Lecture 19: Virtualization

CS343 – Operating Systems

Branden Ghena – Fall 2020

Some slides borrowed from:
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Today’s Goals

- Explore notion of a “virtual machine” and how to virtualize computers.

- Understand challenges and tradeoffs for several approaches
  - Emulation
  - Hypervisors
  - Containers

Outline

- **Virtualization**

- Approaches
  - Emulation
  - Hypervisors
  - Containers

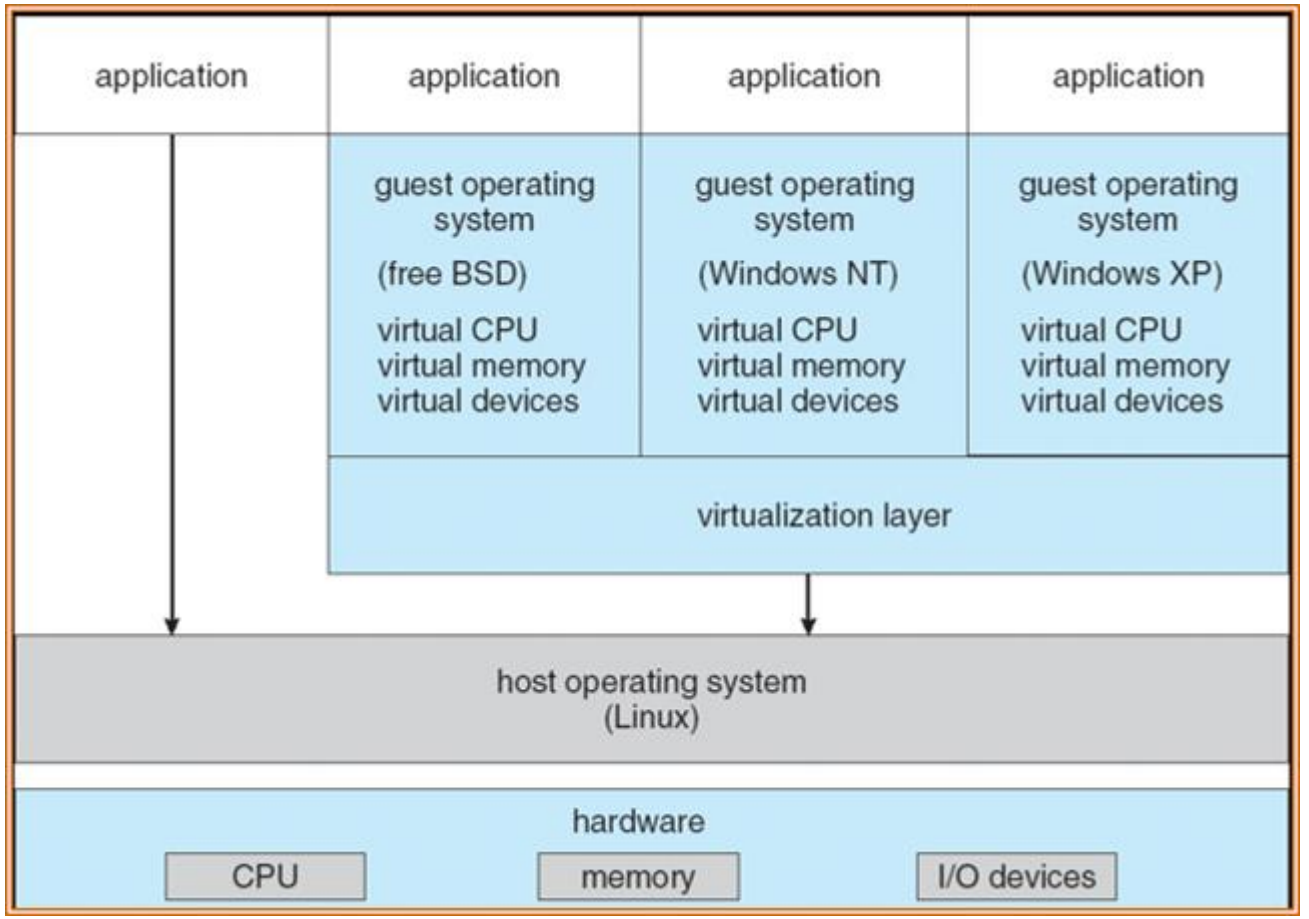
Virtualization

- Virtual versions of real resources are used for protection and limitation
  - Memory – virtual memory
  - CPU – processes and scheduler
  - Disk – files

- OS provides these abstractions to simplify applications
  - And provide security

Virtual Machines

- What about virtualizing the whole computer?
  - Provide interfaces that look like a normal computer
  - But actually interact with software that manages and multiplexes access
- Run an entire OS within an OS



Original motivation: support more applications

- 1960s IBM mainframes had many different OSes
  - But likely only a few or just one mainframe
  - Some applications only written for certain OSes though

- Virtualization allowed multiple OSes to run on a single mainframe
  - Which let one powerful computer serve varied needs of many people

- Still applies today to some degree
  - I have a single desktop machine
  - Run Windows and an Ubuntu VM
    - Want PowerPoint and also terminal environment (vim/make/gcc)
  - Not really a general need for non-developers though

Modern motivation: package and isolate applications

- High-performance applications aren't really stand-alone
  - Assumptions about OS
  - Assumptions about libraries and services
  - Multiple processes working together

- A virtual machine is a method to encapsulate "entire stack"
  - Even down to expectations of hardware

- Cloud computing platforms run many applications together
  - Need isolation from each other in a strongly controllable way
    - Exactly 2 GB of RAM go to this
    - Exactly two processor cores go to that

Virtualization approaches

- Simulate everything in the computer completely
  - Emulation
- Simulate parts of the computer, but not all of it (really use CPU)
  - Hypervisor
- Simulate the operating system (software environment)
  - Containers

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Software emulation

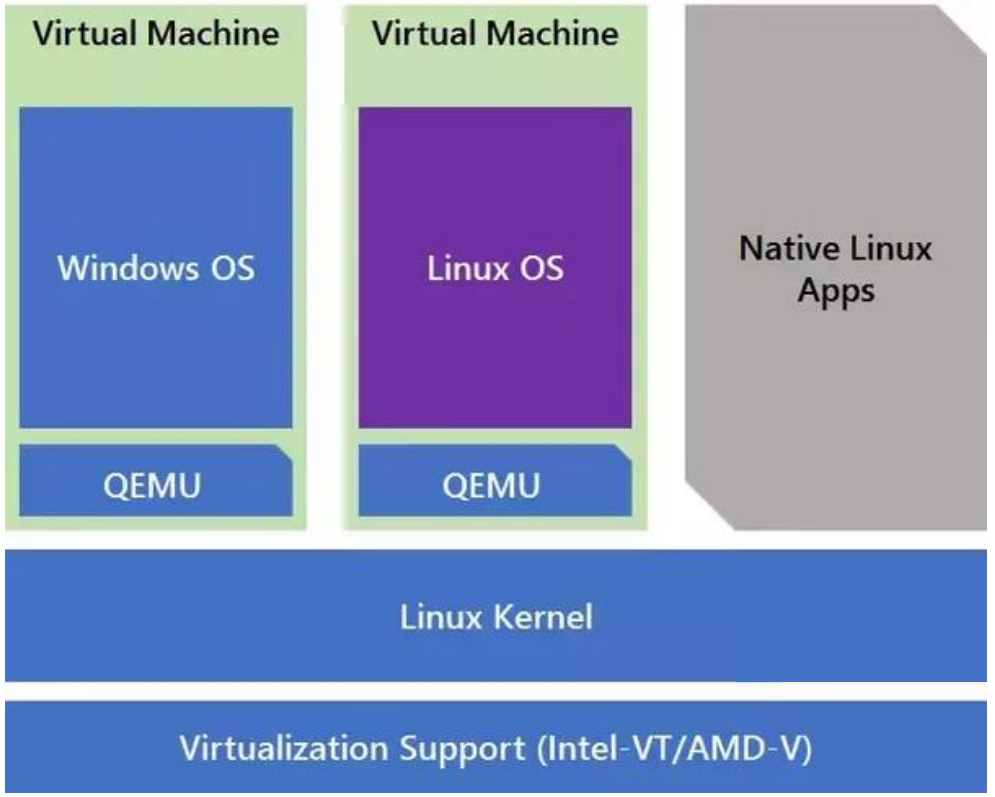
- User software emulates the behavior of every single instruction
  - Data structures for Processor, Memory, I/O, etc.
  - Code for Instruction Cycle:
    - Fetch next instruction
    - Decode
    - Perform operation
    - Update state

Real emulation: QEMU

- We have been using QEMU for lab to simulate an x86-64 computer
  - 2 CPU cores
  - 2 GB of RAM
  - Virtio GPU
  - PS/2 mouse and keyboard
  - 2 PCI IDE interfaces with hard disk and CD-ROM support
    - nautilus.iso connected to CD-ROM
  - Floppy disk
  - PCI and ISA network adapters
  - Serial and parallel ports
    - stdio connected to serial port
    - file parport.out connected to parallel port
  - Intel HD Audio Controller and HDA codec
  - PCI UHCI, OHCI, EHCI or XHCI USB controller and a virtual USB-1.1 hub

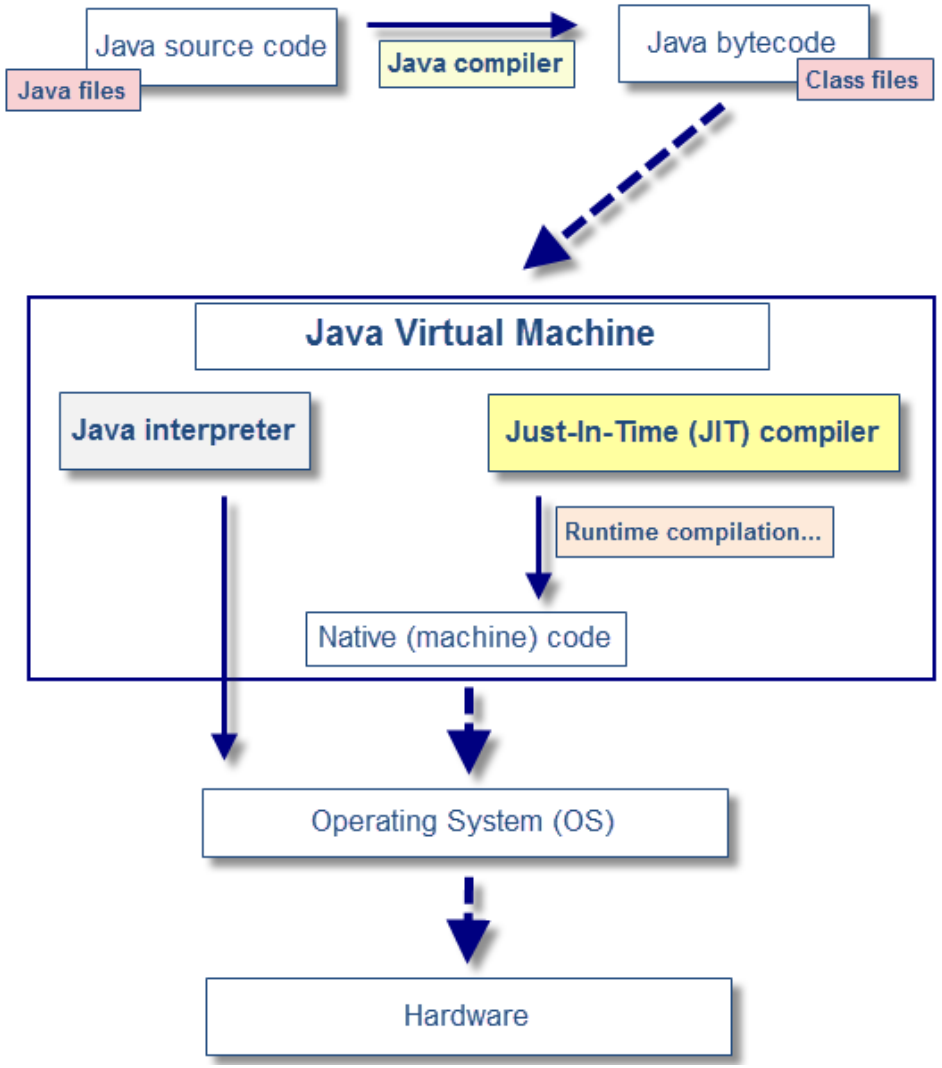
Emulation tradeoffs

- Upsides
  - Any hardware you want
  - Entirely in userspace
- Downside
  - Slower than real hardware by definition



Simple emulators: interpreted languages

- Create a simple environment for code to execute within
- Interpret code instructions (bytecode or lines of code) and perform actions
  - Example: fakes a machine that executes Java bytecode
- Still ties in to many parts of the real machine
  - Filesystem
  - Devices



Not-quite-emulation: binary translation

- ARM on Mac
  - Switching to ARM processor with ARM instruction set
  - Old programs were compiled for x86-64 instruction set
- Solution: translate assembly instructions
  - Can be translated in advance
  - Or just-in-time (JIT)
  - Works fine for applications that are I/O bound
- Simulates a different CPU, but leaves the remainder of the computer the same

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How do we speed up virtual machines?

"Efficiency … demands that a statistically dominant subset of the virtual processor's instructions be executed directly by the real processor, with no software intervention…"

—Popek and Goldberg, 1974

- Need to use some parts of the computer for real while simulating other parts

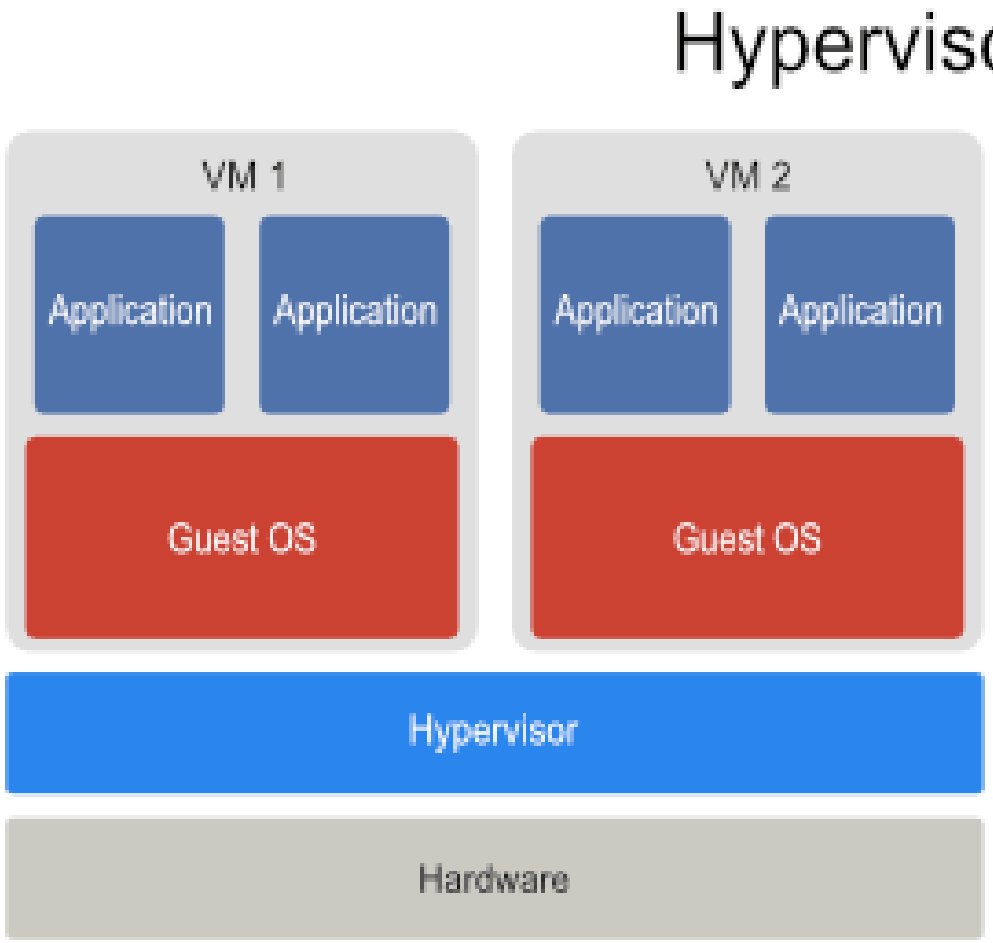
Virtual Machine Monitor (VMM)

- Also known as hypervisors
  - OS kernel is the system "supervisor" and manages the computer
  - Hypervisor manages supervisors

- Creates the illusion that the OS has full control over the hardware
  - And even gives real (limited) access to hardware whenever possible
  - But may actually be sharing full computer resources among several OSes

- Probably what you had in mind as virtual machines
  - VirtualBox, VMWare, Parallels

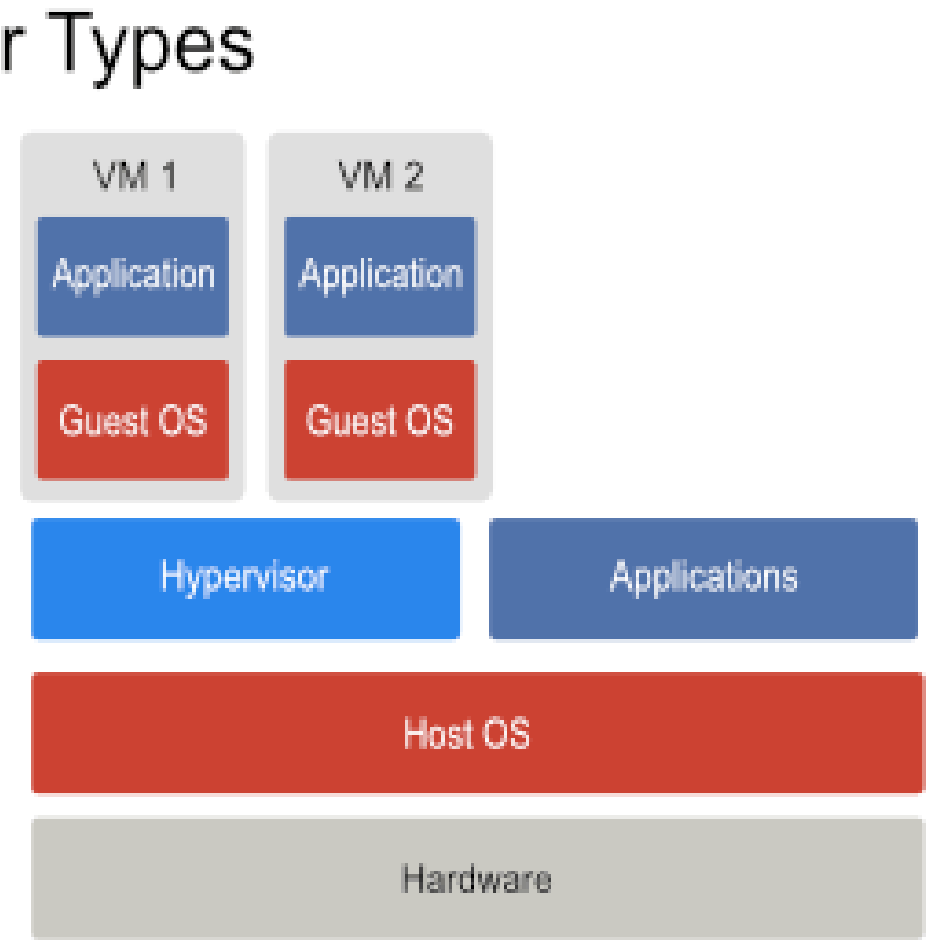
Hypervisor layering



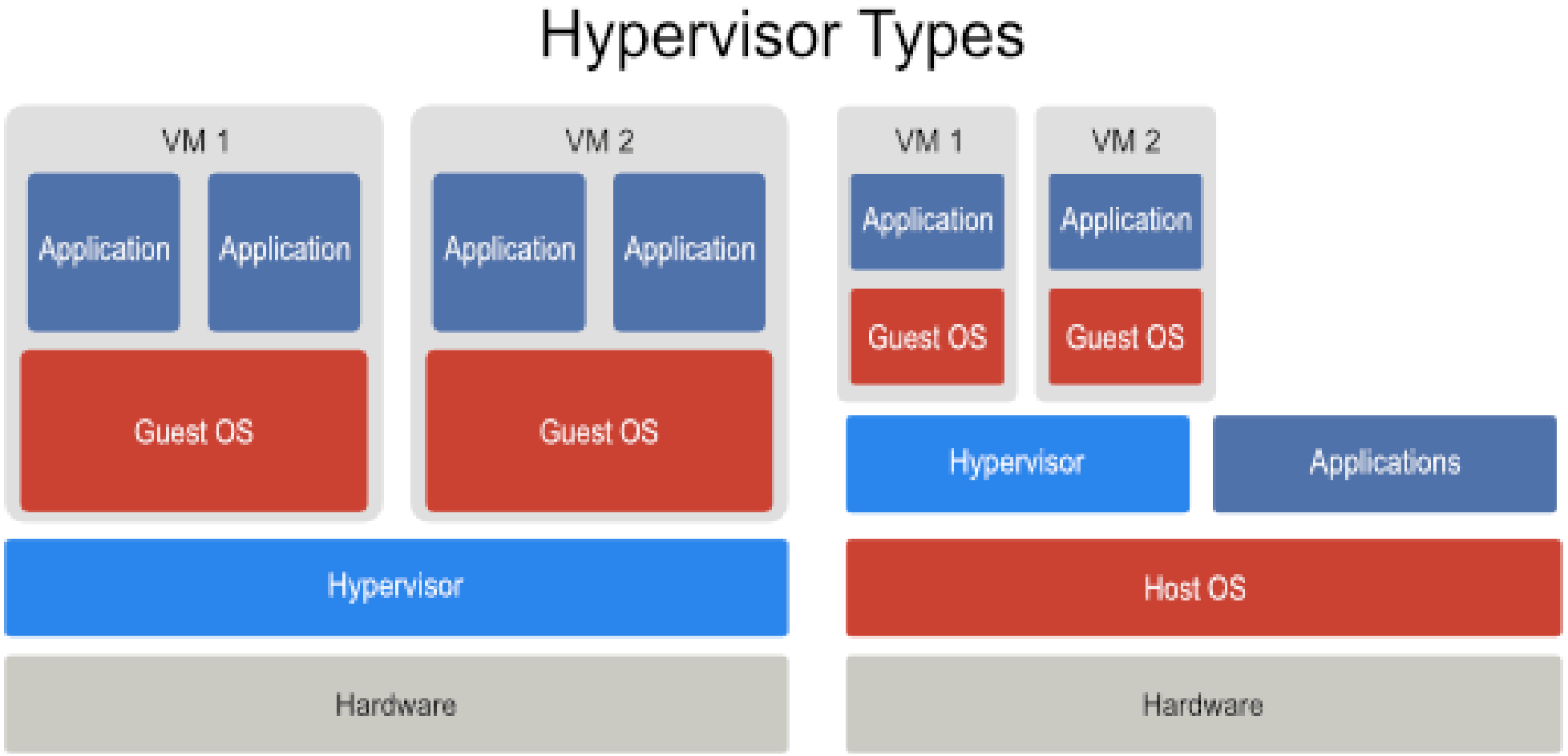
- Hypervisor manages hardware directly
- All operating systems run on top of it
  - "Guest OS" as in it isn't actually in charge of the computer

Hypervisor layering

- Normal operating system runs on hardware
  - Known as "Host OS"
- Hypervisor runs on top of host and coordinates with it to enable interactions with hardware
  - Some coordination may be within the kernel itself



Hypervisor layering

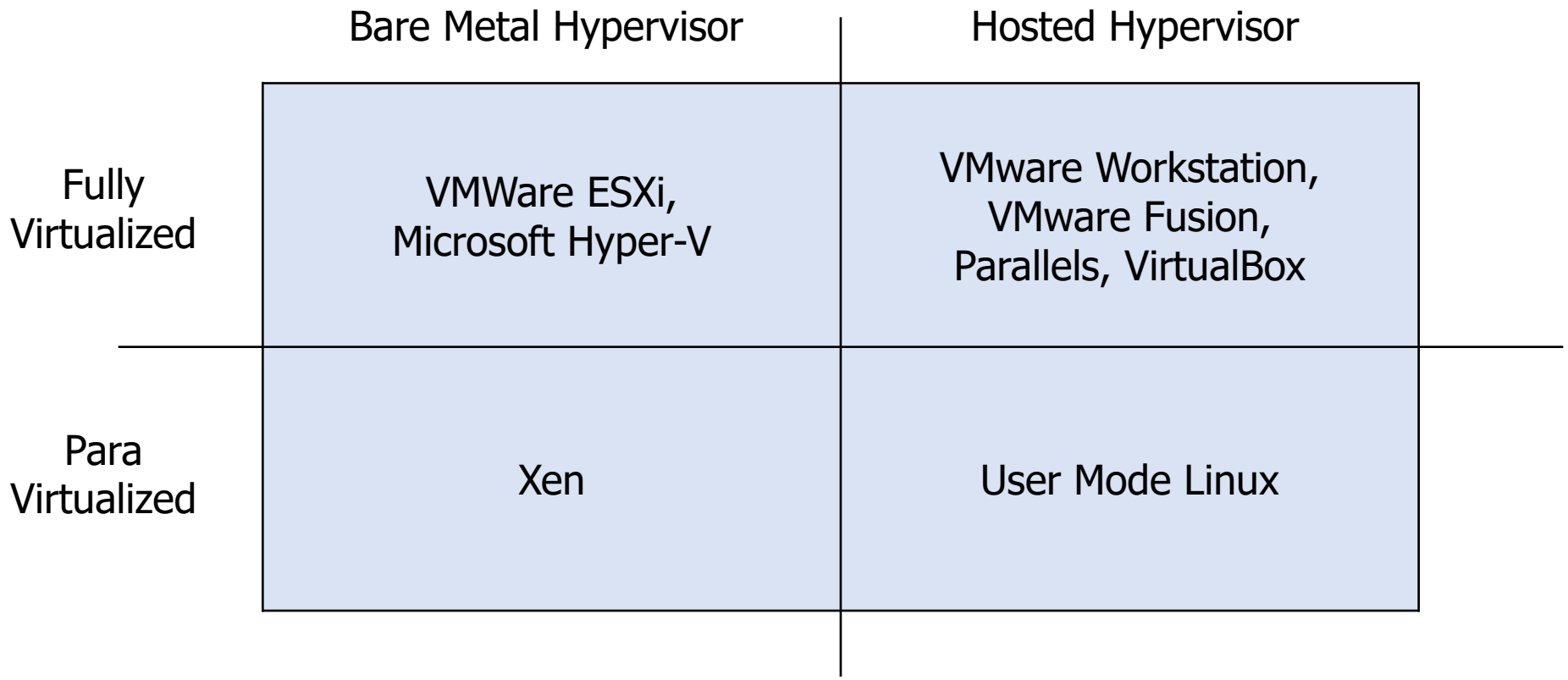


Abstraction choices for hypervisor

- Fully virtualizing hypervisor
  - Virtual machine looks exactly like a physical machine
    - Though not necessarily the same machine it's running on
  - Guest OS does not need to be modified in any way
  - Guest May not even be aware it's running virtually

- Para-virtualizing hypervisor
  - Guest OS has extensions to cooperate with hypervisor
  - Sacrifice transparency for better performance
    - Same abstraction-breaking ideal from previous lectures
  - Might include an API to interact with hypervisor

Arbitrary combinations of these are possible



Hypervisor example: system call

Process	Guest OS	Hypervisor
1. System call: trap to OS		
		2. Receive trap. Call guest OS trap handler
	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		

Hypervisor challenges: privileged instructions

- The guest OS is going to run privileged instructions
  - Scheduling threads, editing page tables, modifying interrupt state
- Cannot let it have full control over the hardware
  - Otherwise it really isn't a "guest" and host might never regain control
- Solution: trap into hypervisor
  - Bare metal: Illegal instruction fault goes directly to hypervisor
  - Hosted: Illegal instruction fault in host OS passed to hypervisor
    - Which can actually do something to handle it!!

Problem: x86 doesn’t virtualize very well

- CPU architecture is virtualizable only if sensitive instructions always trap if run in user mode
- Historically, x86 does not guarantee this
  - Some instructions behave differently in user mode
  - For example: some instructions have no effect when run in user mode
- One solution: binary translation
  - Find all unacceptable instructions in the OS binary (possibly at runtime)
  - Replace with different instructions that trap to hypervisor
    - Which will perform the originally desired operations

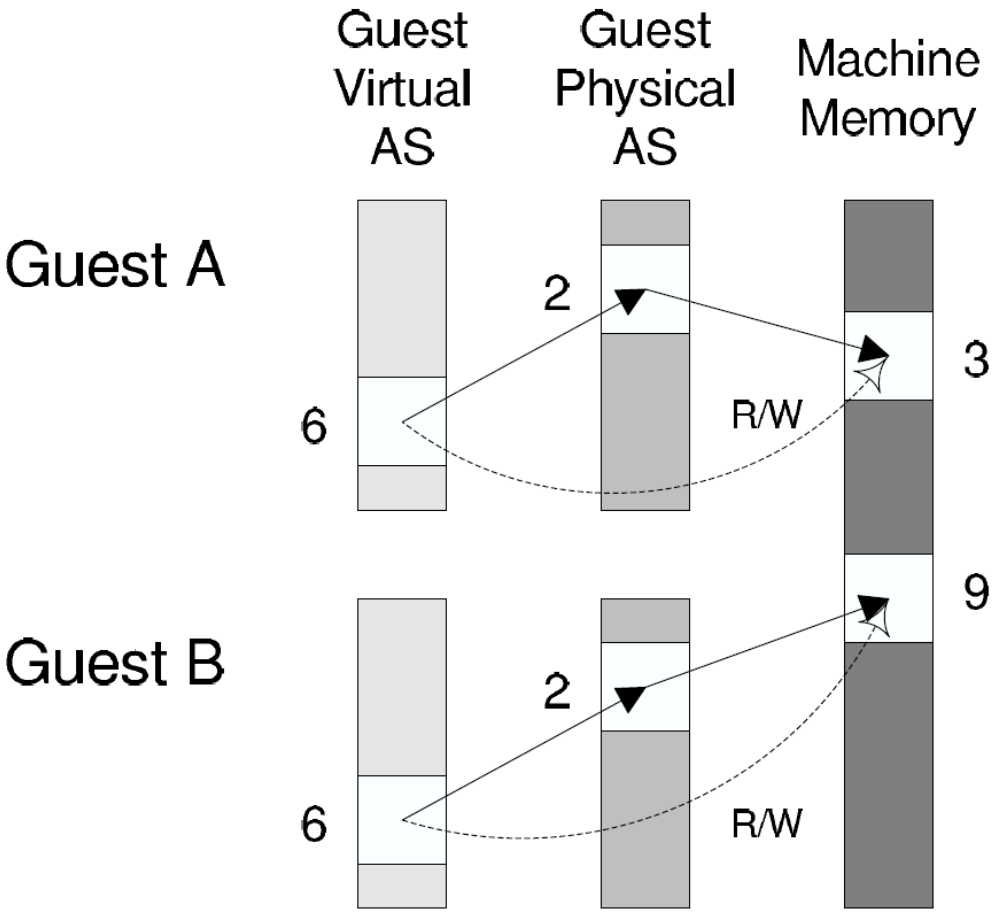
Virtualization extensions to x86

- Intel VT and AMD-V
  - Extensions to instruction set architecture to enable virtualization
  - Fix virtualization problems
  - Also speed up virtualization performance by requiring less trapping

- VM Entry/Exit
  - Swap out Virtual Machine Control Structure (VMCS) that specifies OS state
    - Registers, Address Space, Executing Threads
  - Example optimization: Virtual Processor ID in TLB entries
    - Allows Guest OS and Host OS to share a TLB

Hypervisor challenges: Memory virtualization

- Guest OS maintains its own page tables, mapping virtual to physical memory
  - But the guest itself is running in virtual memory
- Hypervisor maintains "shadow page tables" that map Guest memory pages to actual memory pages
  - Guest modifications to page tables trap to hypervisor that modifies its own tables accordingly
- Virtual extensions can do this double-translation in hardware



Hypervisor challenge: I/O devices

- Difficult to replicate all the different drivers that can exist in a kernel in the hypervisor

- One solution: leverage host OS drivers
  - Present virtual I/O devices to guest OS
  - Guest interacts with virtual I/O through its own device driver
  - Calls get sent to hypervisor, which makes appropriate calls to host drivers

Check your understanding – VirtualBox on ARM Mac

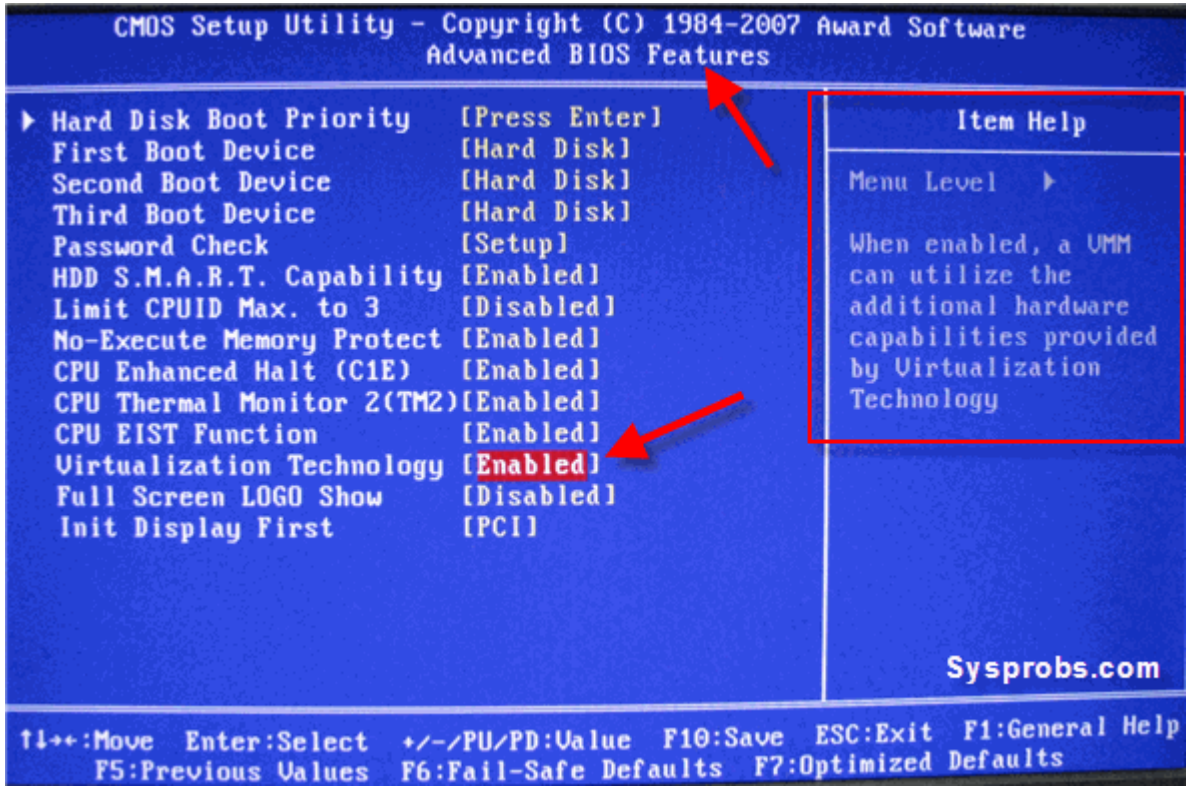
- Will VirtualBox work on the new ARM Macs?
  - Will the program run as-is?
  - What architecture will the guest OS need to be?
  - Could students run CS213 labs in it?

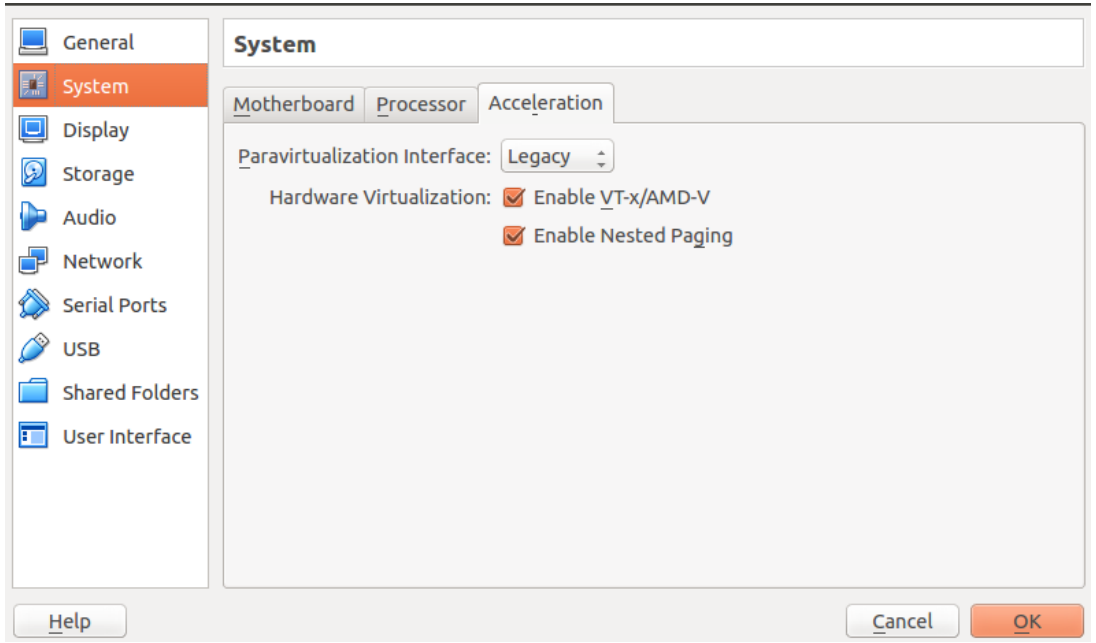
Check your understanding – VirtualBox on ARM Mac

- Will VirtualBox work on the new ARM Macs?
  - Will the program run as-is?
    - No. Currently compiled for x86-64. Needs to be recompiled. But it probably has a bunch of hardware-specific code that needs to be rewritten too… (VirtualBox says they won't be supporting ARM)
  - What architecture will the guest OS need to be?
    - ARM. VirtualBox is a hypervisor that runs code on the actual processor.
    - Windows and Linux do have some ARM support…
  - Could students run CS213 labs in it?
    - Not really… Any x86-64 specific stuff won't work.

Sidebar: virtualization extensions often disabled by default

- Most users will never have a need for them
  - And developers can probably figure out BIOS settings





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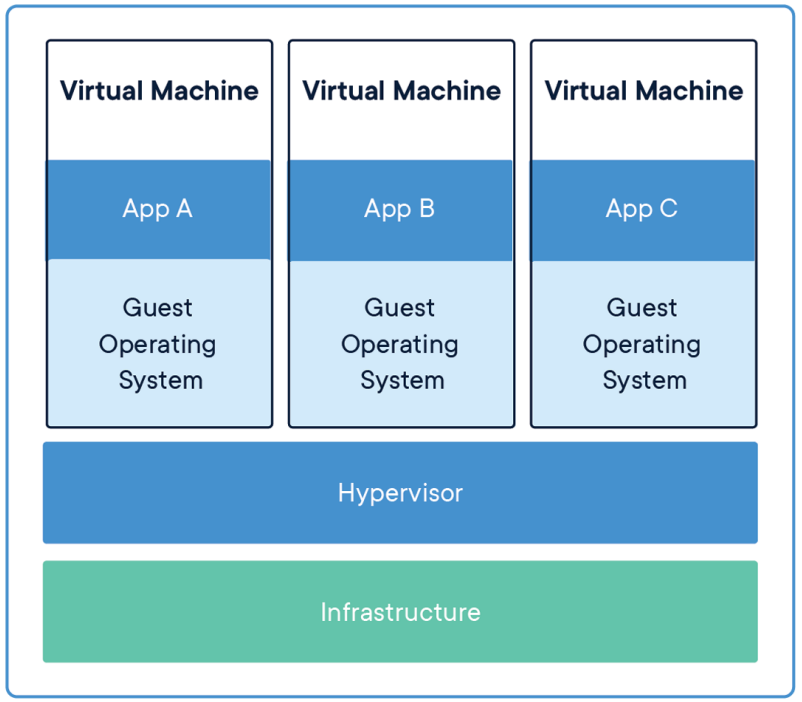
Cloud platform requirements

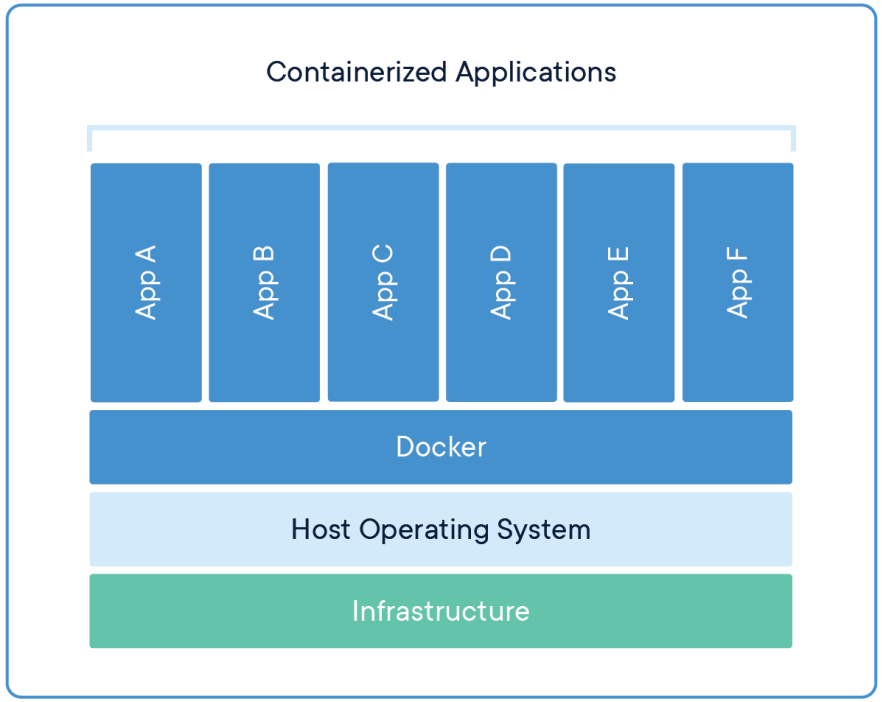
- May want to provide multiple OSes, but can do so with multiple physical machines

- Really want encapsulation and isolation
  - Encapsulation
    - Include particular shared libraries that application needs
    - Without interfering with other applications on system
  - Isolation
    - Guarantee certain processing and memory allocations to each application
    - Limit visibility into the filesystem (without overhead of partition per app)

Containers

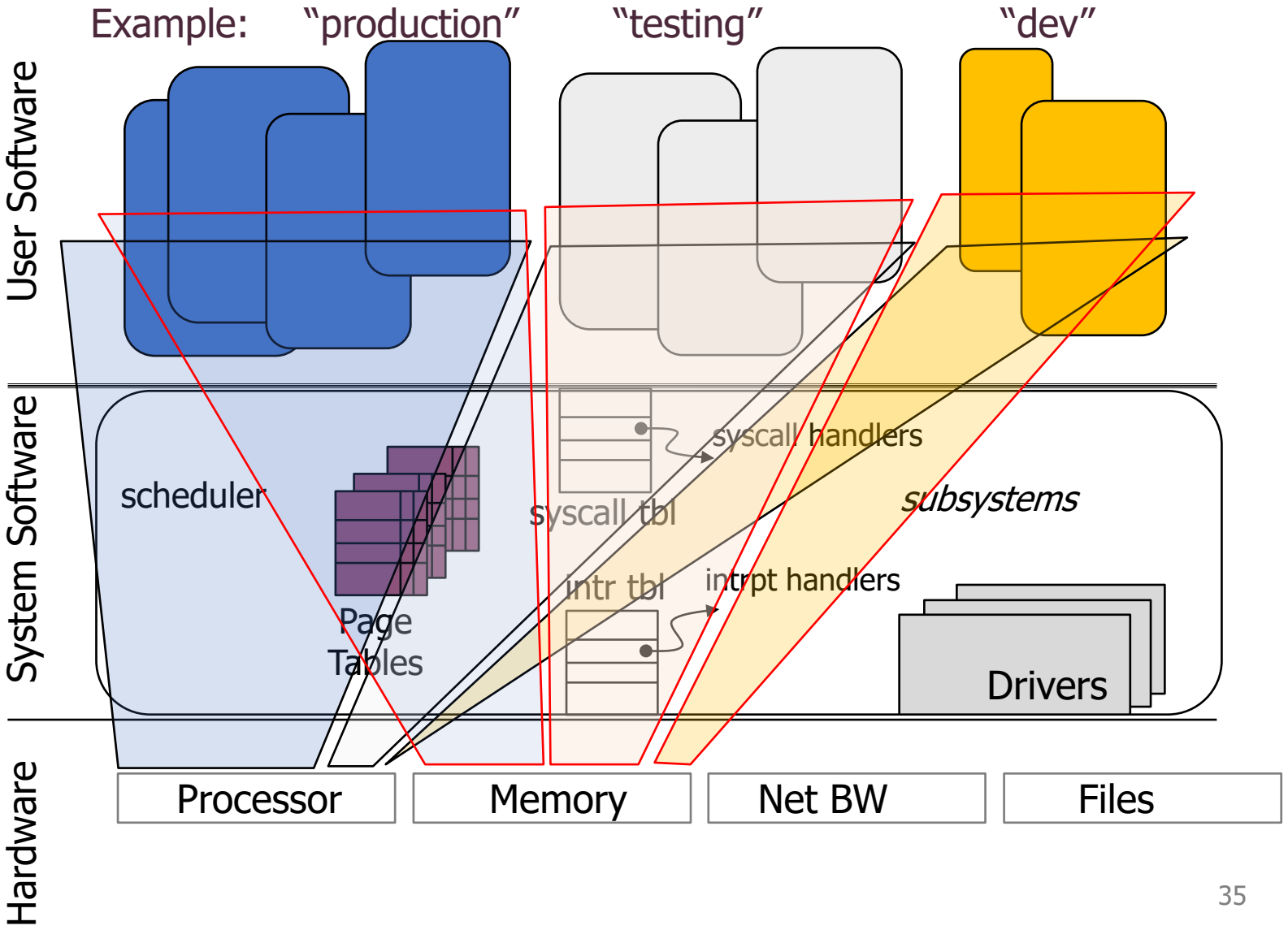
- Provide each guest with illusion of its own dedicated OS
  - Isolated resources: processor and memory
  - Isolated namespace: PIDs, network, filesystem
  - Including only the binaries and libraries it needs





Linux cgroups (control groups)

- Collection of processes treated as a group for resource allocation
- Provider greater performance isolation between cgroups than between processes



Cgroups can be used to build containers

- Devices can be connected or denied to a cgroup
  - Cgroup processes will not be able to detect device at all

- Accounting can be done on cgroup usage
  - Memory, CPU, disk I/O

Docker

- Container packaging, distribution, and execution
  - Also created open standard for container runtimes
- Images
  - Describes starting state of a Docker container
  - Like a snapshot of the system
- Union file system
  - Image describes file system as a sequence of layers
    - Each layer includes some files
  - Overall file system is the *union* of all the layers
  - Layers can be reused in different images

Docker use cases

- Environments are hard to set up
  - Often the hardest part of starting software development
  - Containerized applications encapsulate requirements
  - Can be run on any system that has the same kernel it was built for

- Packages an application and its requirements into a container
  - Can be used by an individual to more easily run an application
  - Can be deployed to a cloud server to run

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