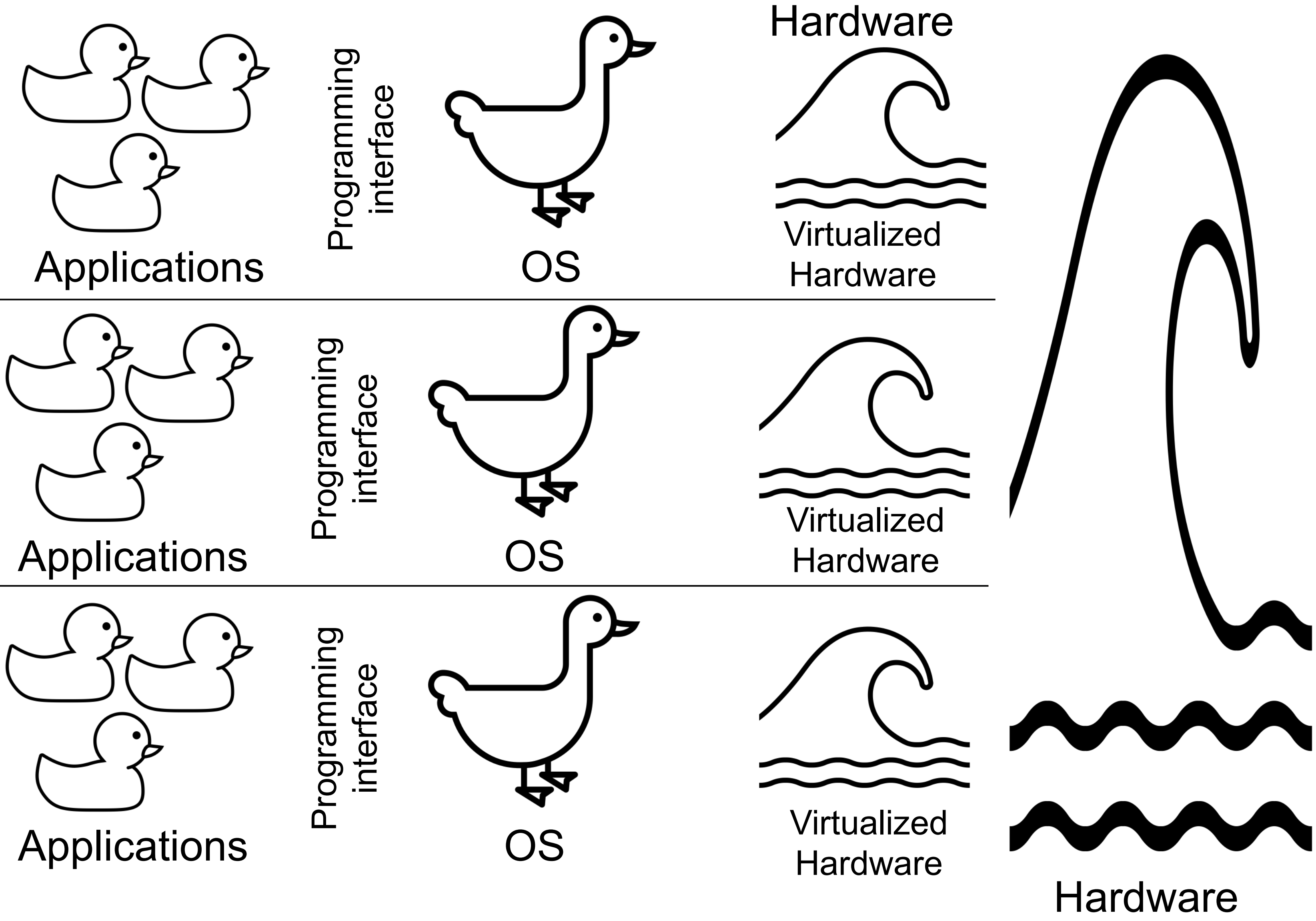
Virtual Machine Monitors

Virtual Machines

- We have seen how the OS virtualizes subsystems
  - CPU, Memory, IO
  - To give applications illusions about owning the system

- What about:
  - Virtualizing the whole system
  - Giving OSes the illusion of a system that isn't real

The Idea



Hardware

Applications

Programming interface

OS

Virtualized Hardware

Applications

Programming interface

OS

Virtualized Hardware

Applications

Programming interface

OS

Virtualized Hardware

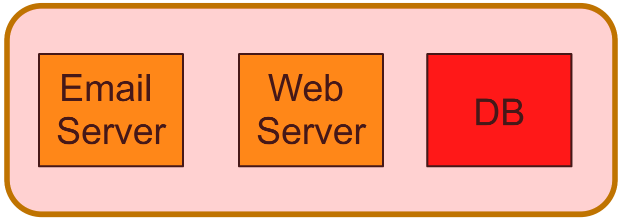
Hardware

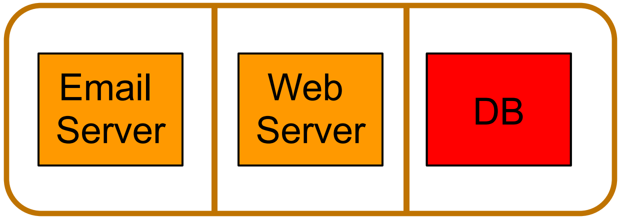
Virtual Machine Monitor (VMM)

- 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**

Why virtualize?

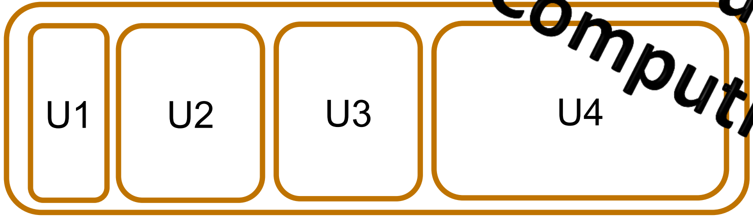
- Isolation and safety
  - SW-related faults more prevalent than HW-related issues
    - Bugs, poor design, mis-configuration, etc.





- Efficiency and cost reduction

A developer testing a new app on different OSs.



Cloud Computing

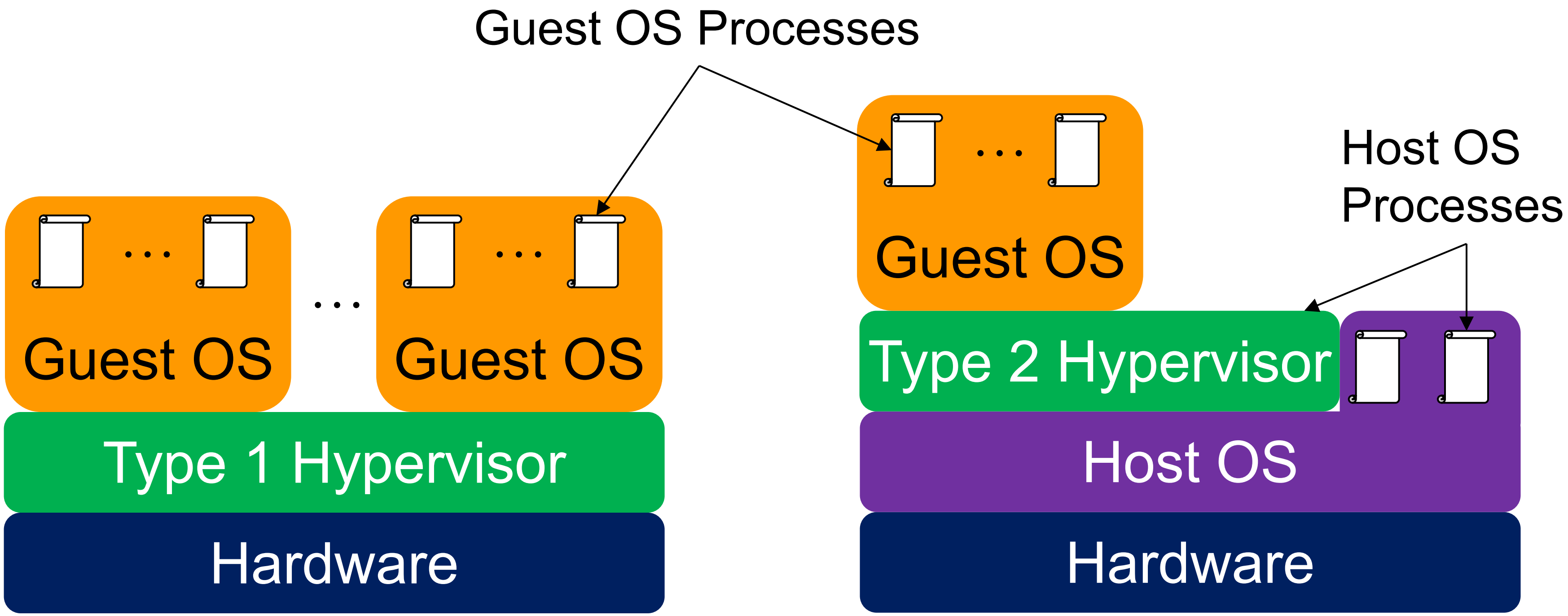
Co-locate different users.

VMM Implementation 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 subsystems

Type 1 and Type 2 Hypervisors



Type 1

Type 2
(a.k.a. hosted hypervisor)

Virtualization Styles

- Full virtualization
  - Virtual machine mimics a physical machine
    - Not necessarily exactly like the underlying hardware itself
  - Run guest OS unchanged
  - VMM is transparent to the OS
- Para-virtualization
  - Guest OS is changed to cooperate with VMM
  - Sacrifice transparency for better performance
  - E.g., VMM can provide “hypervisor API” so guest can perform certain functions, e.g. with optimizations for performance
- Process virtualization
  - Allow running a process written for a different OS
  - Example: Wine

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
  - 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

VMM Implementation

Three main requirements:

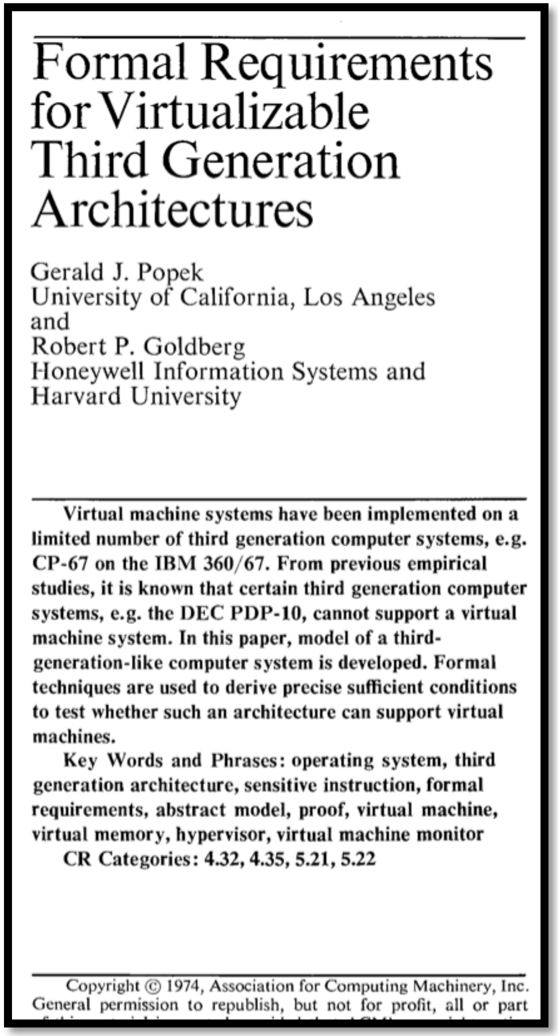
- **Safety**: VMM having full control of virtualized resources
- **Fidelity**: program behaves as if running on bare hardware
- **Efficiency**: minimal intervention and low overhead

Main VMM subsystems:

- Processor Virtualization
- I/O virtualization
- Memory Virtualization

Popek and Goldberg (1974)

- Sensitive instructions:
  - Should be executed in kernel mode for correct behavior
- Privileged instructions:
  - Cause a trap when executed 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, this must trap to VMM so it maintains control.



Formal Requirements for Virtualizable Third Generation Architectures

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Virtual machine systems have been implemented on a limited number of third generation computer systems, e.g. CP-67 on the IBM 360/67. From previous empirical studies, it is known that certain third generation computer systems, e.g. the DEC PDP-10, cannot support a virtual machine system. In this paper, model of a third-generation-like computer system is developed. Formal techniques are used to derive precise sufficient conditions to test whether such an architecture can support virtual machines.

Key Words and Phrases: operating system, third generation architecture, sensitive instruction, formal requirements, abstract model, proof, virtual machine, virtual memory, hypervisor, virtual machine monitor

CR Categories: 4.32, 4.35, 5.21, 5.22

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

Virtualizablity of the x86 Architecture

- 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 it:
  - Replace non-virtualizable instructions with easily virtualized ones statically (Paravirtualization)
  - Perform **Binary Translation** (Full Virtualization)
- In 2005 Intel and AMD added virtualization support
  - Intel: Virtualization Technology (VT), AMD: AMD-V

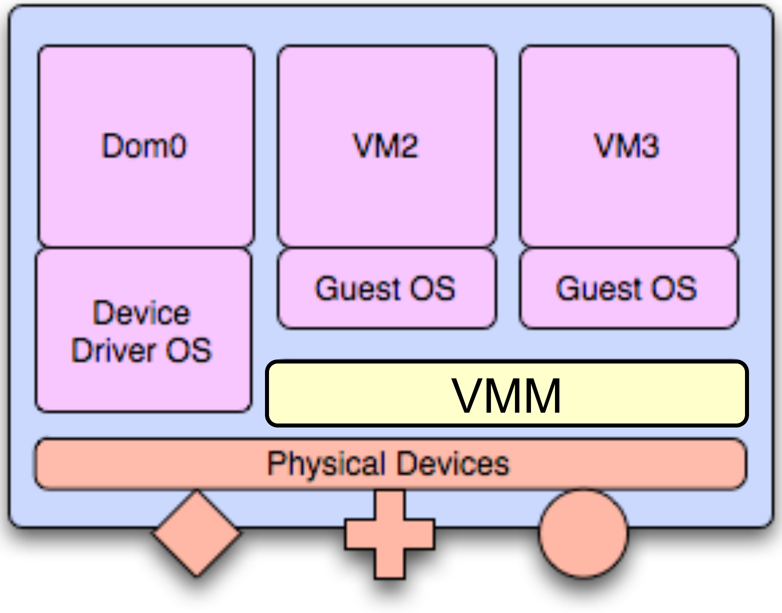
Examples of Hypervisors

	Type 1	**Type 2**
Process Virtualization		Wine
Full Virtualization without HW support	ESX Server 1.0	VMware Workstation 1
Full Virtualization with HW support	Xen Microsoft Hyper-V VMware vSphere	Linux KVM VMWare Fusion
Para-virtualization	Xen 1.0	

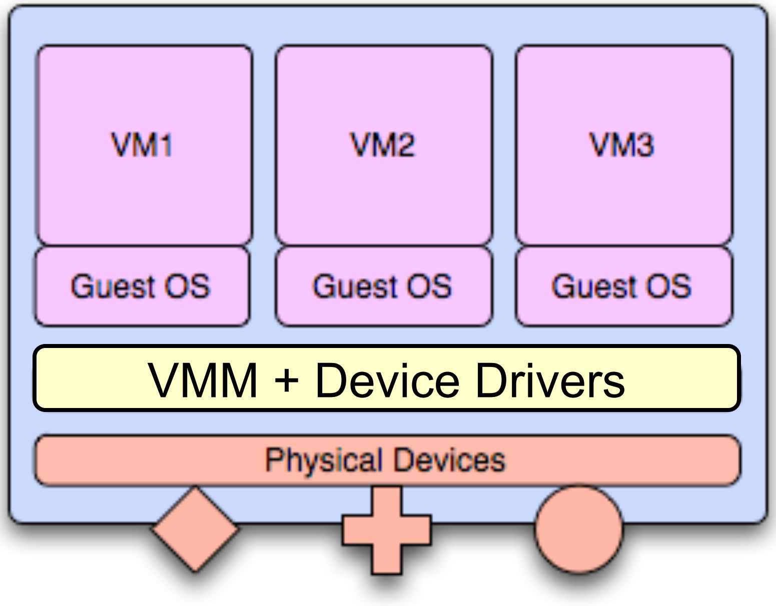
I/O Virtualization

- 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

I/O Virtualization



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



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

Memory Virtualization

- Traditional way is to have the VMM maintain a **shadow page table** per VM
- The shadow page keeps mapping from virtual pages within a VM to real physical pages allotted by VMM
- 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

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

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

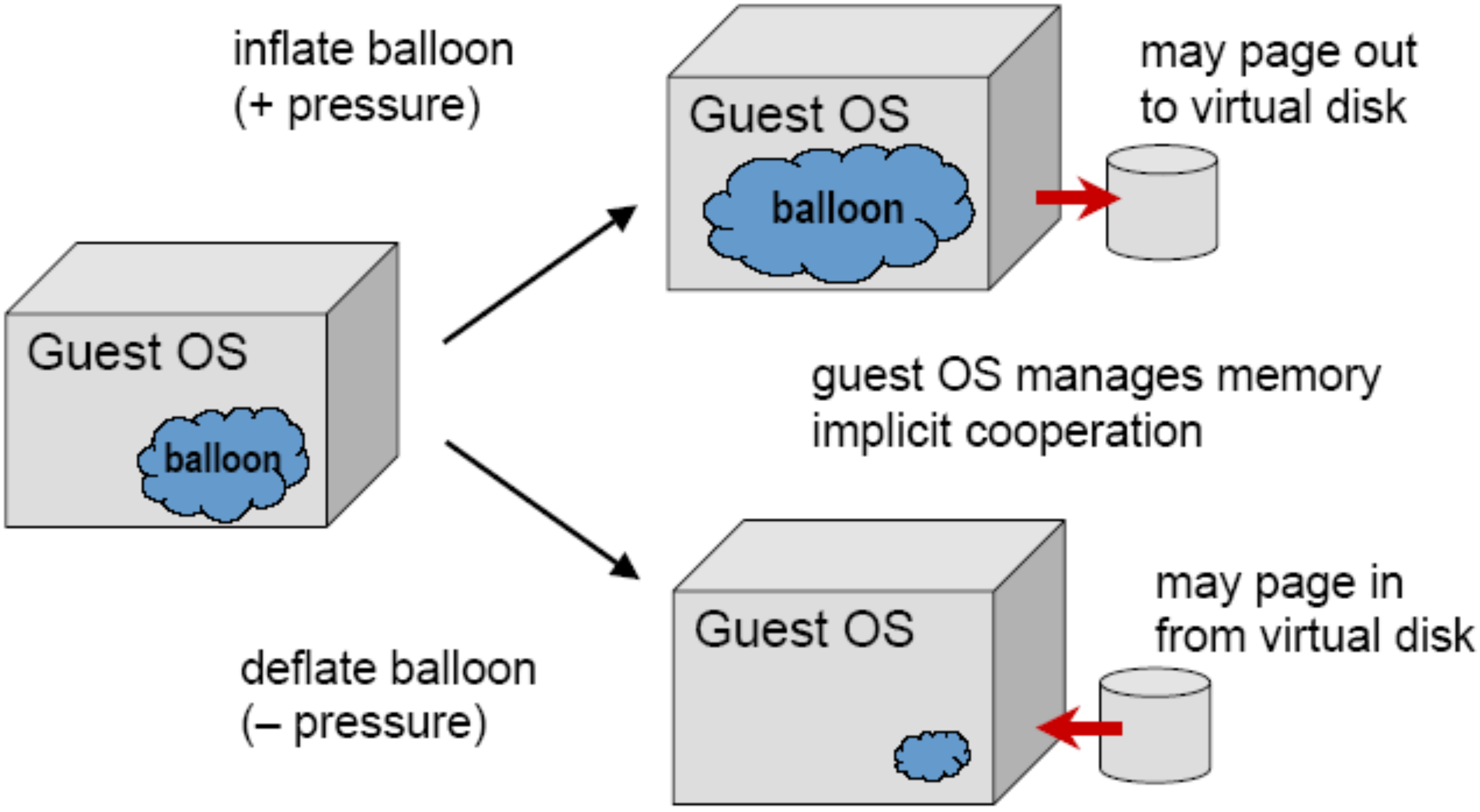
ESX Server – Memory Virtualization

- 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

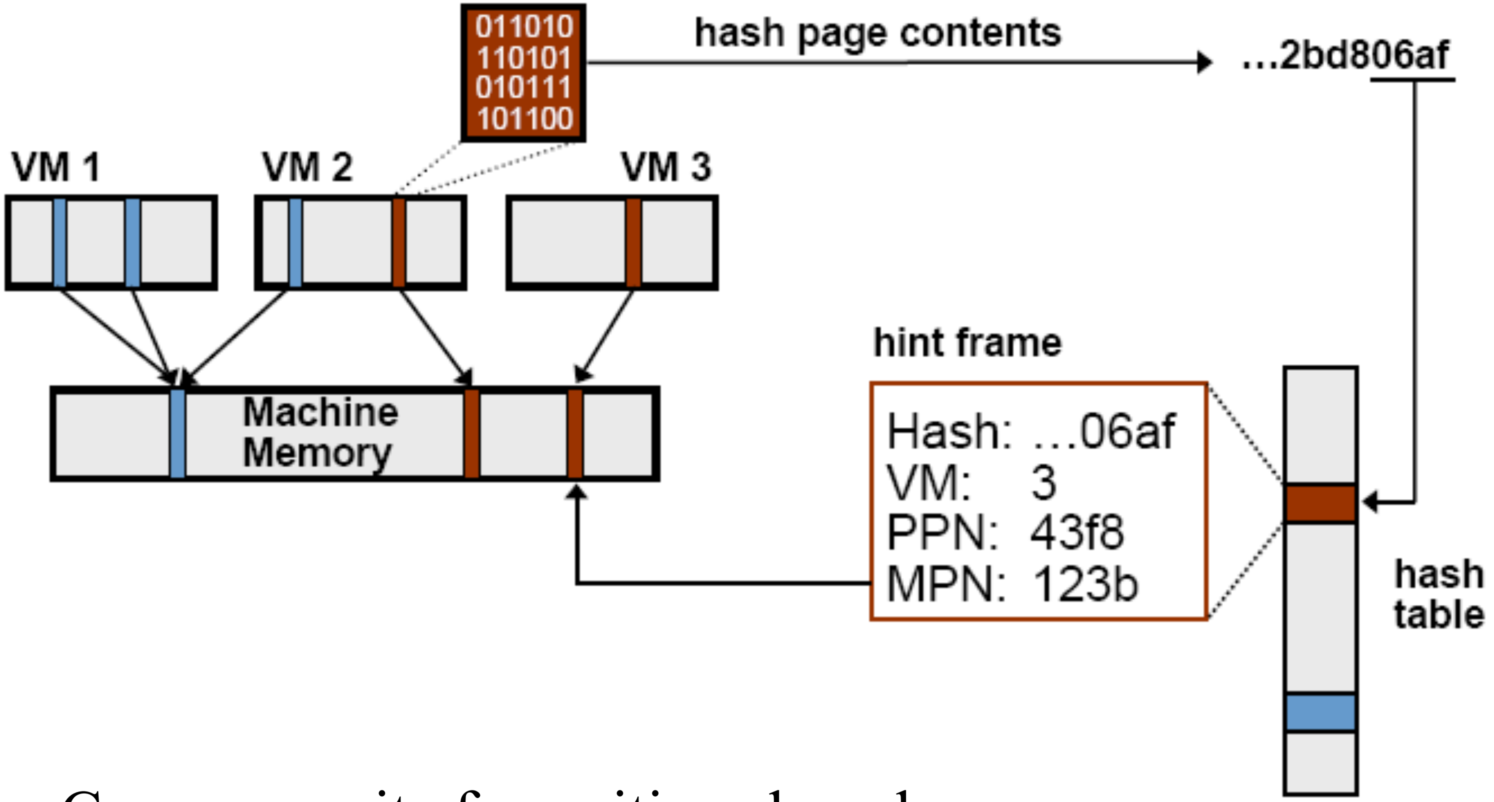
ESX Server – Memory Mgmt

- 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

ESX Server- Ballooning

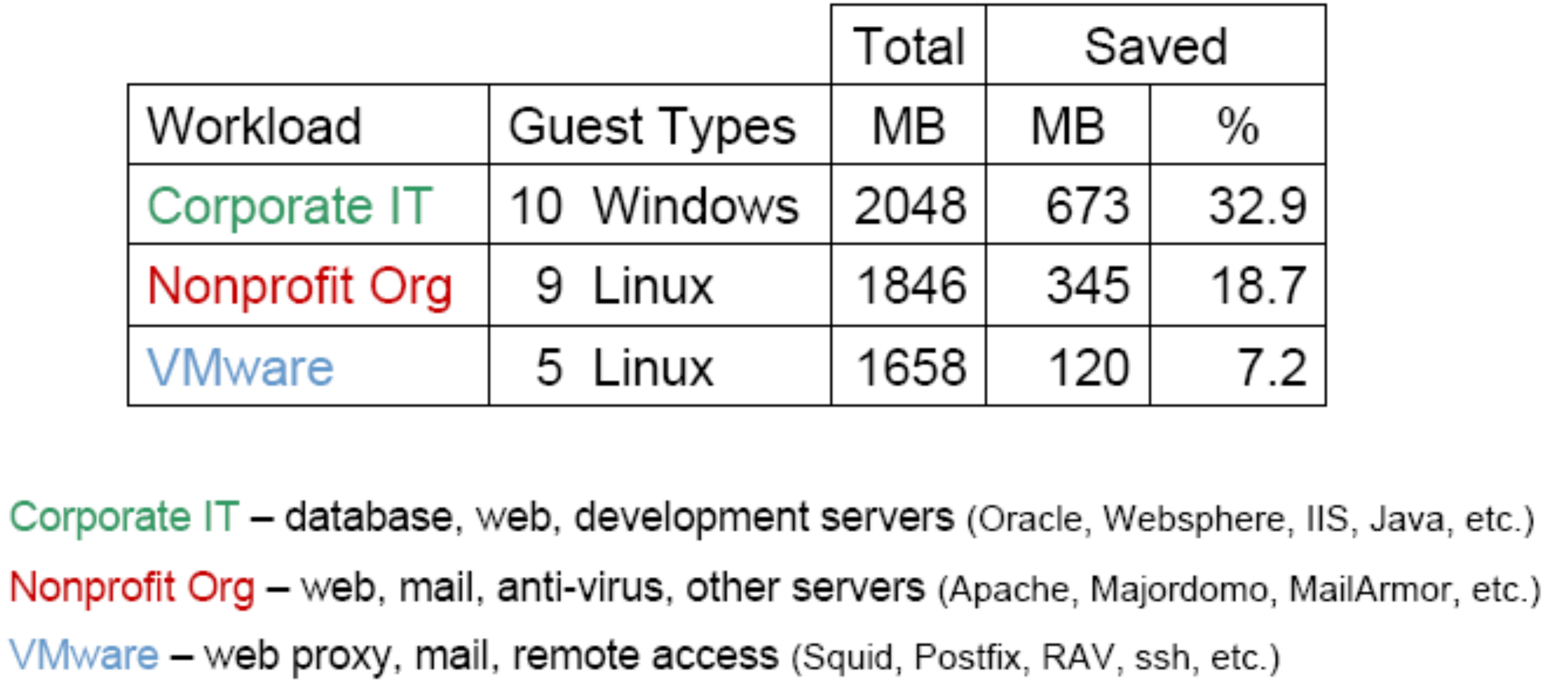


ESX Server – Page Sharing



- Copy-on-write for writing shared pages

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

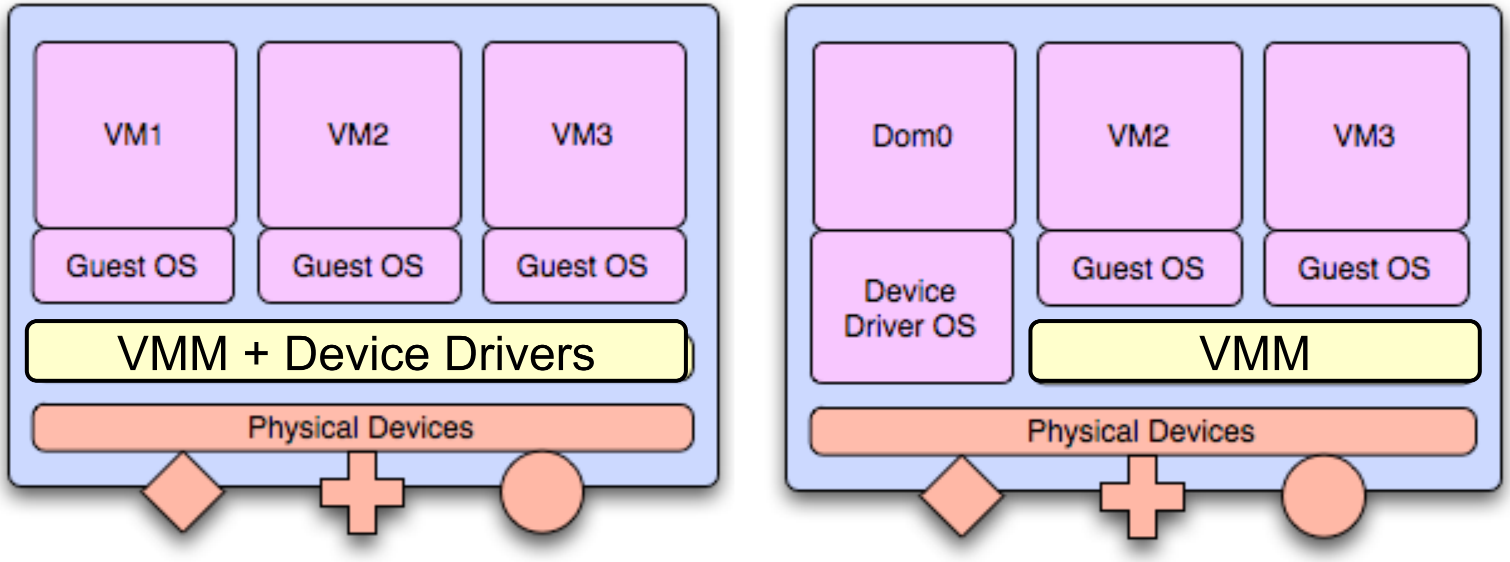
Corporate IT – database, web, development servers (Oracle, Websphere, IIS, Java, etc.)

Nonprofit Org – web, mail, anti-virus, other servers (Apache, Majordomo, MailArmor, etc.)

VMware – web proxy, mail, remote access (Squid, Postfix, RAV, ssh, etc.)

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



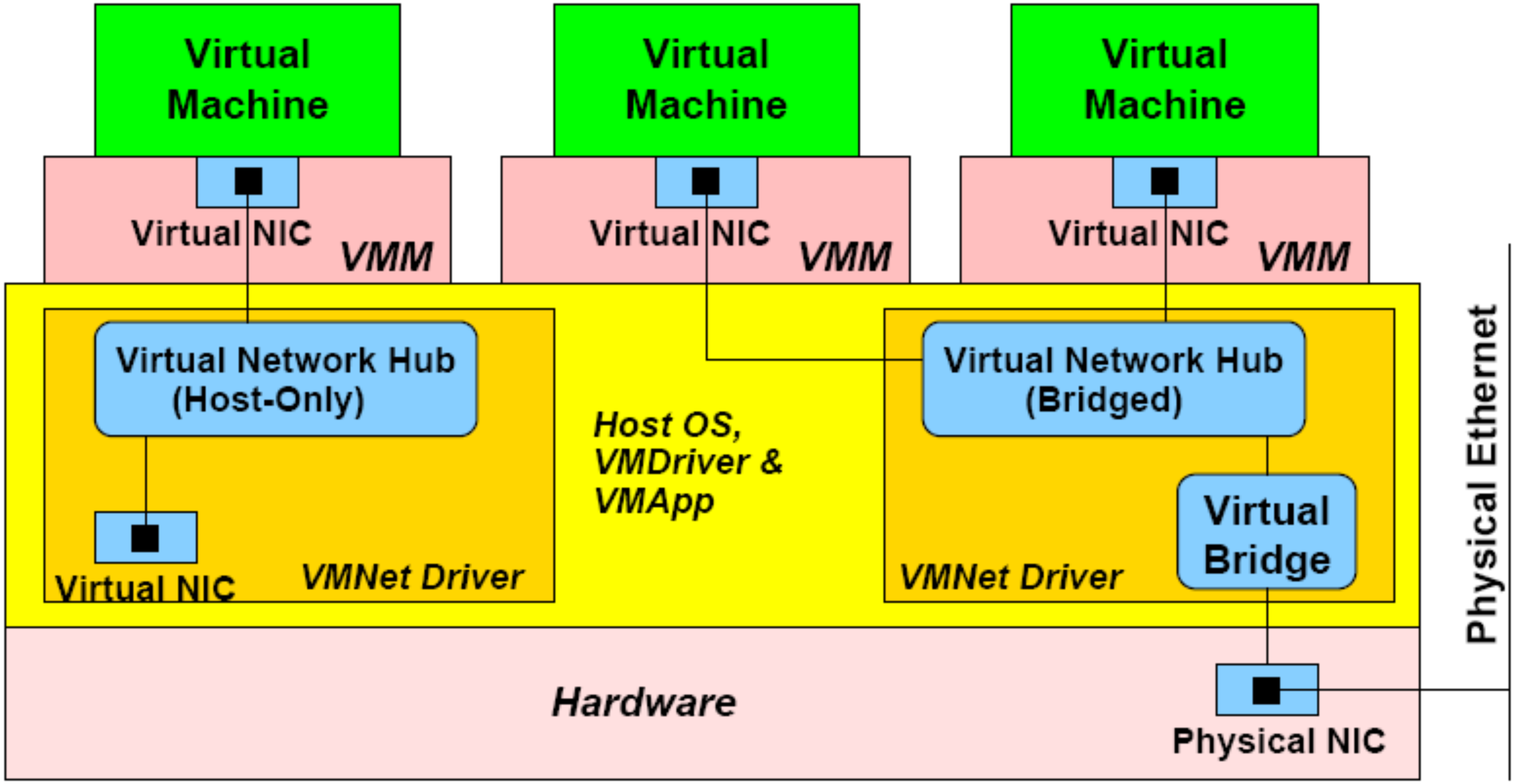
VMware Workstation

- 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

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

Workstation – Virtualize NIC



Xen 1.0

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

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

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

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

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

Summary

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