



Virtual Machine Systems



Question

- Can a “small” operating system simulate the hardware of some machine so that
 - Another operating system can run in that simulated hardware?
 - More than one instance of that operating system run on the same hardware at the same time?
 - More than one **different** operating systems can share the same hardware at the same time?
- **Answer: Yes**



Virtual Machine

- A virtual machine provides interface identical to underlying bare hardware
 - i.e., all devices, storages, memory, page tables, etc.
- Virtual Machine Operating System creates **illusion of multiple processors**
 - Each VM executes independently
 - No sharing, except via network protocols



History – CP67 / CMS

- IBM Cambridge Scientific Center
- Ran on IBM 360/67
 - Alternative to TSS/360, which never sold very well
- Replicated hardware in each “process”
 - Virtual 360/67 processor
 - Virtual disk(s), virtual console, printer, card reader, etc.
- Cambridge Monitor System (CMS)
 - A single user, interactive operating system
- Commercialized as VM370 in mid-1970s



History (cont.)

- Various other attempts with other machines
- VMware
 - Workstation
 - Servers (for IT centers)



“Classic” Virtual Machine

- Copy of a real machine
 - “Any program run under the VM has an effect identical with that demonstrated if the program had been run in the original machine directly” ¹
- Isolated from other virtual machines
 - “...transforms the single machine interface into the illusion of many” ²
- Efficient
 - “A statistically dominant subset of the virtual processor’s instructions is executed directly by the real processor” ²
- Also known as a “system VM”

¹ *“Formal Requirements for Virtualizable Third-Generation Architectures”, G. Popek and R. Goldberg, Communications of the ACM, 17(7), July 1974*

² *“Survey of Virtual Machine Research”, R. Goldberg, IEEE Computer, June 1974*

Traditional Computer and Virtual Machines

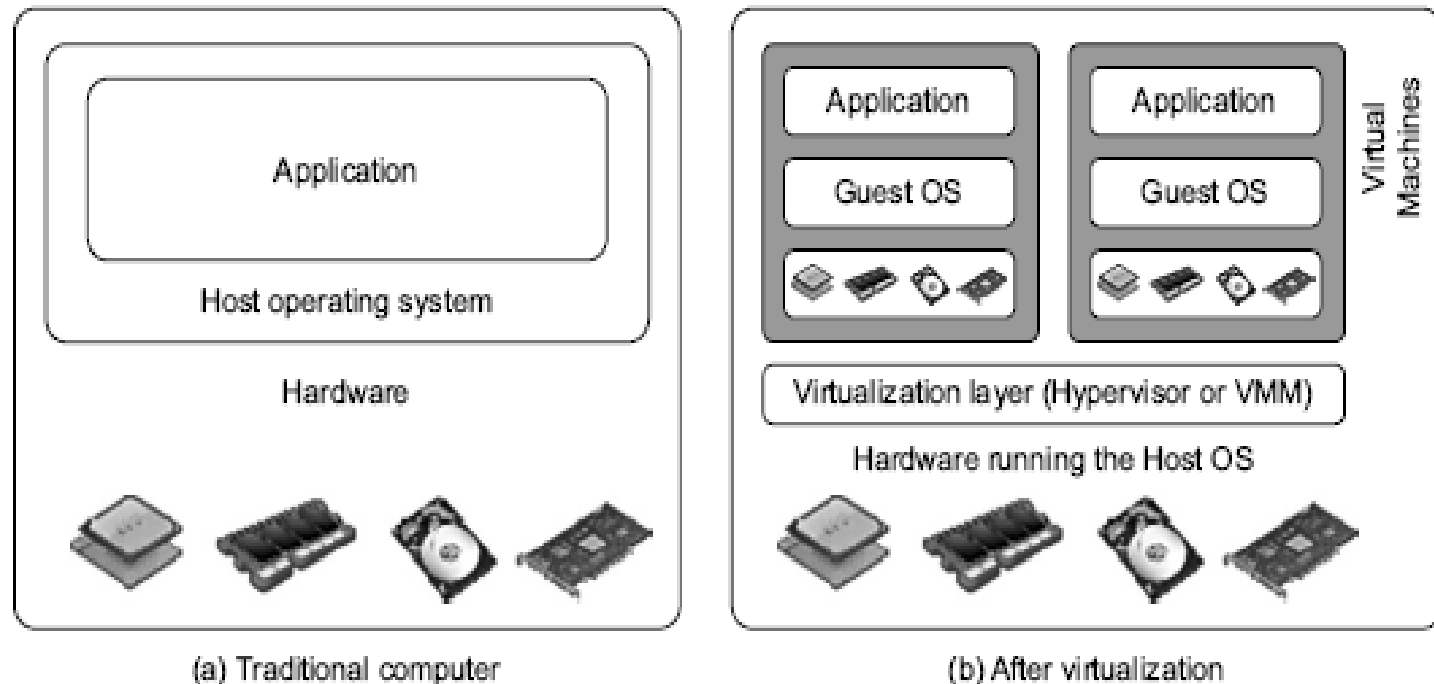
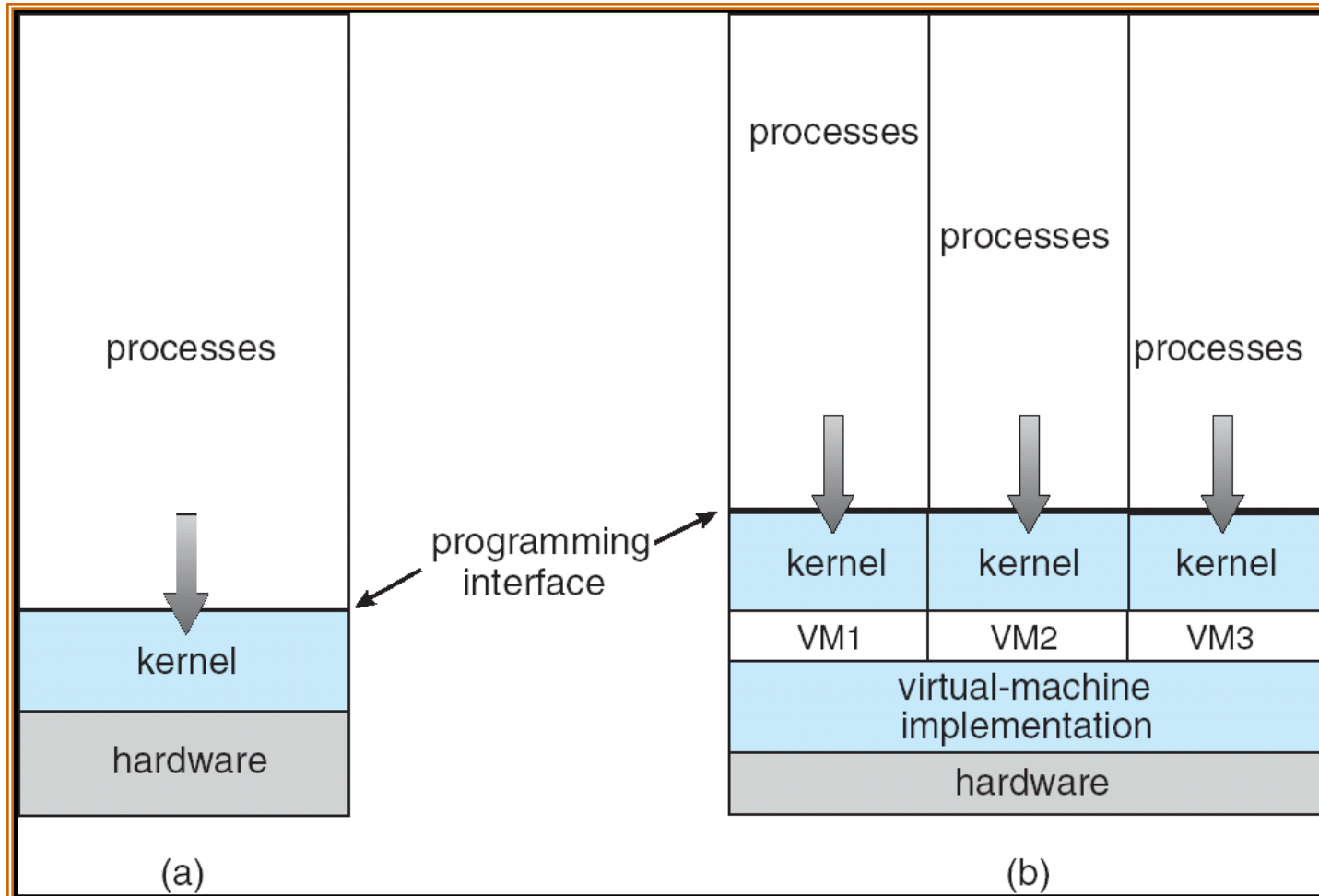


FIGURE 3.1

The architecture of a computer system before and after virtualization, where VMM stands for virtual machine monitor.

(Courtesy of VMWare, 2008)

Virtual Machines



(a) Nonvirtual machine

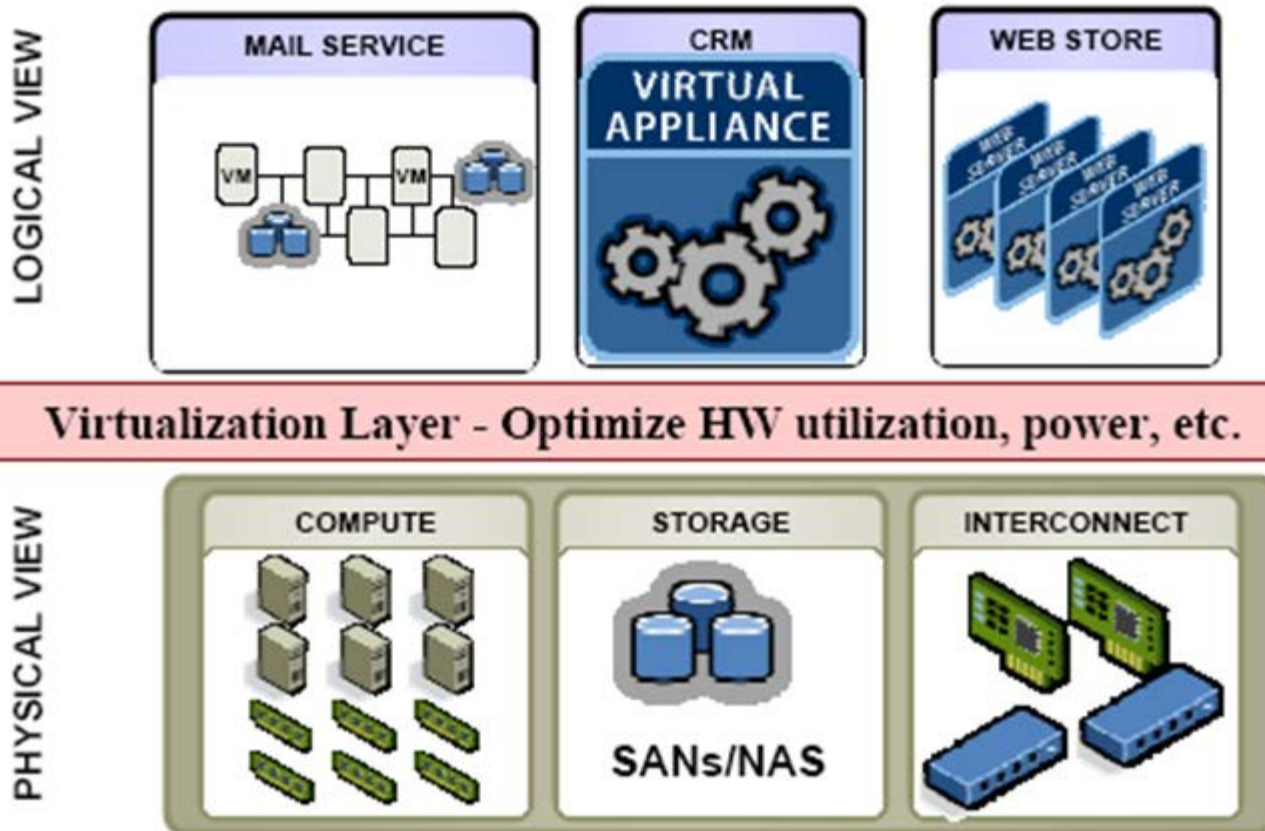
(b) virtual machine

Classic Virtual Machines

- Virtualization of instruction sets (ISAs)
 - Language-independent, binary-compatible (*not* JVM)
- 70's (IBM 360/370..) – 00's (VMware, Microsoft Virtual Server/PC, z/VM, Xen, Power Hypervisor, Intel Vanderpool, AMD Pacifica ...)
- ISA + OS + libraries + software = **execution environment**



User's View of Virtualization

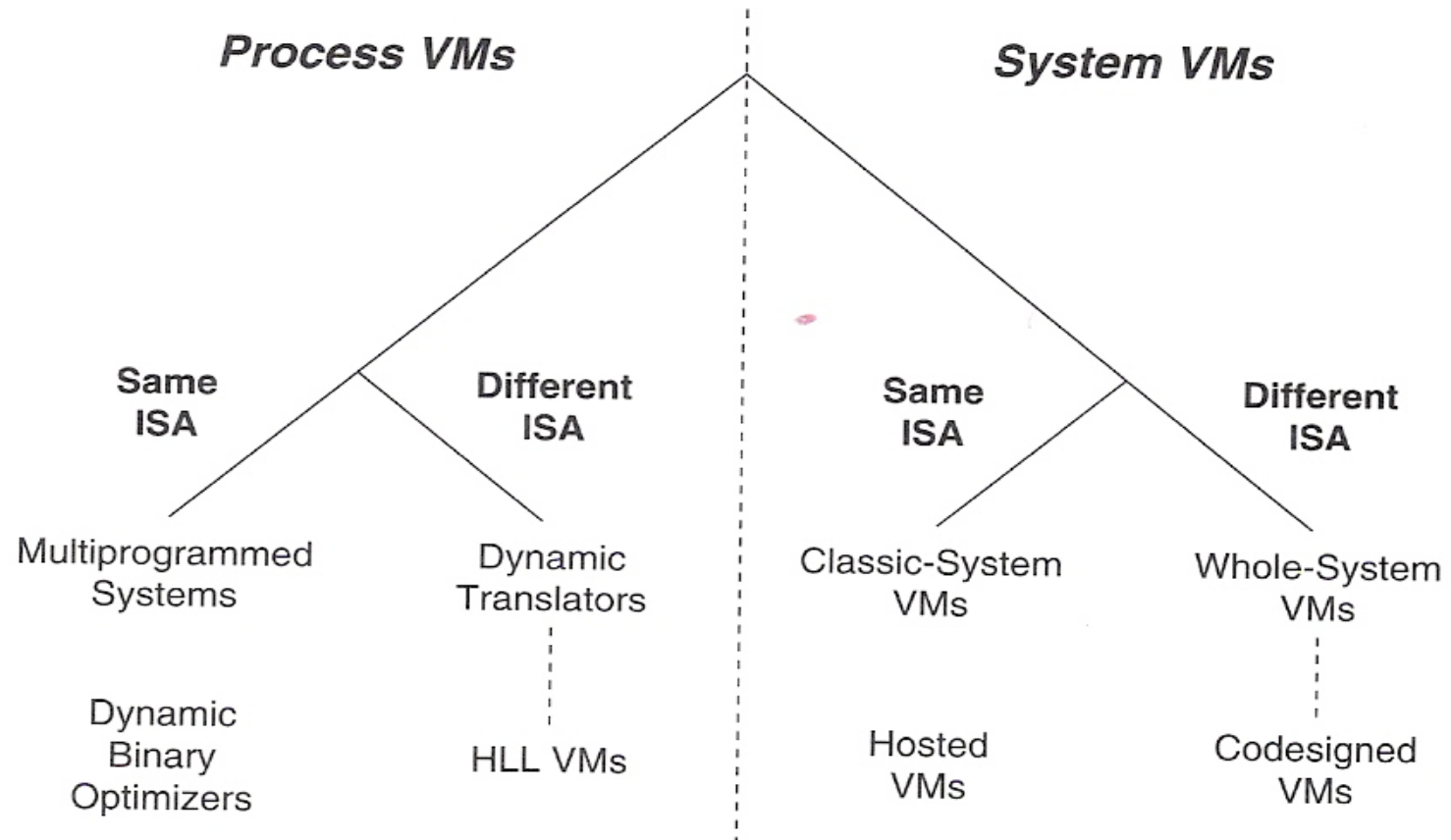




Definitions

- **Host Operating System:**
 - The operating system actually running on the hardware
 - Together with **virtualization layer**, it simulates environment for ...
- **Guest Operating System:**
 - The operating system running in the simulated environment
 - To do some things or resource allocation

A Taxonomy of Virtual Machines



high-level language virtual machine (HLL VM)

System/Process Virtual Machines

- Can view virtual machine as:
 - System virtual machine (i.e. Similar cygwin)
 - Full execution environment that can support multiple processes
 - Support I/O devices
 - Support GUI
 - Process virtual machine
 - Virtual machines can be instantiated for a single program (i.e. Similar Java)
 - Virtual machine terminates when process terminates.



```
-bash
Admin@MALISA:/ $ cd f:
Admin@MALISA:/cygdrive/f $ ll
total 0
drwxr-xr-x 1 Admin None 0 八月 14 2010 $RECYCLE.BIN/
drwxr-xr-x 1 Admin None 0 十二月 28 11:52 AV/
drwxr-xr-x 1 Admin None 0 十二月 28 11:54 MV/
Admin@MALISA:/cygdrive/f $
```



Must Virtual Machine be Replica of Host Machine?

- No, **virtualization layer can simulate any architecture**
 - Typically used for debugging specialized systems
 - Real-time systems, niche products, etc.
- Guest architecture does *not* even have to be real hardware!



Example – Page tables

- Suppose **guest OS** has its own page tables then **virtualization layer** must
 - Copy those tables to its own
 - Trap every reference or update to tables and simulate it
- During page fault
 - **Virtualization layer** must decide whether fault belongs to **guest OS** or self
 - If **guest OS**, must simulate a page fault
- Likewise, **virtualization layer** must trap and simulate every privileged instruction in machine!



Virtual Memory

- Virtual Memory
 - A technique that allows the execution of a process that may not be completely in memory.
- Motivation:
 - An entire program in execution may not all be needed at the same time!
 - e.g. error handling routines, a large array, certain program features, etc



Virtual Memory

- Potential Benefits
 - Programs can be much larger than the amount of physical memory. Users can concentrate on their problem programming.
 - The level of multiprogramming increases because processes occupy less physical memory.
 - Each user program may run faster because less I/O is needed for loading or swapping user programs.
- Implementation: demand paging, demand segmentation (more difficult), etc.



Virtual Machines (cont.)

- The resources of the physical computer are shared to create the virtual machines
 - CPU scheduling can create the appearance in which each user has own processor
 - A normal user time-sharing terminal serves as the virtual machine operator's console
 - Spooling and a file system provide
 - virtual card readers, virtual line printers
 - Disk partitioned to provide virtual disks



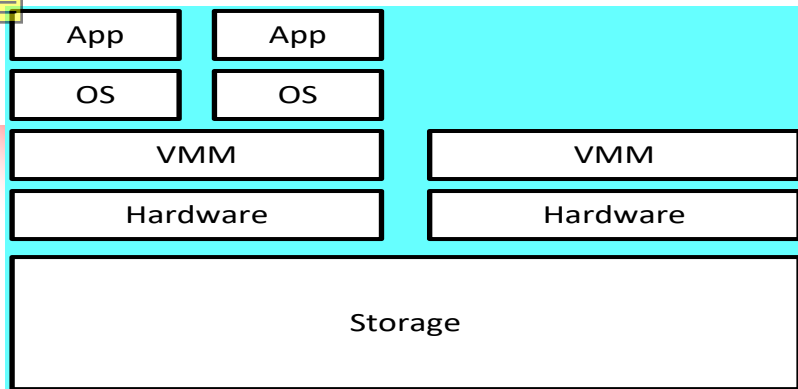
Virtual Machines (cont.)

- Virtual-machine concept provides complete protection of system resources
 - Each **virtual machine** is isolated from all other virtual machines.
 - However, it does not directly share the resources.
 - Virtualization layer
- Virtual-machine system is a good vehicle for operating-systems research and development.
 - System development is done on the virtual machine does not disrupt normal operation.
 - Multiple concurrent developers can work at same time.

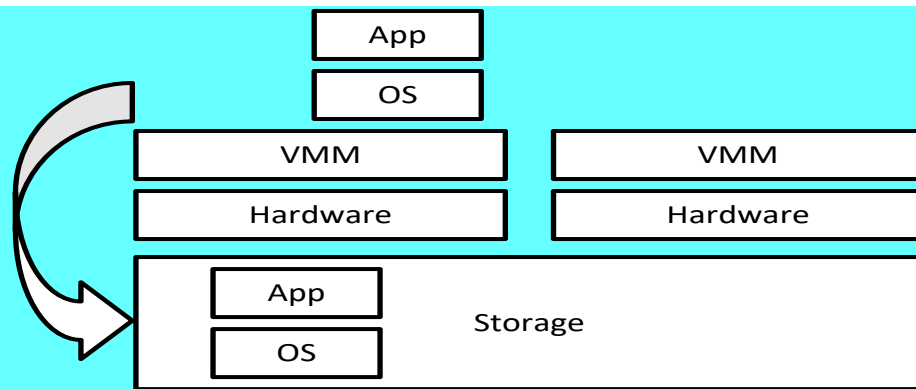


Virtual Machines (cont.)

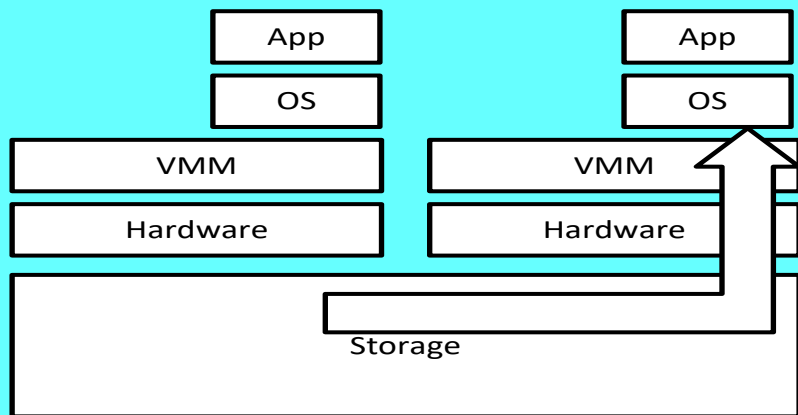
- Some hardware architectures or features are impossible to virtualize
 - Certain registers or state not exposed
 - Unusual devices and device control
 - Clocks, time, and real-time behavior



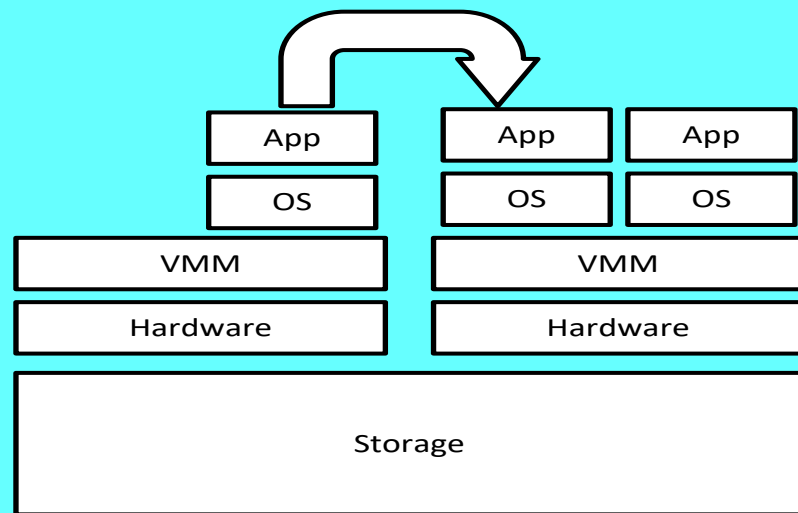
(a) Multiplexing



(b) Suspension(Storage)



(c) Provision(Resume)



(d) Life Migration

Figure 3.2 Virtual machine multiplexing, suspension, provision, and migration in a distributed computing environment



Virtualization at Hardware Abstraction Level

Hypervisor

- Virtualization is performed right on top of the bare metal hardware.
- It generates virtual hardware environments for VMs.
 - Xen, Hyper V, KVM, Virtual PC, Denali.
- Advantage: higher performance and good application isolation.
- Shortcoming and limitations: very expensive to implement due to its complexity.



Hypervisor

- A hypervisor is a hardware virtualization technique allowing multiple operating systems, called guests, to run on a host machine.
 - called the **Virtual Machine Monitor (VMM)**.
- **Type 1 hypervisor or the bare metal hypervisor** sits on the bare metal computer hardware like the CPU, memory, etc.
- All the guest operating systems are a layer above the hypervisor.
- The hypervisor is the first layer over the hardware, such as the original CP/CMS hypervisor developed by IBM.
 - An example is Microsoft Hyper-V



Hypervisor

- **Type 2 or the hosted hypervisor** does not run over the bare metal hardware, but over a host operating system.
 - The hypervisor is **the second layer** over the hardware.
- The guest operating systems runs a layer over the hypervisor and forms **the third layer**.
 - An example is FreeBSD.
 - The operating system is usually unaware of the virtualization



Full virtualization vs. Para-virtualization

- **Full virtualization** does not need to modify guest OS, and critical instructions are emulated by software through the use of binary translation.
 - The advantage is not having to modify OS.
 - However, this approach of binary translation slows down the performance considerably.
- **Para-virtualization** needs to modify guest OS, and non-virtualizable instructions are replaced by hypercalls that communicate directly with the hypervisor or VMM.



Full virtualization vs. Para-virtualization

- Para-virtualization reduces the overhead, but the cost of maintaining para-virtualized OS is high.
 - The improvement depends on the workload.
- VMware Workstation applies full virtualization, which uses binary translation to automatically modify x86 software on-the-fly to replace critical instructions.
- The para-virtualization is supported by Xen, Denali and VMware ESX

Full Virtualization

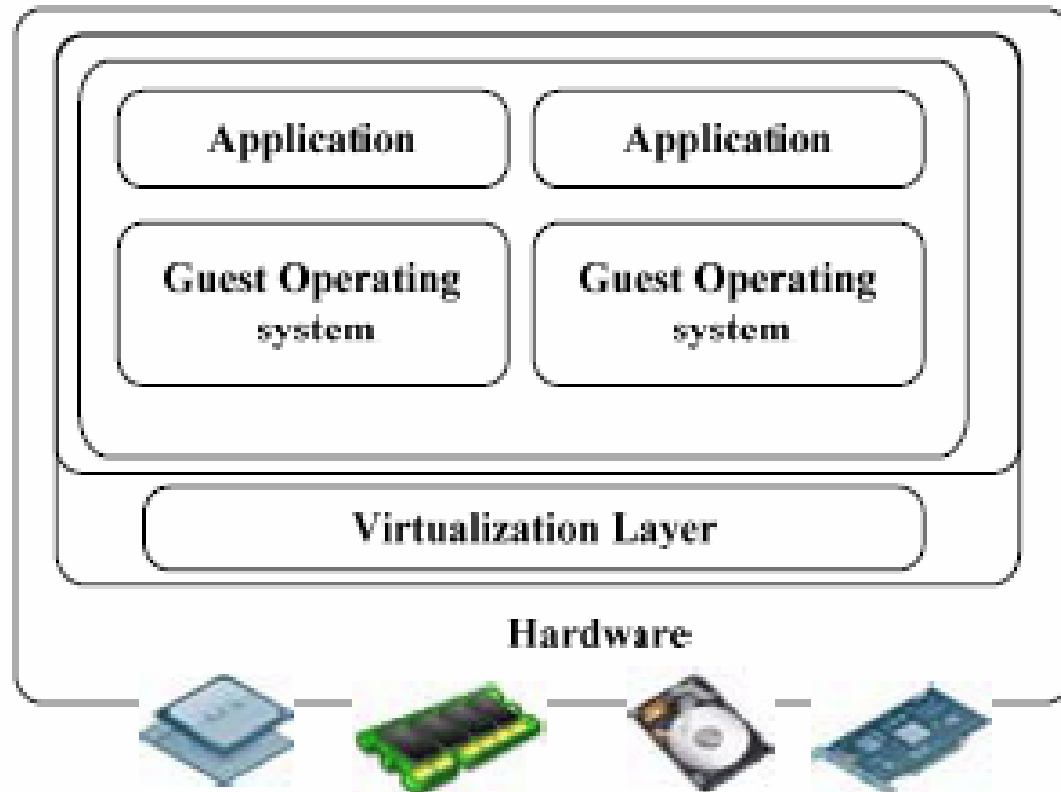


Figure 6.9 The concept of full virtualization using a hypervisor or a VMM directly sitting on top of the bare hardware devices. Note that no host OS is used here as in Figure 6.11.

Virtual Machine Architectures

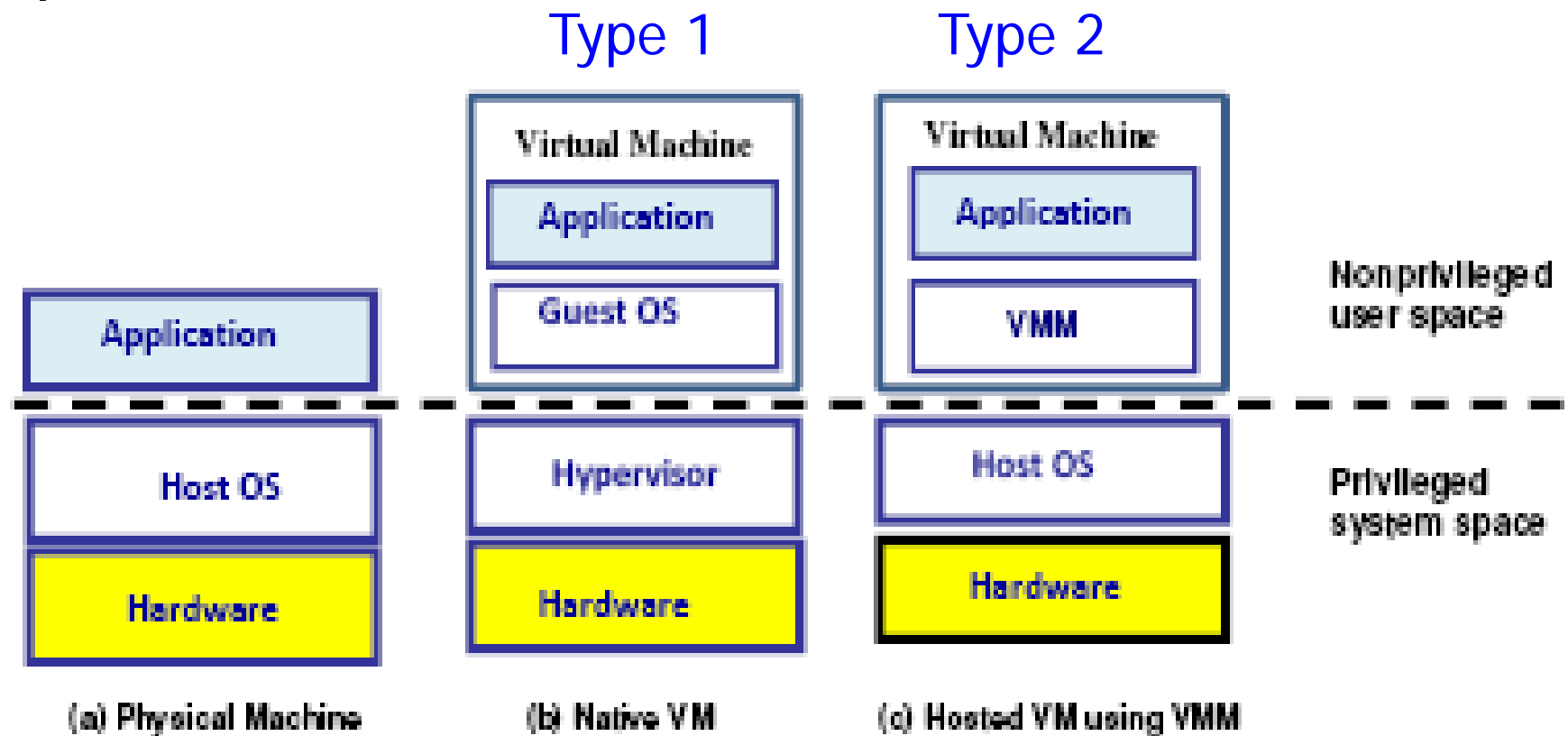


Figure 1.20 Three major components of a conventional physical machine is shown in Part (a). Native VM shown in Part (b) is created by a hypervisor sitting on top of bare metal hardware. A hosted VM shown in Part (c) is created by a VMM middleware in cooperation with the host OS.


Table 3.4

Hypervisors or VM monitors for generating VMs

Hypervisor	Host CPU	Host OS	Guest OS	Architecture, Applications, and User Community
XEN	x86, x86-64, IA-64	NetBSD, Linux	Linux, Windows, BSD, Solaris	Native hypervisor (Example 3.1) developed at Cambridge University
KVM	x86, x86-64, IA-64, S-390, PowerPC	Linux	Linux, Windows, FreeBSD, Solaris	Hosted hypervisor based on paravirtualization at the user space
Hyper V	x86 based	Server 2003	Windows servers	Windows-based native hypervisor, marketed by Microsoft
VMWare Workstation, VirtualBox	x86, x86-64	Any host OS	Windows, Linux, Darwin Solaris, OS/2, FreeBSD	Hosted hypervisor with a paravirtualization architecture

Hypervisor and the XEN Architecture

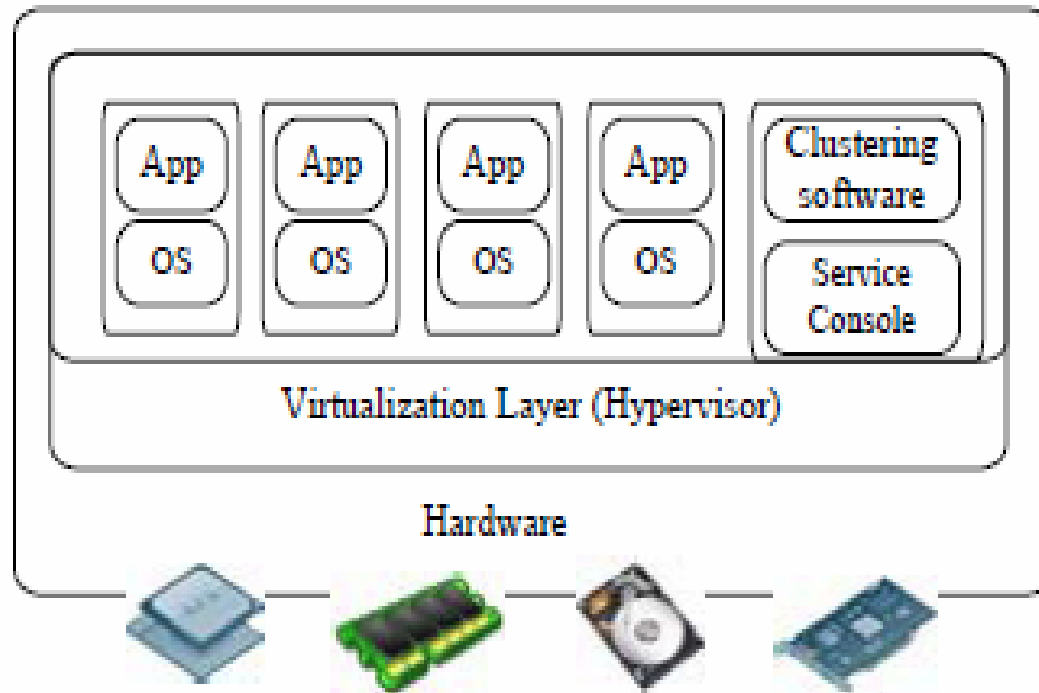


Figure 6.7 A hypervisor is the software layer for virtualization of the bare metal hardware. This layer can be implemented as a micro-kernel of the OS. It converts physical devices into virtual resources for user applications to run on the virtual machines deployed.

The XEN Architecture (1)

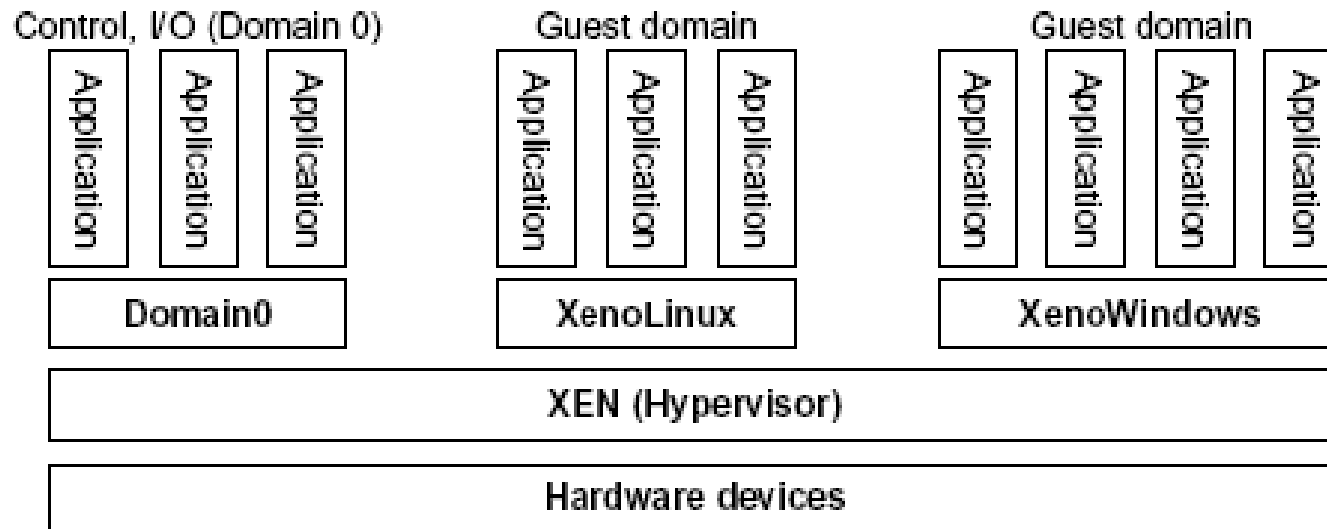


FIGURE 3.5

The Xen architecture's special domain 0 for control and I/O and several guest domains for user applications.



The XEN architecture (2)

- **Xen Project** is a **hypervisor** using a microkernel design, providing services that allow multiple computer **operating systems** to execute on the same **computer hardware** concurrently.
 - It was developed by the **University of Cambridge** and is now being developed by the Linux Foundation with support from Intel.
- The Xen Project community develops and maintains Xen Project as free and open-source software.
- Xen Project is currently available for the IA-32, x86-64 and ARM instruction sets.
- Xen Project runs in a more privileged CPU state than any other software on the machine.



The XEN Architecture (3)

- Responsibilities of the hypervisor include memory management and CPU scheduling of all virtual machines ("domains"), and for launching the most privileged domain ("**dom0**") - **the only virtual machine which by default has direct access to hardware.**
- From the dom0, the hypervisor can be managed and **unprivileged domains ("**domU**")** can be launched.
- The dom0 is typically a version of Linux or BSD.



The XEN Architecture (4)

- User domains may **either** be traditional operating systems, such as Microsoft Windows under which privileged instructions are provided by hardware virtualization instructions (if the host processor supports x86 virtualization, e.g., Intel VT-x and AMD-V), **or**
- *para-virtualized* operating systems whereby the operating system is aware that it is running inside a virtual machine, and so makes hypercalls directly, rather than issuing privileged instructions.
- Xen Project boots from a bootloader such as GNU GRUB, and then usually loads a paravirtualized host operating system into the host domain (dom0).

VMware hardware virtualization (hypervisors) and hosted software for virtualization

Category	VMware software products or third party software
Native (Hypervisor)	Adeos, CP/CMS, Hyper-V, KVM (Red Hat Enterprise Virtualization), LDomS / Oracle VM Server for SPARC, LynxSecure, SIMMON, VMware ESXi (VMware vSphere, vCloud), VMware Infrastructure, Xen XenClient), z/VM
Hosted (Specialized)	Basilisk II, bhyve, Bochs, Cooperative Linux, DOSBox, DOSEMU, LLinux, Mac-on-Linux, Mac-on-Mac, SheepShaver, SIMH, Windows on Windows, Virtual DOS machine, Win4Lin
Hosted (Independent)	Microsoft Virtual Server, Parallels Workstation, Parallels Desktop for Mac, Parallels Server for Mac, PearPC, QEMU, VirtualBox, Virtual Iron, VMware Fusion, VMware Player, VMware Server VMware Workstation, Windows Virtual PC
Other tools	Ganeti, oVirt, Virtual Machine Manager

VMWare ESX Server for Para-virtualization

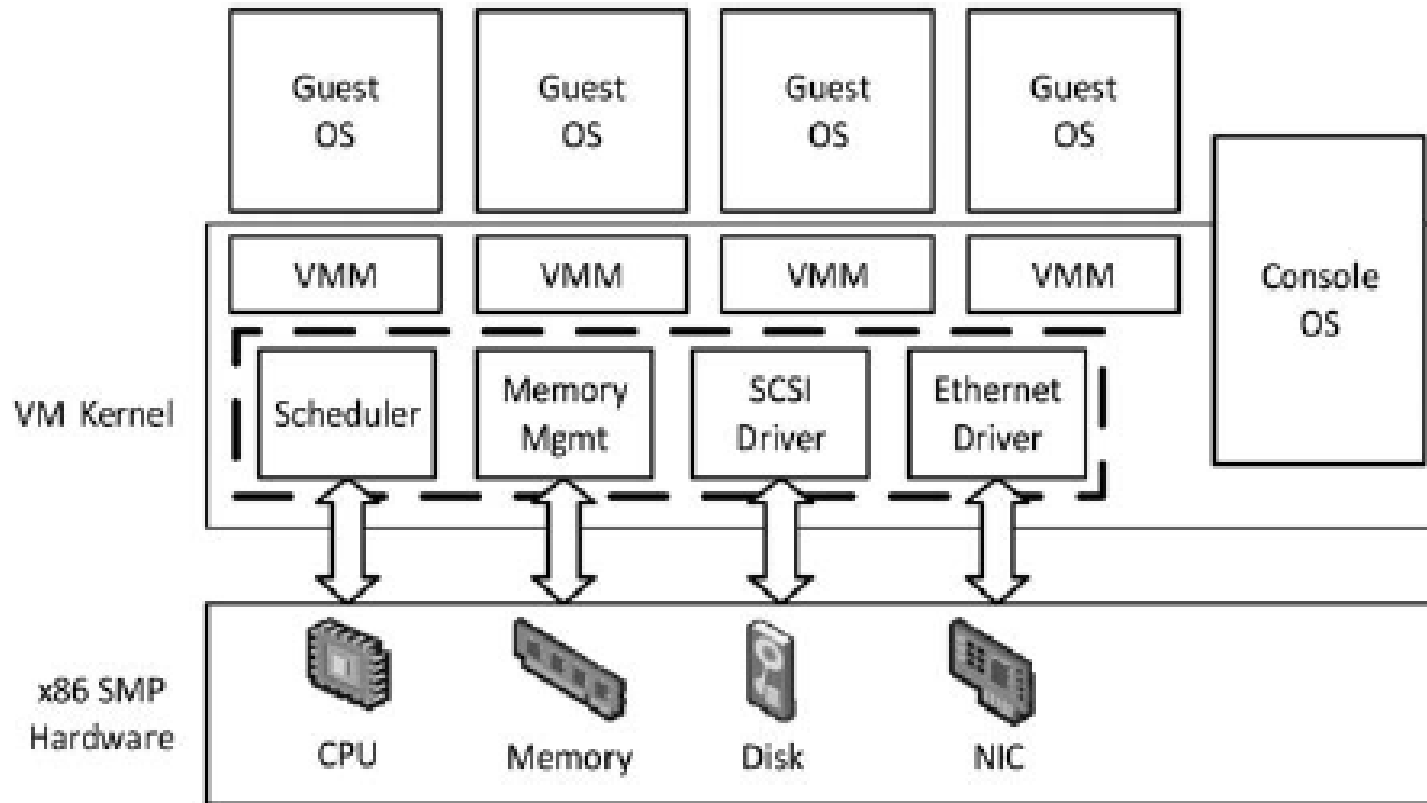


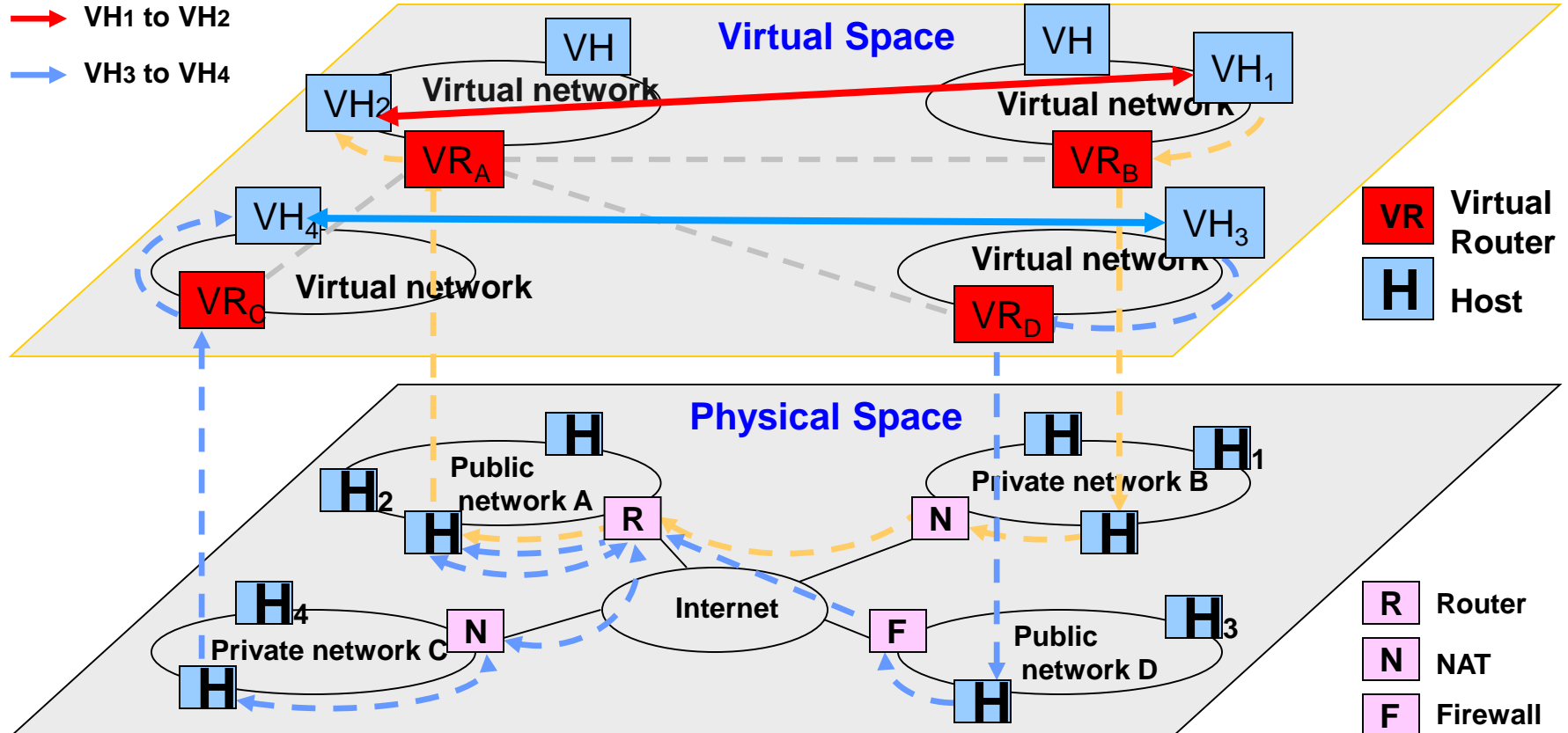
Figure 3.11

The VMWare ESX server architecture using para-virtualization. Courtesy of VMware, 2011, <http://www.vmware.com/products>.

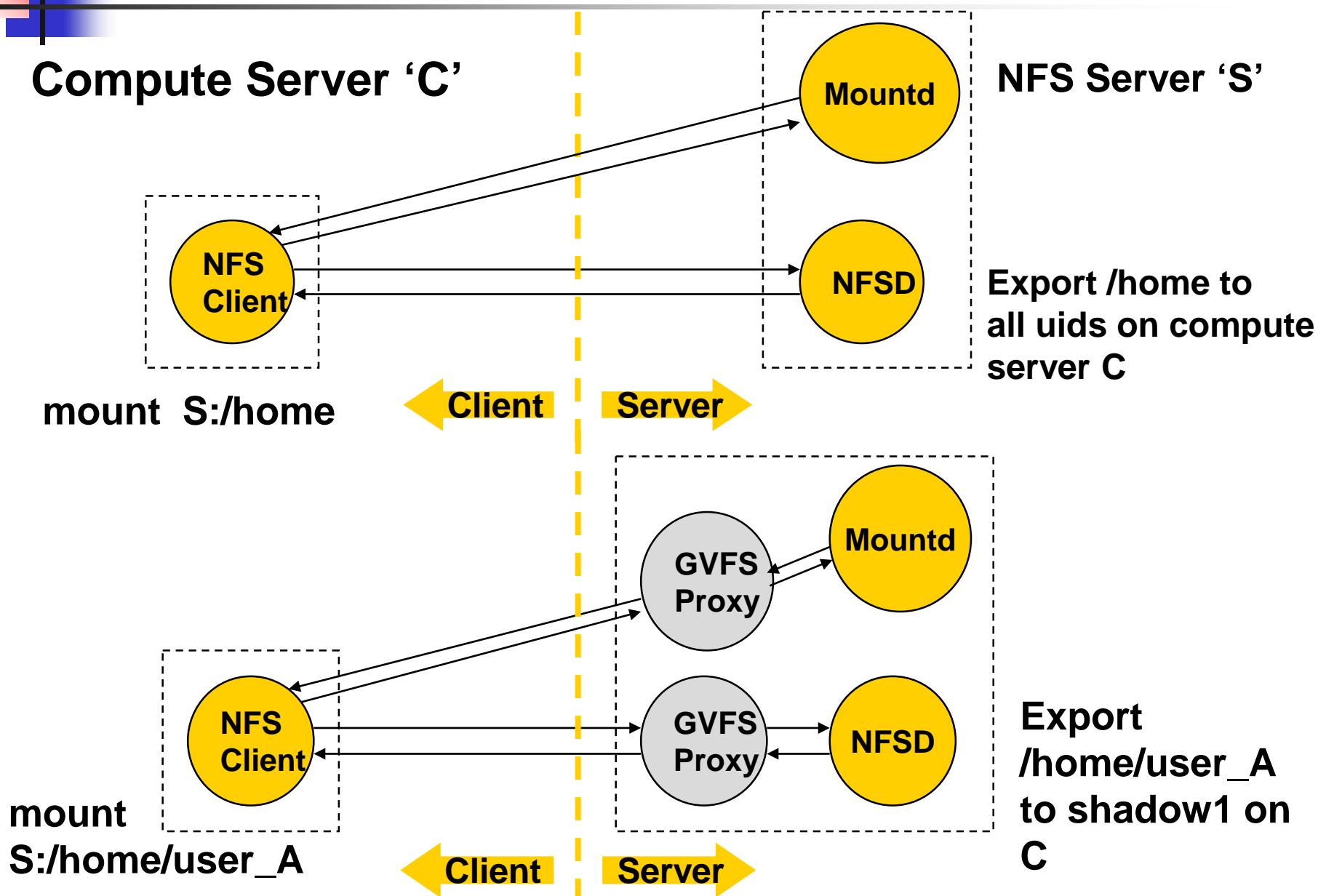
Virtual networks

- Logical links:

- multiple physical links, routing via native Internet routing
- tunneling, virtual routers, switches, ...
- partial to total isolation



Virtualization Data/File





Grid Virtual File System (GVFS)

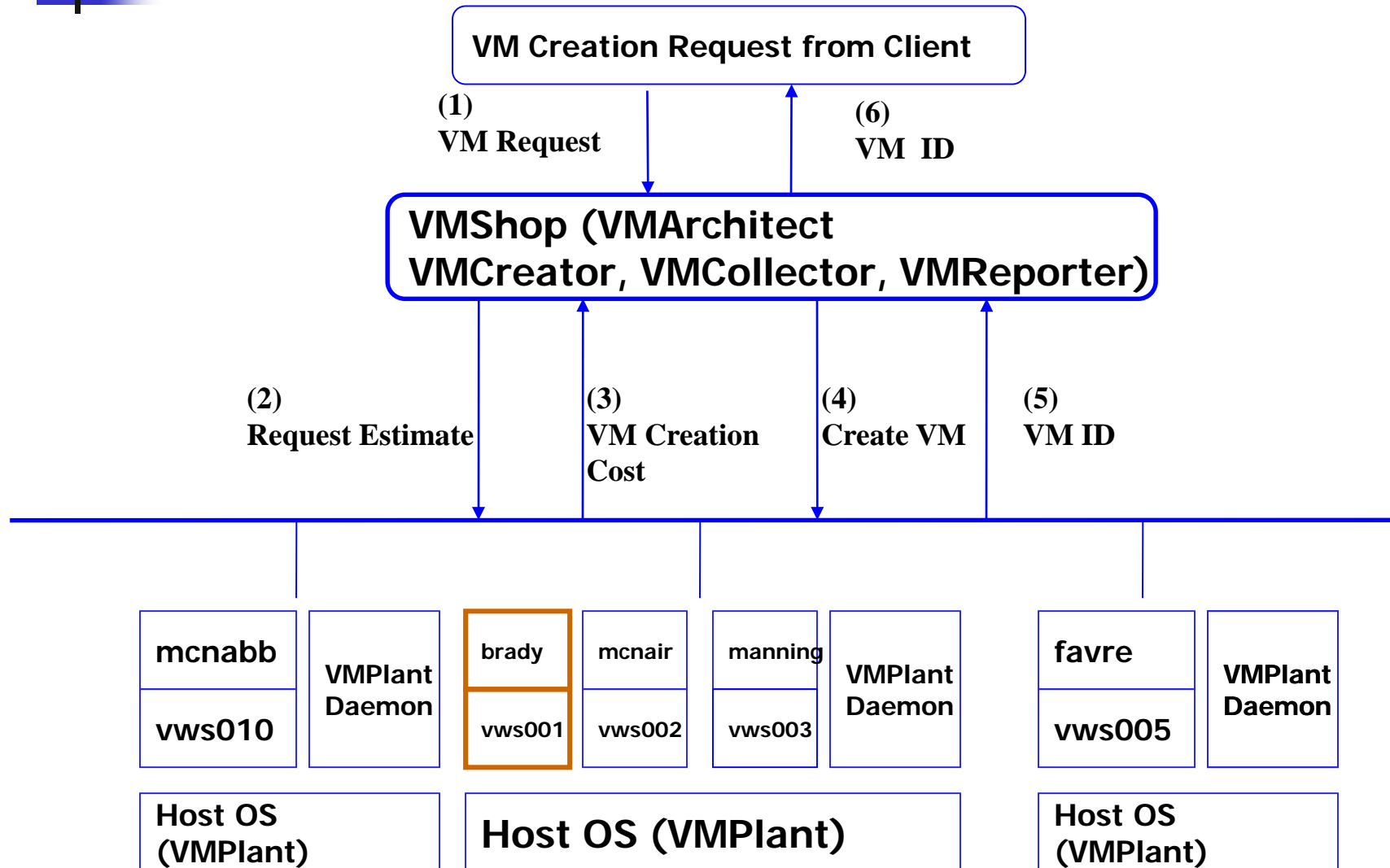
- Originally named PVFS, is a virtualized distributed file system
 - providing high-performance data access in grid environments and seamless integration with unmodified applications.
- It leverages existing NFS (Network File System) support in operating systems, and uses user-level proxies to authenticate and forward RPC (Remote Procedure Call) requests between the native NFS client and server, and map user identities between different domains.



A Grid-building Recipe

- ① Virtualize to fit needed environments
 - ② Use services to generate “virtuals”
 - ③ Aggregate and manage “virtuals”
 - ④ Repeat ① ② ③ as needed
- The result:
 - Users interact with virtual entities provided by services
 - Middleware interacts with physical resources

Architectural Components of VM Service

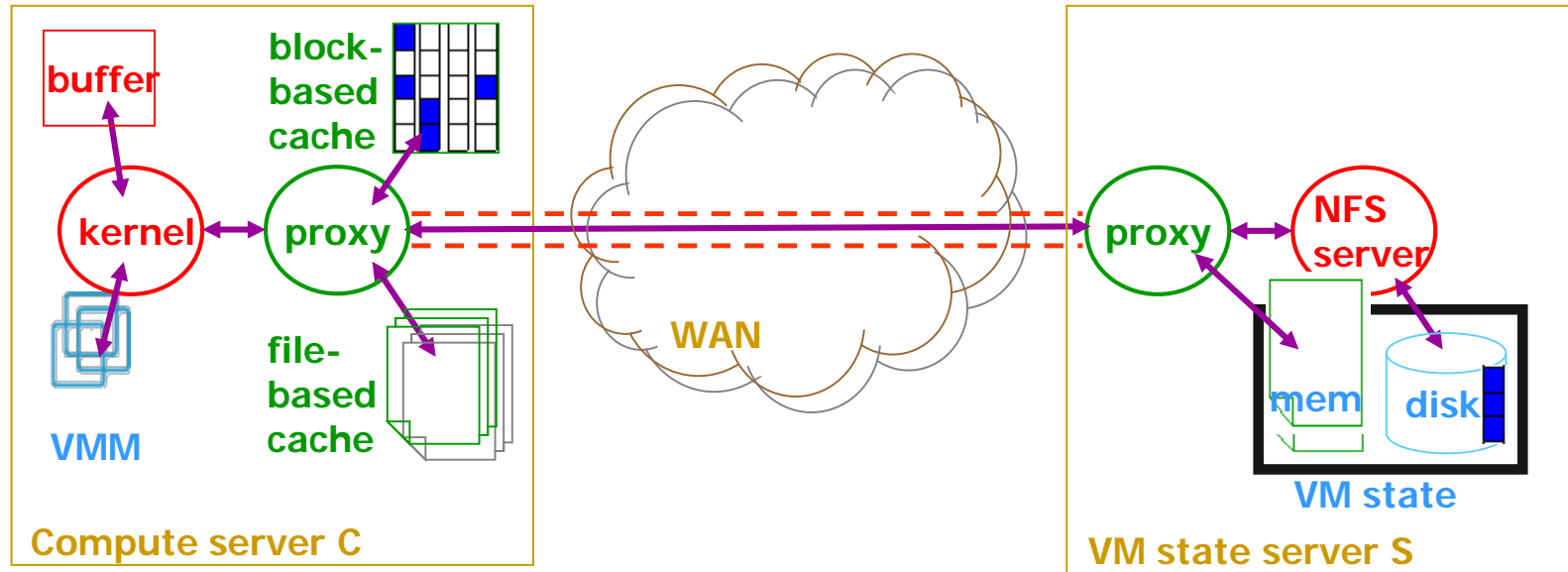




Create VM Steps

1. Clone VM
 - Instantiate a new container
 - Fast copying of a base VM image
 - Virtual disk
 - Suspended memory (if available)
2. Configure VM
 - Execute scripts/jobs inside container to modify to a particular instance
 - Communicate crossing container boundaries to provide inputs/retrieve outputs
3. Destroy VM
 - Terminate container, delete non-persistent state

User-level Extensions



- **Client-side proxy disk caching**
- **Application-specific meta-data handling**
- **Encrypted file system channels and cross-domain authentication**
- *[Zhao, Zhang, Figueiredo, HPDC'04]*

Docker Engine and Containers

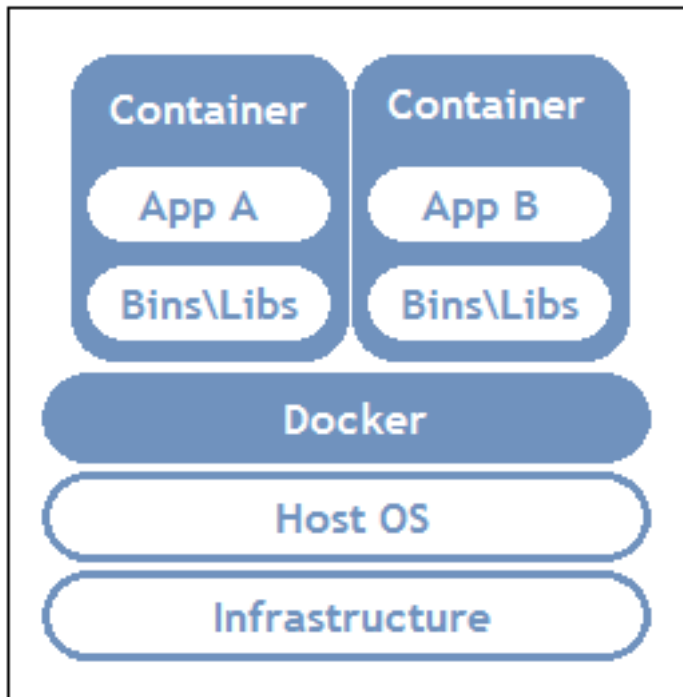
- Docker engine works with host OS to produce application software containers
- The App software container does not use a guest OS, thus it is highly scalable
- Virtual clusters are studied with the use either VMs or containers



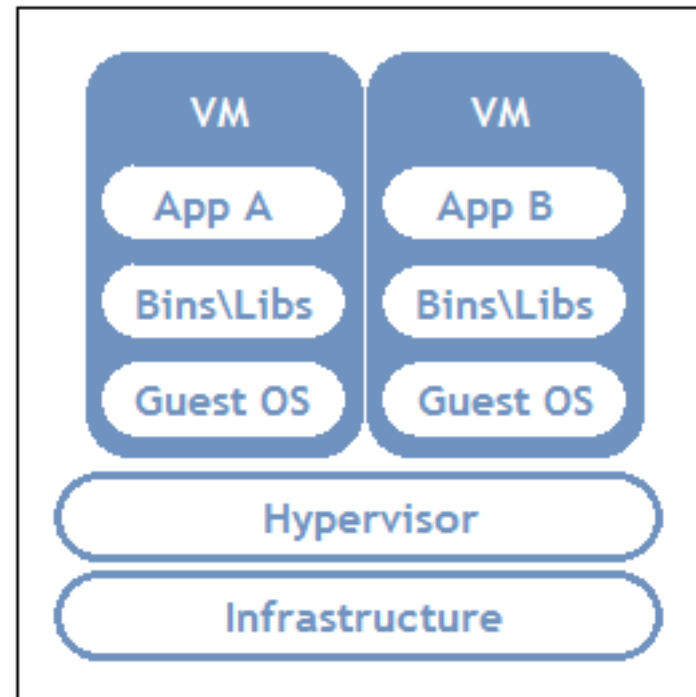
Docker Engine

- **Docker** is a set of platform-as-a-service (PaaS) products that use OS-level virtualization to deliver software in packages called containers.

Container Based Implementation



Virtual Machine Implementation





Docker Engine

- Containers are isolated from one another and bundle their own software, libraries and configuration files; they can communicate with each other through well-defined channels.
- All containers are run by a single operating-system kernel and are thus more lightweight than virtual machines.
- The software that hosts the containers is called **Docker Engine**.



Virtualization at the Operating System Level

- An abstraction layer between traditional OS and user.
- This virtualization creates isolated containers on a single physical server and the OS-instance to utilize the hardware and software in datacenters.
 - Typical systems: Jail / Virtual Environment / Ensim's VPS / FVM
- **Advantage:** has minimal startup/shutdown cost, low resource requirement, and high scalability; synchronizes VM and host state changes.
- **Shortcoming and limitation:** all VMs at the operating system level must have the same kind of guest OS; poor application flexibility and isolation.

Virtualization Ranging from Hardware to Applications

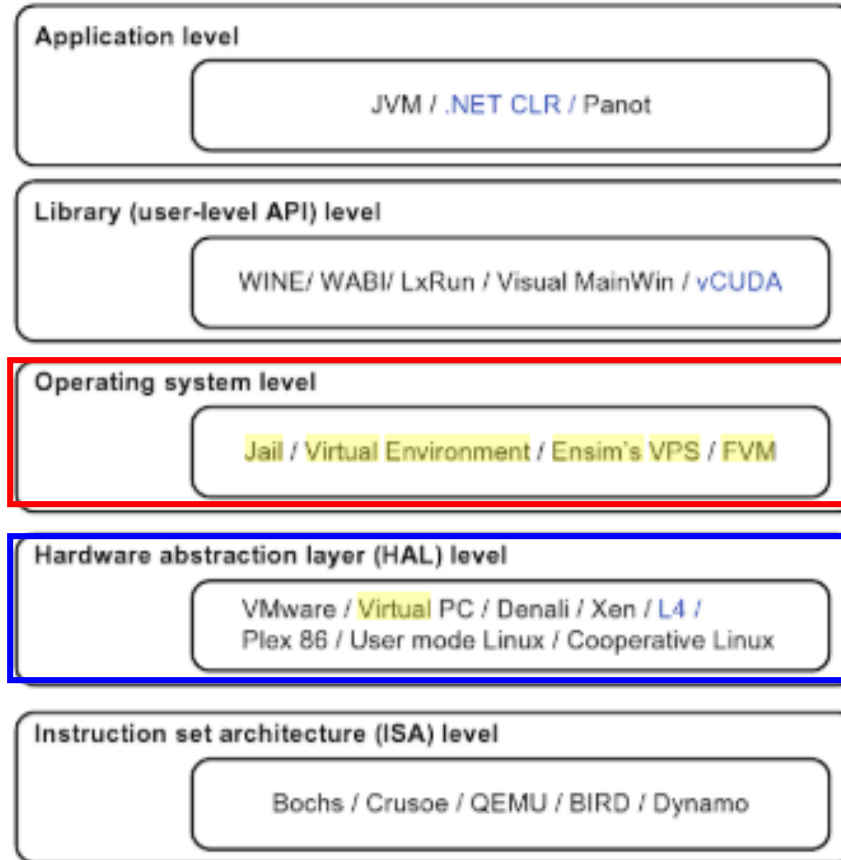
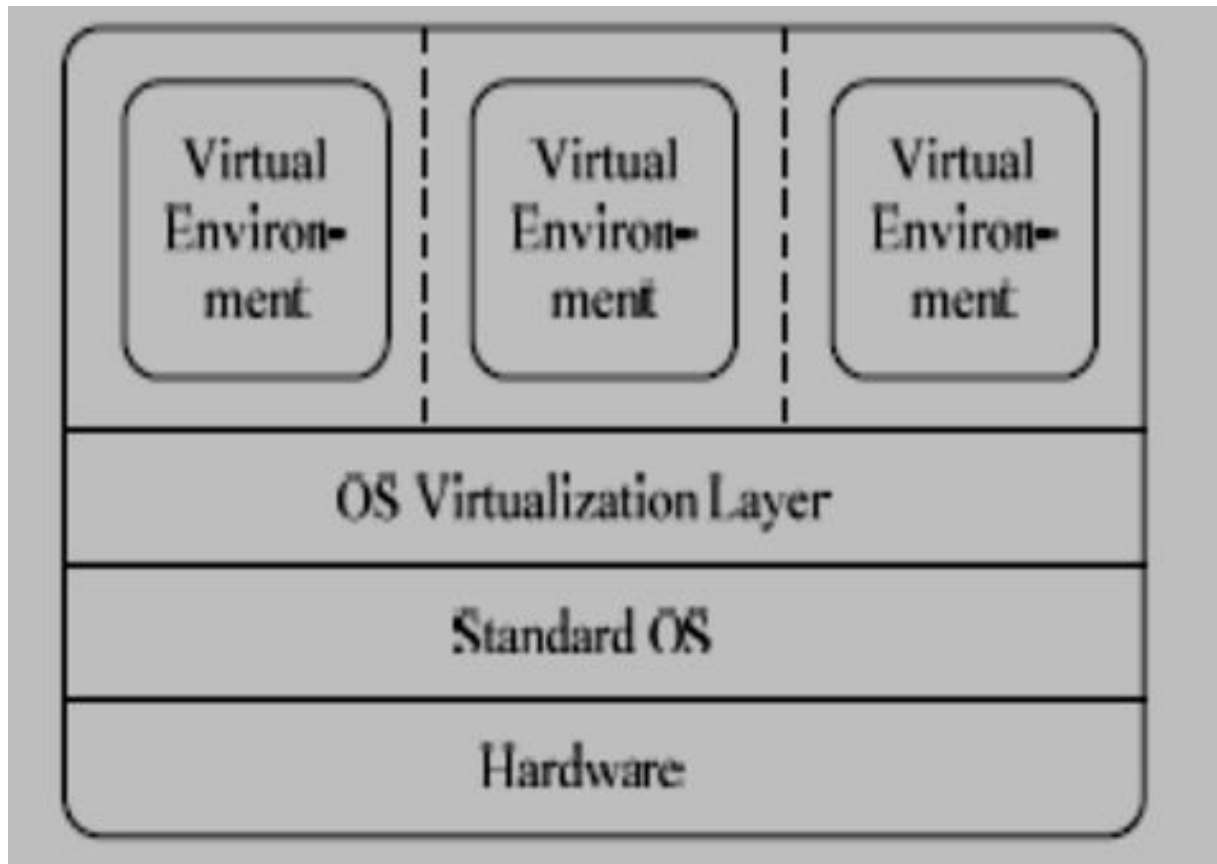


FIGURE 3.2

Virtualization ranging from hardware to applications in five abstraction levels.

Virtualization at OS level





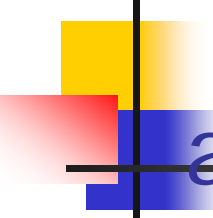
Virtualization at OS level

Advantages of OS extension for virtualization

1. VMs at OS level has minimum startup/shutdown costs
2. OS-level VM can easily synchronize with its environment

Disadvantage of OS Extension for Virtualization

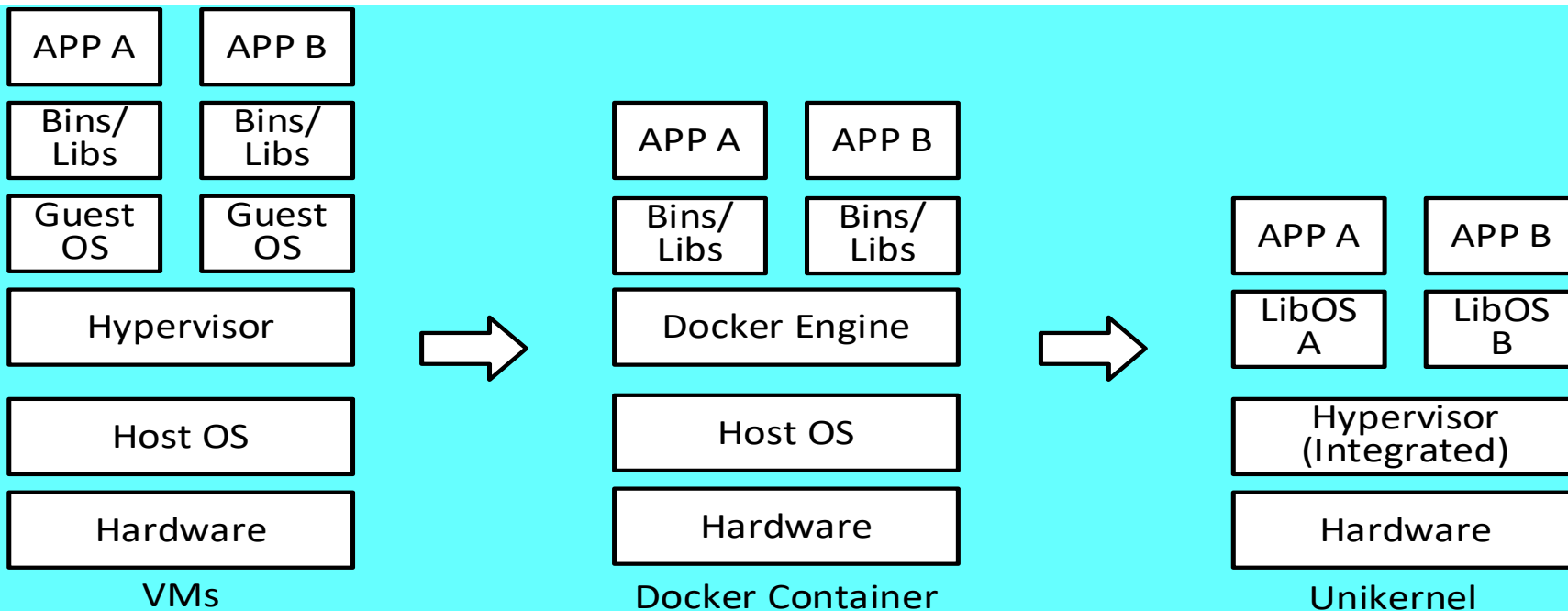
1. All VMs in the same OS container must have the same or similar guest OS, which restricts application flexibility of different VMs on the same physical machine



Assessing the use of virtual machines and docker containers in today's clouds

- Both VMs and software containers will **co-exist** for some time in today's clouds.
- The VMs have high software portability on different types of hardware platforms.
- VMs are heavily weighted with the use of heavy duty guest OS.
 - This may weaken its acceptance in the future.
- The docker containers are light-weight and more cost-effective to implement and to apply in scalable applications.
 - Eventually, most clouds will use containers over Linux hosts

Architectural Evolution from VMs to Docker Containers and Unikernels



Autonomic Cloud Management

Develop methodologies and tools to automate the process of cloud management in 4 objectives

1. Manage resources to provisioning of service quality assurance and adaptation

Resource Management

Power Management

3. Manage energy consumption under SLA constraints

Capacity Management

Autonomic Cloud Management

Load Balancing

2. Automate the configuration process of VMs and virtual clusters

Admission Control

Reliability Management

4. Develop fault prediction models for proactive failure management

Cloud OS for Building Private Clouds

Table 3.6 VI Managers and Operating Systems for Virtualizing Data Centers [9]

Manager/ OS, Platforms, License	Resources Being Virtualized, Web Link	Client API, Language	Hypervisors Used	Public Cloud Interface	Special Features
Nimbus Linux, Apache v2	VM creation, virtual cluster, www .nimbusproject.org/	EC2 WS, WSRF, CLI	Xen, KVM	EC2	Virtual networks
Eucalyptus Linux, BSD	Virtual networking (Example 3.12 and [41]), www .eucalyptus.com/	EC2 WS, CLI	Xen, KVM	EC2	Virtual networks
OpenNebula Linux, Apache v2	Management of VM, host, virtual network, and scheduling tools, www.opennebula.org/	XML-RPC, CLI, Java	Xen, KVM	EC2, Elastic Host	Virtual networks, dynamic provisioning
vSphere 4 Linux, Windows, proprietary	Virtualizing OS for data centers (Example 3.13), www .vmware.com/products/vsphere/ [66]	CLI, GUI, Portal, WS	VMware ESX, ESXi	VMware vCloud partners	Data protection, vStorage, VMFS, DRM, HA



Eucalyptus: An open-source cloud operating system

- A software platform developed by Eucalyptus Systems, Inc., (started 2008 and stable release 2010)
- Written in Java, C, running with Linux, can host Linux and Windows VMs
- Uses hypervisors (Xen, KVM and VMWare) and compatible with EC2 and S3 services
- Eucalyptus stands for “Elastic Utility Computing Architecture for Linking Your Programs To Useful Systems”
- For use in developing IaaS-style private cloud or hybrid cloud on computer cluster, working with AWS API
- License: Proprietary or GPLv3 for open-core enterprise edition. Open-source edition available
- Website: <https://www.eucalyptus.cloud/>

Amazon Web Services (AWS) EC
Amazon Simple Storage Service (S3)

Eucalyptus is open source software for building AWS-compatible private and hybrid clouds.

As an Infrastructure as a Service (IaaS) product, Eucalyptus allows your users to provision your compute and storage resources on-demand.



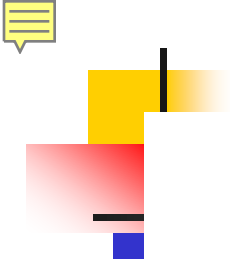
FastStart



Images



Community



OpenStack

main services and components

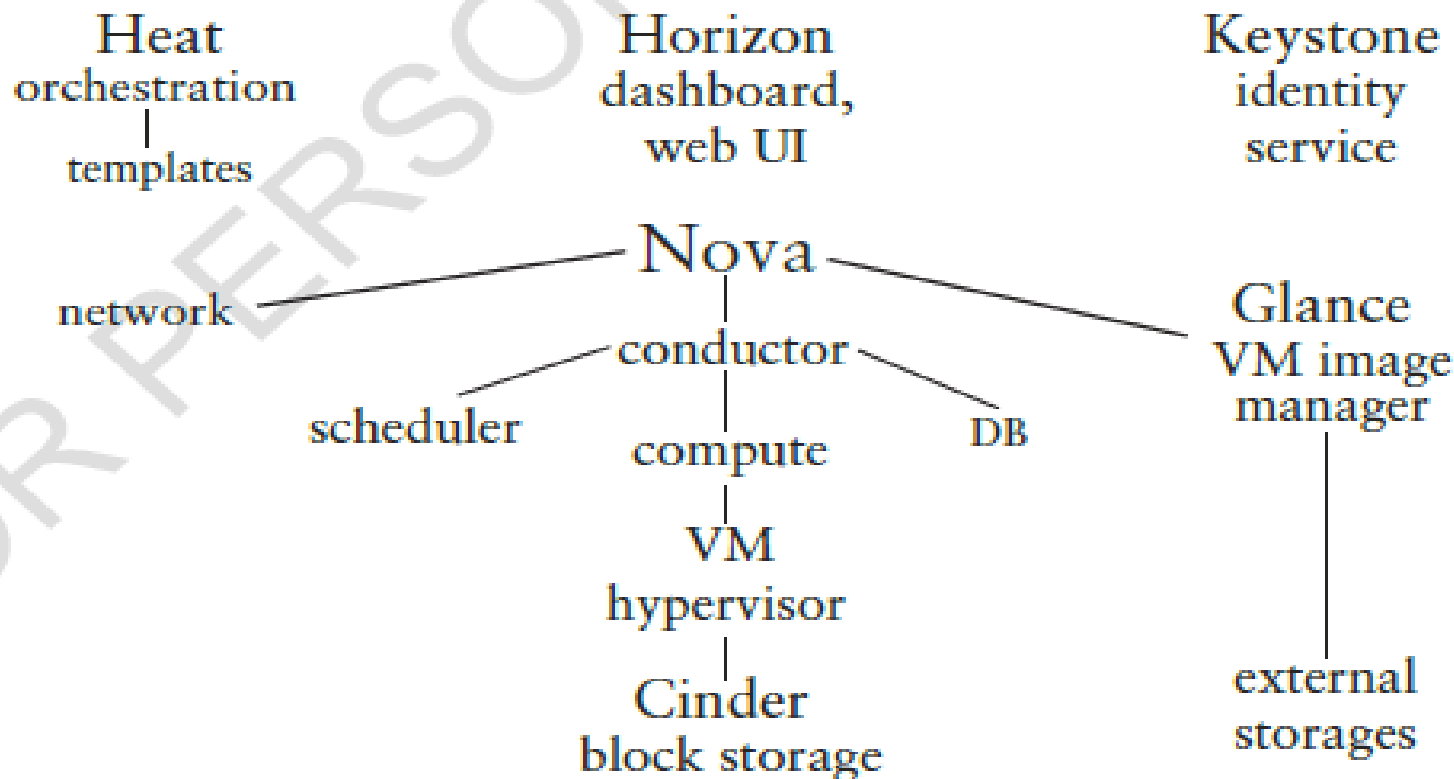


Figure 3.24

OpenStack for constructing private or public clouds in IaaS services. Courtesy of OpenStack, <http://openstack.org>, Apache License 2.0.



Openstack: An IaaS cloud project launched by Rackspace and NASA in 2010

- Currently, 120 companies have joined Openstack
- Openstack is used to create private cloud and offer cloud computing (Nova), object storage (Swift) and image services (Glance)
- The project offers free open source software under the Apache license.
- The Openstack cloud software is written in Python:
<http://openstack.org/>



Openstack: An IaaS Cloud Library

- Nova site:
<http://openstack.org/projects/compute/>
<http://launchpad.net/nova/>
- Swift site:
<http://openstack.org/projects/storage/>
<http://launchpad.net/swift/>
- Glance site:
<http://openstack.org/projects/image-service/>
<http://launchpad.net/glance/>

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Deployed by thousands. Proven production at scale. OpenStack is a set of software components that provide common services for cloud infrastructure.

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VMware –

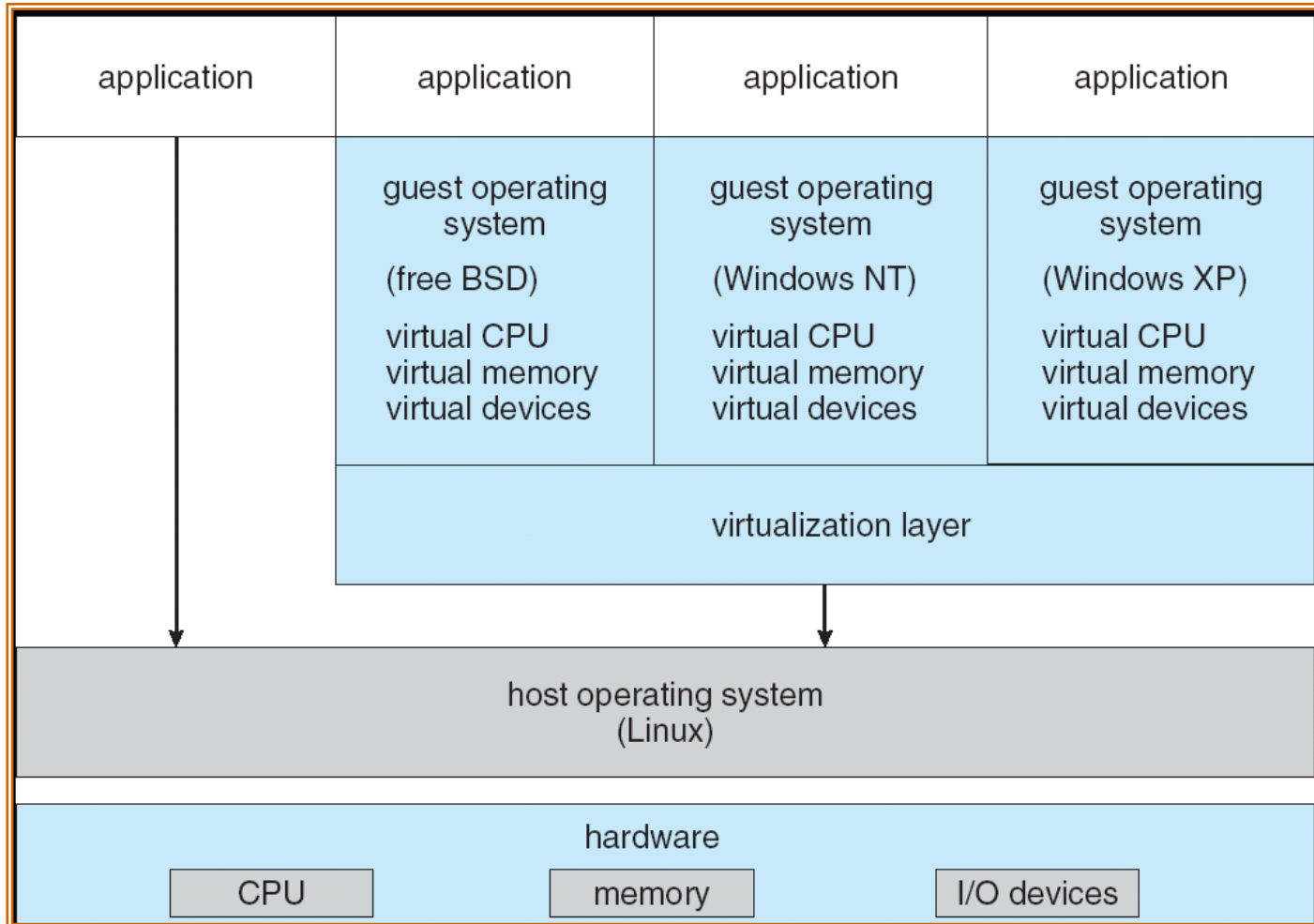
Modern Virtual Machine System

- Founded 1998, Mendel Rosenblum *et al.*
 - Research at Stanford University
- VMware Workstation
 - Separates **Host OS** from **virtualization layer**
 - Host OS may be Windows, Linux, etc.
 - Wide variety of Guest operating systems
 - < \$200
- <http://www.vmware.com/>



A screenshot of the VMware website homepage. The top navigation bar includes links for '產品' (Products), '支援' (Support), '下載' (Downloads), '諮詢顧問' (Consulting), '合作夥伴' (Partners), and '公司' (Company). The main content area features a large graphic with a hand pointing at a cloud, with the text '一個雲端，所有應用程式無所不在' (One cloud, all applications everywhere) and '在單一的整合混合雲上支援最新、未來以及新一代的 App。' (Supports the latest, future, and next-generation apps on a single integrated hybrid cloud). Below this is a link '探索 vCloud Air 的優勢 >'. On the right side, there are three main sections: '探究產品' (Explore Products) with a sub-link '產品選擇工具' (Product Selection Tool); '取得支援' (Get Support) with a search bar and a '登入 My VMware' (Log in to My VMware) link; and '下載軟體' (Download Software) with a sub-link '試用版和免費產品' (Trial and Free Products).

VMware Architecture





VMware Server

- Free version released in 2006
 - <http://www.vmware.com/products/server/>
 - Runs on any x86 server hardware and OS
 - Windows Server and Linux Host OS's
- Partition a physical server into multiple virtual server machines
 - Target market – IT centers providing multiple services
 - Allows separate virtual servers to be separately configured for separate IT applications
 - Portability, replication, etc.



VMware Server ESX

- Total decoupling between hardware and applications
- High-end, high-performance IT applications
 - Oracle, SQL Server, Microsoft Exchange server, SAP, Siebel, Lotus Notes, BEA WebLogic, Apache
- Dynamically move **running** application to different hardware
 - Maintenance, hardware replacement
 - Provisioning new versions, etc.