# COS 318: Operating Systems

# Virtual Machine Monitors

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http://www.cs.princeton.edu/courses/archive/fall10/cos318/

# Introduction

- Have been around since 1960's on mainframes
  - used for multitasking
  - Good example – VM/370
- Have resurfaced on commodity platforms
  - Server Consolidation
  - Web Hosting centers
  - High-Performance Compute Clusters
  - Managed desktop / thin-client
  - Software development / kernel hacking

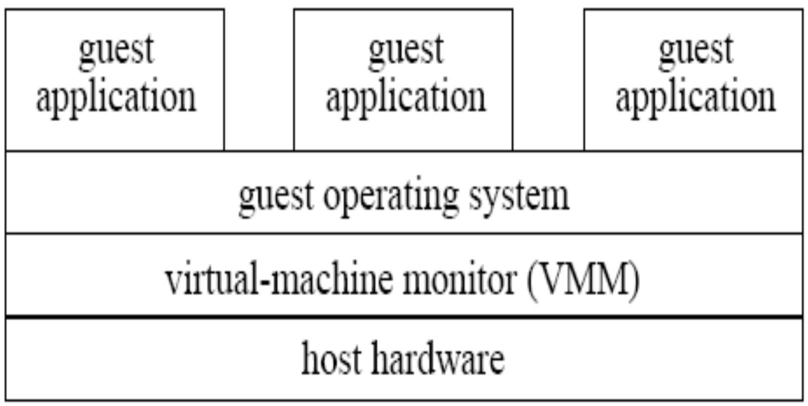
# Why do we care?

- Manageability
  - Ease maintenance, administration, provisioning, etc.
- Performance
  - Overhead of virtualization should be small
- Isolation
  - Activity of one VM should not impact other active VMs
  - Data of one VM is inaccessible by another
- Scalability
  - Minimize cost per VM

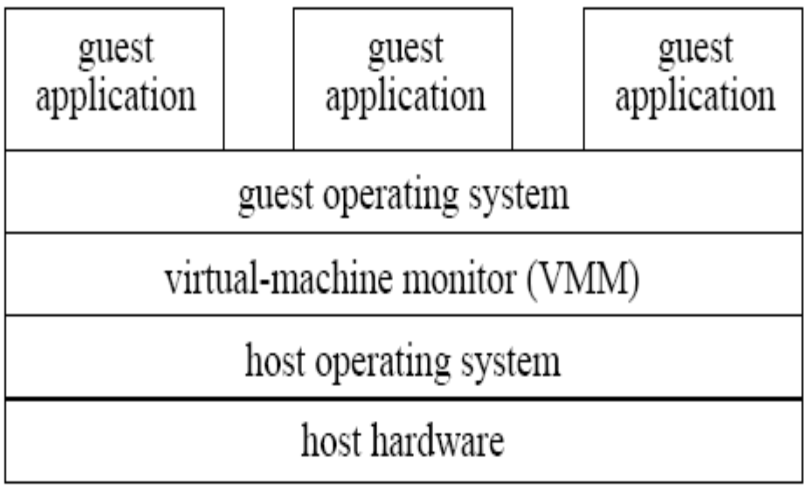
# Virtual Machine Monitor (VMM)

- Resides as a layer below the operating system
- Presents a hardware interface to an OS
- Multiplexes resources between several virtual machines (VMs)
- Performance Isolates VMs from each other

# VMM Types




Type I VMM




Type II VMM

# Virtualization Styles

- Fully virtual*izing* VMM

- Para- virtual*izing* VMM

# VMM Classification

| | Type I | Type II |
|---|---|---|
| Fully-virtualized | VMware ESX | VMware Workstation |
| Para-virtualized | Xen | User Mode Linux |

# 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

# 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

- When guest OS runs a sensitive instruction, must trap to VMM so it maintains control

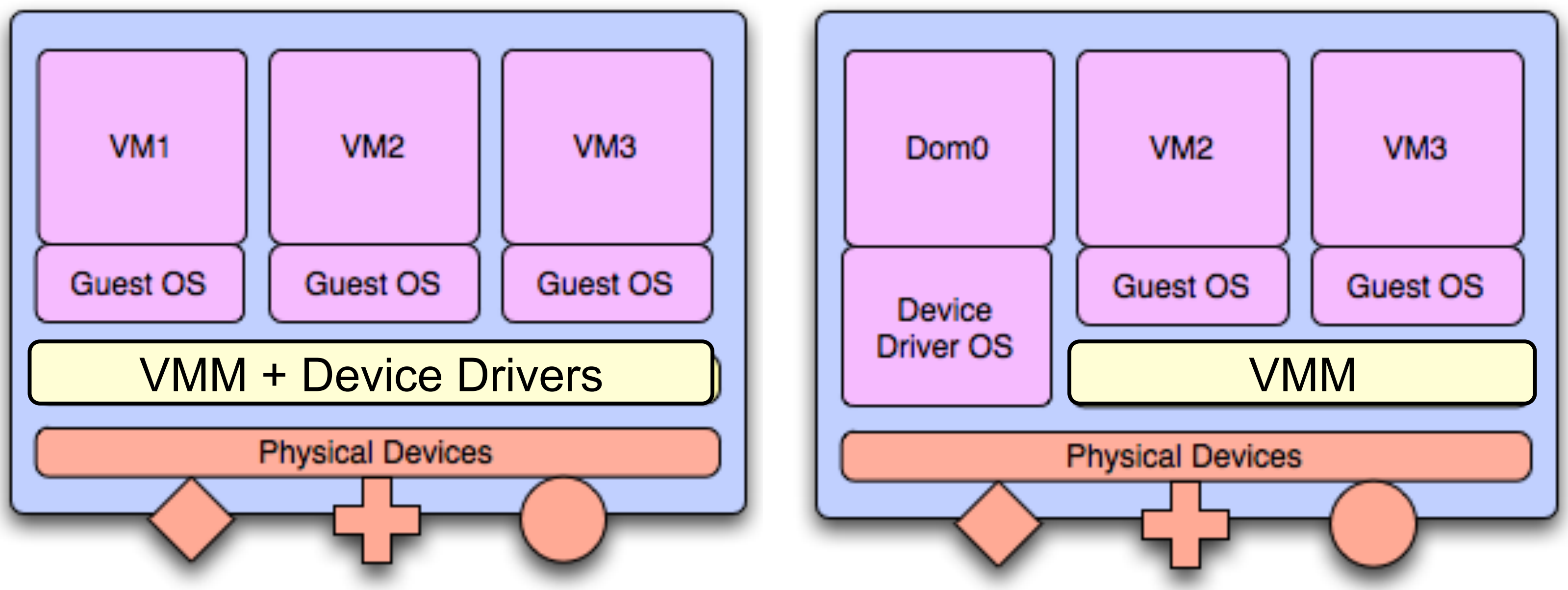
# x86 Processor Virtualization

- x86 architecture is not fully virtual*izable*
  - Certain privileged instructions behave differently when run in unprivileged mode
  - Certain unprivileged instructions can access privileged state
- Techniques to address inability to virtualize x86
  - Replace non-virtualizable instructions with easily virtualized ones statically (Paravirtualization)
  - Perform Binary Translation (Full Virtualization)

# 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
- Solution: Present *virtual* I/O devices to *guest* VMs and channel I/O requests to a trusted *host* VM running popular OS

# I/O Virtualization



# Memory Virtualization

- Traditional way is to have the VMM maintain a shadow of the VM's page table
- The shadow page table controls which pages of machine memory are assigned to a given VM
- When guest OS updates its page table, VMM updates the shadow

# 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
- 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

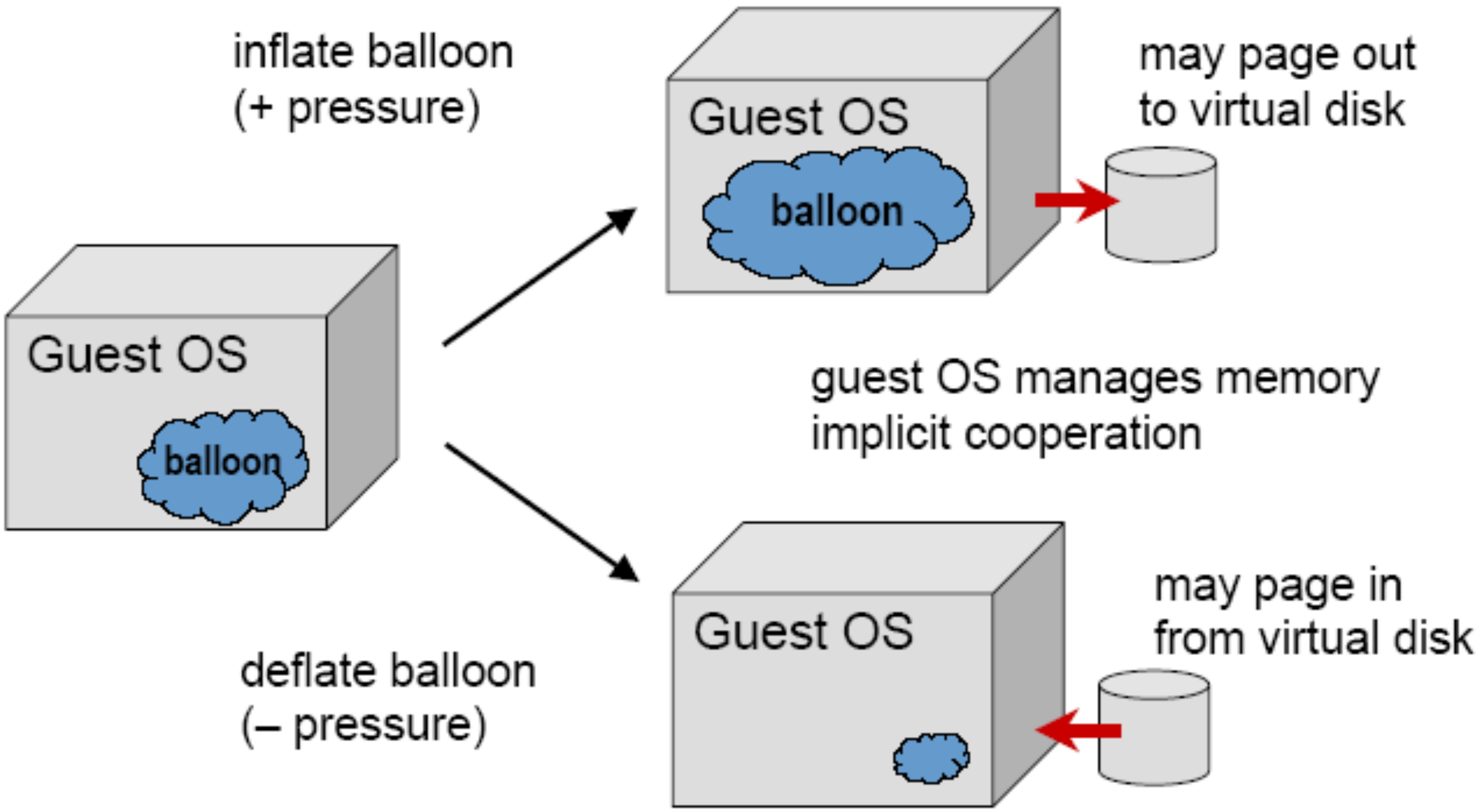
# ESX Server – Memory Virtualization

- Maintains shadow page tables with virtual to machine address mappings.
- Shadow page tables are used by the physical processor
- ESX maintains the pmap data structure for each VM with “physical” to machine address mappings
- ESX can easily remap a machine page

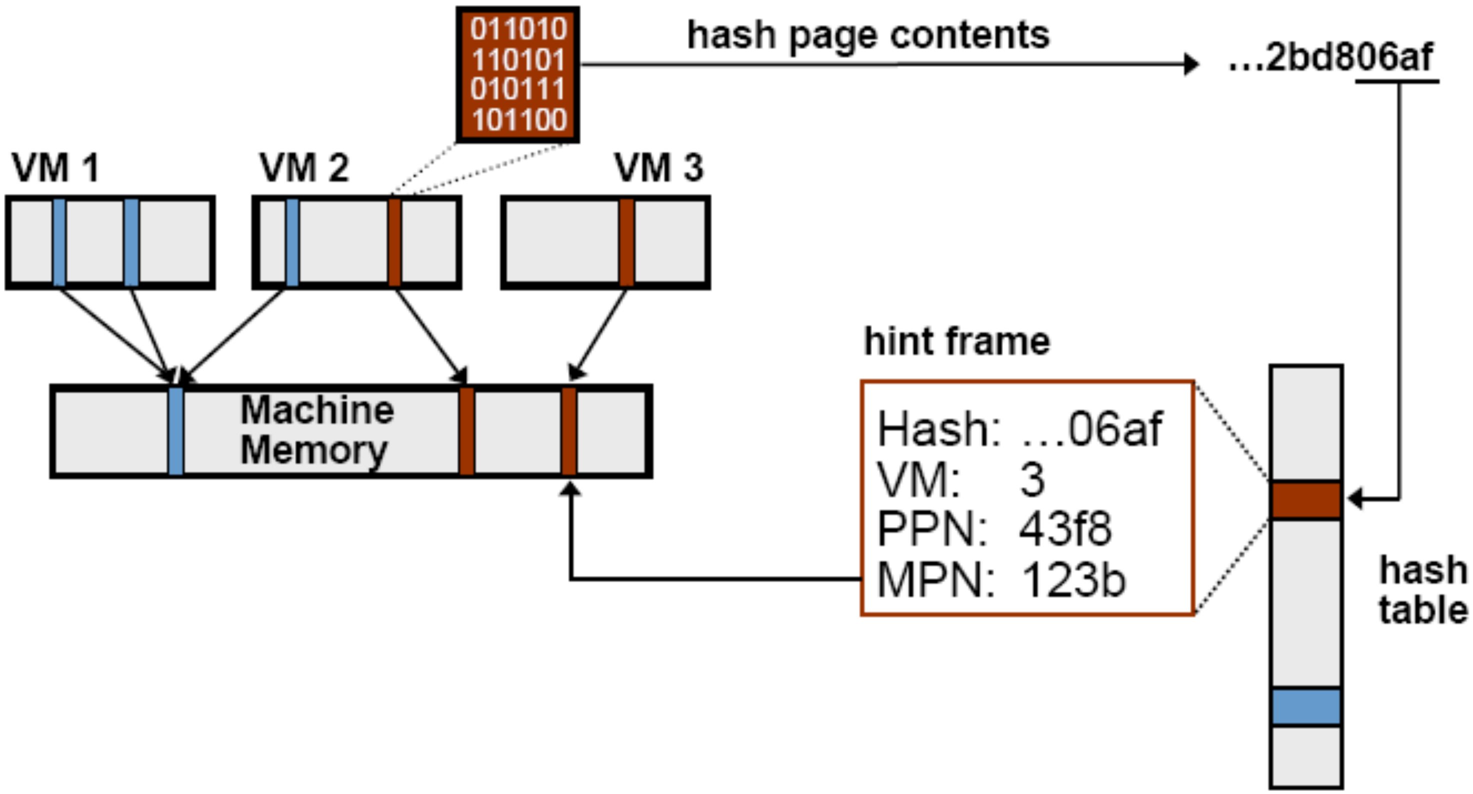
# ESX Server – Memory Mgmt

- Page reclamation – Ballooning technique
  - Reclaims memory from other VMs when memory is overcommitted
- Page sharing – Content based sharing
  - Eliminates redundancy and saves memory pages when VMs use same operating system and applications

# ESX Server- Ballooning



# ESX Server – Page Sharing



# 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.)

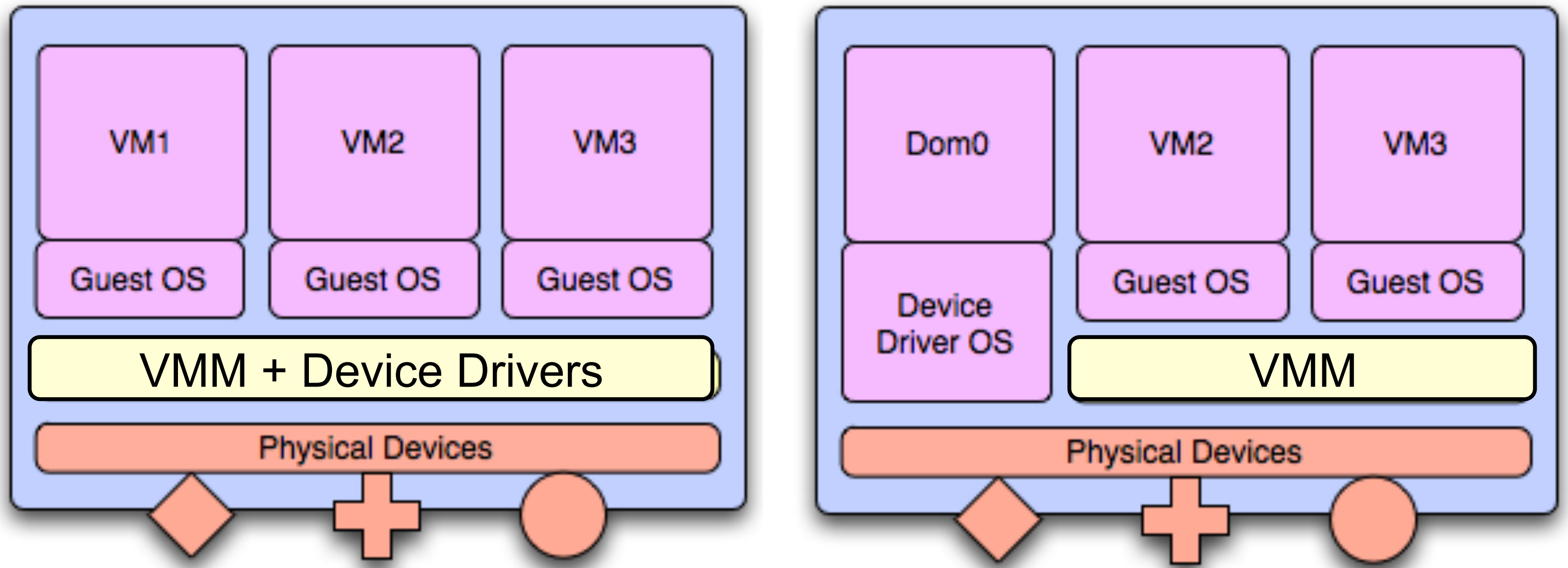
Nonprofit Org – web, mail, anti-virus, other servers (Apache, Majordomo, MailArmor, etc.)

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 the Linux kernel to talk directly to the device
- Low performance devices are channeled to special "host" VM, which runs a full Linux OS

# I/O Virtualization



# 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

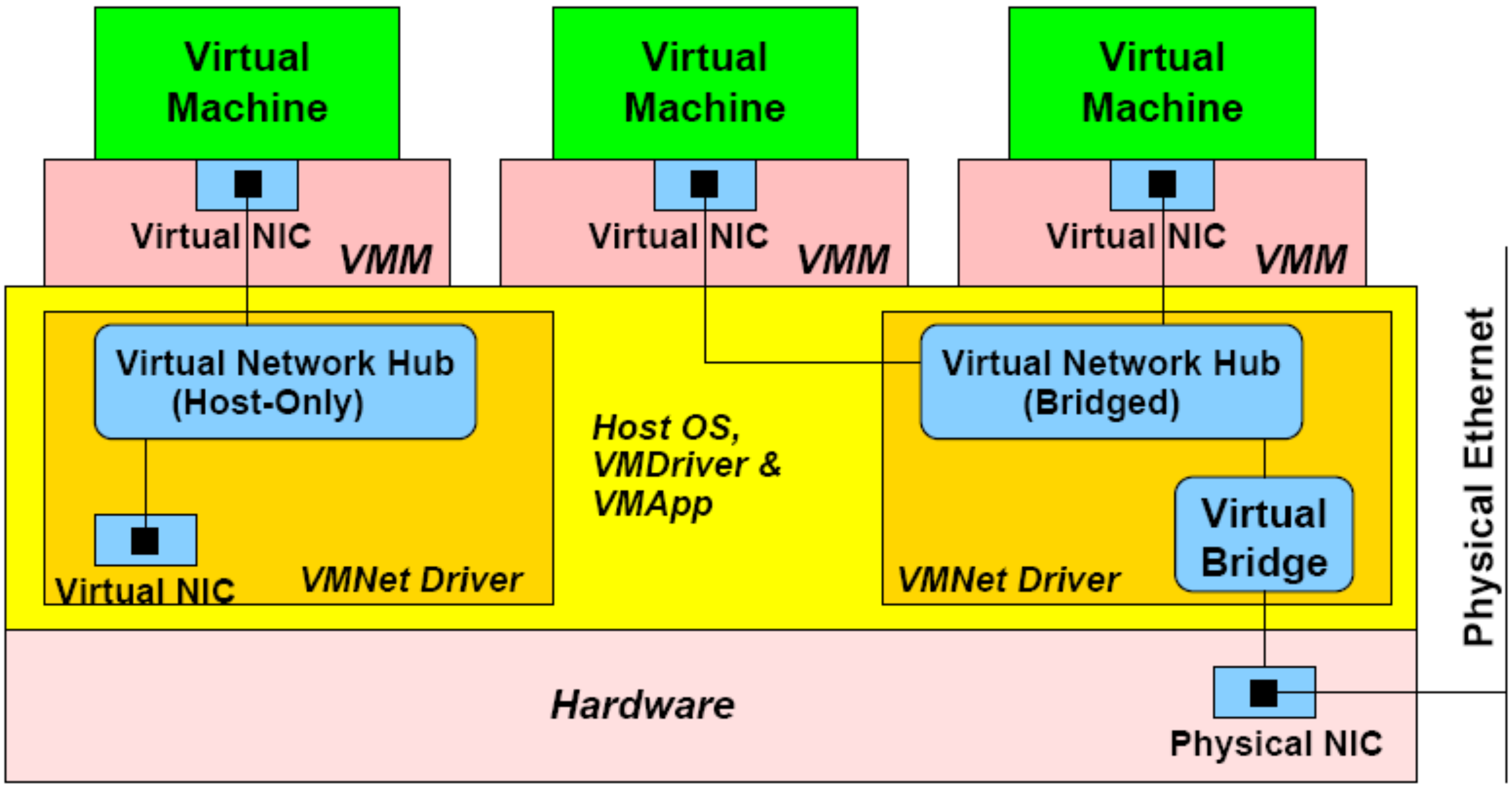
# Workstation - Virtualization

- 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.

# Workstation – I/O Virtualization

- VMM must be able to intercept all I/O operations issued by the Guest OS
- These are trapped by the VMM and emulated either in VMM or VMApp.
- Any access that interact with physical hardware have to be handled by VMApp
- I/O intensive workload performs poorly due to extra host switches between the Host and the VMM worlds

# Workstation – Virtualize NIC



# Xen

- 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
  - Xen runs in Ring 0

# 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
- Xen exists in the top 64 MB section at the top of every address space to avoid TLB flushes when entering and leaving the VMM

# Xen – I/O Virtualization

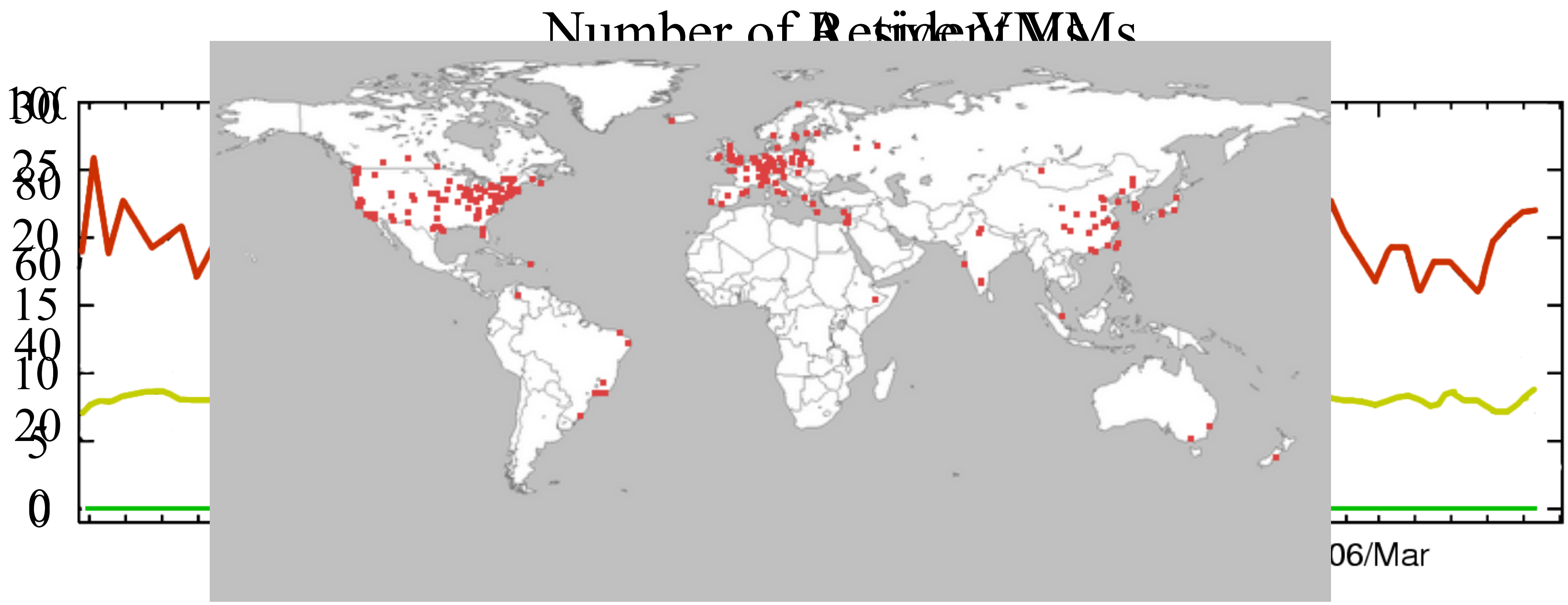
- Xen exposes a set of clean and simple device abstractions
- I/O data is transferred to and from each domain via Xen, using shared memory, asynchronous buffer descriptor rings
- Xen supports lightweight event delivery mechanism used for sending asynchronous notifications to domains

# VMMs the only way to Virtualize?

- Alternative: Container-based OS (COS)
  - Eg., Solaris 10, Linux-Vserver, OpenVZ

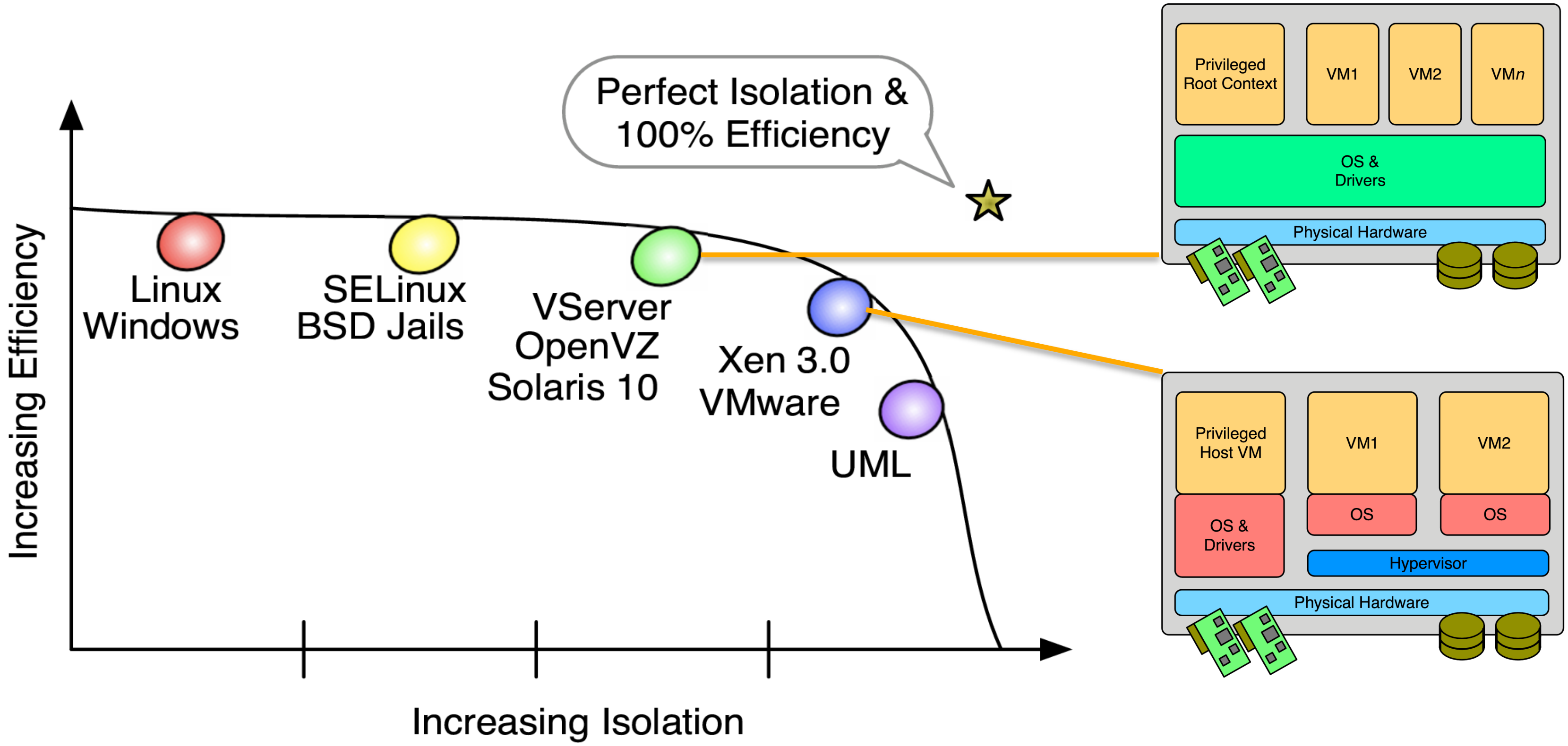
| **Features** | **VMM** | **COS** |
|---|---|---|
| Multiple kernels | ✔ | ✘ |
| Administrative power (root) | ✔ | ✔ |
| Manageability | ✔ | ✔ |
| Scalability | ✔ | ✔✔ |
| Isolation | ✔✔ | ✔ |
| Efficiency | ✔ | ✔✔ |

# PlanetLab (circa 2005) Usage




- Typical Node (2.4GHz, 1GB, 100GB disk)
- ~250-300 configured VM file systems on disk
- 40-90 resident VMs with ≥ 1 process
- 5-20 active VMs using CPU

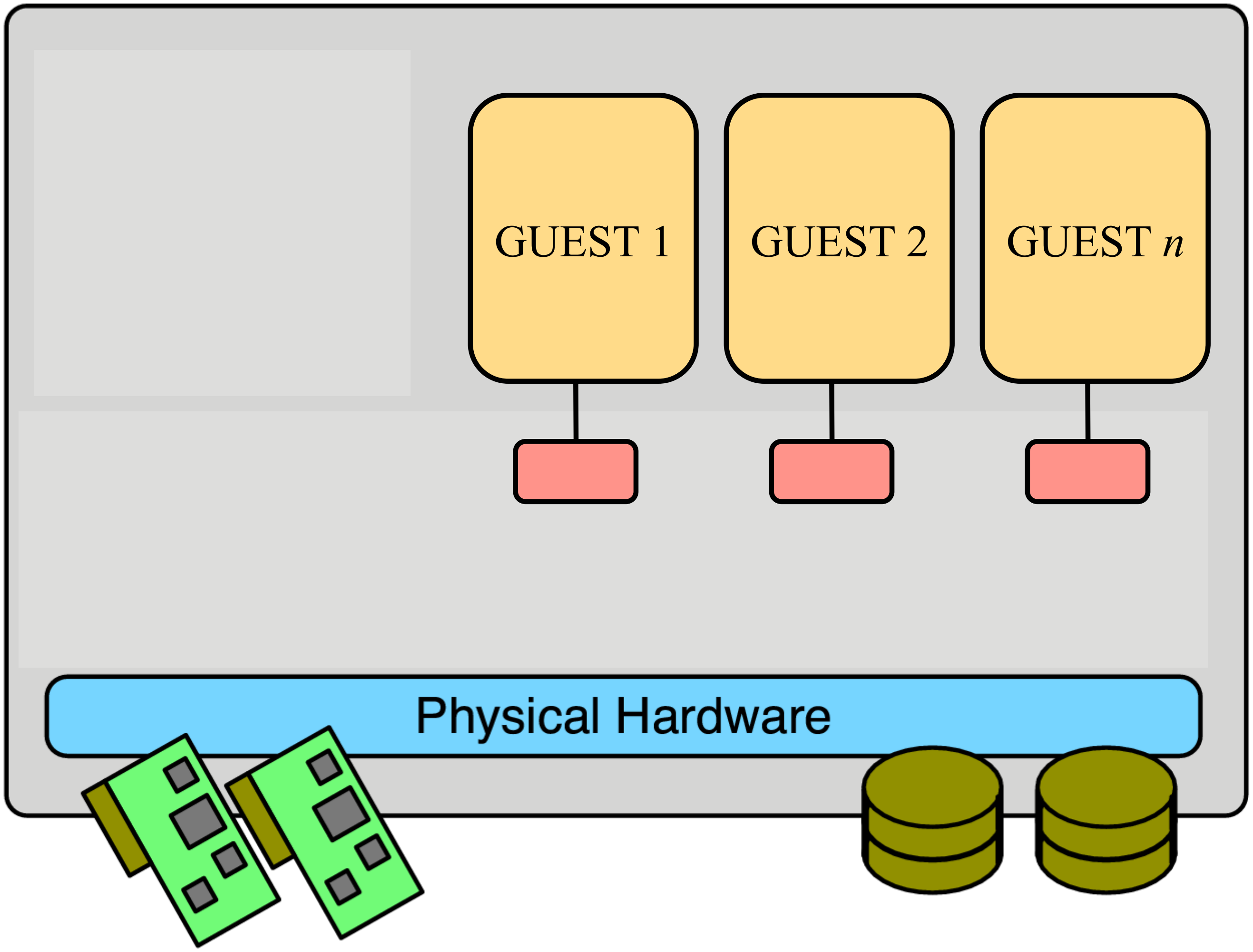
# Container vs. Hypervisor Virtualization:
## What is the Trade-Off?



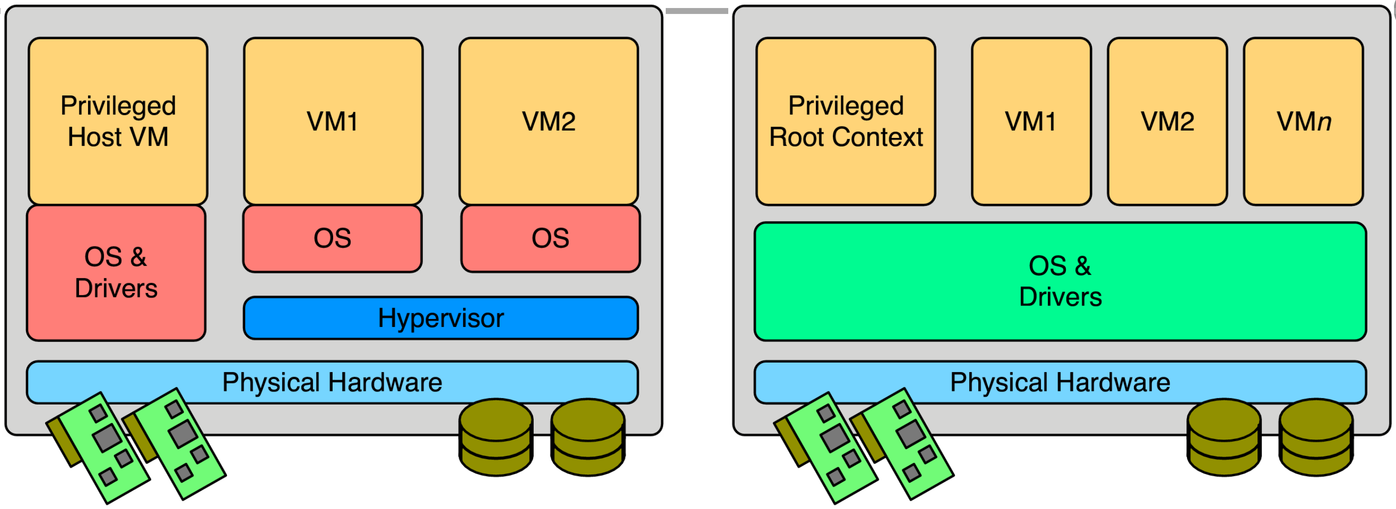

•Stephen Soltesz, Herbert Pötzl, Marc Fiuczynski, Andy Bavier, Larry Peterson. *Container-based operating system virtualization: A scalable, high-performance alternative to hypervisors.* EuroSys 2007

•Herbert Pötzl and Marc Fiuczynski. *Linux-VServer: Resource-Efficient OS-level Virtualization*, Ottawa Linux Sym. 2007

# Container Design

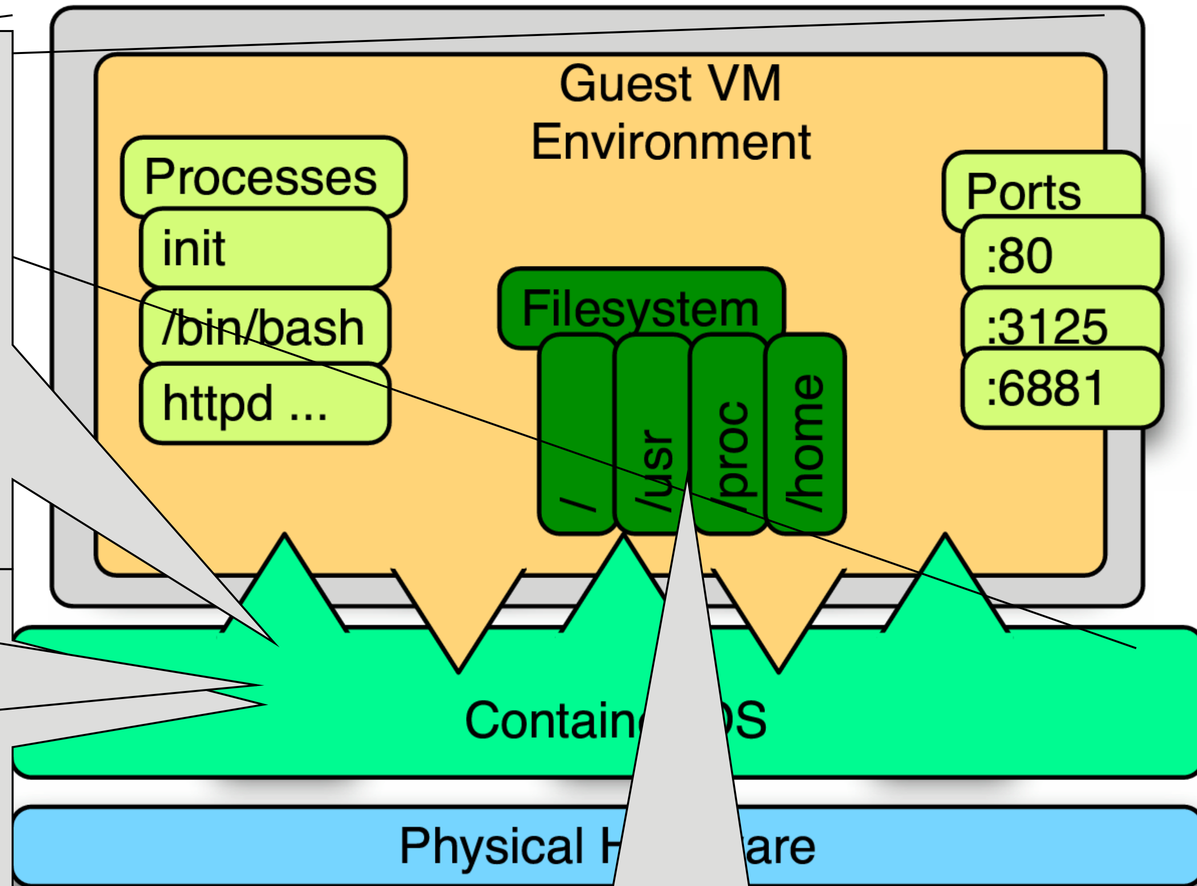


# Feature Comparison




| | Hypervisor | Container | |
|---|---|---|---|
| Multiple Kernels | ✓ | X | |
| Load Arbitrary Modules | ✓ | X | |
| Local Administration (root) | ✓ | ✓ | All |
| Live Migration | ✓ | ✓ | OpenVZ |
| Cross Version Migration | X | ✓ | Zap |

# Linux-VServer Overview




**Resource Control**
- Map Container to
  - HTB for Network
  - CFQ for Disk
- Logical Limits
  - Processes
  - Open FD

**Scheduler**
- Single Level
- Token Bucket Filter
- preserves O(1) scheduler

  - Context ID Filter
  - User IDs
  - SHM & IPC address
  - File system Barriers

**Optimizations**
- File-level Copy-on-write

# COS vs. VMM Summary

- COS=Linux-Vserver VMM=Xen
- Performance
  - COS 1.25x – 2x more efficient than VMM
- Scalability
  - COS scales ~10x better
- Isolation
  - COS almost as good as VMM

# Summary

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

# Review Topics

- OS structure
- Process management
- CPU scheduling
- Virtual memory
- Disks and file systems
- General concepts

# Operating System Structure

- Abstraction
- Protection and security
- Kernel structure
  - Layered
  - Monolithic
  - Micro-kernel
- Virtualization
  - Virtual machine monitor

# Process Management

- Implementation
  - State, creation, dispatching, context switch
  - Threads and processes
- Synchronization
  - Race conditions and inconsistencies
  - Mutual exclusion and critical sections
  - Semaphores: P() and V()
    - Producer & Consumer problems
    - Scheduling problems
  - Semaphore implementations
    - Atomic operations: interrupt disable, test-and-set.
  - Monitors and Condition Variables
  - Deadlock detection and prevention

# CPU Scheduling

- Allocation -- Non-preemptible resources
- Scheduling -- Preemptible resources
  - FIFO
  - Round-robin
  - STCF
  - Lottery

# Virtual Memory

- Mechanisms
  - Base and bounds
  - Paging
  - Segmentation
  - Page and segmentation
  - TLBs
- Page replacement
  - LRU and clock
  - Thrashing, working sets and WSClock

# Disks and File Systems

- Disks
  - Disk behavior
  - Disk scheduling
  - RAID
  - Volume manager
- File access pattern and layout
- Directories and implementation
- File system performance
  - Layout for performance
  - Buffer cache
- File system reliability
  - Crash recovery and logging
- NFS and NetApp file system
- Deduplication file system

# Major Concepts

- Locality
  - Spatial, temporal and working set
- Scheduling
  - Optimal algorithms know future, but we use past instead
- Layering
  - Synchronization, transactions, file systems, etc
- Caching
  - Translation look aside buffer, VM, buffer cache, etc

# Operating System as Illusionist

Physical reality

- Single CPU
- Interrupts
- Limited memory
- No protection
- Raw storage device

Abstraction

- Infinite number of CPUs
- Cooperating sequential threads
- Unlimited virtual memory
- Each address has its own machine
- Organized and reliable storage system

**Future courses**

Networking: COS 461
Security: COS 429
Advanced OS: COS 518
Parallel Arch & Prog. COS 598A