

Lecture 18: Virtualization

CS343 – Operating Systems
Branden Ghen a – Fall 2024

Some slides borrowed from:

Jaswinder Pal Singh (Princeton), Harsha V. Madhyastha (Michigan), and UC Berkeley CS162

Administrivia

- Today is the last lecture!
- No class on Thursday
- PagingLab due Thursday
 - Still okay to use slip days or late penalties on it

Administrivia

- Midterm exam 2
 - Wednesday, December 11th from 12:00-1:20 pm in the lecture hall
 - Normal 80-minute exam
 - Expect a similar format to the previous exam
 - Covers Device I/O through Virtualization
 - Lectures 9 through 18
 - Does NOT cover scheduling or concurrency
 - Practice materials on Canvas homepage
 - May bring: **one** 8.5x11" sheet with notes on front and back

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

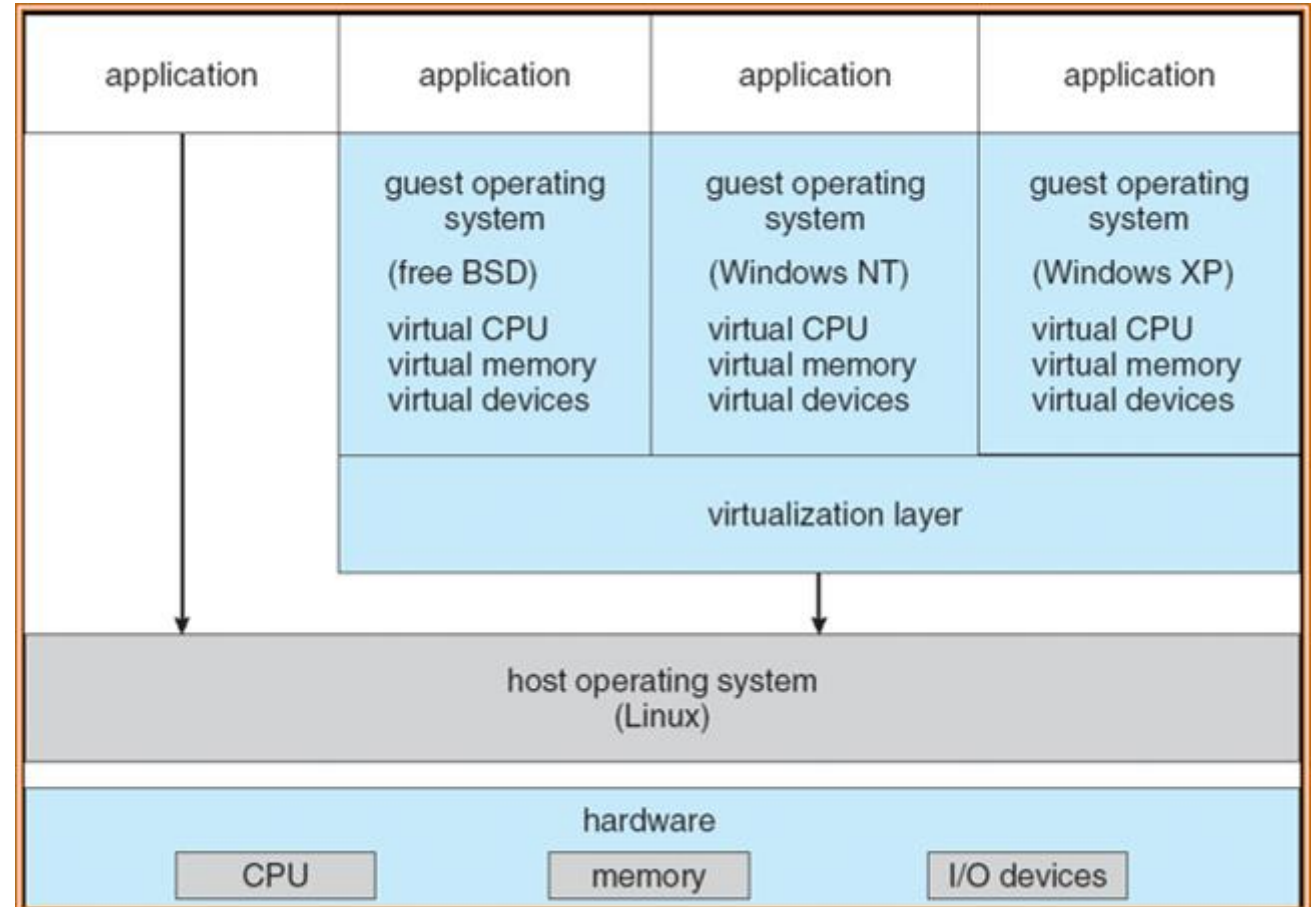
- **Virtualization**
- Approaches
 - Emulation
 - Hypervisors
 - Containers

Virtualization

- Virtual (fake) versions of real resources are often provided to users
 - Memory – virtual memory
 - CPU – processes and scheduler
 - Disk – files
- OS provides these abstractions to simplify applications
 - And provide security!

Virtual Machines (VMs)

- 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
 - 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
 - Windows + Ubuntu VM
 - Want PowerPoint and also terminal environment (vim/make/gcc)
 - MacOS + Windows VM
 - Various Windows-only programs
 - Often dual boot rather than VM if you don't need to run them simultaneously

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

1. Simulate everything in the computer completely
 - Emulation
2. Simulate parts of the computer, but not all of it (actually use CPU)
 - Hypervisor
3. 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
- Example: Gameboy emulator
 - Simulates every behavior as-if it were actually Gameboy hardware

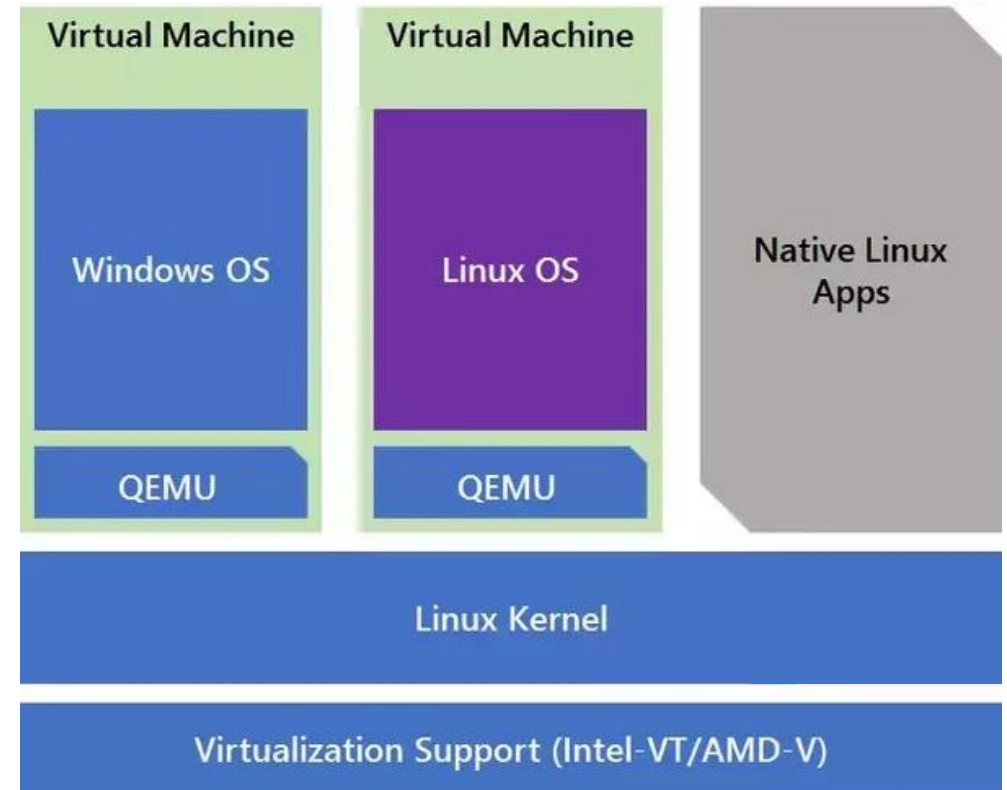
Emulation example: QEMU

- 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
 - Serial and parallel ports
 - stdio connected to serial port
 - file parport.out connected to parallel port
 - Other stuff
 - Floppy disk
 - PCI and ISA network adapters
 - Intel HD Audio Controller and HDA codec
 - PCI UHCI, OHCI, EHCI or XHCI USB controller and a virtual USB-1.1 hub

Emulation tradeoffs

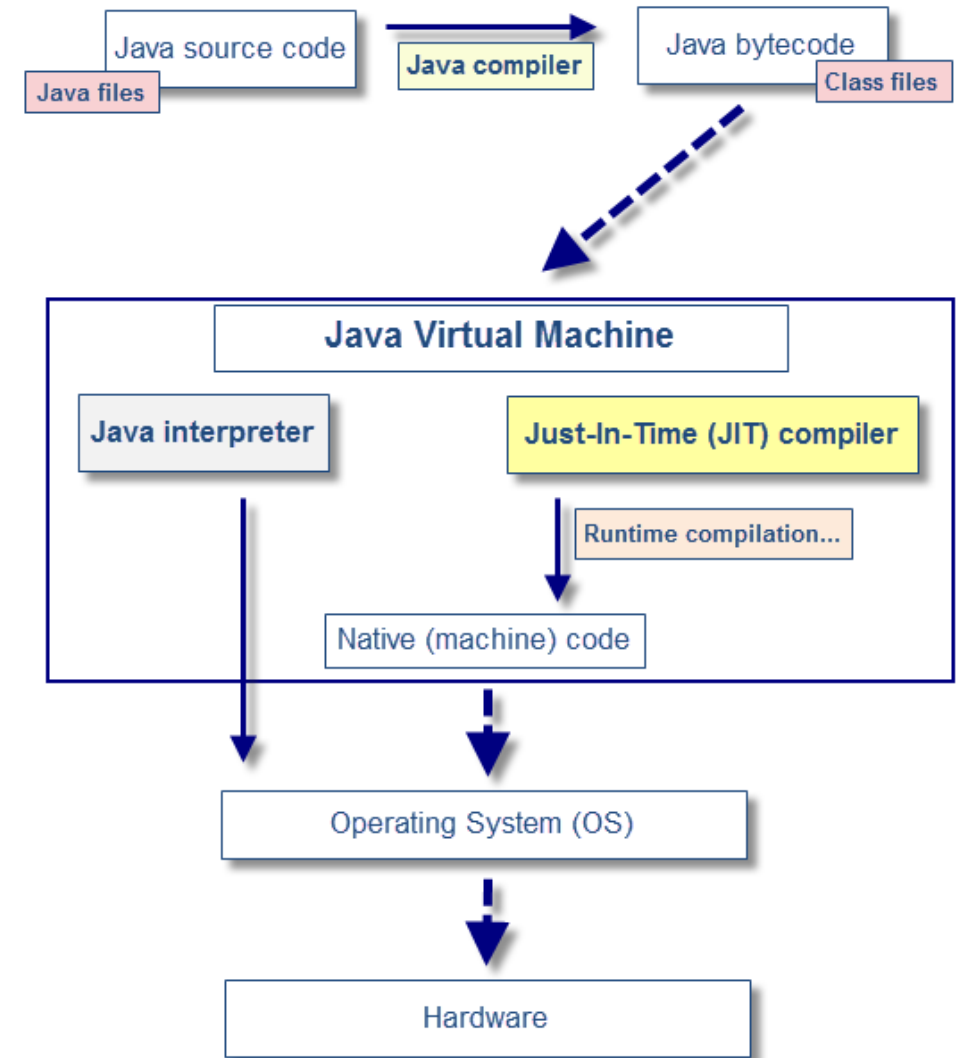
- Upsides
 - Any hardware you want
 - Entirely in userspace
 - You could even run multiple emulators simultaneously if you wanted to
- Downsides
 - Accurate behavior is difficult to provide
 - Software runs slower than the hardware would

(But modern hardware might run software faster than old hardware)



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



WebAssembly: modern version of a language emulator

- WebAssembly (Wasm) is a compilation target
 - Like x86-64 or ARM
- Compilers generate Wasm from languages like C, C++, or Rust
- Web browser runs a virtual machine that understands and executes the Wasm instructions
 - With an API to make requests to the actual computer OS
- End result: C/C++ programs can run in Web browsers
 - While maintaining decent performance

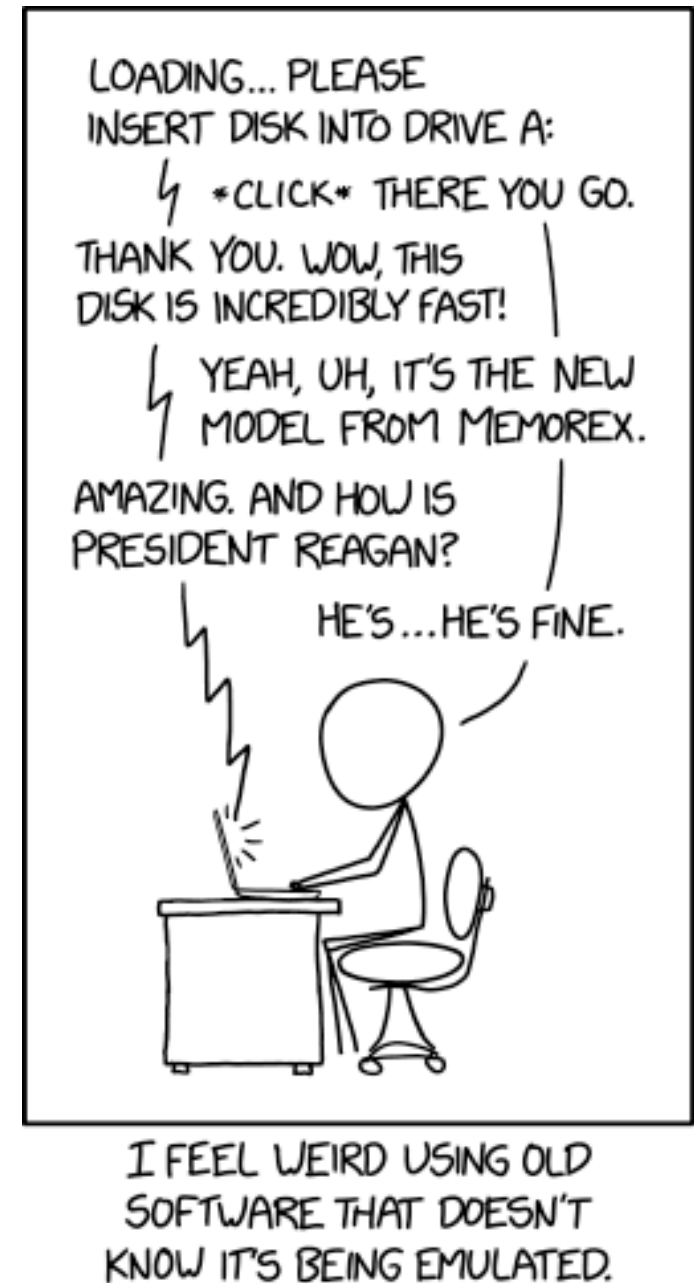
Not-quite-emulation: binary translation

- MacOS on ARM (M1)
 - Uses 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



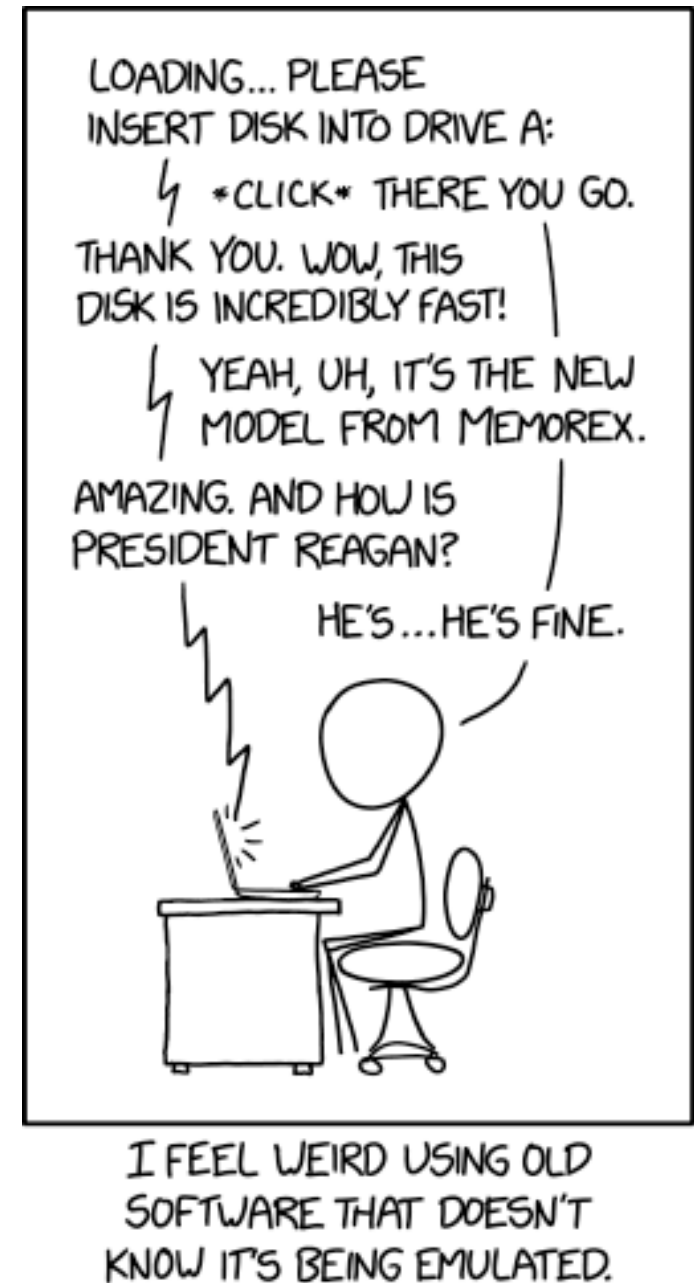
Break + Question + Comic

- What are the best use cases for hardware emulation?



Break + Question + Comic

- What are the best use cases for hardware emulation?
 - Non-standard, slow machines (example: old gaming consoles)
 - Where people do not have access to the original hardware
 - The original hardware was slower than modern hardware
 - And there are existing application binaries that they want to run
 - Application-level simulation/testing (example: Nautilus!)
 - Still hopefully for the above (for performance)
 - Entirely controlled environment: makes debugging easier
 - Nautilus does run significantly slower in QEMU, but that's okay for our purposes



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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

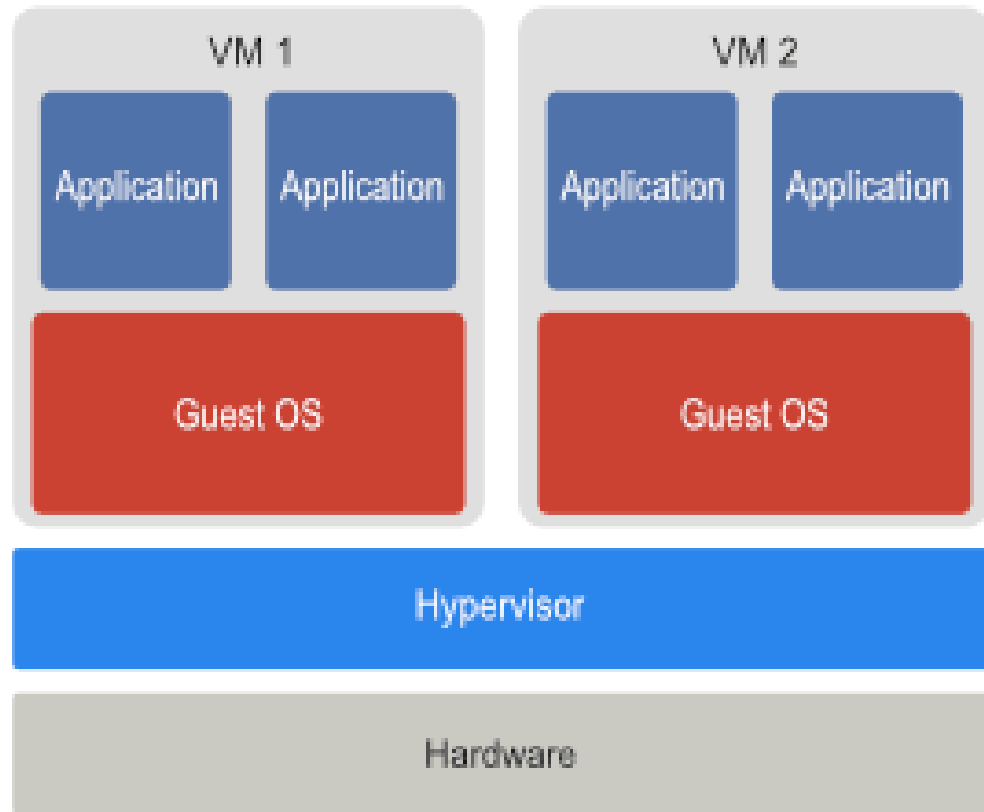
Virtual Machine Monitor (VMM)

- 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

Hypervisors use real hardware for performance

- **Big idea:** Hypervisors run the guest OS on the real hardware for performance
- Normal code runs directly on hardware as usual
 - Assembly instructions, accessing memory, normal application stuff
 - Significantly faster than emulation
- Accesses requiring kernel permissions go through the hypervisor first, then get redirected to the guest OS
 - Context switching, virtual memory changes, device access, etc.
 - Hypervisor may intervene on some of these

Hypervisor layering option: directly on hardware

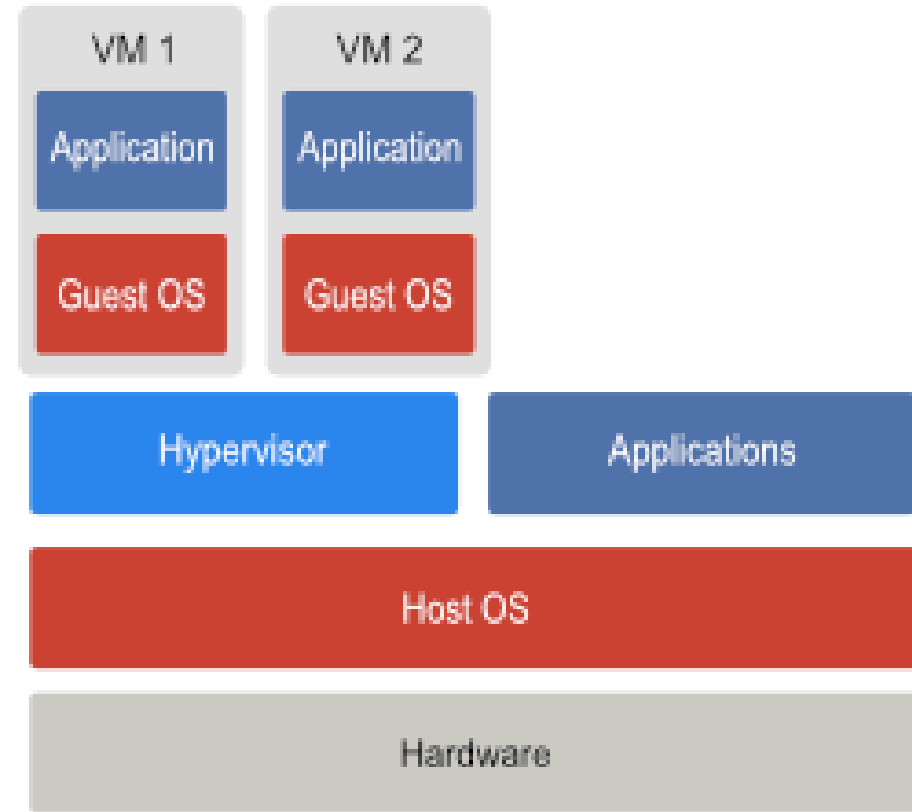


Type 1
"Bare Metal" Hypervisor

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

Hypervisor layering option: on top of Host OS

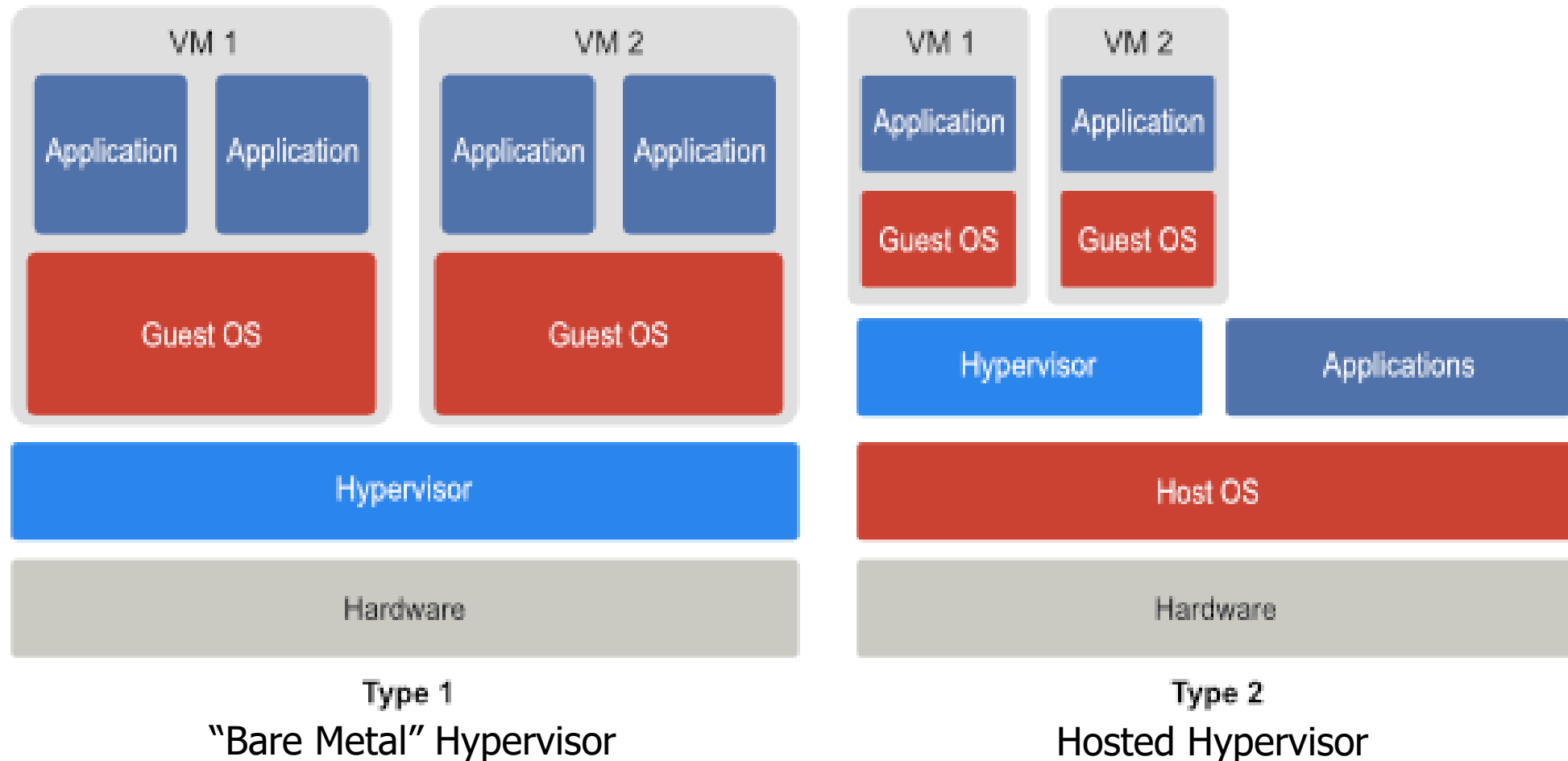
- Normal operating system runs on hardware
 - Known as "Host OS"
- Hypervisor runs on top of host and coordinates with it to enable interactions with hardware
 - Some coordination may be within the host kernel itself



Type 2
Hosted Hypervisor

Hypervisor layering options: comparison

Hypervisor Types



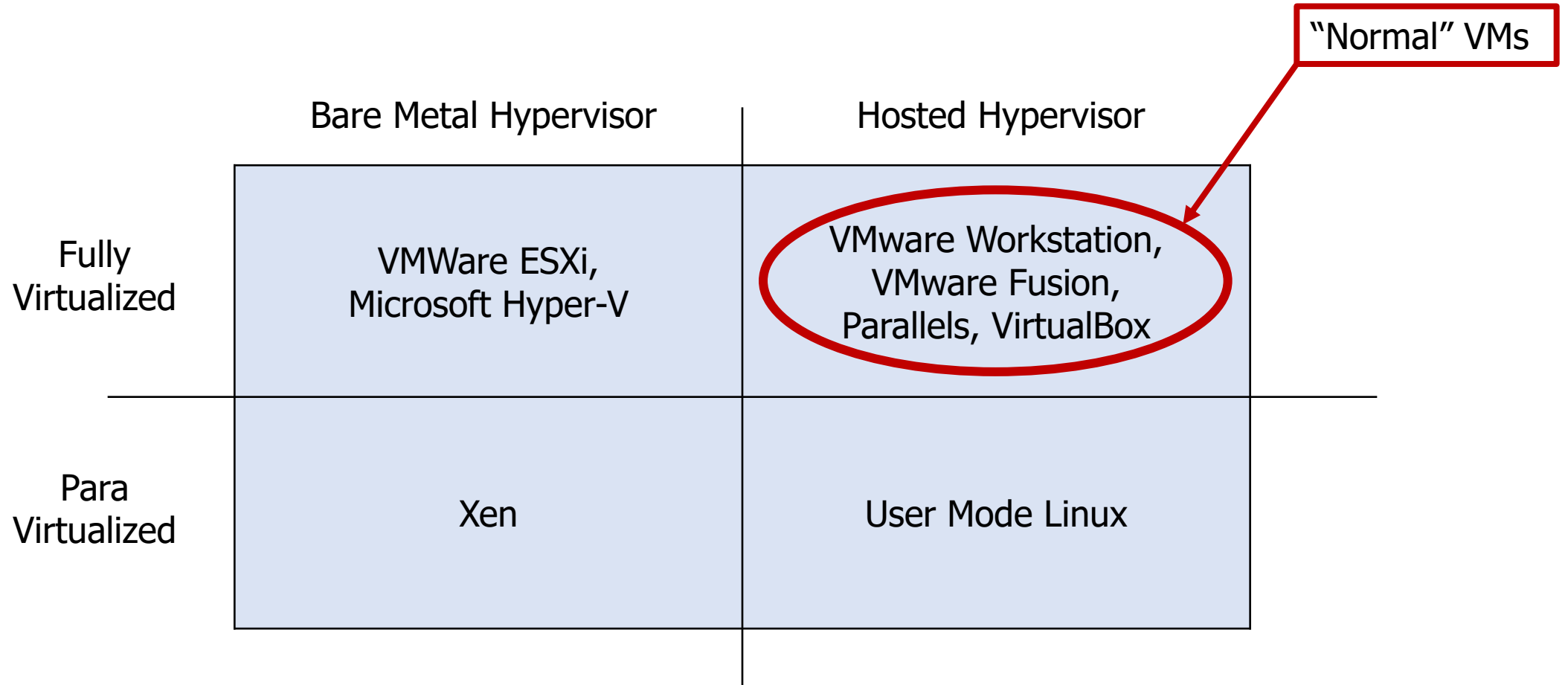
Abstraction choices for hypervisor

- Fully virtualizing hypervisor
 - Virtual machine looks exactly like a physical machine
 - Though not necessarily the exact same machine it's actually 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
 - Guest OS likely can skip some stuff the hypervisor handles instead

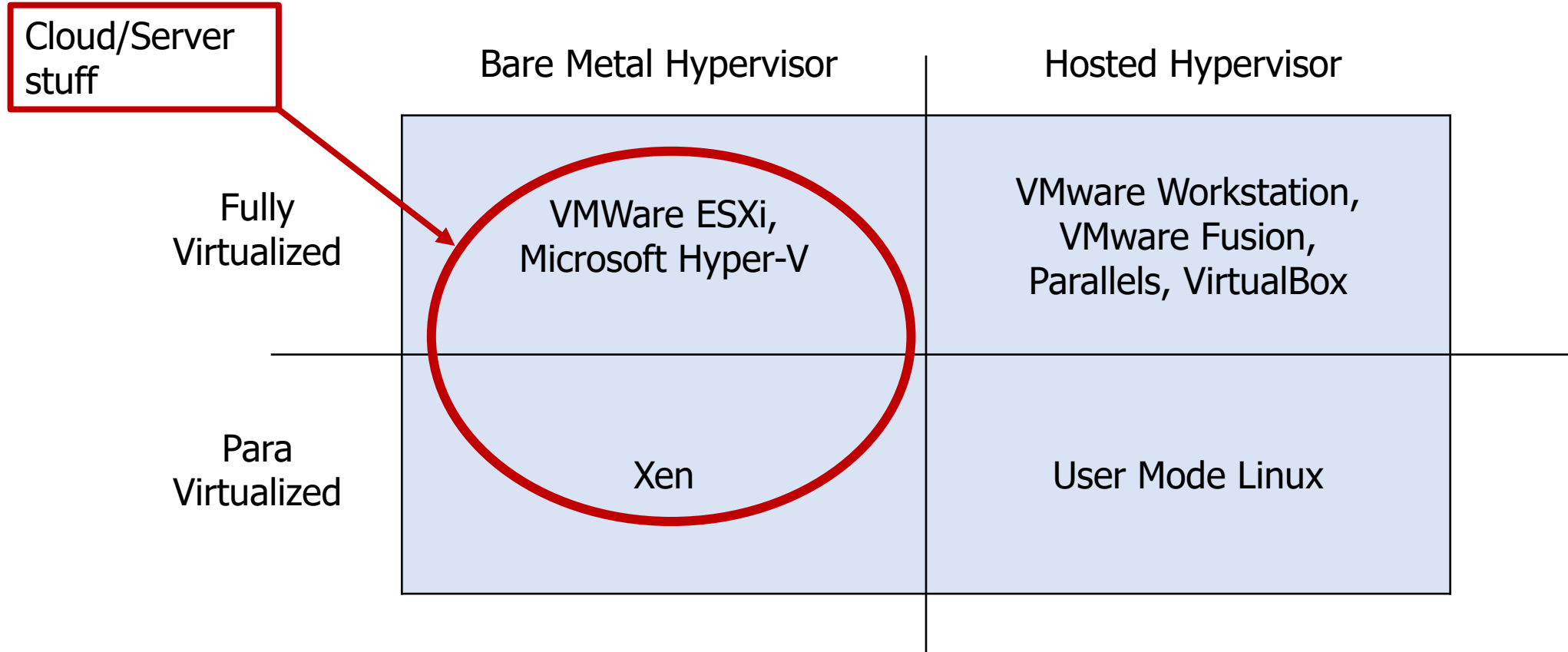
Arbitrary combinations of these are possible

	Bare Metal Hypervisor	Hosted Hypervisor
Fully Virtualized	VMWare ESXi, Microsoft Hyper-V	VMware Workstation, VMware Fusion, Parallels, VirtualBox
Para Virtualized	Xen	User Mode Linux

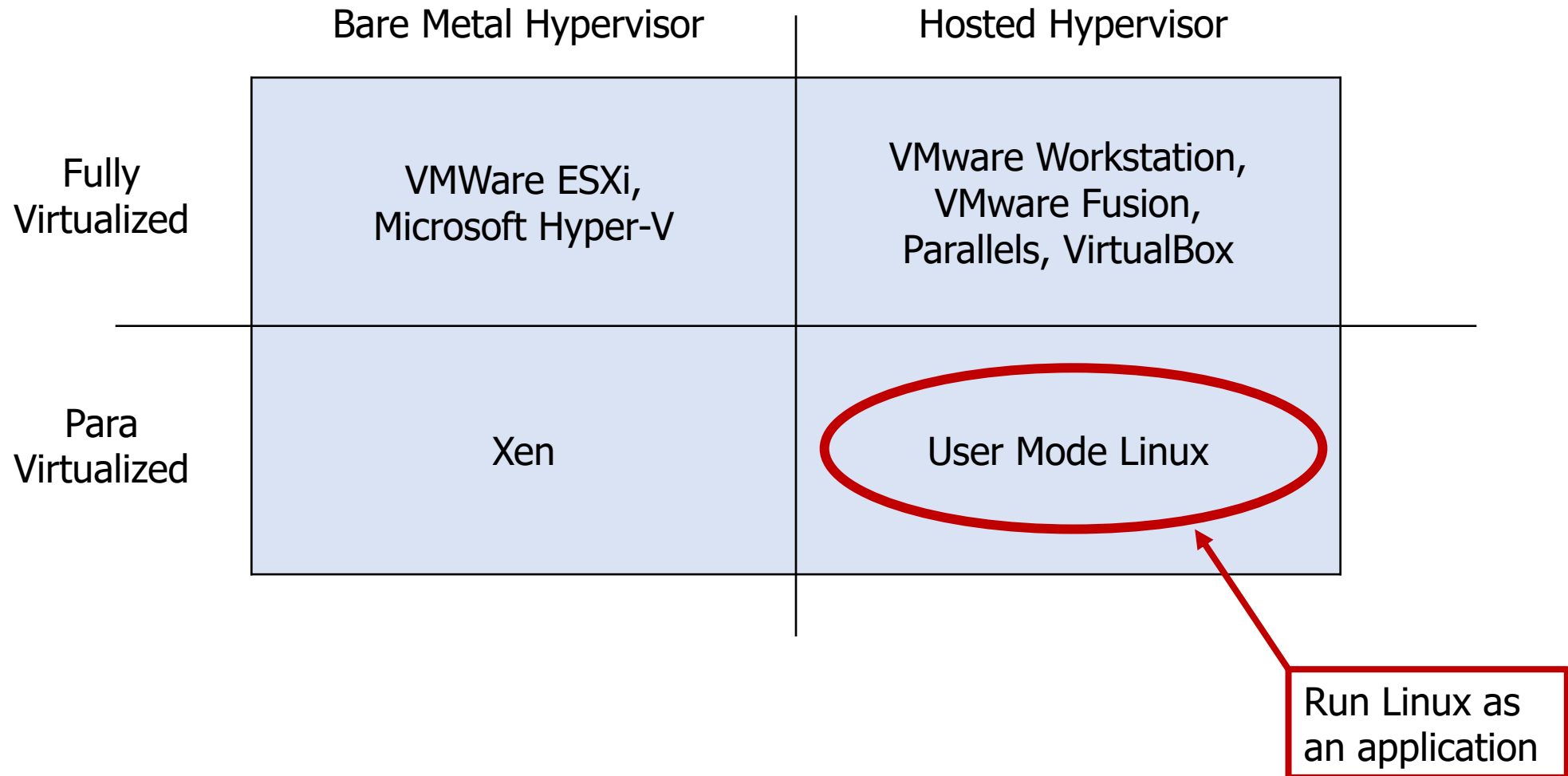
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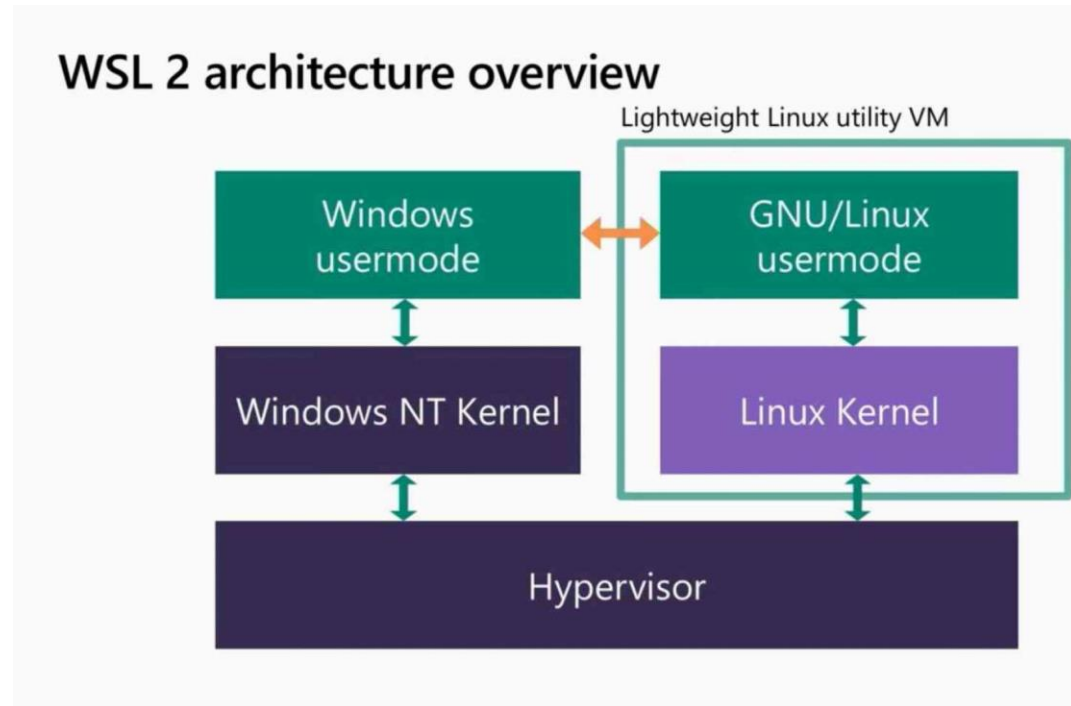


Arbitrary combinations of these are possible



Windows Subsystem for Linux (WSL 2)

- Provides Linux environment on a Windows computer
- Windows Hyper-V provides a fully-virtualized system
 - Windows and Linux both run on top of it
- Differences:
 - WSL2 also enables communication between userspaces rather than fully isolating the two
 - They can both share access to the file system, for example
 - Windows is a “privileged” guest with full control of the system



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!!

Hypervisor example: system call

Process

1. System call: trap to OS

Guest OS

3. OS trap handler:
Decode trap and execute
syscall. When done issue
return-from-trap

Hypervisor

2. Receive trap. Call guest
OS trap handler

4. OS tried to return from
trap. Do real return-from-
trap

5. Resume execution

Problem: x86 doesn't virtualize very well

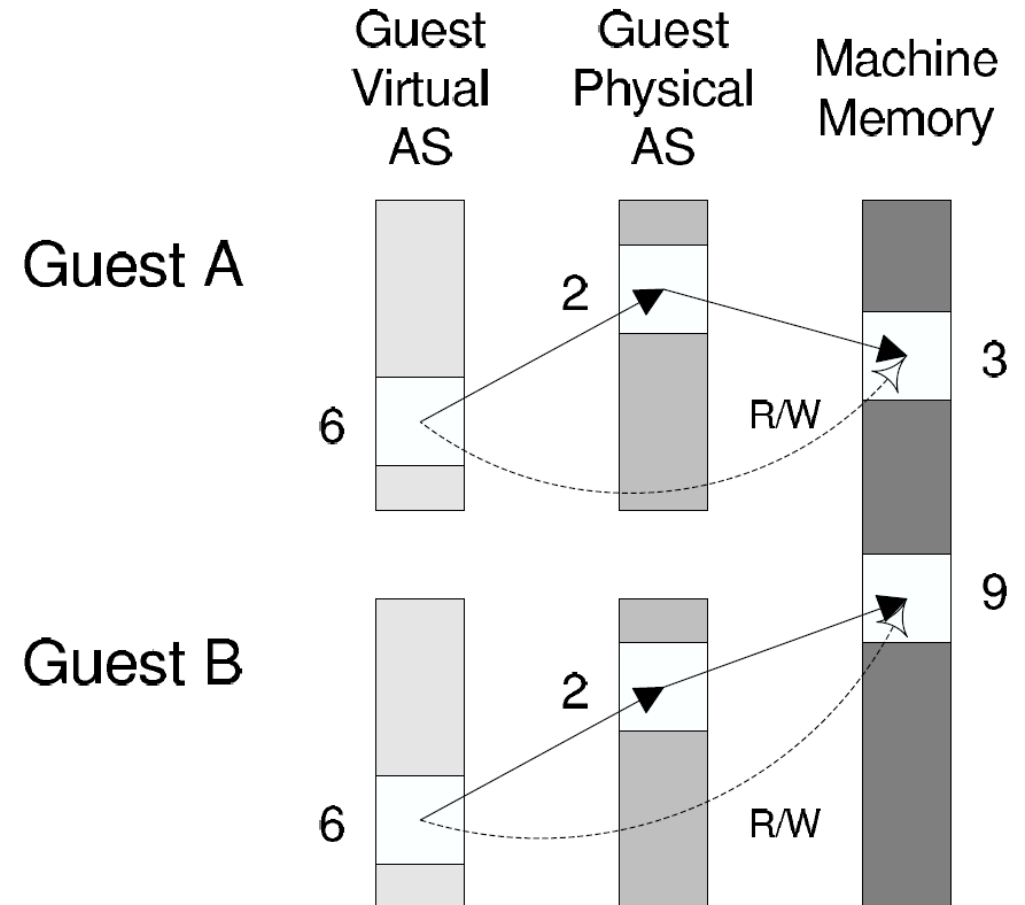
- CPU architecture is virtualizable only if sensitive instructions always trap if run in user mode
- Historically, x86 does not guarantee this
 - Some instructions behave differently in user mode
 - For example: some instructions have no effect when run in user mode
- One solution: binary translation
 - 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

Break + Questions – VirtualBox on ARM Mac

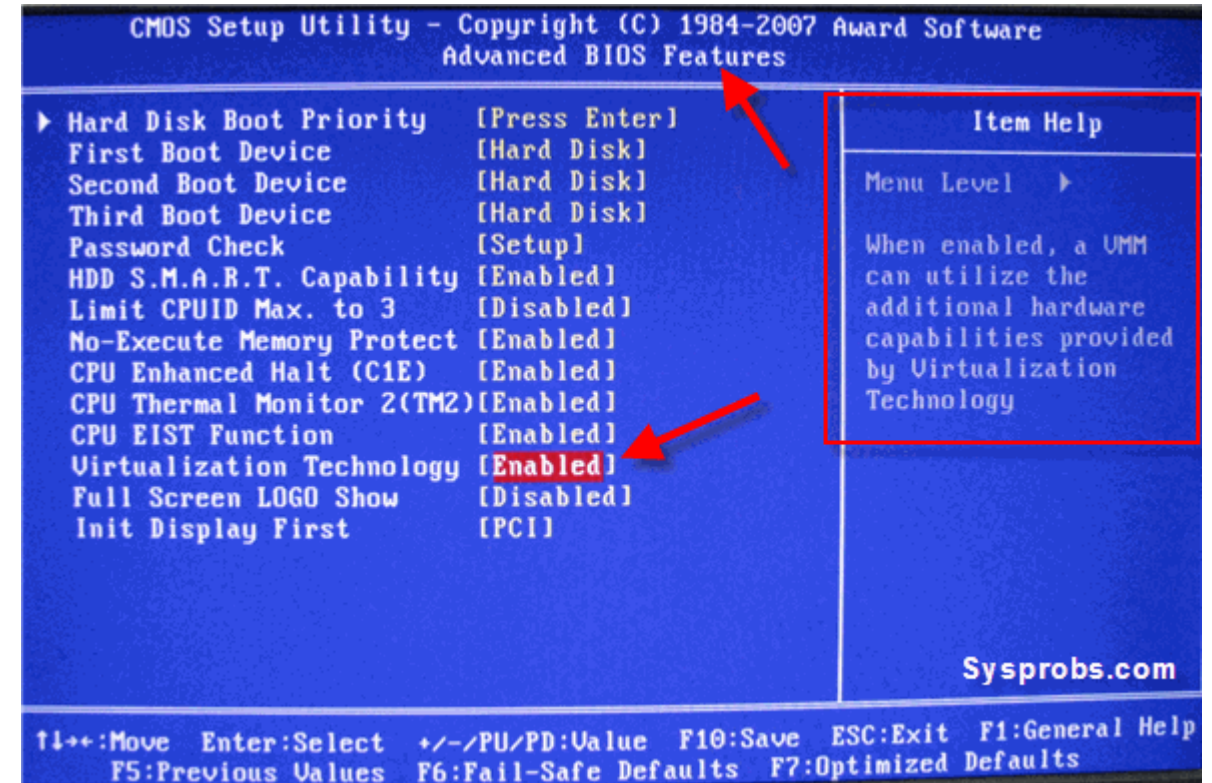
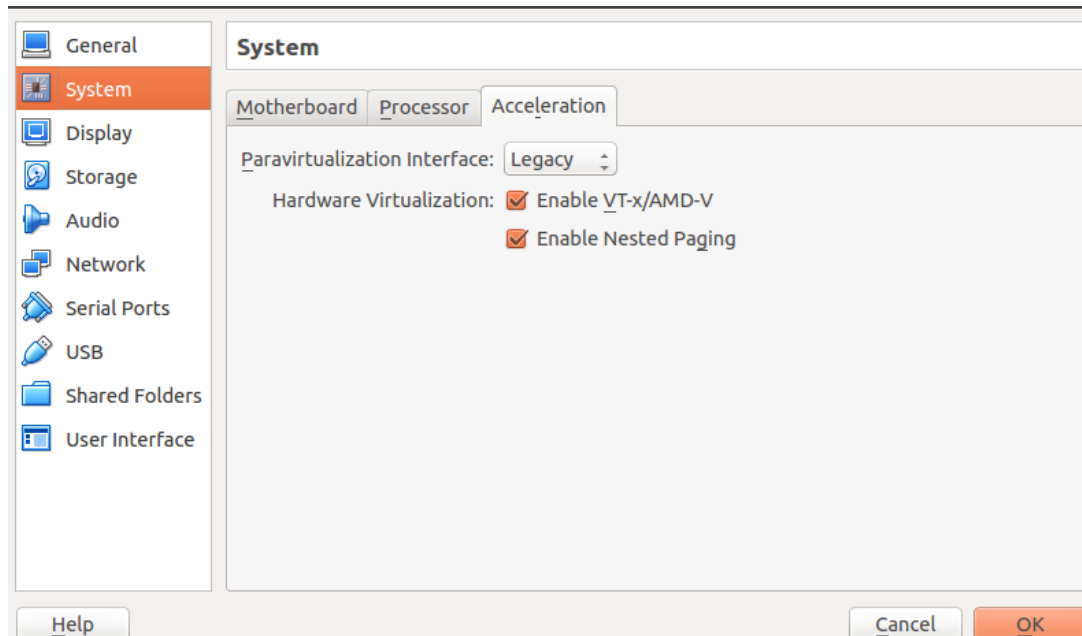
- Will VirtualBox work on the ARM Macs?
 - Will old versions of VirtualBox work?
- What architecture will the guest OS need to be?
- Could students run CS213 labs in it?

Break + Questions – VirtualBox on ARM Mac

- Will VirtualBox work on the ARM Macs?
 - Will old versions of VirtualBox work?
 - No. Originally compiled for x86-64 only. Needs a new version written for ARM. Support exists as of October 2022!
 - 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.
 - They would need an emulator for x86-64 assembly

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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Not-quite-containers: Compatibility layer

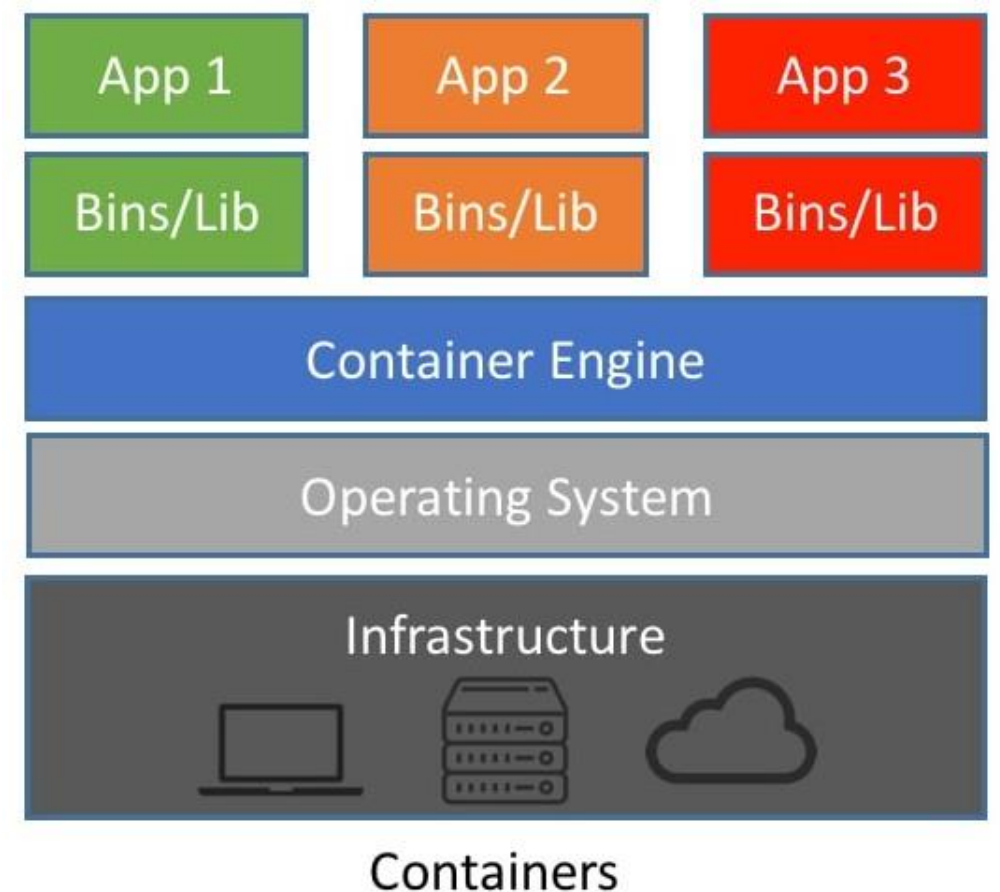
- To allow software to run on another OS, provide an interface that can translate system calls
 - Essentially emulating an OS, rather than computer hardware
- Wine
 - Provides dynamic libraries that mirror those that exist in Windows
 - But new implementations make Linux system calls
- WSL (1.0)
 - Translates Linux system calls into Windows system calls

Cloud platform requirements

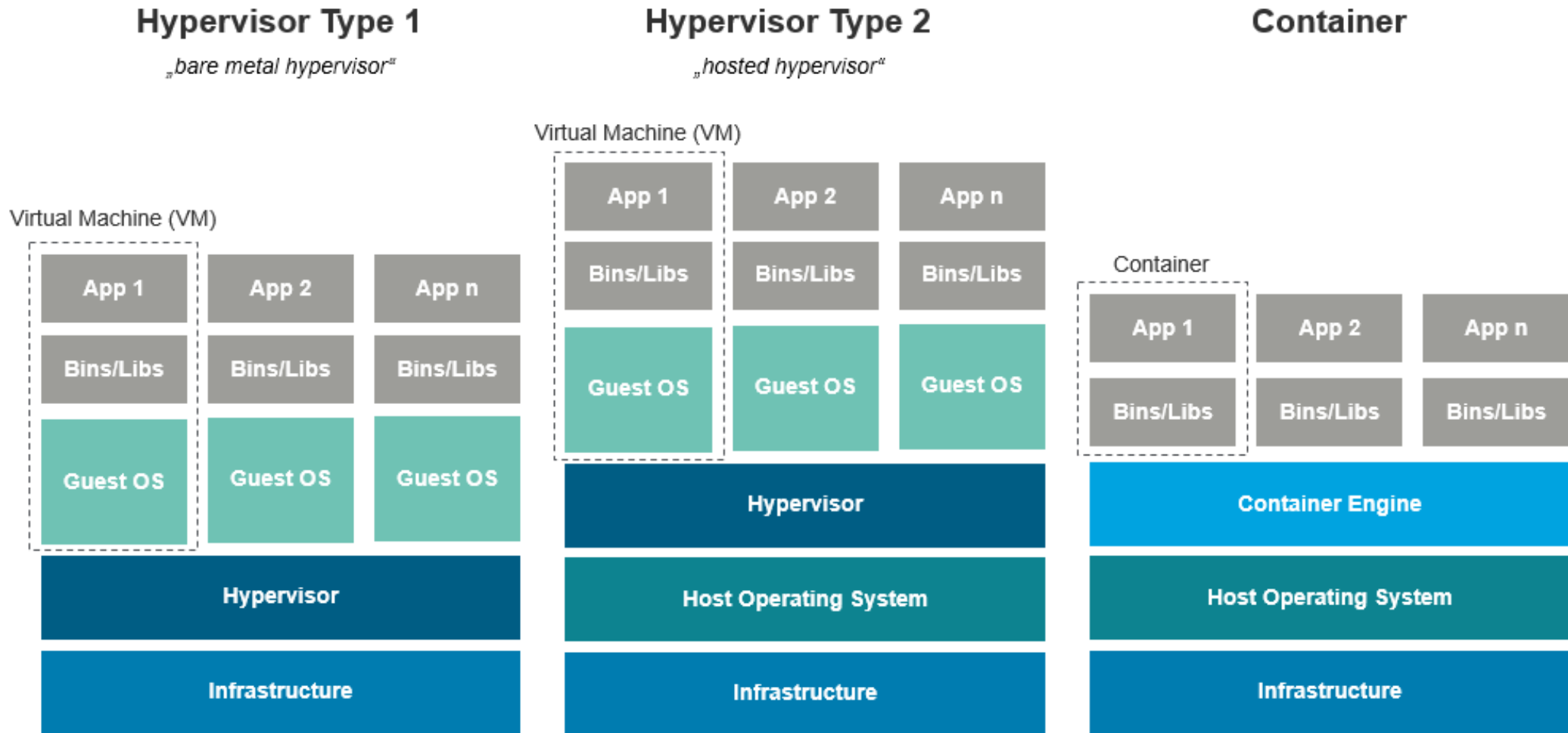
- May want to provide multiple OSes, but can do so with multiple physical machines
- Really want encapsulation and isolation
 - Encapsulation
 - Include particular shared libraries that application needs
 - Without interfering with other applications on system
 - Isolation
 - Guarantee certain processing and memory allocations to each application
 - Limit visibility into the filesystem (without overhead of partition per app)

Containers

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



Visual comparison of Hypervisors and Containers

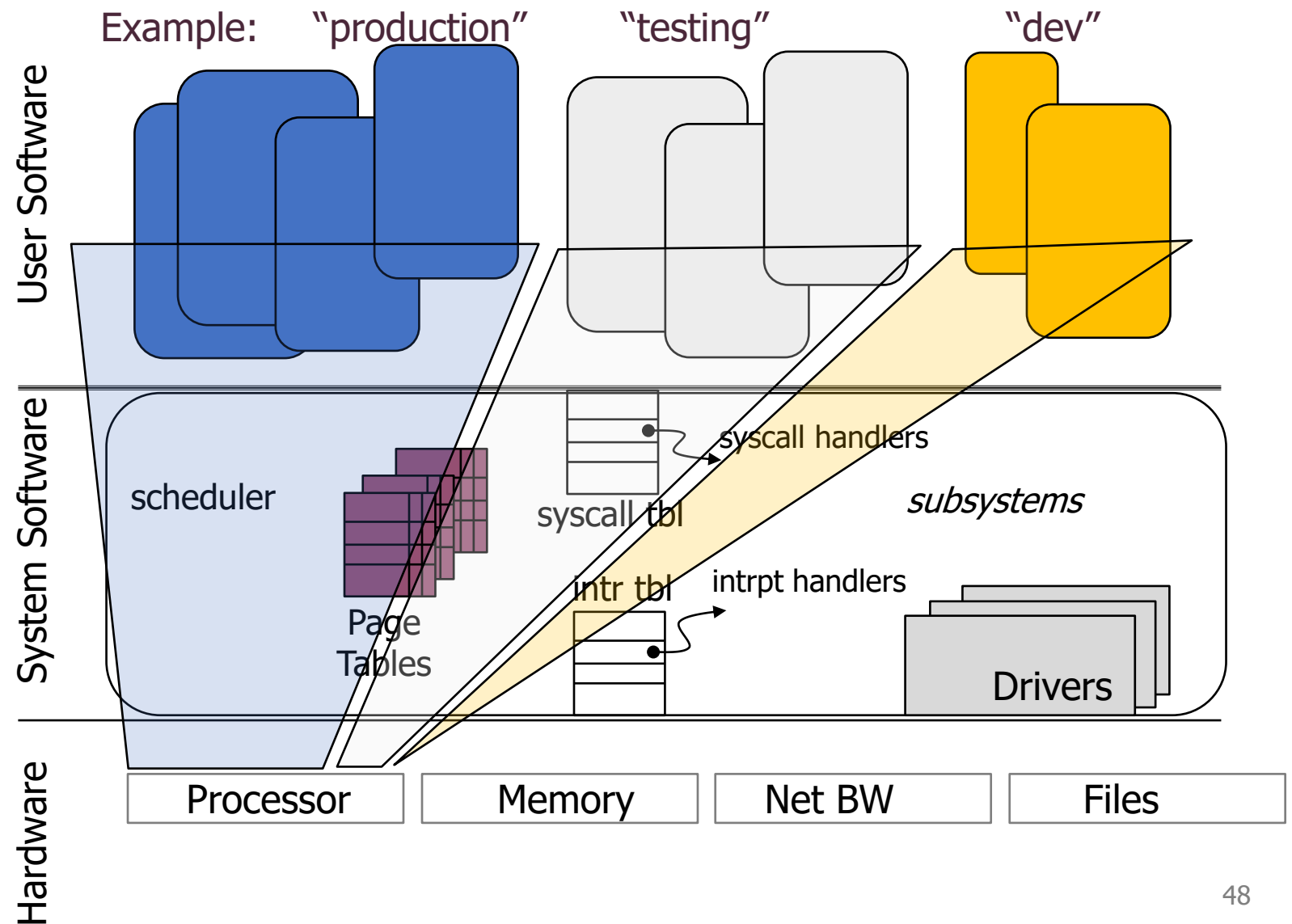


How to implement containers

- Needs the ability to isolate one process from the effects of another
 - More strongly than a normal OS does anyways
- On Linux, there is a related idea which is the basis for containers
 - cgroups

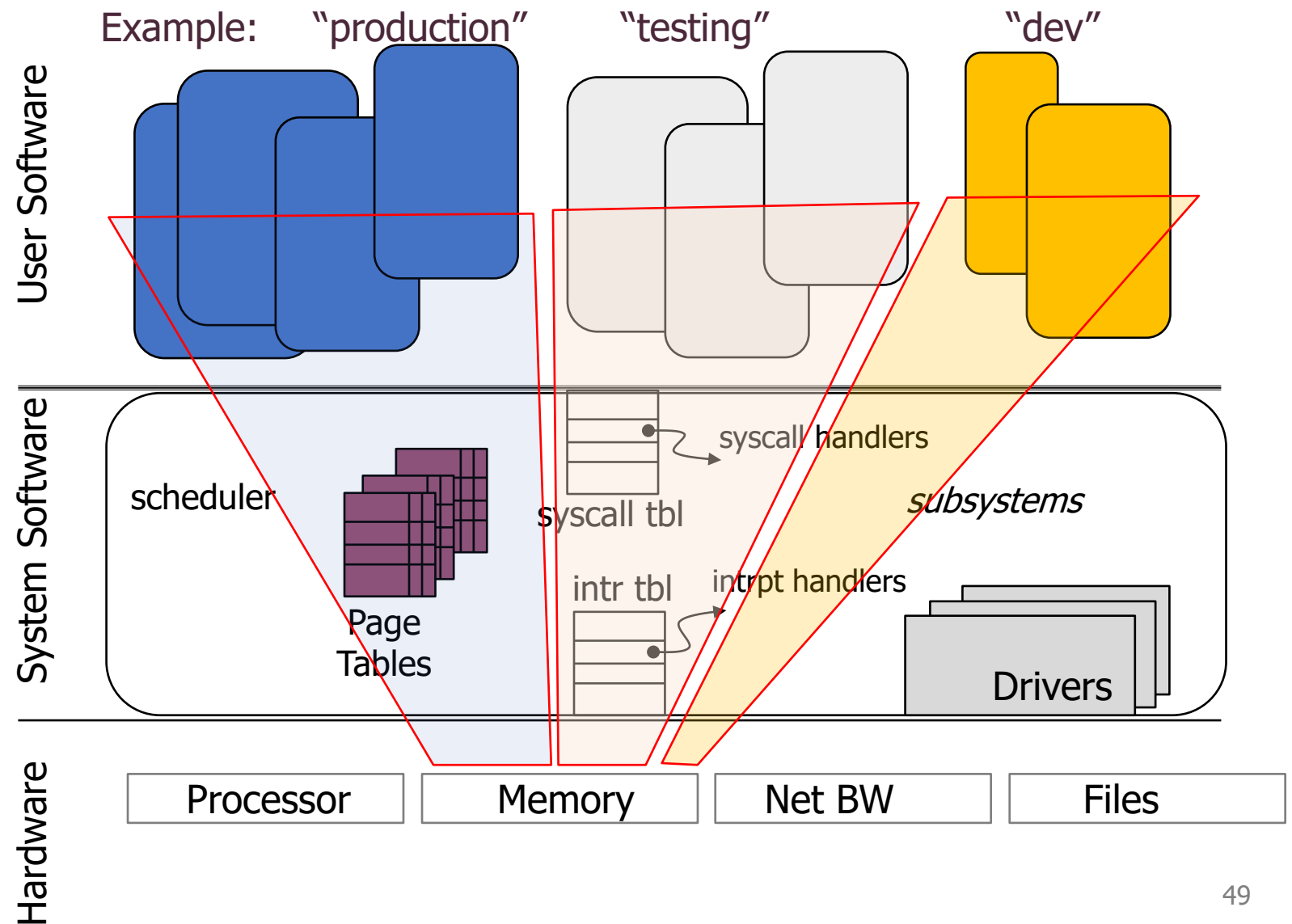
Linux cgroups (control groups)

- Collection of processes treated as a group for resource allocation
- Provide greater performance isolation between cgroups than between processes
 - Firm limits per group



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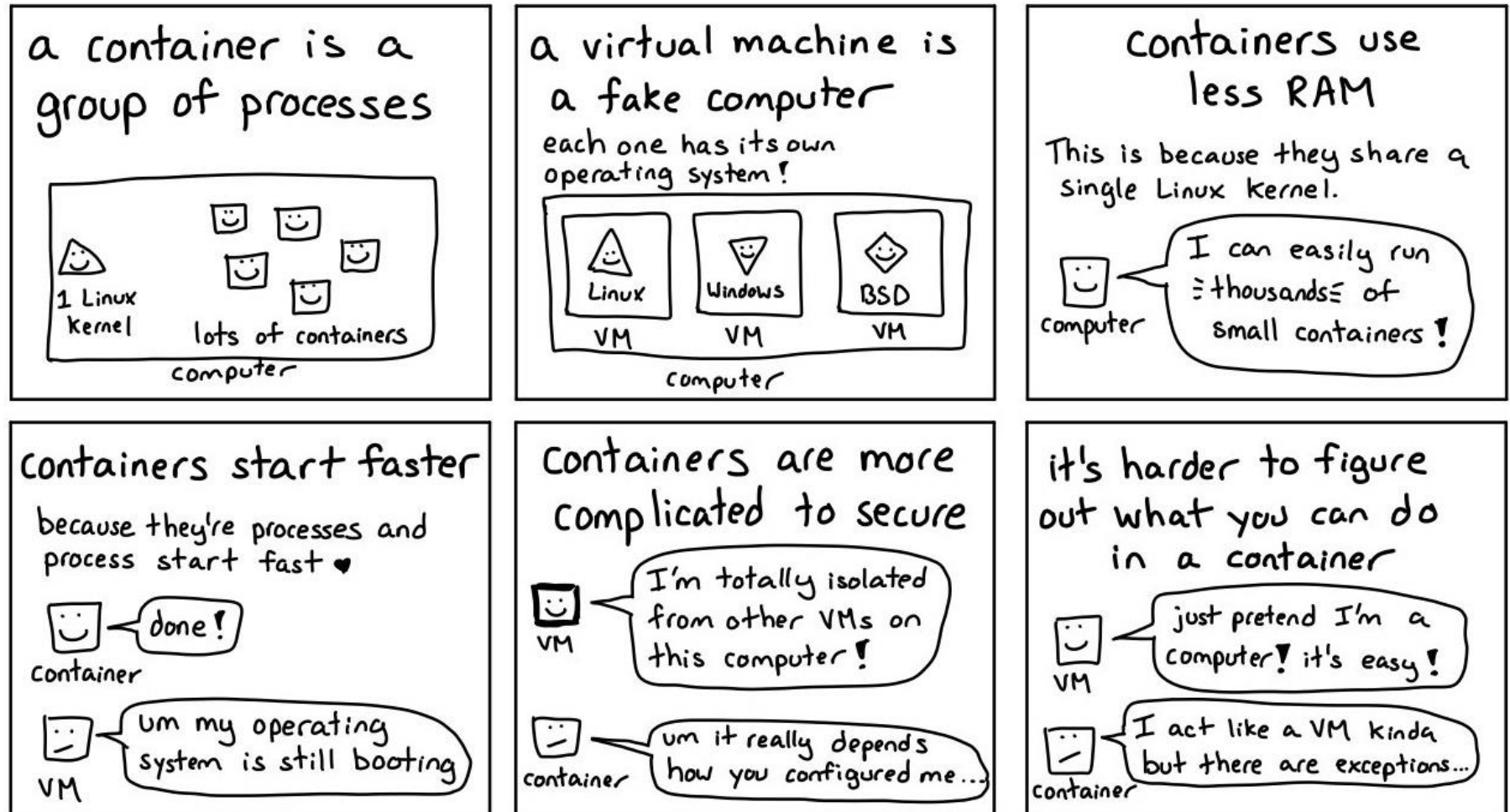
cgroups can be used to build containers

- 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

Bonus explanation

JULIA EVANS
@b0rk

containers vs VMs



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
- Example: could use Docker for QEMU + Nautilus
 - Need a very specific version of QEMU, with all the proper libraries

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