Virtual Machine Monitors

Dr. Marc E. Fiuczynski
Research Scholar
Princeton University

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

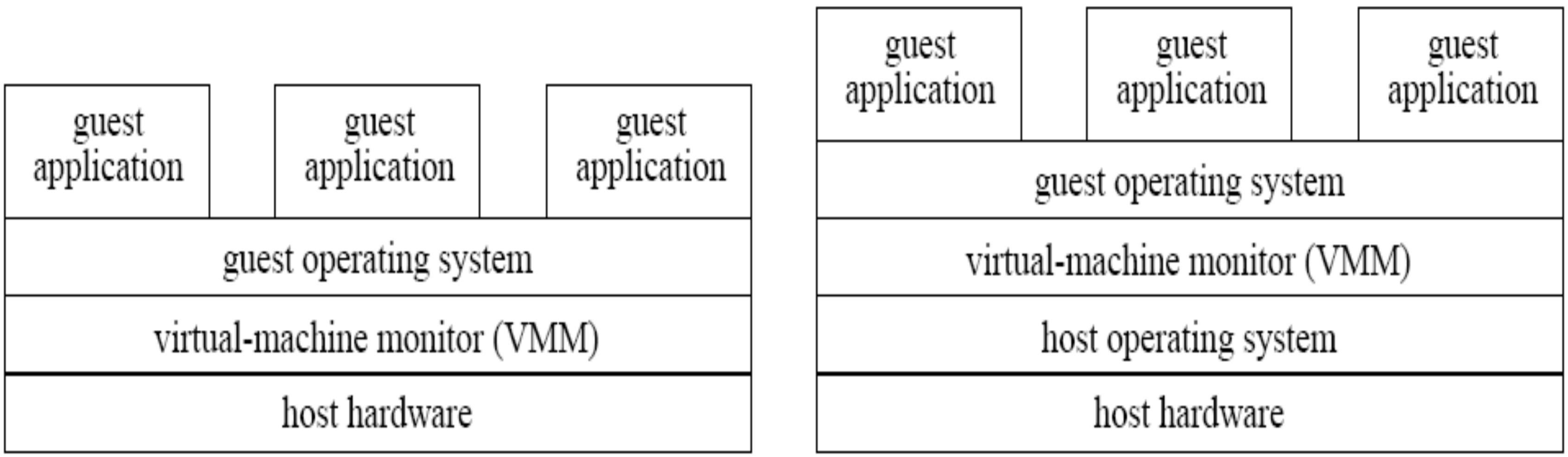
Why do we care?

- 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
- Memory Virtualization
- I/O virtualization

Processor Virtualization

Popek and Goldberg (1974)

- All instructions that can inspect and modify privileged machine state will trap when executed from any but the most privileged state
- CPU architecture virtualizable if it supports running VCPU state on real CPU, and VMM retains real control of CPU

x86 Processor Virtualization

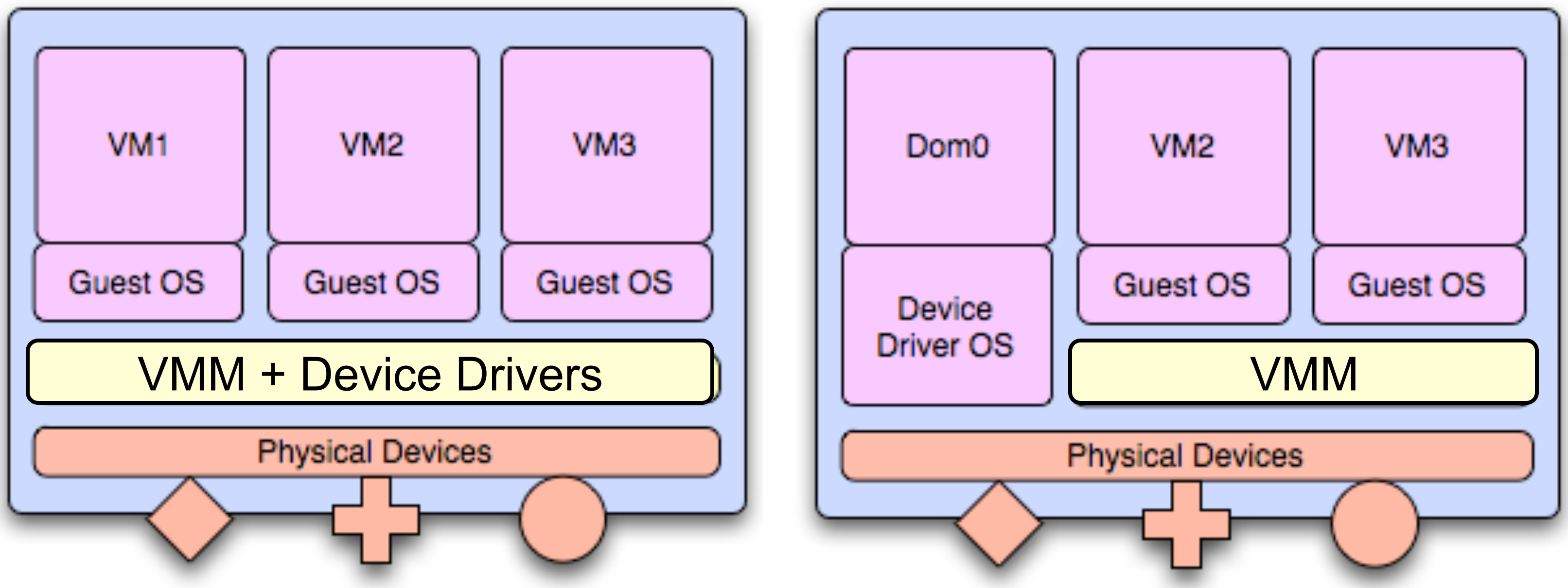
- x86 architecture is not fully virtual*izable*
  - Certain privileged instructions behave differently when run in unprivileged mode
  - Certain unprivileged instructions can access privileged state

- 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 OS updates it's 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

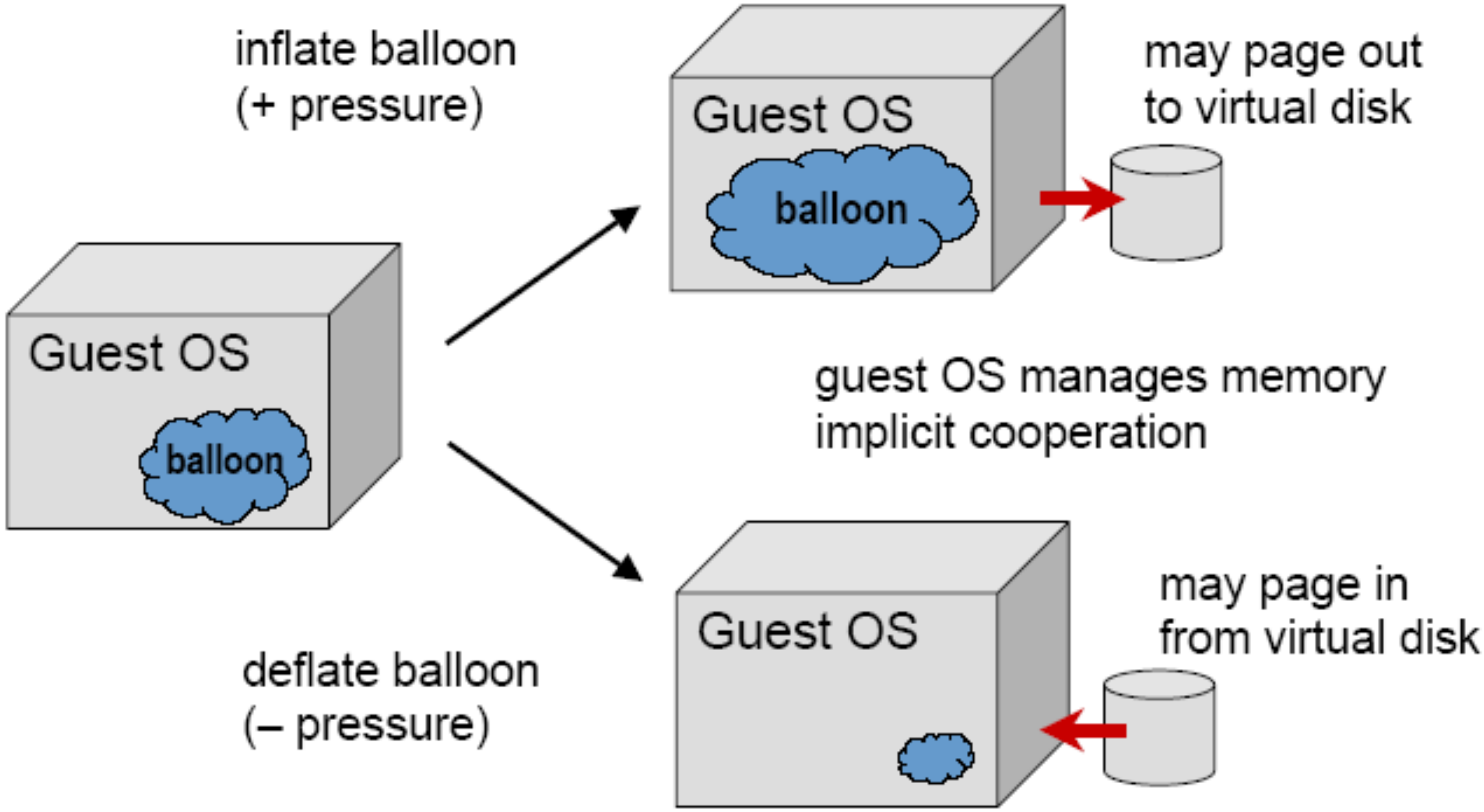
ESX Server – Memory Virtualization

- 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

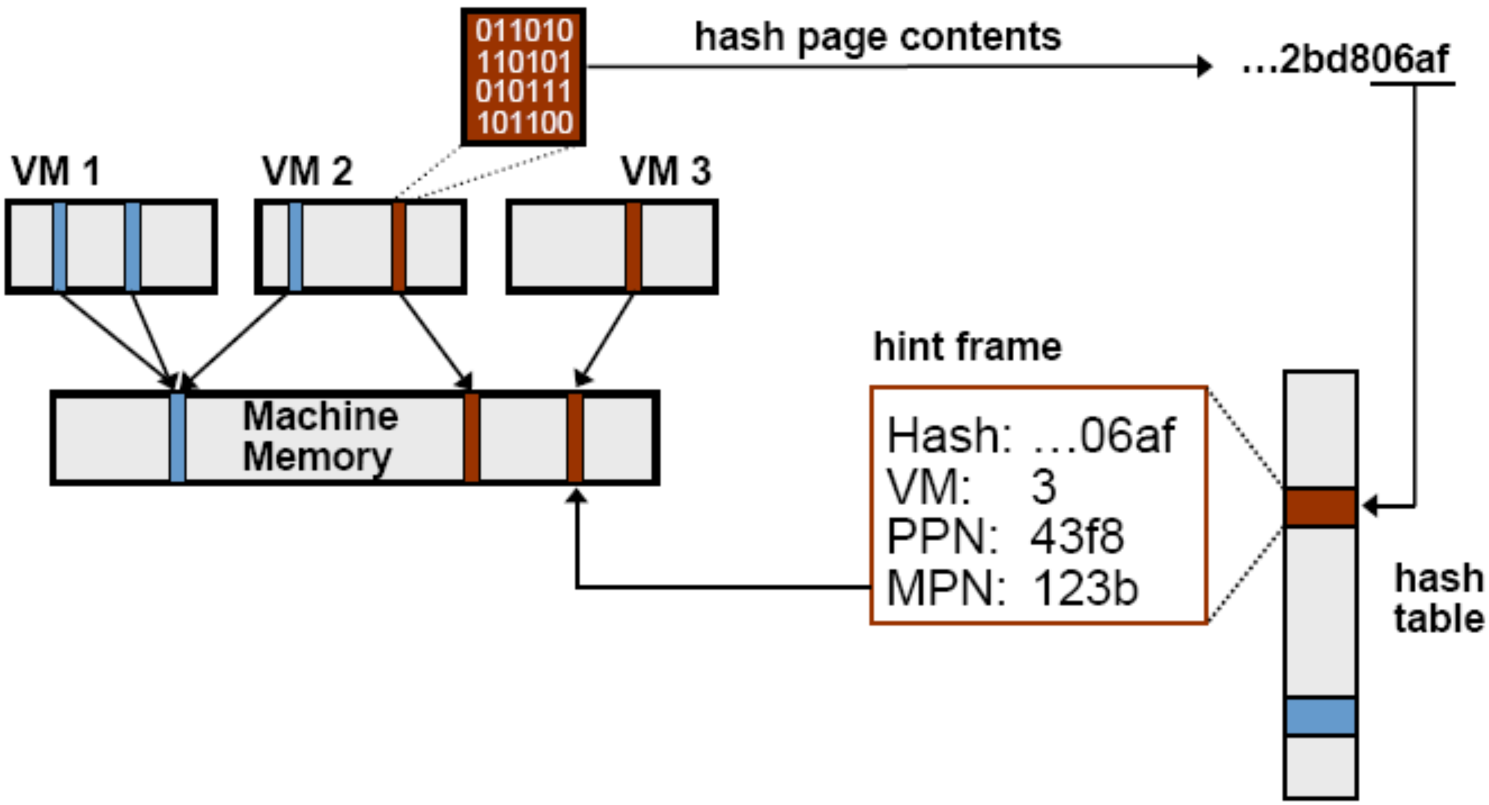
ESX Server – Memory Management

- 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.)

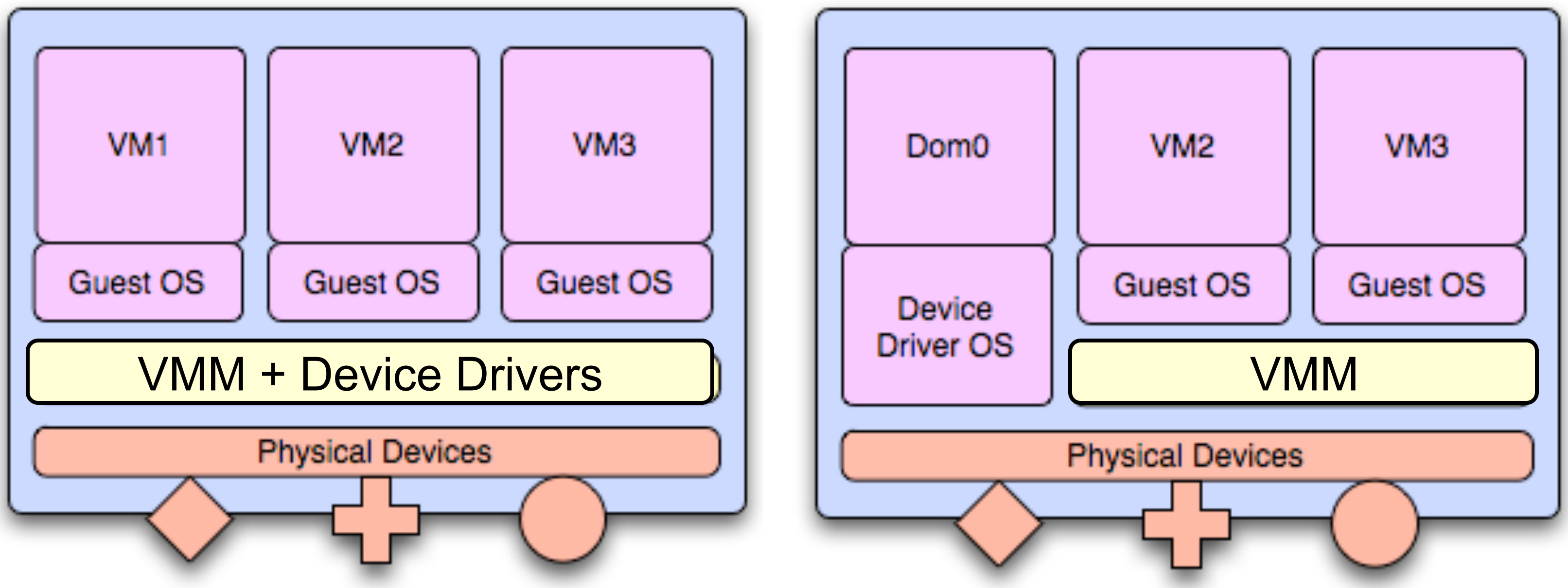
Nonprofit Org – web, mail, anti-virus, other servers (Apache, Majordomo, MailArmor, etc.)

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 Guest OS
- When run VMApp uses the driver loaded in the host VMDriver to load the VMM.
  - Host world v/s VMM world

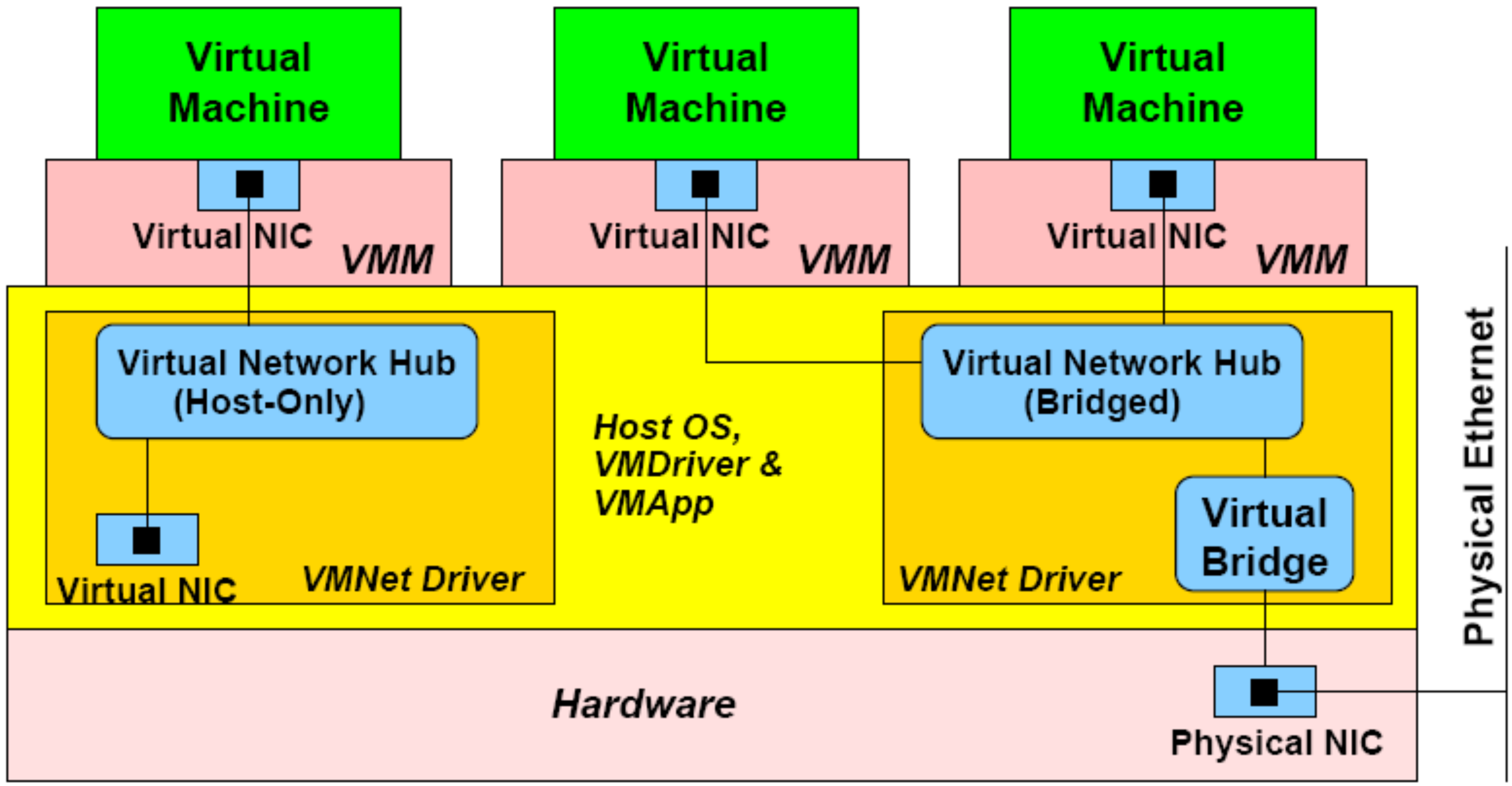
Workstation - Virtualization

- 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

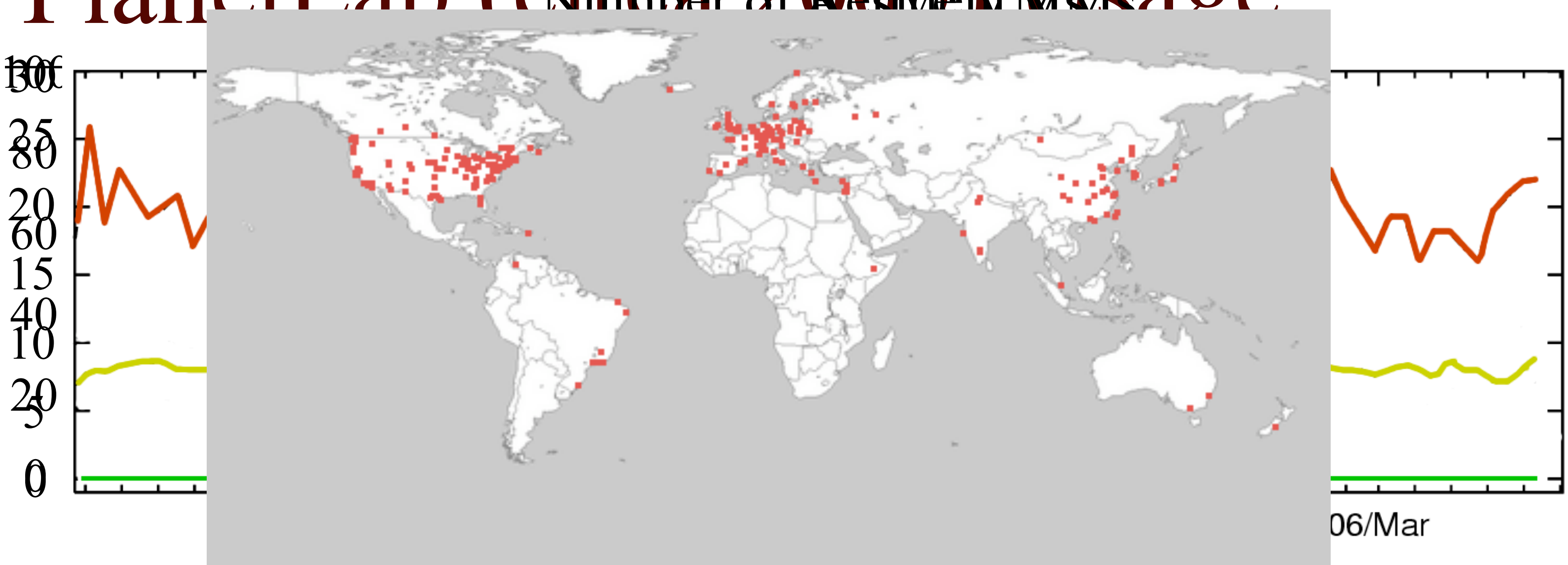
- Xen exposes a set of clean and simple device abstractions
- I/O data is transferred to and from each domain via Xen, using shared memory, asynchronous buffer descriptor rings
- Xen supports lightweight event delivery mechanism used for sending asynchronous notifications to domains

VMMs the only way to Virtualize?

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

Features	**VMM**	**COS**
Multiple kernels	[illegible]	✕
Administrative power (root)	[illegible]	[illegible]
Manageability	[illegible]	[illegible]
Scalability	[illegible]	[illegible] [illegible]
Isolation	[illegible] [illegible]	[illegible]
Efficiency	[illegible]	[illegible] [illegible]

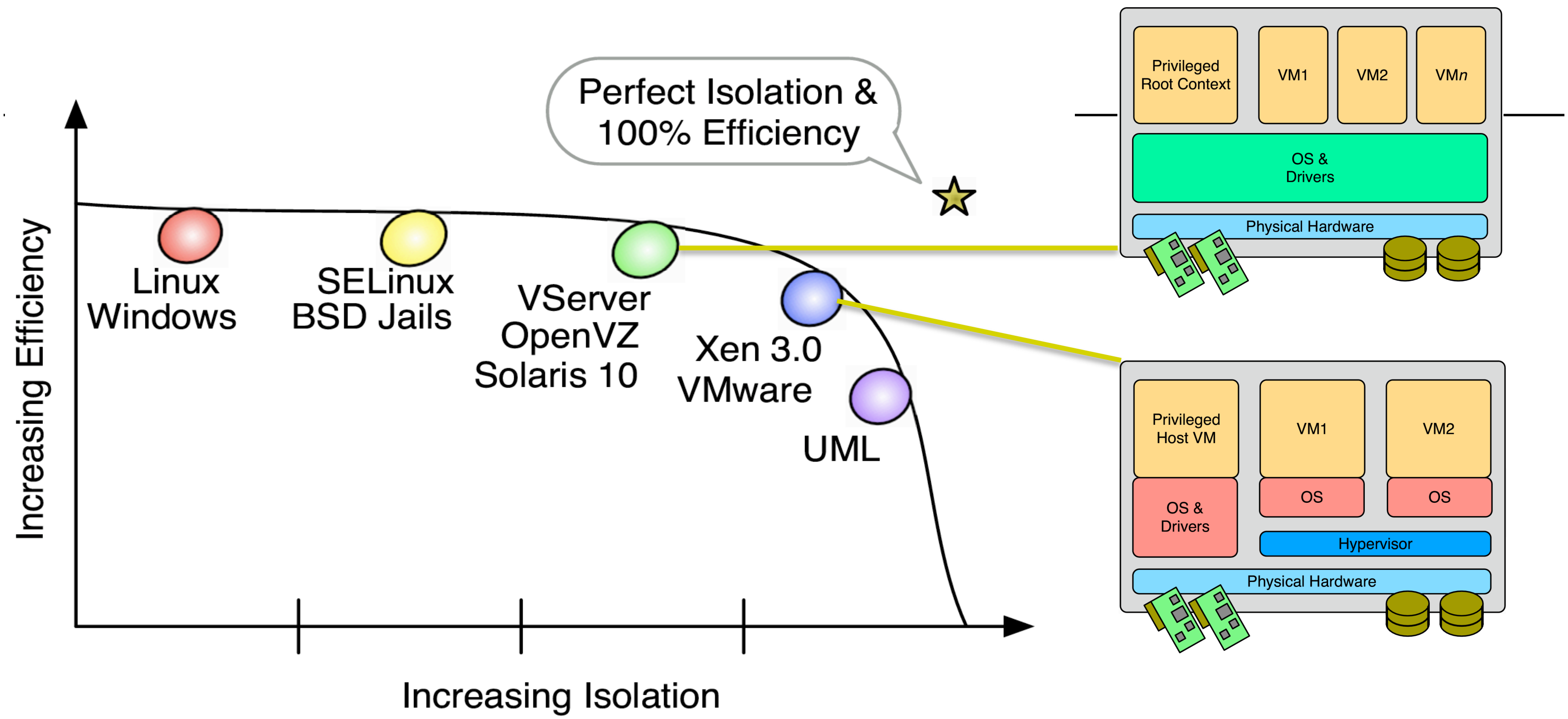
PlanetLab (circa 2005) Usage



- 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

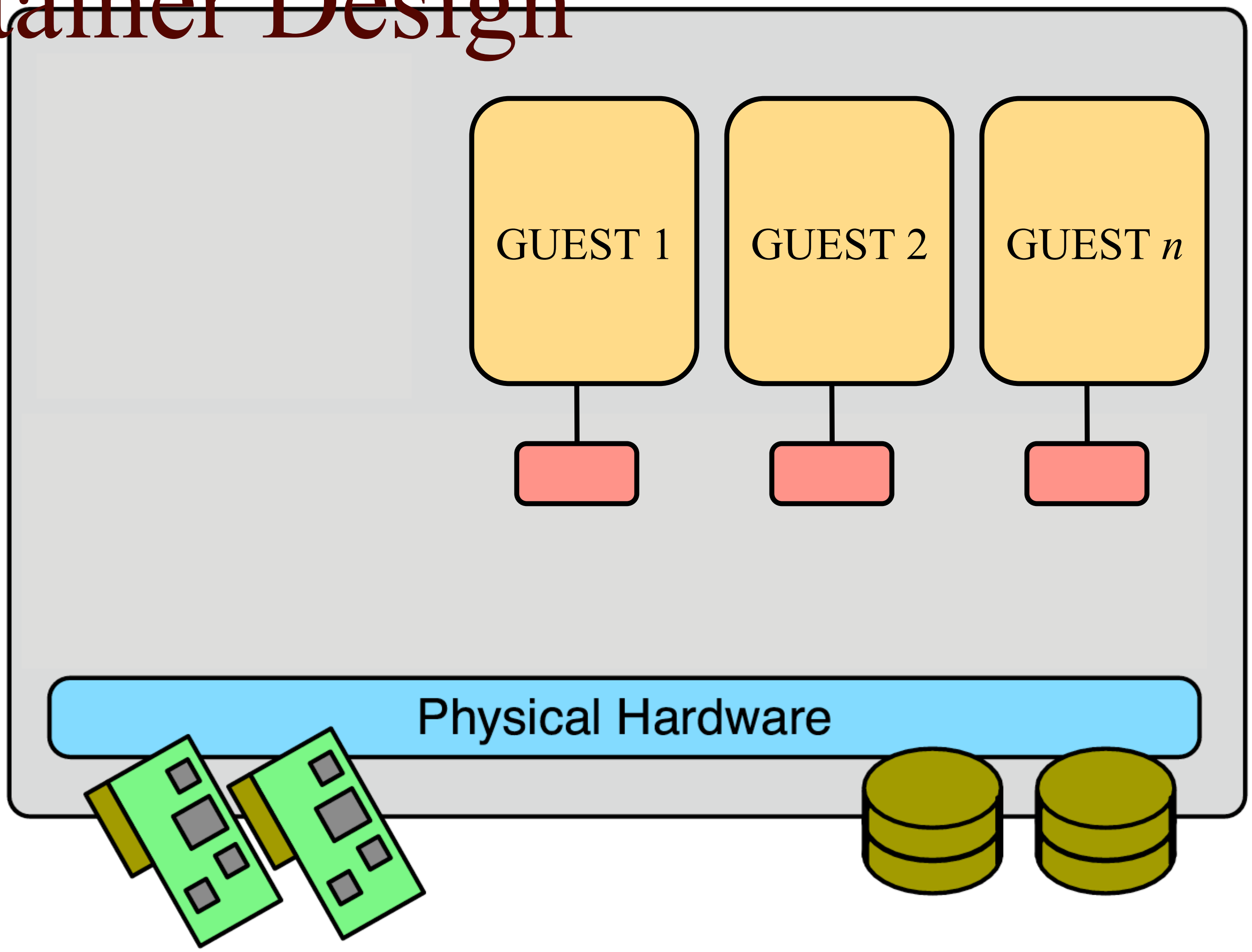
Container vs. Hypervisor Virtualization:

What is the Trade-Off?

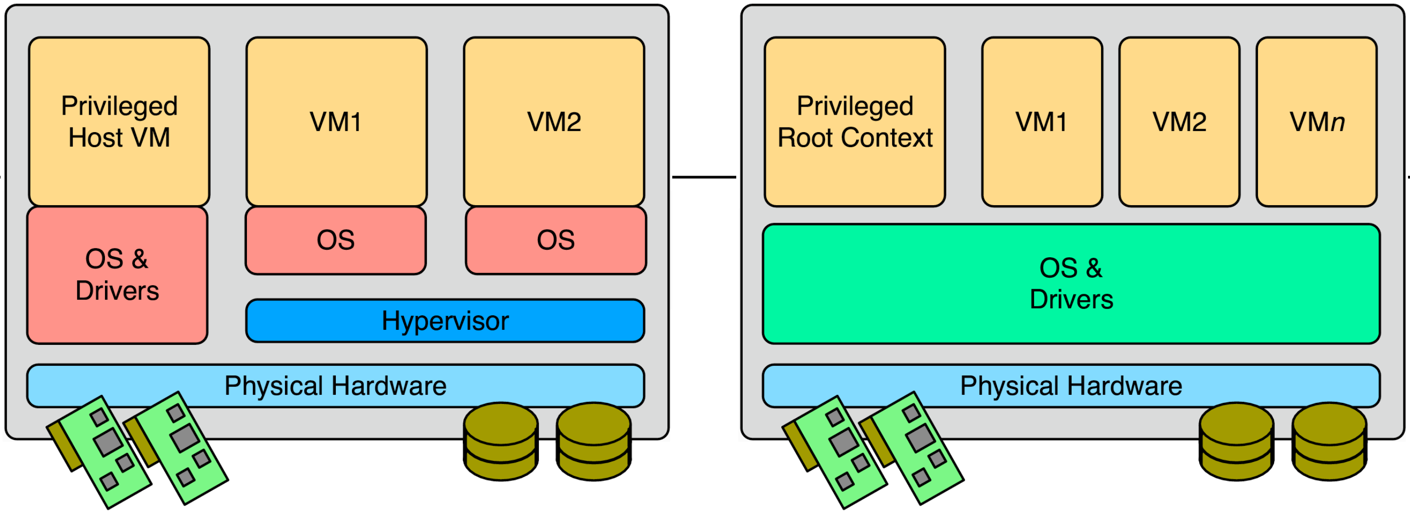


- Stephen Soltesz, Herbert Pötzl, Marc Fiuczynski, Andy Bavier, Larry Peterson. Container-based operating system virtualization: A scalable, high-performance alternative to hypervisors. EuroSys 2007
- Herbert Pötzl and Marc Fiuczynski Linux-VServer: Resource-Efficient OS-level Virtualization, Ottawa Linux Symposium 2007

Container Design



Feature Comparison



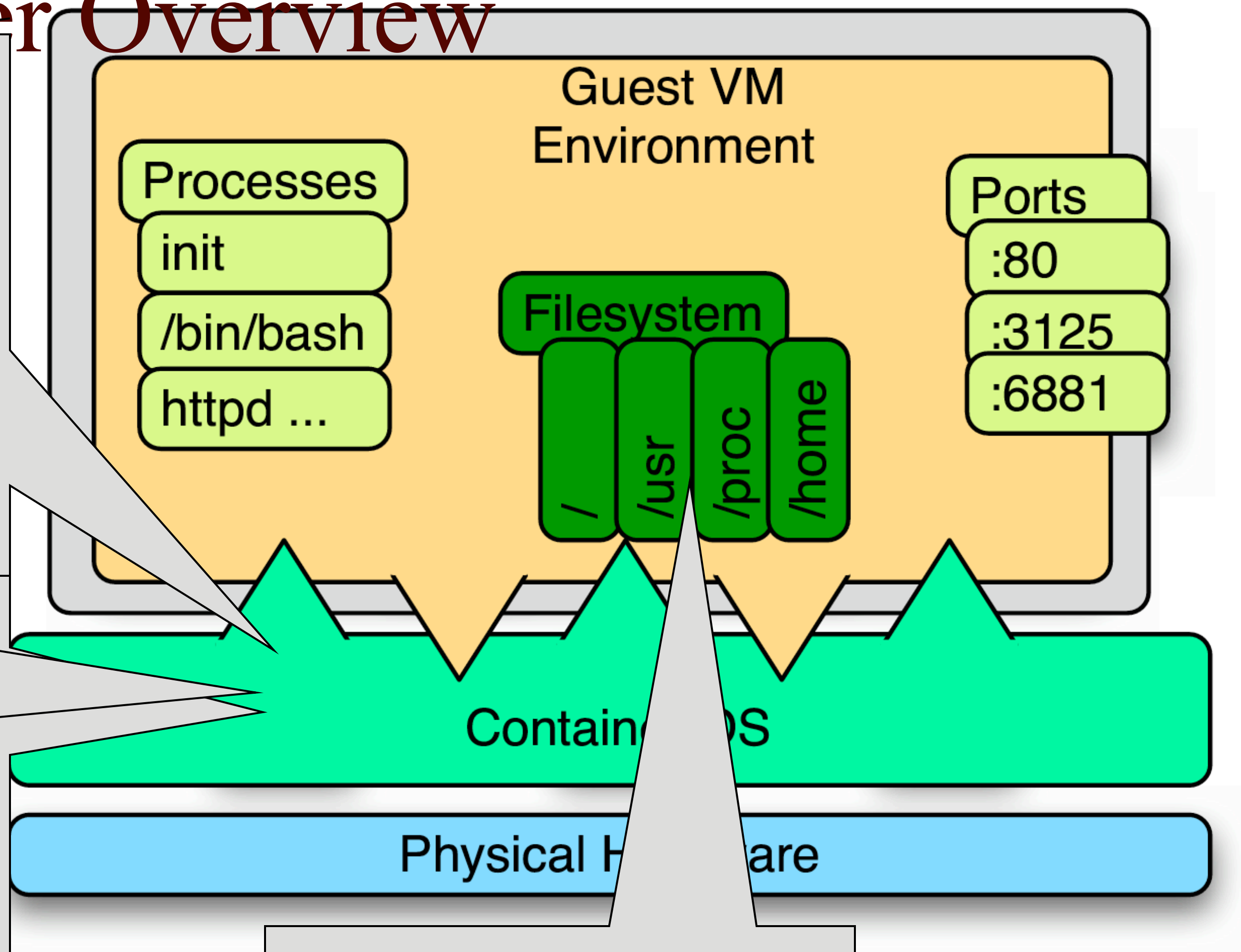
	Hypervisor	Container
Multiple Kernels	✓	X
Load Arbitrary Modules	✓	X
Local Administration (root)	✓	✓ All
Live Migration	✓	✓ OpenVZ
Cross Version Migration	X	✓ Zap

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 Comparison 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

Usage Scenarios

- Efficiency -> Performance
  - IT Data Centers, Grid, HPC Clusters
  - Telco Deployments
- Efficiency -> L[illegible]ead
  - Laptops
  - CPE Network Gateways
- Efficiency -> Scalability
  - Web Hosting (Virtual Private Servers)
  - PlanetLab, VINI Network Research

1-5 Gbps per node from disk to network -> coblitz

TR35 2007 Young Innovator

Making anti-virus software obsolete -> one laptop per child

TR10: HashCache
Special Report: 10 Emerging Technologies 2009 -> BRIDGES

-> DreamHost

THANK YOU !