Virtual Machines

CS 256/456

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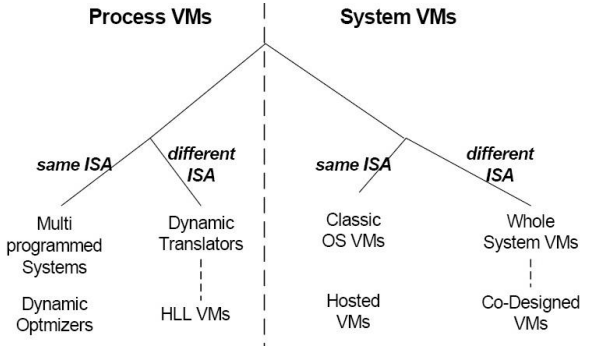
Virtualization

- *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]

A Taxonomy of Virtual Machine Architectures



History

- VM/370
  - Developed by IBM for OS/360 in the 1970s.
  - Introduced timesharing.
  - Provided multiprogramming and an extended machine with a more convenient interface than bare hardware.

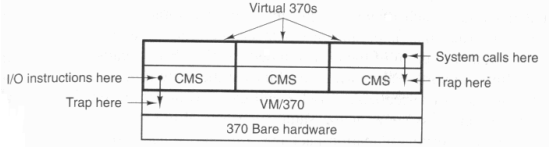
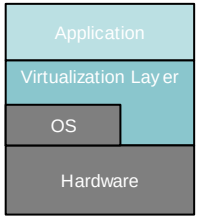


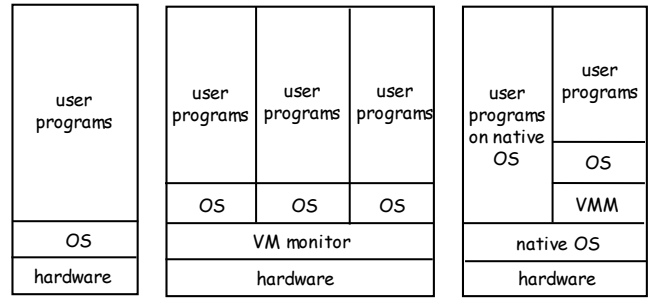
Figure 1-28. The structure of VM/370 with CMS.

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 Virtual Machines



Non-VM Support | Native VM Support | Hosted VM Support

OS sees VM as an actual machine – raw hardware – CPU, memory, I/O

Emulation

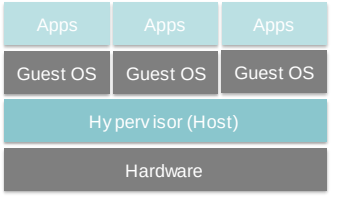
- Providing an interface to a system so that it can run on a system with a different interface [10].
  - Lets compiled binaries, OSes run on architectures with different ISA (binary translation)
  - Performance usually worse than classic virtualization.
- Example: QEMU [11]
  - Breaks CPU instructions 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).

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 Approach – Direct Execution

- Directly executing VM code to attain high speed
- CPU virtualization
  - VM monitor catches timer interrupts and switches VM if necessary
- I/O access virtualization
  - cause a trap to VM monitor, which processes appropriately
  - extra overhead is not too bad
- Memory virtualization
  - a trap at each memory access is not a very good idea
  - How?

System VMs – Processors

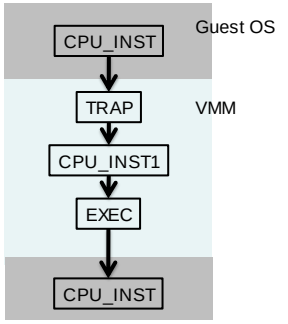
- Instruction execution can be through interpretation or binary translation. Can also use direct native execution (only if ISAs are identical)
- Must address issue of "sensitive" and "privileged" instruction references

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
  - Instructions that manage system resources or switch modes are sensitive
  - Instructions affected by location in memory are also sensitive
- *Privileged Instruction:* Any instruction which traps when executed in user (OS) mode.
  - Instructions that update memory are privileged, also sensitive
- All sensitive instructions *must* be privileged instructions [8]

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).



Challenges – Instruction Architecture

- "Sensitive" – May only be executed in kernel mode
- "Privileged" – Cause a trap if executed in user mode
  - "Trap" – Switch to kernel mode for execution.
- For a system to be virtualizable, the sensitive instructions must be a subset of the privileged instructions (Popek and Goldberg, 1974)
- Historically, not all ISAs provided this guarantee

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

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.

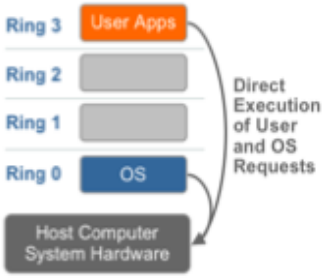


Image Source: VMWare White Paper, "Understanding Full Virtualization, Paravirtualization, and Hardware Assist", 2007.

ISA Challenge: Potential Solution

- Paravirtualization
  - Remove (some or all) sensitive instructions from the guest OS and replace them with hypervisor calls
  - The VMM basically acts as a microkernel by emulating guest OS system calls

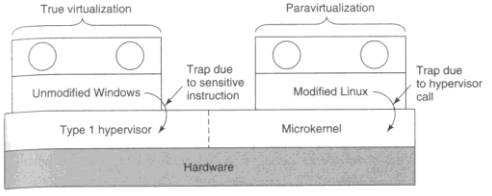


Figure 8-27. A hypervisor supporting both true virtualization and paravirtualization.

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

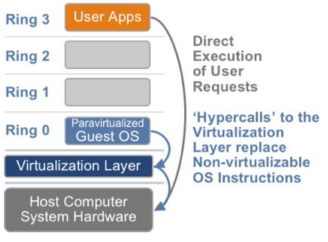


Image Source: VMWare White Paper, "Understanding Full Virtualization, Paravirtualization, and Hardware Assist", 2007.

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.

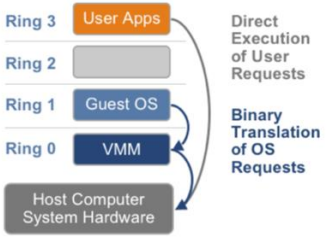


Image Source: VMWare White Paper, "Understanding Full Virtualization, Paravirtualization, and Hardware Assist", 2007.

ISA Challenge: Potential Solution

- Architecture design can limit potential for virtualizability
  - Some ISAs have instructions that can read sensitive information without trapping (Ex: Pentium)
- Solution: Design from the start with virtualization in mind
  - Ex: Intel Core 2 Duo (VT) and AMD Pacific (SVM)

Hardware-Assisted Virtualization

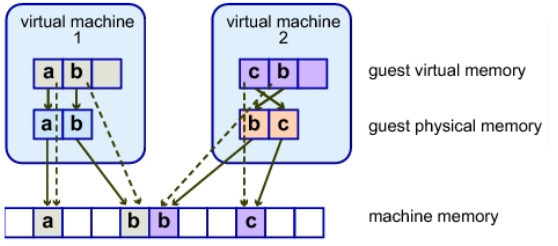
- Hardware virtualization-assist released in 2006 [5].
  - Intel, AMD both have technologies of this type.
- Introduces new VMX runtime mode.
  - Two modes: guest (for OS) and root (for VMM).
  - Each mode has all four CPL privilege levels available [8].
  - Switching from guest to VMM does not require 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.

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.

System VMs – Memory

- Example: VMware's ESX Server



Memory Virtualization Under Direct Execution (protected page table)

- From the VM OS's view, the page table contains mapping from virtual to VM physical addresses
- For proper operation, the page table hooked up with MMU must map virtual to real machine addresses
- VM OS cannot directly access the page table
  - each page table read is trapped by VM monitor, the physical address field is translated (from real machine address to VM physical address)
  - each page table write is also trapped, for a reverse translation and for security checking

Memory Virtualization Under Direct Execution (shadow page table)

- VM OS maintains virtual to VM physical (V2P) page table
- VM monitor
  - maintains a VM physical to machine (P2M) mapping table
  - combines V2P and P2M table into a virtual to machine mapping table (V2M)
  - supplies the V2M table to the MMU hardware
- Page table updates
  - any VM change on its V2P page table must be trapped by VM monitor
  - VM monitor modifies V2M table appropriately

System VMs – I/O

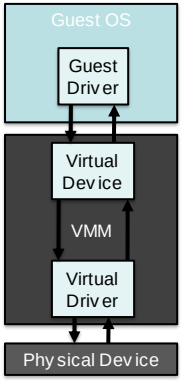
- Challenging for VMM, but can adapt techniques from time-sharing of I/O devices on typical systems
- Create a virtualized version of system devices. VMM intercepts request by guest VM and converts the request to equivalent physical device request

System VMs – I/O

- The VMM can catch and virtualize the I/O action at three levels:
  - I/O operation level
  - device driver level
  - system call level
- Virtualizing at the device driver level is most practical

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].

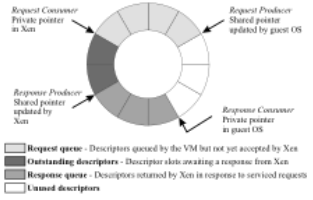


Image Source: Barham, P. et al. "Xen and the Art of Virtualization", SOSP 2003.

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.

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