

OS Virtualization

CSC 456 Final Presentation
Brandon D. Shroyer

Virtualization Basics

- Motivation
- Types of Virtualization
 - Process virtualization (Java)
 - System virtualization (classic, hosted)
 - Emulation (QEMU)
- OS Virtualization
 - Formal Requirements
 - The *guest operating system* model

Introduction

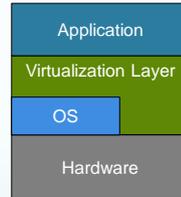
- *Virtualization*: Providing an interface to software that maps to some underlying system.
 - A one-to-one mapping between a guest and the host on which it runs [9, 10].
- Virtualized system should be an “efficient, isolated duplicate” [8] of the real one.
- *Process virtual machine* just supports a process; *system virtual machine* supports an entire system.

Why Virtualize?

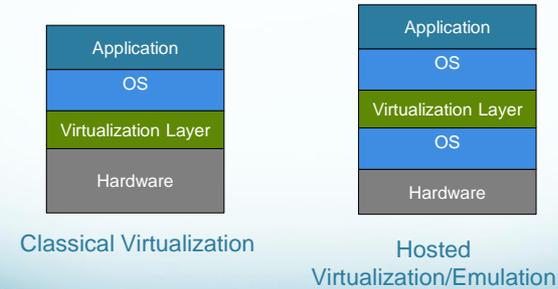
- Reasons for Virtualization
 - Hardware Economy
 - Versatility
 - Environment Specialization
 - Security
 - Safe Kernel Development
 - OS Research [12]

Process Virtualization

- VM interfaces with single process
- Application sees “virtual machine” as address space, registers, and instruction set [10].
- Examples:
 - Multiprogramming
 - Emulation for binaries
 - High-level language VMMs (e.g., JVM)



System Virtualization



System Virtualization

- Interfaces with operating system
- OS sees VM as an actual machine—memory, I/O, CPU, etc [10].
- *Classic virtualization*: virtualization layer runs atop the hardware.
 - Usually found on servers (Xen, VMWare ESX)
- *Hosted or whole-system virtualization*: virtualization runs on an operating system
 - Popular for desktops (VMWare Workstation, Virtual PC)

Emulation

- Providing an interface to a system so that it can run on a system with a different interface [10].
 - Lets compiled binaries, OSes run on architectures with different ISA (binary translation)
 - Performance usually worse than classic virtualization.
- Example: QEMU [11]
 - Breaks CPU instructions into small ops, coded in C.
 - C code is compiled into small objects on native ISA.
 - dyngen utility runs code by dynamically stitching objects together (dynamic code generation).

OS Virtualization: Some Important Terms

- *Virtual Machine (VM)*: An instance of of an operating system running on a virtualized system. Also known as a *virtual* or *guest OS*.
- *hypervisor*: The underlying virtualization system sitting between the guest OSES and the hardware. Also known as a *Virtual Machine Monitor (VMM)*.
 - The analogous construct in process virtualization is the runtime (the JVM, for instance).

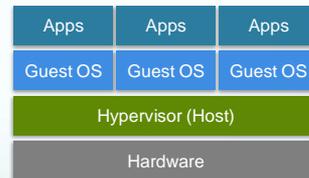
Requirements of a VMM

Developed by Popek & Goldberg in 1974 [8]:

1. Provides environment identical to underlying hardware.
2. Most of the instructions coming from the guest OS are executed by the hardware without being modified by the VMM.
3. Resource management is handled by the VMM (this all non-CPU hardware such as memory and peripherals).

Guest OS Model

- Hypervisor exists as a layer between the operating systems and the hardware.
- Performs memory management and scheduling required to coordinate multiple operating systems.
- May also have a separate controlling interface.

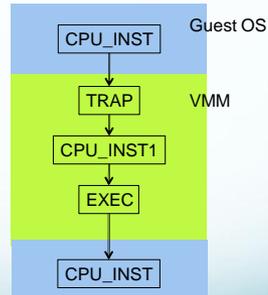


Virtualization Challenges

- Performance Requirements
 - Holding down the cost of VMM activities.
- Privileged Instructions
 - Handling architecture-imposed instruction privilege levels.
- Memory Management
 - Managing multiple address spaces efficiently.
- I/O Virtualization
 - Handling I/O requests from multiple operating systems.

Performance

- Modern VMMs based around trap-and-emulate [8].
- When a guest OS executes a privileged instruction, control is passed to VMM (VMM "traps" on instruction), which decides how to handle instruction [8].
- VMM generates instructions to handle trapped instruction (emulation).
- Non-privileged instructions do not trap (system stays in guest context).



Trap and Emulate Basics [8]

- User and superuser modes in [8] roughly correspond to guest OS & VMM modes
 - Analogous to user and kernel modes
- *Trap*: To switch to VMM mode
- *Sensitive Instruction*: Instruction that must be executed in superuser (VMM) mode
 - E.g., instructions that manage system resources or switch modes
- *Privileged Instruction*: Any instruction that traps when executed in user (guest OS) mode
- All sensitive instructions *must* be privileged instructions [8]

Trap-and-Emulate Problems

- Trap-and-emulate is expensive
 - Requires context-switch from guest OS mode to VMM.
- x86 is not trap-friendly
 - Guest's CPL privilege level is visible in hardware registers; cannot change it in a way that the guest OS cannot detect [5].
 - Some instructions are not privileged, but access privileged systems
 - Example: instructions that access page tables do not require 0-level CPL privilege, but anything that affects the MMU does [5].
 - A read is fair game for the user, but if it causes a page fault, a new page has to be fetched by the MMU

Direct Access

- Direct access to hardware is not permitted by the Popek and Goldberg model [8].
- VMWare and Xen both bend this rule, allow guests to access hardware directly in certain cases.
- Xen uses validated access model [3].
 - Fine-grained control over direct access.
- VMWare allows user-mode instructions to bypass BT, go straight to CPU [5].
- Memory accesses are sometimes batched to minimize context switches.

Virtualizing Privileged Instructions

- x86 architecture has four privilege levels (rings).
- The OS assumes it will be executing in Ring 0.
- Many system calls require 0-level privileges to execute.
- Any virtualization strategy must find a way to circumvent this.

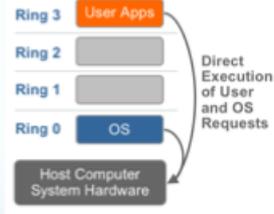


Image Source: VMWare White Paper, "Understanding Full Virtualization, Paravirtualization, and Hardware Assist", 2007.

Full Virtualization

- "Hardware is functionally identical to underlying architecture." [3]
- Typically accomplished through interpretation or binary translation.
- Advantage: Guest OS will run without any changes to source code.
- Disadvantage: Complex, usually slower than paravirtualization.

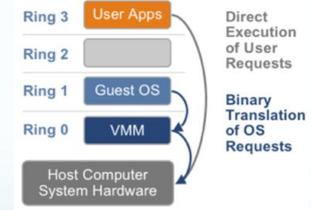


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Paravirtualization

- Replace certain unvirtualized sections of OS code with virtualization-friendly code.
- Virtual architecture "similar but not identical to the underlying architecture." [3]
- Advantages: easier, lower virtualization overhead
- Disadvantages: requires modifications to guest OS

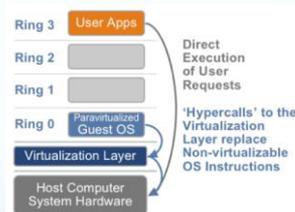


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VMWare Virtualization

- Full virtualization implemented through dynamic binary translation [5].
 - Translated code is grouped and stored in translation caches (TCs).
 - Callout method replaces traps with stored emulation functions.
 - In-TC emulation blocks are even more efficient.
 - Adaptive binary translation rewrites translated blocks to minimize PTE traps [5].
- Direct execution of user-space code further reduces overhead [5].

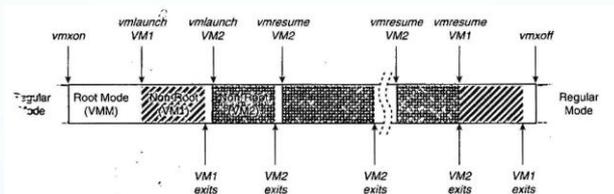
Xen Virtualization

- Xen occupies privilege level 0; guest OS occupies privilege level 1
- OS code is modified so that high-privilege calls (hypercalls) are made to and trapped by Xen [3]
- Xen traps guest OS instructions using table of exception handlers
 - Frequently used handlers (e.g., system calls) have special handlers that allow guest OS to bypass privilege level 0 [3]
 - Page faults require special handling since they need access to a register accessible containing the trapping address that is accessible only in privileged mode
- Handlers are vetted by Xen before being stored

Hardware-Assisted Virtualization

- Hardware virtualization-assist released in 2006 [5].
 - Intel, AMD both have technologies of this type.
- Introduces new VMX runtime mode.
 - Two modes: guest (for OS) and root (for VMM).
 - Each mode has all four CPL privilege levels available [8].
 - Switching from guest to VMM does not require changes in privilege level.
 - Root mode supports special VMX instructions.
 - Virtual machine control block [5] contains control flags and state information for active guest OS.
 - New CPU instructions for entering and exiting VMM mode.
- Does not support I/O virtualization.

Intel VT-X



- Both modes have no restrictions on privilege
 - No need for software-based depriving

Image Source: Smith, J. and Nair, R. *Virtual Machines*, Morgan Kaufmann, 2005.

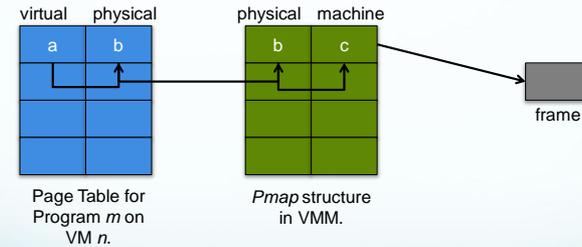
Applications of VT-X

- Xen uses Intel VT-x to host fully-virtualized guests alongside paravirtualized guests [6].
 - System has root (VMM) and non-root (guest) modes, each with privilege levels 0-3.
 - QEMU/Bochs projects provide emulations
- VMWare does not make use of VT technology [5].
 - VMWare's software-based VMMs significantly outperformed VT-X-based VMMs [5].
 - VT-X virtualization is trap-based, and DBT tries to eliminate traps wherever possible.

Virtualizing Memory

- Virtualization software must find a way to handle paging requests of operating systems, keeping each set of pages separate.
- Memory virtualization must not impose too much overhead, or performance and scalability will be impaired.
- Guest OS must each have an address space, be convinced that it has access to the entire address space.
- SOLUTION: most modern VMMs add an additional layer of abstraction in address space [4].
 - Machine Address*—bare hardware address.
 - Physical Address*—VMM abstraction of machine address, used by guest OSes.
 - Guest maintains virtual-to-physical page tables.
 - VMM maintains pmap structure containing physical-to-machine page mappings.

Memory Lookup Problem

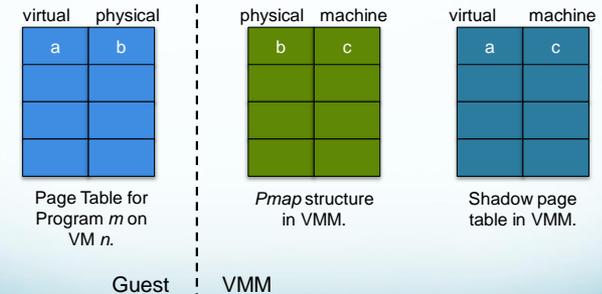


That's a lot of lookups!

Solution: Shadow Page Tables

- Shadow page tables* map virtual memory to machine memory [4].
 - One page table maintained per guest OS.
 - TLB caches results from shadow page tables.
- Shadow page tables must be kept consistent with guest pages.
 - VMM updates shadow page tables when pmap (physical-to-machine) records are updated.
- VMM now has access to virtual addresses, eliminating two page table lookups.

Shadow Page Tables



Shadow Page Table Drawbacks

- Updates are expensive
 - On a write, the VMM must update the VM and the shadow page table.
- TLB must be flushed on world switch.
 - TLB from other guest will be full of machine addresses that would be invalid in the new context.

Memory Load Balancing Problem

- Assume VMM divides address space evenly among guests.
- If guest workload is not balanced, one guest could be routinely starved for memory.
- Other guests have way more than they need.
- Solution: memory overcommitment



Memory Overcommitment

- *Overcommitment*: committing more total memory to guest OSes than actually exists on the system [4].
 - Guest memory can be adjusted according to workload.
 - Higher-workload servers get better performance than with a simple even allocation.
- Requires some mechanism to reclaim memory from other guests [4].
- Poor page replacement schemes can result in *double paging* [4].
 - VMM marks page for reclamation, OS immediately moves reclaimed page out of memory
 - Most common in high memory-usage situations.

Ballooning

- Mechanism for page reclamation.
 - Technique to induce page-ins, page-outs in a guest OS.
- “Balloon module” [4] loaded on guest OS reserves physical pages; can be expanded or contracted.
- VMWare and Xen both support ballooning.

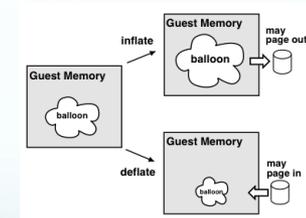


Image Source: Waldspurger, C. "Memory Resource Management in VMware ESX Server", OSDI 2002.

Ballooning, continued

- When VMM wants to reclaim memory, balloon “inflates”.
 - Region of reserved pages expands.
- Guest OS has less memory to work with, starts experiencing memory pressure and begins paging out more memory.
- Later on, the VMM “deflates” the balloon.
 - Releases physical memory, which the guest can use.

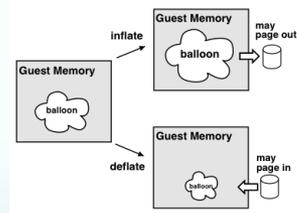


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Ballooning Issues

Pros

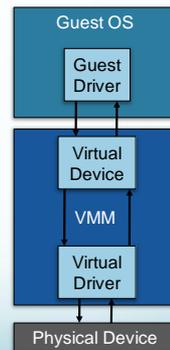
- Piggybacks off guest OS memory management algorithms.
 - Guest decides which pages to release
- Low trap overhead [4].
 - VMM indicates when to inflate, deflate balloon, but does not get involved otherwise.

Cons

- Stretches the definition of full virtualization [2].
- Is not guaranteed to work, or release sufficient memory.
 - Xen and VMWare both have fallback page replacement algorithms [3], [4].

I/O Virtualization

- Performance is critical for virtualized I/O
 - Many I/O devices are time-sensitive or require low latency [7].
- Most common method: device emulation
 - VMM presents guest OS with a virtual device [7].
 - Preserves security, handles concurrency, but imposes more overhead.



I/O Virtualization Problems

- Multiplexing
 - How to share hardware access among multiple OSes.
- Switching Expense
 - Low-level I/O functionality happens at the VMM level, requiring a context switch.

Packet Queuing

- Both major VMMs use an asynchronous ring buffer to store I/O descriptors.
- Batches I/O operations to minimize cost of world switches [7].
- Sends and receives exist in same buffer.
- If buffer fills up, an exit is triggered [7].

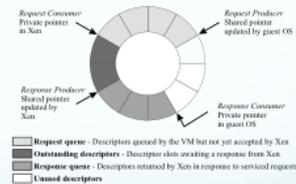


Image Source: Barham, P. et al. "Xen and the Art of Virtualization", SOSP2003.

I/O Rings, continued

Xen

- Rings contain memory descriptors pointing to I/O buffer regions declared in guest address space.
- Guest and VMM deposit and remove messages using a producer-consumer model [2].
- Xen 3.0 places device drivers on their own virtual domains, minimizing the effect of driver crashes.

VMWare

- Ring buffer is constructed in and managed by VMM.
- If VMM detects a great deal of entries and exits, it starts queuing I/O requests in ring buffer [7].
- Next interrupt triggers transmission of accumulated messages.

Summary

- Current VMM implementations provide safe, relatively efficient virtualization, albeit often at the expense of theoretical soundness [8].
- The x86 architecture requires a) binary translation, b) paravirtualization, or c) hardware support to virtualize.
- Binary translation and instruction trapping costs are currently the largest drains on efficiency [5].
- Management of memory and other resources remains a complex and expensive task in modern virtualization implementations.

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