Introduction to Virtual Machines

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From
"HSSV", Bugnion, Neih, Tsafrir
"Virtual Machines", Smith and Nair, Chapter 1
Also, Chapter 7 Andrew Tanenbaum's book

- “Virtual machines have finally arrived. Dismissed for a number of years as merely academic curiosities, they are now seen as cost-effective techniques for organizing computer systems resources to provide extraordinary system flexibility and support for certain unique applications”.

  —Robert. P. Goldberg, IEEE Computer, 1974

The Rise and Fall of Virtual Machines

- 1970s:
  - IBM mainframes run VMs and hardware supports not just single-level, but also nested virtualization.
  - Hundreds of papers on virtualization.
  - Goldberg and Popek’s seminal paper on formal requirements of virtualization support.

- 1980s and 1990s:
  - Personal computers (temporarily) obviate the need for VMs.
  - x86. MIPS, Sparc processors have no hardware support for virtualization
  - UNIX, Windows, Linux don’t include virtualization support.

VMs — Back from Dead (or the Second Coming)

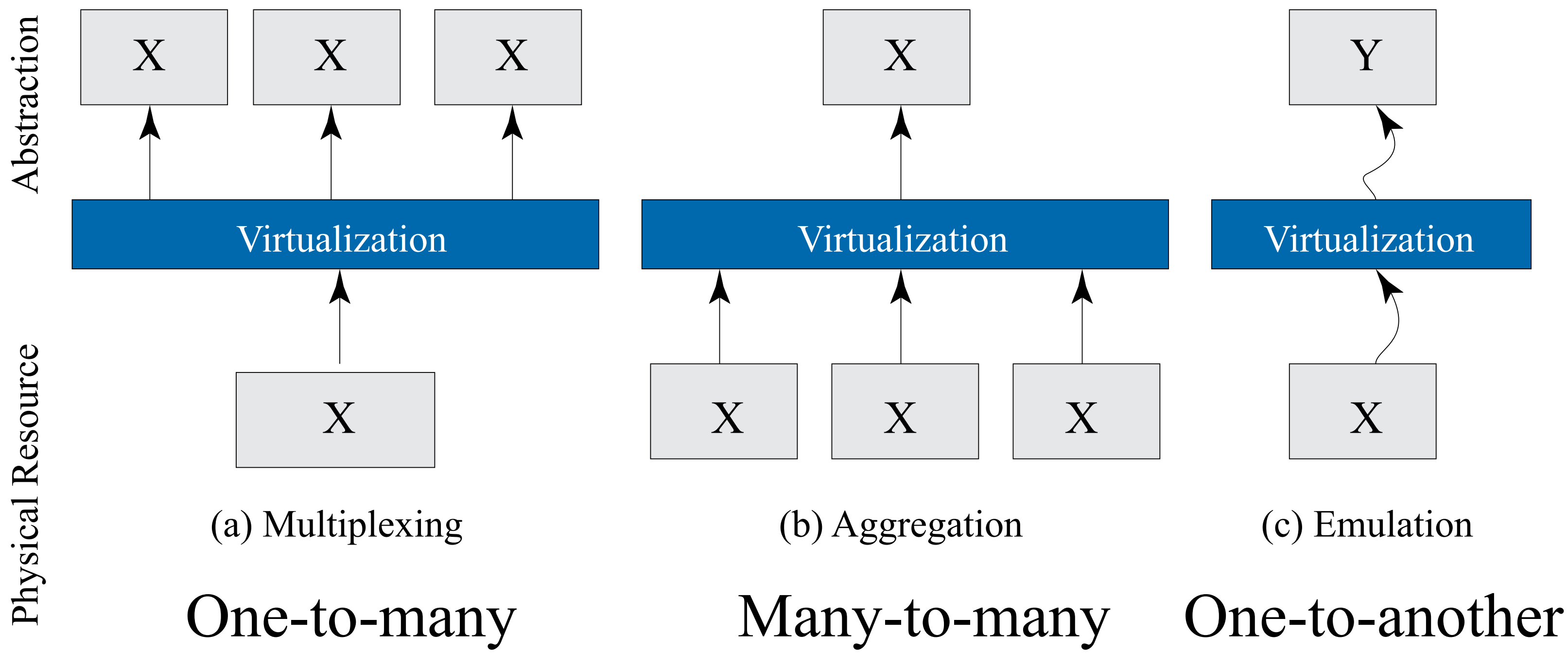
- 1997: DISCO paper revisits for running commodity OS on SMP machines
- 1999: VMWare releases VMWare workstation for x86 CPUs.
- Early 2000s:
  - VMWare ESX server, VirtualPC, Xen, Denali, Cells.
  - Still no hardware support for virtualization
- Late 2000s
  - AMD-V, Intel VT-x, VT-d etc.
  - Turtles paper: Nested Virtualization revisited
- 2010s:
  - Multi-billion $ industry.
  - All cloud platforms are virtualized.

- But wait…the cycle may be turning back.
  - Bare-metal clouds
  - “Say Goodbye to Virtualization for a Safer Cloud”, HotCloud 2018

Definitions

- Virtualization is the application of the layering principle through enforced modularity, [whereby the exposed virtual resource is identical to the underlying physical resource being virtualized.]
- A virtual machine is an abstraction of a complete compute environment through the com- bined virtualization of the processor, memory, and I/O components of a computer.
- The hypervisor is a specialized piece of system software that manages and runs virtual ma- chines.
- The virtual machine monitor (VMM) refers to the portion of the hypervisor that focuses on the CPU and memory virtualization.

Forms of Virtualization



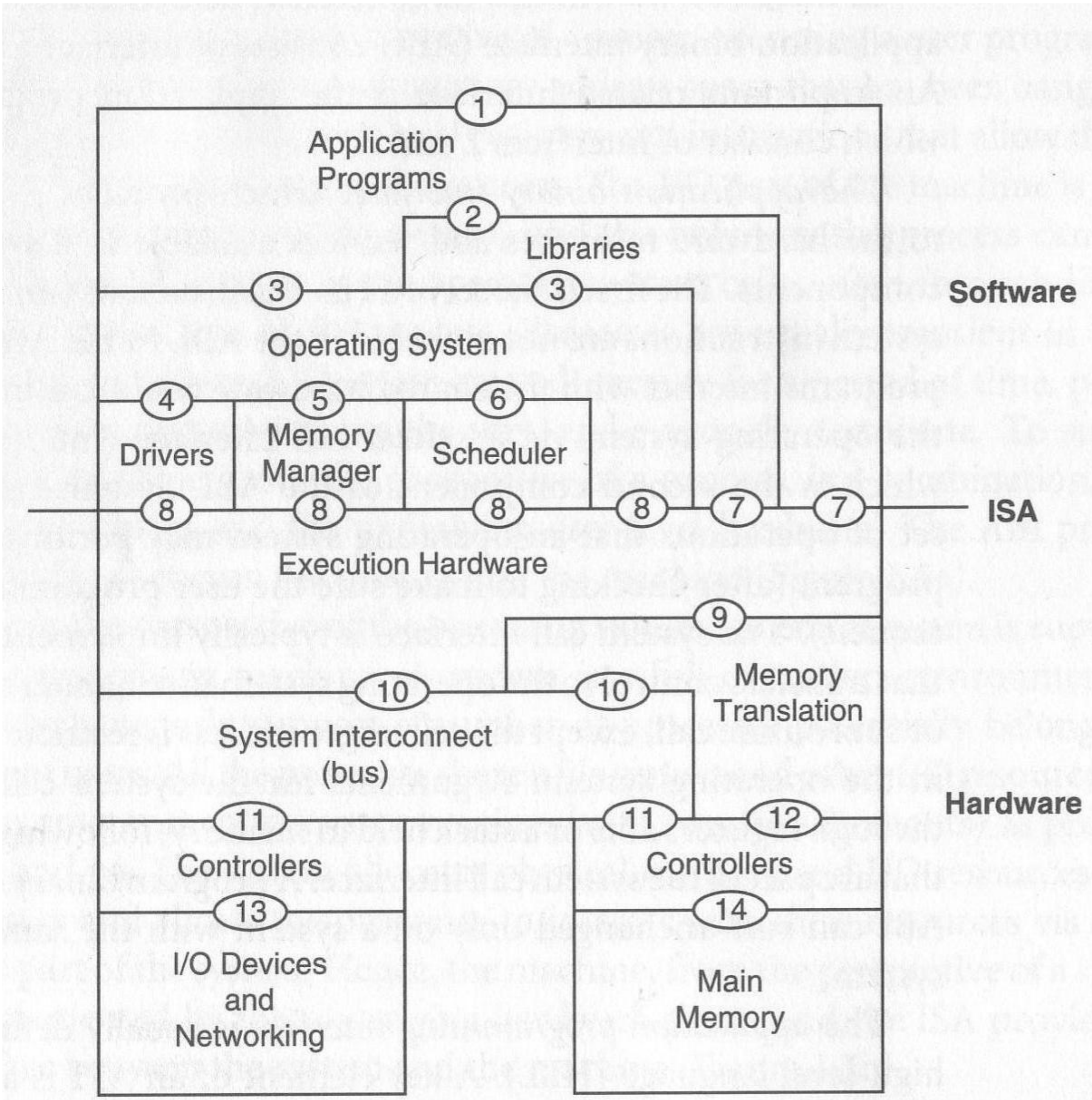
Note that the three are not mutually exclusive.

- Many-to-many virtualization
- Emulating many I/O devices on a single physical disk

Virtual Machines

- Logical/Emulated representations of full computing system environment
  - CPU + memory + I/O
  - Implemented by adding layers of software to the real machine to support the desired VM architecture.
- Uses:
  - Multiple OSes on one machine, including legacy OSes
  - Isolation
  - Enhanced security
  - Live migration of servers
  - Virtual environment for testing and development
  - Platform emulation
  - On-the-fly optimization
  - Realizing ISAs not found in physical machines

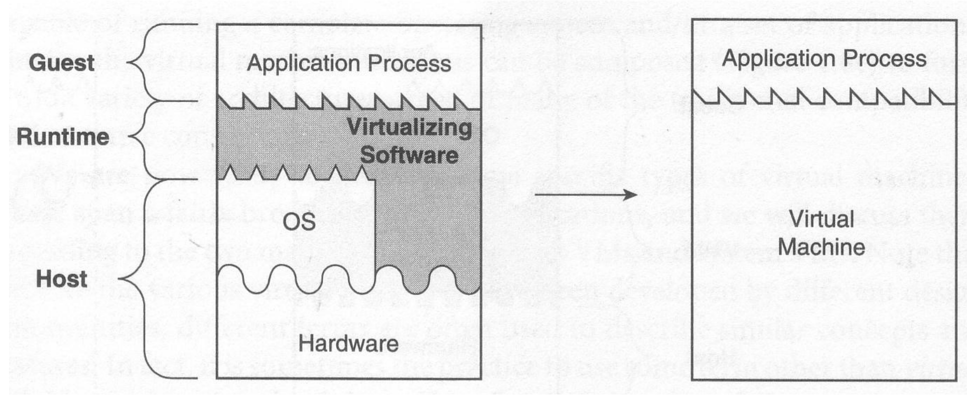
Interfaces of a computer system



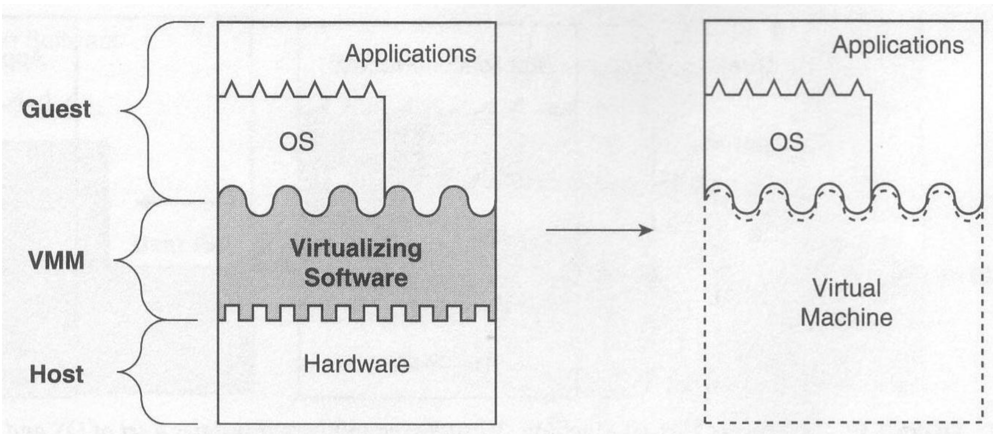
User ISA : 7
System ISA : 8
Syscalls : 3
ABI : 3, 7
API : 2,7

Two Types of VMs

- Process VM
  - Virtualizes the ABI
  - Virtualization software = Runtime
    - Runs in non-privileged mode (user space)
    - Performs binary translation.
  - Terminates when guest process terminates.

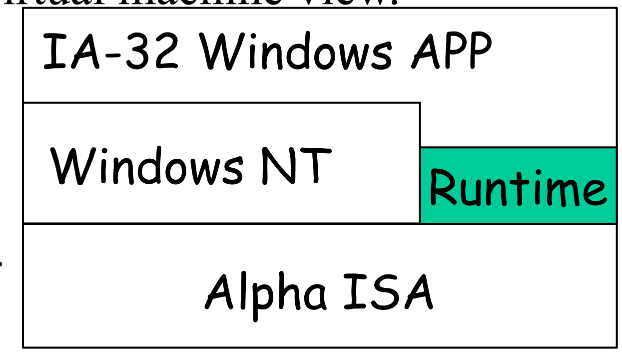


- System VM
  - Virtualizes the ISA
  - Virtualization software = Hypervisor
    - Runs in privileged mode
    - Traps and emulates privileged instructions
  - Lasts as long as physical host is alive



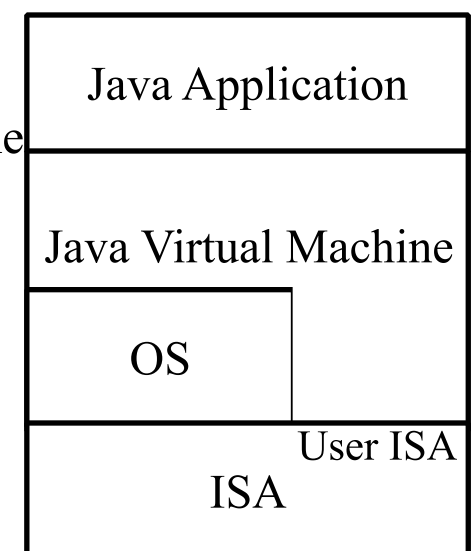
Process Virtual Machines

- Process in a multiprogramming OS
  - Standard OS syscall interface + instruction set
  - Multiple processes, each with its own address space and virtual machine view.
- Emulators
  - Support one ISA on hardware designed for another ISA
  - Interpreter:
    - Fetches, decodes and emulates individual instructions. Slow.
  - Dynamic Binary Translator:
    - Blocks of source instructions converted to target instructions.
    - Translated blocks cached to exploit locality.



Digital FX!32 Emulator

- Same ISA Binary Optimizers
  - Optimize code on the fly
  - Same as emulators except source and target ISAs are the same
- Language-based VMs
  - Virtual ISA (bytecode) designed for platform independence
  - Platform-dependent VM executes virtual ISA
  - E.g. Sun's JVM and Microsoft's CLI (part of .NET)
  - Both are stack-based VMs that run on register-based m/c.

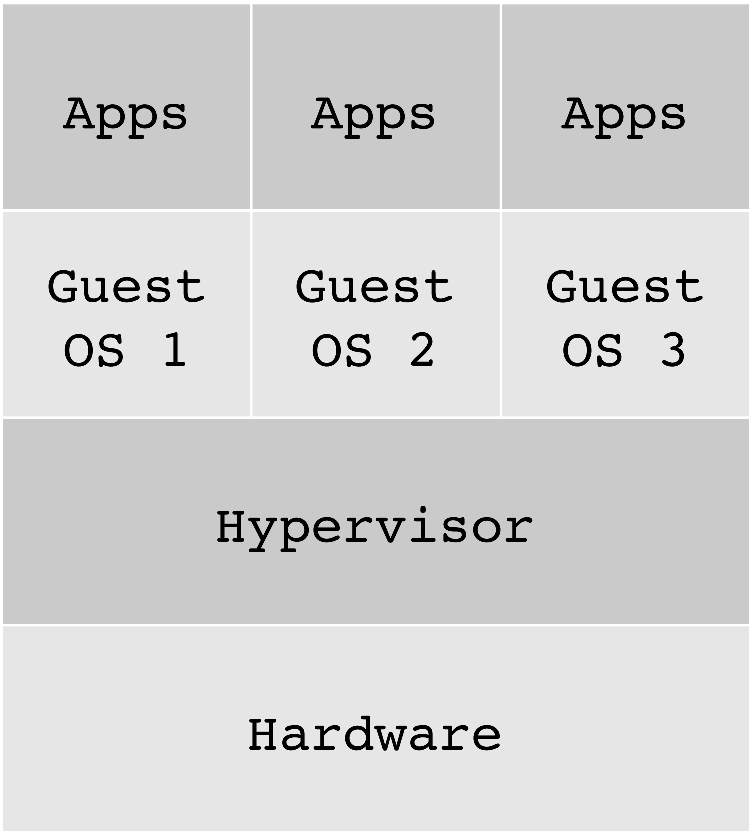


System Virtual Machines

(focus of this lecture)

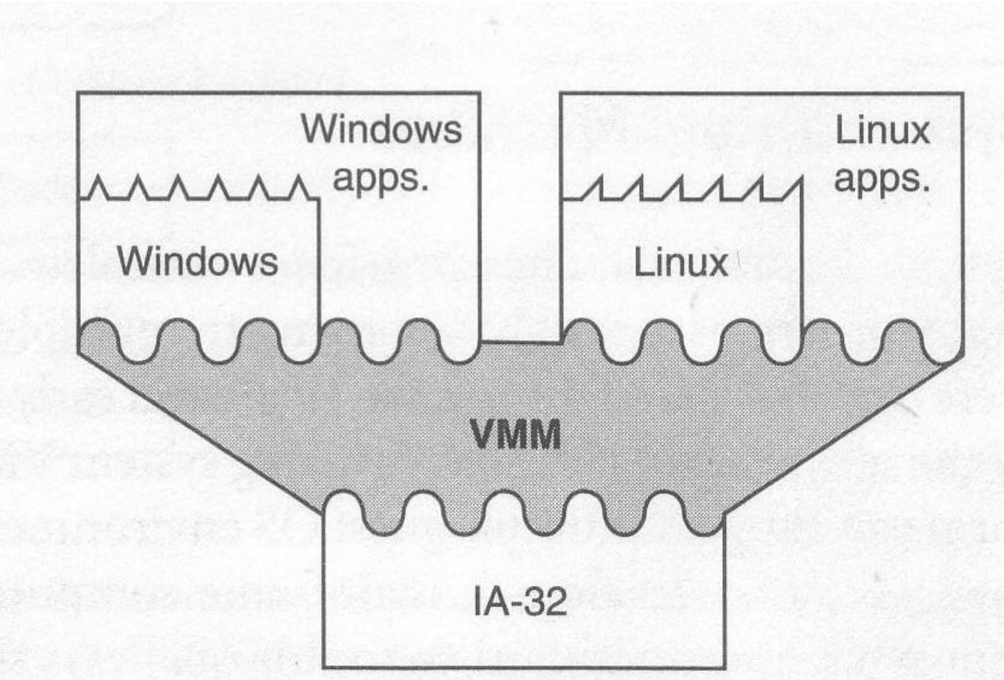
Hypervisor

- Also called Virtual Machine Monitor (VMM)
- A hypervisor is an operating system for operating systems
  - Provides a virtual execution environment for an entire OS and its applications
  - Controls access to hardware resources
  - When guest OS executes a privileged instruction, Hypervisor intercepts the instruction, checks for correctness and emulates the instruction.



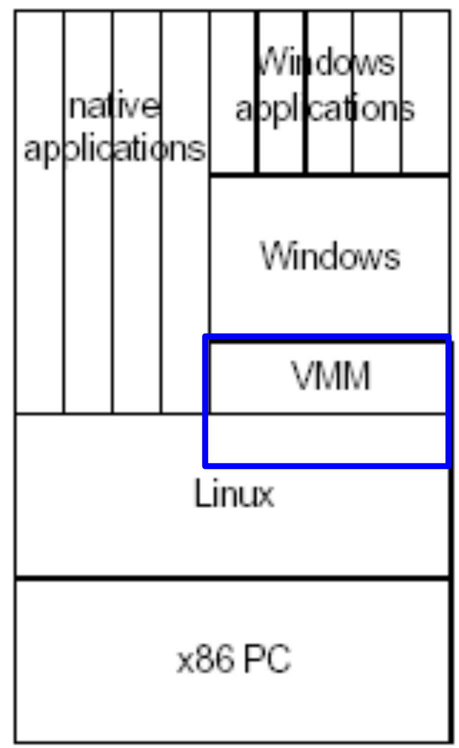
Type 1 Hypervisors (Classical System VMs)

- Hypervisor executes natively on the host ISA
- Hypervisor directly controls hardware and provides all device drivers
- Hypervisor emulates sensitive instructions executed by the Guest OS
- E.g. KVM and VMWare ESX Server



Type-2 Hypervisors (Hosted VMs)

- A host OS controls the hardware
- The Hypervisor runs partly in process space and partly in the host kernel
- Hypervisor Relies on host OS to provide drivers
- E.g. VMWare Desktop Client



Para-virtualized VMs

- ❑Modify guest OS for better performance

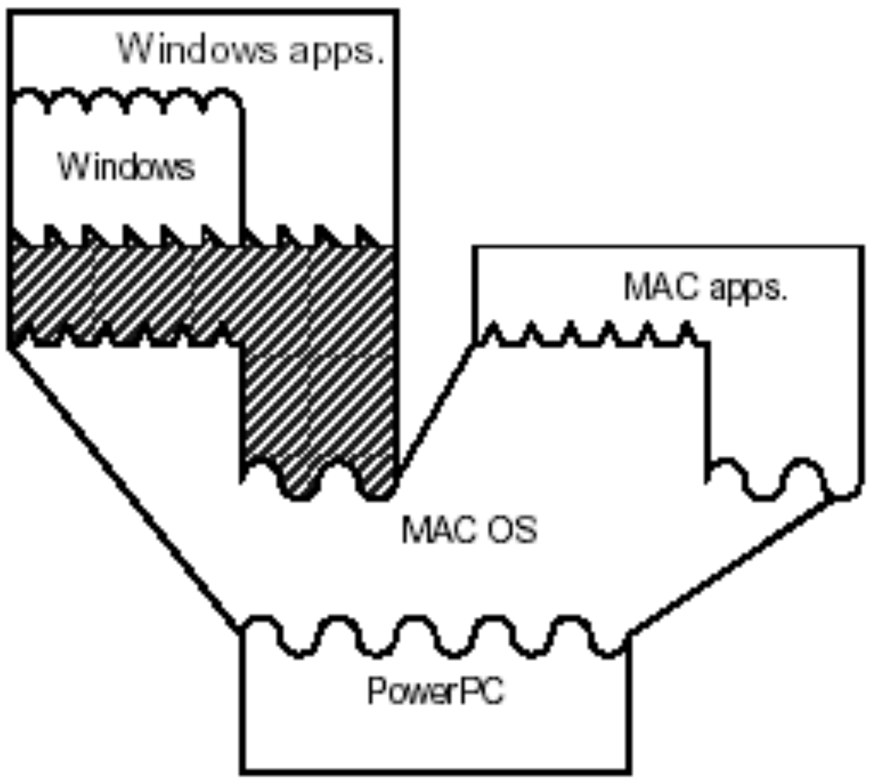
- ❑ Traditional Hypervisors provide full-virtualization
  - They expose to VMs virtual hardware that is functionally identical to the underlying physical hardware.
  - Advantage : allows unmodified guest OS to execute
  - Disadvantage: Sensitive instructions must be trapped and emulated by Hypervisor.
  - E.g. KVM and VMWare ESX provide full virtualization

- ❑ Para-virtualized VM
  - Sees a virtual hardware abstraction that is <u>similar, but not identical</u> to the real hardware.
  - Guest OS is modified to replace sensitive instructions with “hypercalls” to the Hypervisor.
  - Advantage: Results in lower performance overhead
  - Disadvantage: Needs modification to the guest OS.
  - E.g. Xen provides both para-virtual as well as full-virtualization

- ❑ Often traditional Hypervisors are partially para-virtualizated
  - ❑ Device drivers in guest OS may be para-virtualized whereas CPU and Memory may be fully virtualized.

Whole System VMs: Emulation

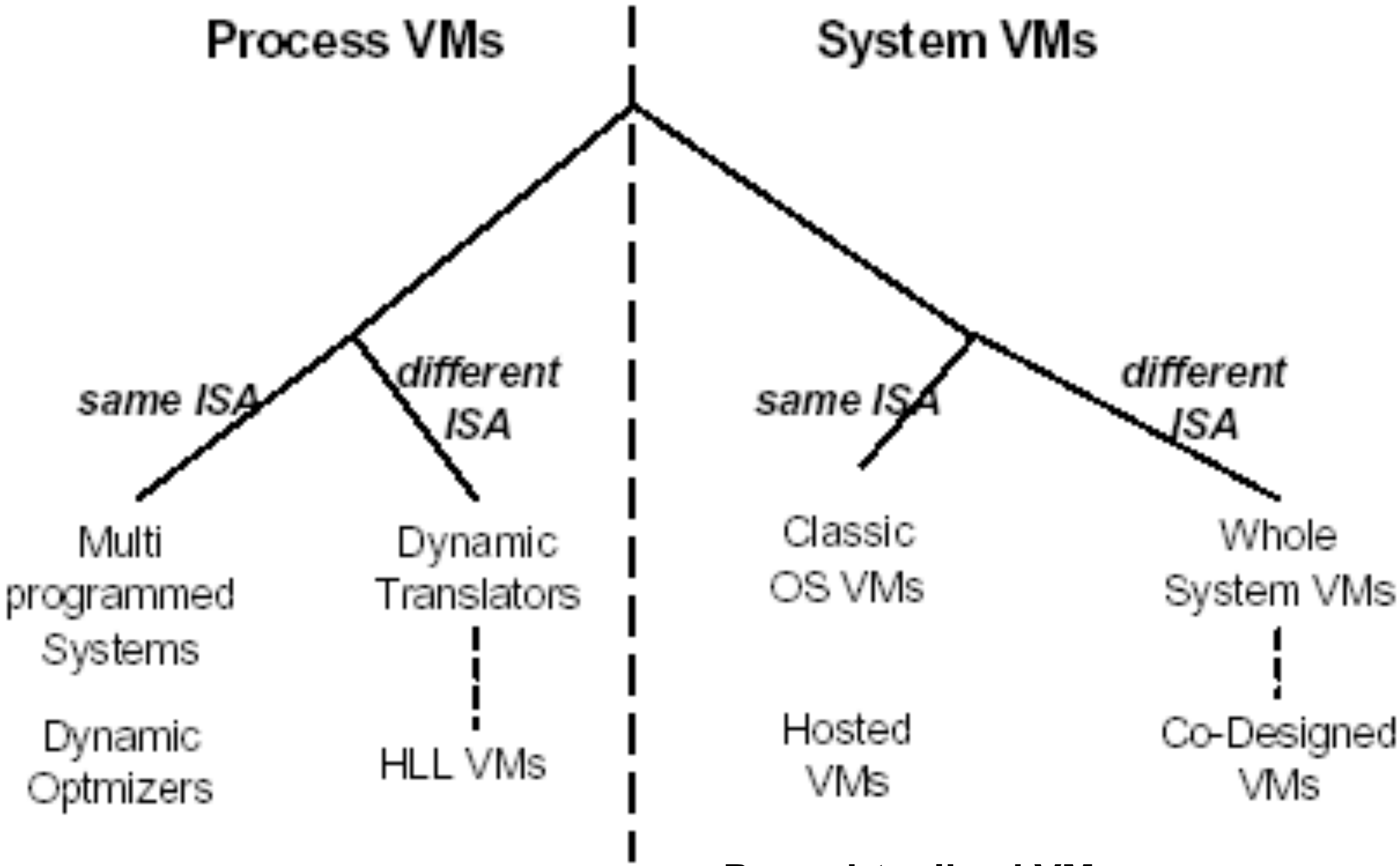
- Host and Guest ISA are different
- So emulation is required
- Hosted VM + emulation
- E.g. Virtual PC (Windows on MAC)



Co-designed VMs

- The hypervisor is designed closely with (and possibly built into) a specific type of hardware ISA (or native ISA).
- Goal: Performance improvement of existing ISA (or guest ISA) during runtime.
- Hypervisor performs Emulation from Guest ISA to Native ISA.
- E.g. Transmeta Crusoe
  - Native ISA based on VLIW
  - Guest ISA = x86
  - Goal power savings

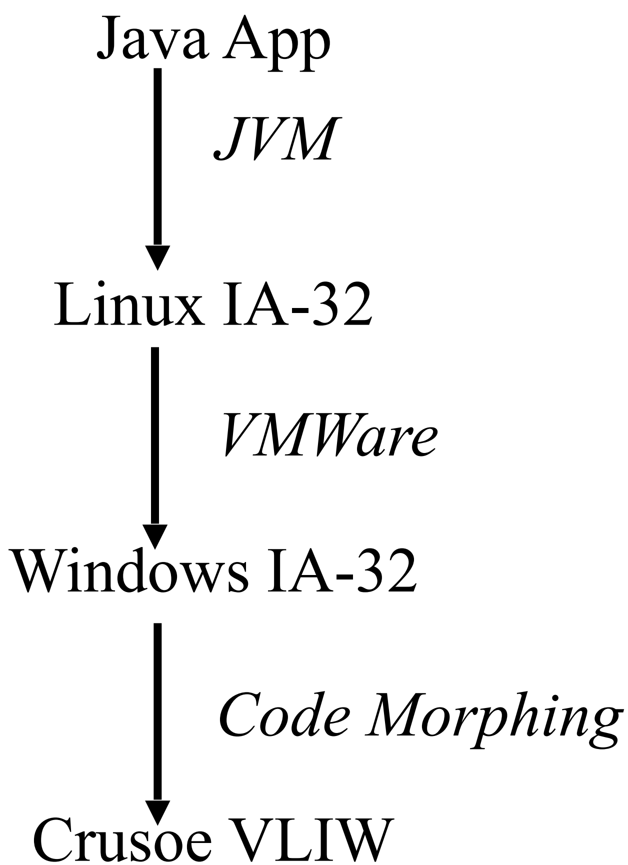
Taxonomy



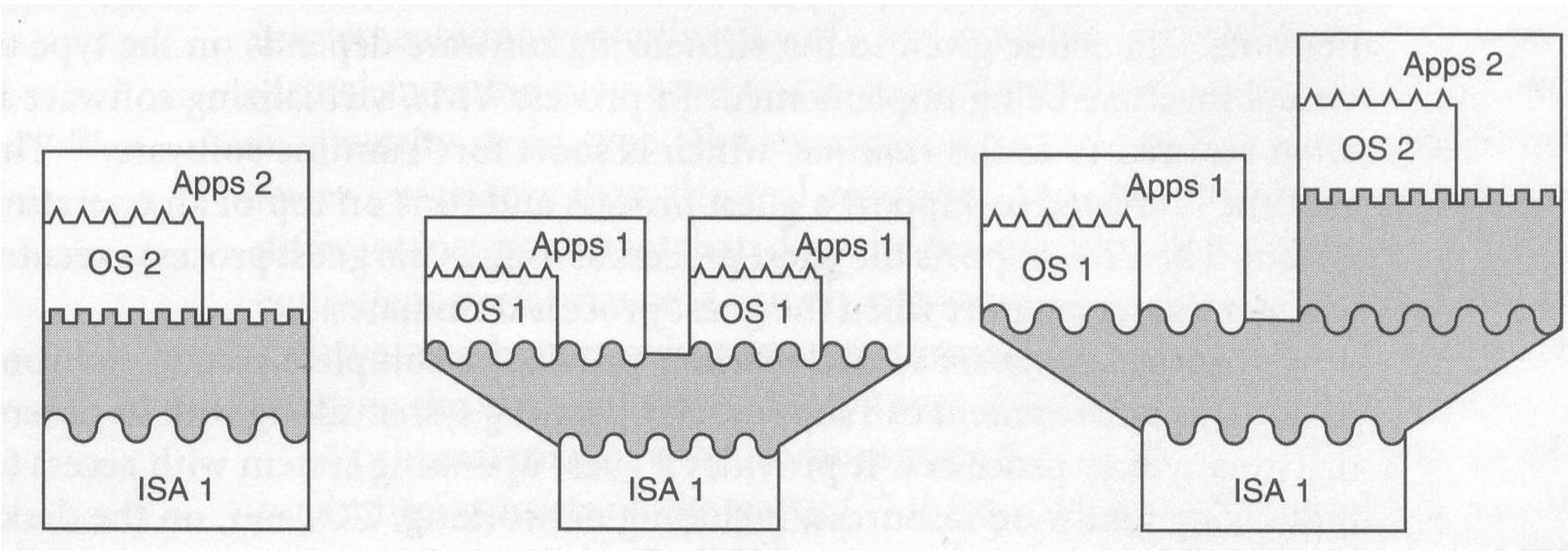
Para-virtualized VMs

Hardware Virtual Machines

Versatility



What can you do with system VMs?



Emulation & Optimization

Replication

Composition

- ❑ Emulation: Mix-and-match cross-platform portability
- ❑ Optimization: Usually done with emulation for platform-specific performance improvement
- ❑ Replication: Multiple VMs on single platform
- ❑ Composition: form more complex flexible systems

Virtualizing individual resources in System VMs

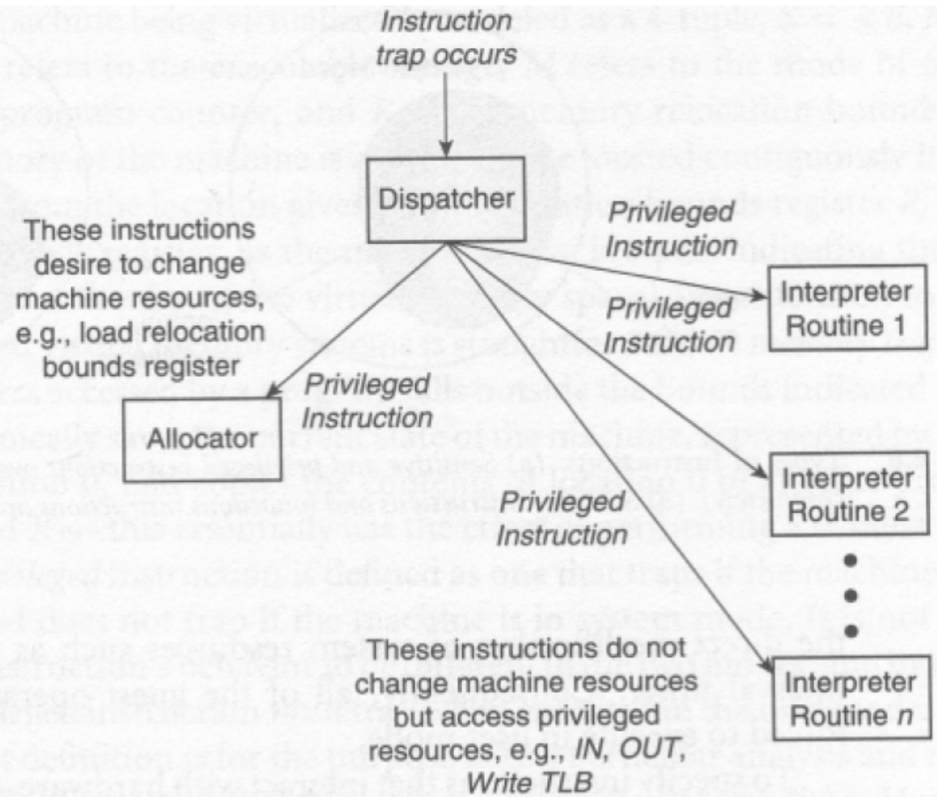
CPU Virtualization for VMs

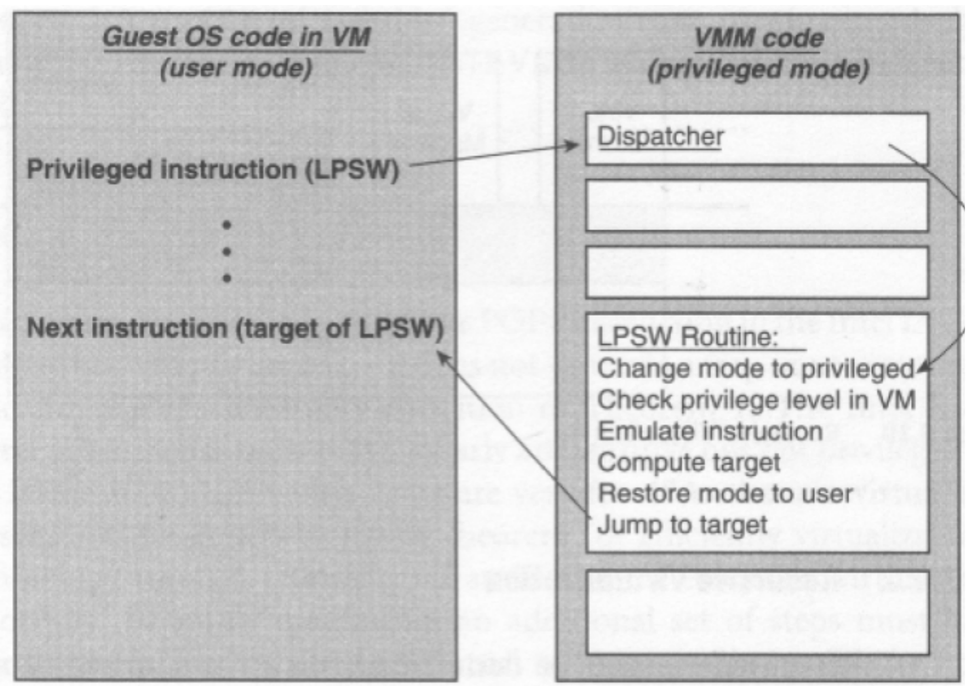
- Each VM sees a set of "virtual CPUs"
- Hypervisors must emulate privileged instructions issued by guest OS.
- Modern ISAs provide special interfaces for Hypervisors to run VMs
  - Intel provides the VTx interface
  - AMD provides the AMD-v interface

- These special ISA interfaces allow the Hypervisors to efficiently emulate privileged instructions executed by the guest OS.

- When guest OS executes a privileged instruction
  - Hardware traps the instruction to the hypervisor
  - Hypervisor checks whether instruction must be emulated.
  - If so, Hypervisor reproduces the effect of the privileged operation.

Execution of Privileged Instruction by Guest





Resource Control

- Issue: How to retain control of resources in the Hypervisor?
- Timer interval control performed by Hypervisor
- Also, guest OS is not allowed to read the timer value
  - Guest OS sees a virtual interval timer
- Hypervisor also gains control whenever guest OS executes privileged instructions.

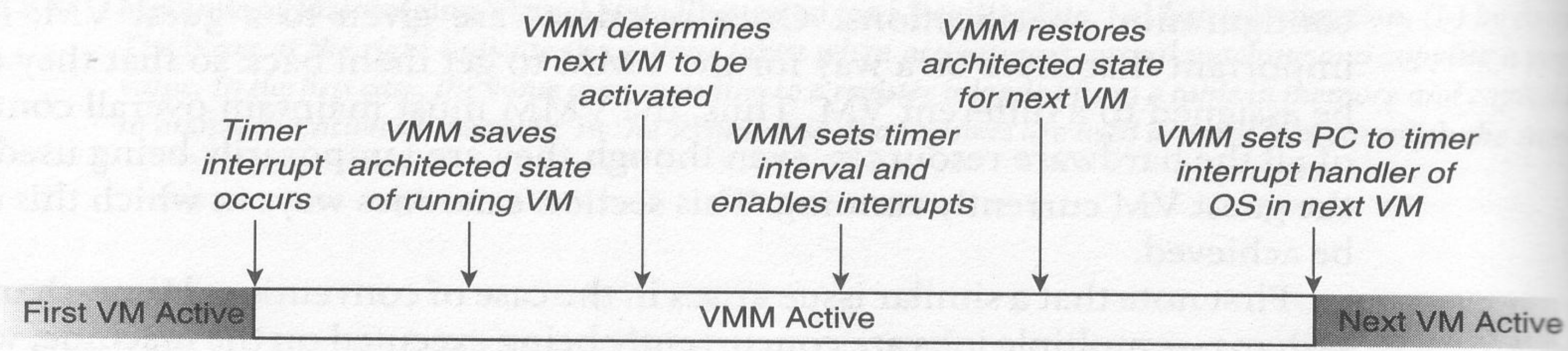
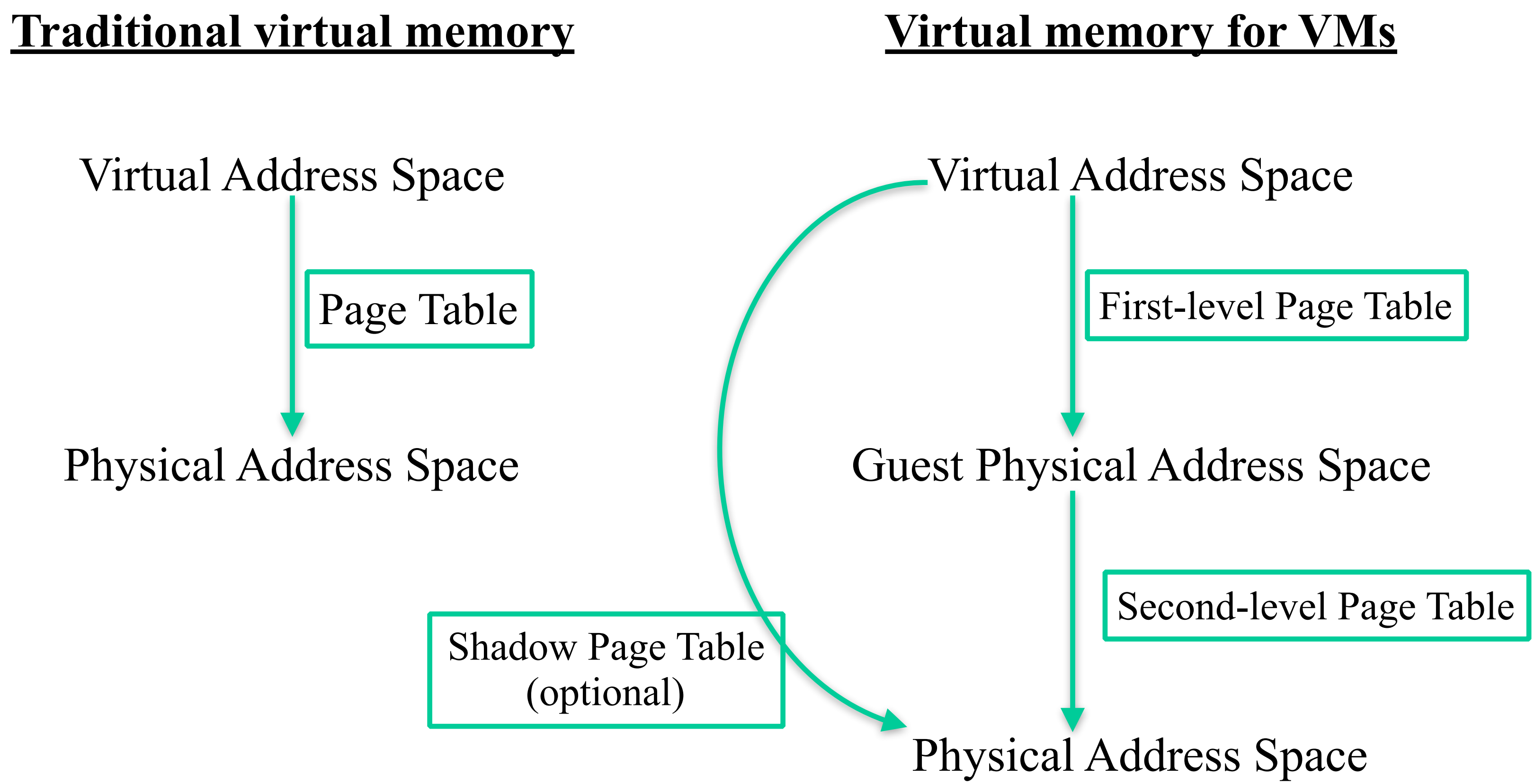


Figure 8.4 Actions Taken by the VMM in Retiring One Virtual Machine and Activating the Next Virtual Machine

Memory Virtualization for VMs



- Guest OS in each VM sees a "guest"-physical address (GPA) space instead of the physical addresses
- Often hardware supports two-level page tables
  - EPT in Intel VT-x and NPT in AMD-v
- When hardware doesn't, then Hypervisor needs to emulate two-level page tables using "shadow page tables".

I/O Virtualization for VMs

- Hypervisor provides a virtual version of each physical device
- I/O activity directed at the virtual device is trapped by Hypervisor and converted to equivalent request for the physical device.
- Options:
    - Device emulation
        - Hypervisor traps and emulates each I/O instruction from Guest in Hypervisor.
        - Very slow.
        - Difficult to emulate the effect of combinations of I/O instructions.
    - Para-virtual devices
        - Special device drivers inserted in guest OS to talk to Hypervisor.
        - Most common.
    - Direct device access
        - Allow the VM to directly access physical device.
        - Fastest option but not scalable.
        - Requires IOMMU and VT-d support from hardware.