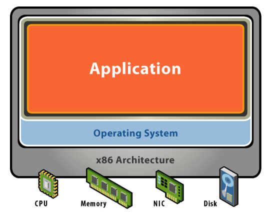
Virtualization

Based on materials from:
Introduction to Virtual Machines by Carl Waldspurger
Understanding Intel® Virtualization Technology (VT) by N. B. Sahgal and D. Rodgers
Intel Virtualization Technology Roadmap and VT-d Support in Xen by Jun Nakajima
A Performance Comparison of Container-based Virtualization Systems for MapReduce Clusters by M. G. Xavier, M. V. Neves, and C.A.F. De Rose

1

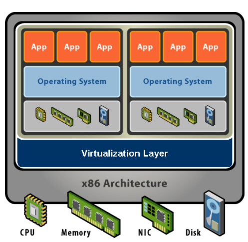
Starting Point: A Physical Machine



- **Physical Hardware**
  - Processors, memory, chipset, I/O devices, etc.
  - Resources often grossly underutilized
- **Software**
  - Tightly coupled to physical hardware
  - Single active OS instance
  - OS controls hardware

2

What is a Virtual Machine?



- **Software Abstraction**
  - Behaves like hardware
  - Encapsulates all OS and application state
- **Virtualization Layer**
  - Extra level of indirection
  - Decouples hardware, OS
  - Enforces isolation
  - Multiplexes physical hardware across VMs

3

Virtualization Properties

- **Isolation**
  - Fault isolation
  - Performance isolation
- **Encapsulation**
  - Cleanly capture all VM state
  - Enables VM snapshots, clones
- **Portability**
  - Independent of physical hardware
  - Enables migration of live, running VMs
- **Interposition**
  - Transformations on instructions, memory, I/O
  - Enables transparent resource overcommitment, encryption, compression, replication …

4

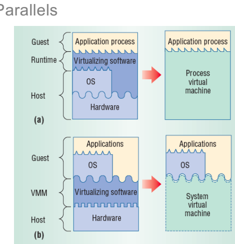
Virtualization Applications

- **Server consolidation**
- **Data center management**
- **Desktop management**
- **Development, test and deployment**
- **Application and OS flexibility**
- **Fast, automated recovery**
- **Fault tolerance**

5

Types of Virtualization

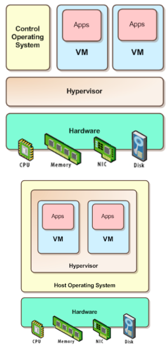
- **Process Virtualization**
  - Language-level Java, .NET, Smalltalk
  - OS-level processes, Solaris Zones, BSD Jails, Docker Containers
  - Cross-ISA emulation Apple 68K-PPC-x86
- **System Virtualization**
  - VMware Workstation, Microsoft VPC, Parallels
  - VMware ESX, Xen, Microsoft Hyper-V



6

Types of Virtualization

- **Native/Bare metal (Type 1)**
  - Higher performance
  - ESX, Xen, HyperV, KVM
- **Hosted (Type 2)**
  - Easier to install
  - Leverage host's device drivers
  - VMware Workstation, Parallels



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7

What is a Virtual Machine Monitor?

- **Classic Definition (Popek and Goldberg '74)**

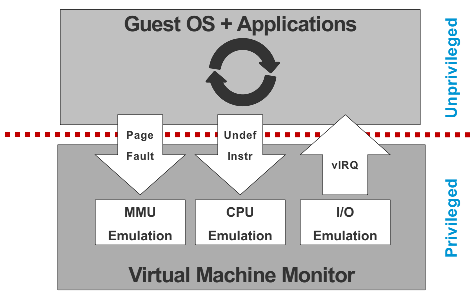
> A virtual machine is taken to be an *efficient, isolated duplicate* of the real machine. We explain these notions through the idea of a *virtual machine monitor* (VMM). See Figure 1. As a piece of software a VMM has three essential characteristics. First, the VMM provides an environment for programs which is essentially identical with the original machine; second, programs run in this environment show at worst only minor decreases in speed; and last, the VMM is in complete control of system resources.

- **VMM Properties**
  - Equivalent execution: Programs running in the virtualized environment run identically to running natively.
  - Performance: A statistically dominant subset of the instructions must be executed directly on the CPU.
  - Safety and isolation: A VMM most completely control system resources.

8

What Needs to Virtualized Virtualized?

- **Processor**
- **Memory**
- **IO**



9

Processor Virtualization

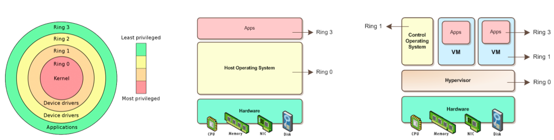
An architecture is classically/strictly virtualizable if all its sensitive instructions (those that violate safety and encapsulation) are a subset of the privileged instructions.

- **all instructions either trap or execute identically**
- **instructions that access privileged state trap**

10

Trap and Emulate

- **Run guest operating system deprivileged**
- **All privileged instructions trap into VMM**
- **VMM emulates instructions against virtual state**
  e.g. disable virtual interrupts, not physical interrupts
- **Resume direct execution from next guest instruction**



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11

x86 Virtualization Challenges

- **Not Classically Virtualizable**
  - x86 ISA includes instructions that read or modify privileged state
  - But which don't trap in unprivileged mode
- **Example: POPF instruction**
  - Pop top-of-stack into EFLAGS register
  - EFLAGS.IF bit privileged (interrupt enable flag)
  - POPF silently ignores attempts to alter EFLAGS.IF in unprivileged mode!
  - So no trap to return control to VMM
- **Deprivileging not possible with x86!**

12

x86 Virtualization Approaches

- Binary translation
- Para virtualization
- HW support

13

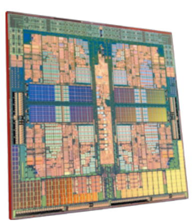
Processor Paravirtualization

- Make OS aware of virtualization
- Present to OS software interface that is similar, but not identical to underlying hardware
- Replace dangerous system calls with calls to VMM
  - Page table updates
- Advantages: High performance
- Disadvantages: Requires porting OS
- Examples: Xen

14

HW Support

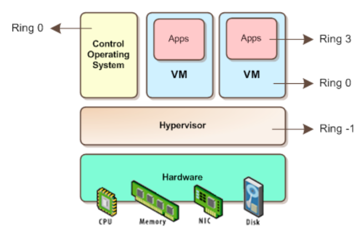
- Intel VT-x
  - Codenamed "Vanderpool"
  - Available since Itanium 2 (2005), Xeon and Centrino (2006)
- AMD-V
  - Codename “Pacifica”
  - Available since Athlon 64 (2006)



15

Intel VT-x

- VT extends the original x86 architecture to eliminate holes that make virtualization hard.



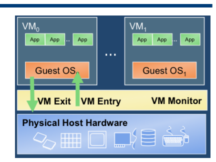
16

Operating Modes

- VMX root operation:
  - Fully privileged, intended for VM monitor
- VMX non-root operation:
  - Not fully privileged, intended for guest software
  - Reduces Guest SW privilege w/o relying on rings
  - Solution to Ring Aliasing and Ring Compression

17

VM Entry and VM Exit



- VM Entry
  - Transition from VMM to Guest
  - Enters VMX non-root operation
    Loads Guest state and Exit criteria from VMCS
  - VMLAUNCH instruction used on initial entry
    VMRESUME instruction used on subsequent entries
- VM Exit
  - VMEXIT instruction used on transition from Guest to VMM
  - Enters VMX root operation
  - Saves Guest state in VMCS
  - Loads VMM state from VMCS
- VMM can control which instructions cause VM exists
  - CR3 accesses, INVLPG

18

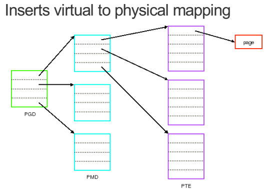
Benefits: VT Helps Improve VMMs

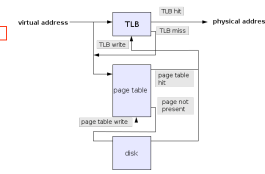
- **VT Reduces guest OS dependency**
  - Eliminates need for binary patching / translation
  - Facilitates support for Legacy OS
- **VT improves robustness**
  - Eliminates need for complex SW techniques
  - Simpler and smaller VMMs
  - Smaller trusted-computing base
- **VT improves performance**
  - Fewer unwanted Guest ⇔ VMM transitions

19

x86 Memory Management Primer

- **The processor operates with virtual addresses**
- **Physical memory operates with physical addresses**
- **x86 includes a hardware translation lookaside buffer (TLB)**
  - Maps virtual to physical page addresses
- **x86 handles TLB misses in HW**
  - CR3 points to page table root
  - HW walks the page tables
  - Inserts virtual to physical mapping

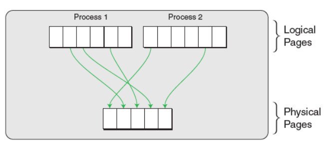




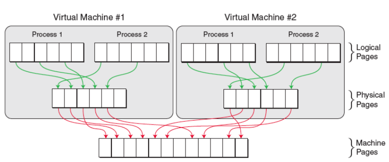
20

Memory Virtualization

- **Native**



- **Virtualized**



21

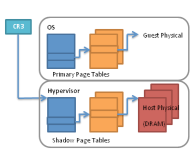
Memory Virtualization Techniques

- **Shadow page tables**
- **Paravirtualization**
- **HW supported nested page tables**

22

Shadow Page Tables

- **Keep a second set of page tables hidden from guest**
- **Map between guest virtual and machine pages**
- **Detect when guest changes page tables**
  - TLB invalidation requests, page table creation, write to existing page tables
- **Update shadow page accordingly**
- **On context switch, install shadow page instead of guest page**
- **Advantages: Can support unmodified guest**
- **Disadvantages: Significant overhead to maintain consistency**
- **Examples: VMware and Xen HVM**



23

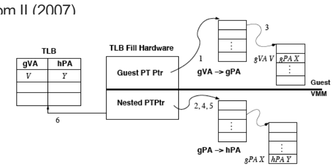
Memory Paravirtualization

- **Page table maps between virtual and machine addresses**
- **OS and VMM share page tables**
- **OS can only read**
- **Changes to page table require hyper call**
  - VMM validates that guest owns machine address
- **Advantages: Higher performance can be achieved by batching updates**
- **Disadvantages: Requires changes to the OS**
- **Examples: Xen**

24

Hardware Support

- Nested page tables
- HW keeps a second set of page tables that map from physical to machine addresses.
- On a TLB miss, first find physical address from guest page tables, then map to machine address
- Intel EPT (Extended Page Table)
  - Since Corei7 (2008)
- AMD RVI (Rapid Virtualization Indexing)
  - Since Opteron and Phenom II (2007)



25

Issues with Nested Page Tables

- Positives
  - Simplifies monitor design
  - No need for page protection calculus
- Negatives
  - Guest page table is in physical address space
  - Need to walk PhysMap multiple times
    - Need physical-to-machine mapping to walk guest page table
    - Need physical-to-machine mapping for original virtual address

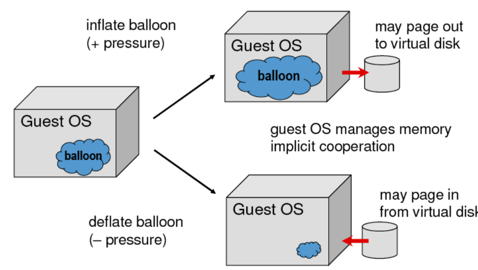
26

Memory Reclamation

- Balloning: guest driver allocates pinned PPNs, hypervisor deallocates backing MPNs
- Swapping: hypervisor transparently pages out PPNs, paged in on demand
- Page sharing: hypervisor identifies identical PPNs based on content, maps to same MPN copy-on-write

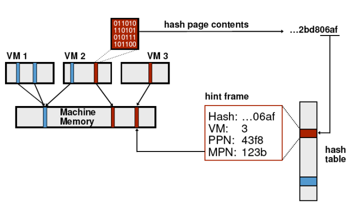
27

Ballooning



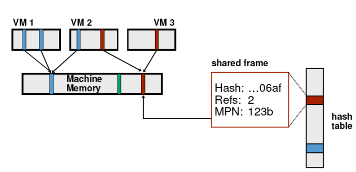
28

Page Sharing



29

Page Sharing



30

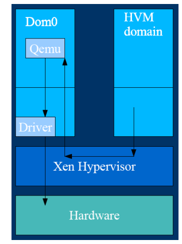
I/O Virtualization

- Emulation
- Paravirtualization (split driver)
- Direct mapped/PCI passthrough
- Hardware support

31

Emulation

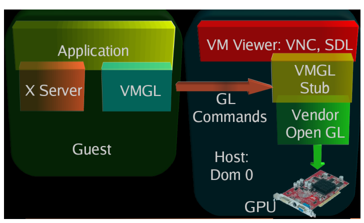
- Guest runs original driver
- VMM emulates HW in SW
- Advantages: Can run unmodified guest
- Disadvantages: Slow



32

IO Paravirtualization

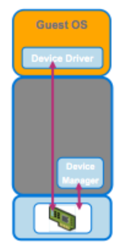
- Slip driver approach
- Privileged domain interact with IO devices, exports high level interface as back-end drive
- Guest domain implements front end driver
- Front and back end drivers



33

Direct Mapped/PCI Passthrough

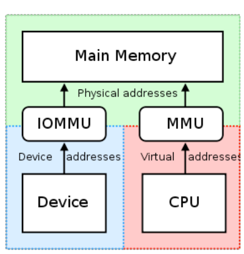
- Allocate a physical device to a specific domain
- Driver runs of guest domain
- Cannot use DMA
  - DMA uses physical addresses.
  - Breaks isolation



34

Hardware Support

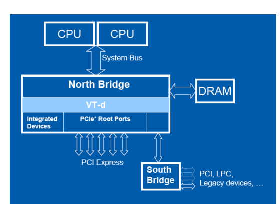
- IOMMU (IO Memory Management Unit)
- Translates memory addresses from “IO space” to “physical space”
- Provides isolation. Limits device’s ability to access machine memory.
- Intel VT-d
  - Core 2 (2008)
- AMD-Vi
  - Six Core Opteron (2010)



35

Intel VT-d

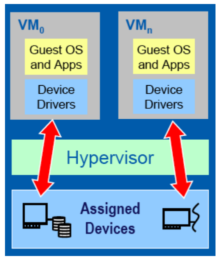
- Provides infrastructure for I/O virtualization
- DMA and interrupt remapping



36

VT-d Applied to Pass-through Model

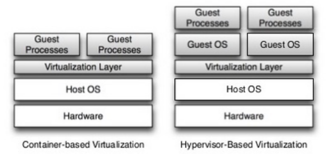
- Direct Device Assignment to Guest OS
  - Guest OS directly programs physical device
  - VMM sets up guest- to host-physical DMA mapping
- PCI-SIG I/O Virtualization Working Group
  - Activity towards standardizing natively sharable I/O devices
  - IOV devices provide virtual interfaces, each independently assignable to VMs
- Advantages: High performance and simple VMM
- Disadvantages: Limits VM migration



37

Operating System Level Virtualization

- aka Container-based Virtualization
- Shared operating system
- A group of OS processes in an insolated environment
- Lightweight virtualization layer



38

Operating System-Level Virtualization

- Each container has:
  - Own virtual network interface (and IP Address)
  - Own filesystem
  - Isolation
    - Processes in different containers can not see each other
    - Allocation of RAM, CPU, I/O
- Examples
  - Linux Vserver, OpenVZ, LXC

39

Hypervisor vs. System-Level Virtualization

Hypervisor	OS-Level/Container
Different Kernel OS	Single Kernel
Device Emulation	Syscall
Limits per machine	Limits per process
Higher overhead	Lower overhead
More secure	Less secure

40