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

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 on commodity platforms
  - 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

Goals

- Manageability
  - Creation, 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

Same goals as for many subsystems
VMM Types

- Fully virtualizing VMM
  - Virtual machine looks exactly like a (some) physical machine
    - Not necessarily exactly like the underlying hardware itself
  - Run guest OS unchanged
  - VMM is transparent to the OS

- Para-virtualizing VMM
  - Guest OS is changed to cooperate with VMM
  - Sacrifice transparency for better performance
  - E.g. VMM can provide idealized view of some hardware
  - E.g. VMM can provide "hypervisor API" so guest can perform certain functions, e.g. with optimizations for performance

VMM Classification

- Type I VMM
  - Fully-virtualized
    - VMware ESX
    - VMware Workstation, VirtualBox, Virtual PC
  - Para-virtualized
    - Xen
    - User Mode Linux

- Type II VMM
  - VMware Workstation, VirtualBox, Virtual PC
  - 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
  - i.e. sensitive instructions will always trap if run in user mode
- When guest OS, which runs in user mode, runs a sensitive instruction, must trap to VMM so it maintains control

Example: System Call (Type 1 Hypervisor)

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)

x86 Processor Virtualization

- x86 architecture is not fully virtualizable
  - 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 inability to virtualize x86
  - Replace non-virtualizable instructions with easily virtualized ones statically (Paravirtualization)
  - Perform Binary Translation (Full Virtualization)
  - Note: both basically remove problematic (non-virtualizable) instructions from the guest OS

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 of the VM's page table
- The shadow page keeps mapping from virtual pages within a VM to real physical pages
- 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 reclamnation
  - 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

- Inflat balloon (+ pressure)
- Deflate balloon (- pressure)
- Guest OS manages memory implicit cooperation
- May page out to virtual disk

ESX Server – Page Sharing

- Copy-on-write for writing shared pages
Real World Page Sharing

<table>
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<tr>
<th>Workload</th>
<th>Guest Types</th>
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<th>MB</th>
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Corporate IT – database, web, development servers (Oracle, WebSphere, IIS, Java, etc.)
Nonprofit – web, mail, anti-virus, other servers (Apache, Nagios, Mailsender, etc.)
VMware = web proxy, mail, remote access (Spark, Postfix, WA, vsh, 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

- Virtual NIC
- Physical NIC
- Virtual Network Hub (Host-Only)
- Virtual Network Hub (Brigade)
- Hard Drive
- Virtual Machine

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 (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