UNIVERSITY of VIRGINIA

# CS4740
# CLOUD COMPUTING

## Virtualization

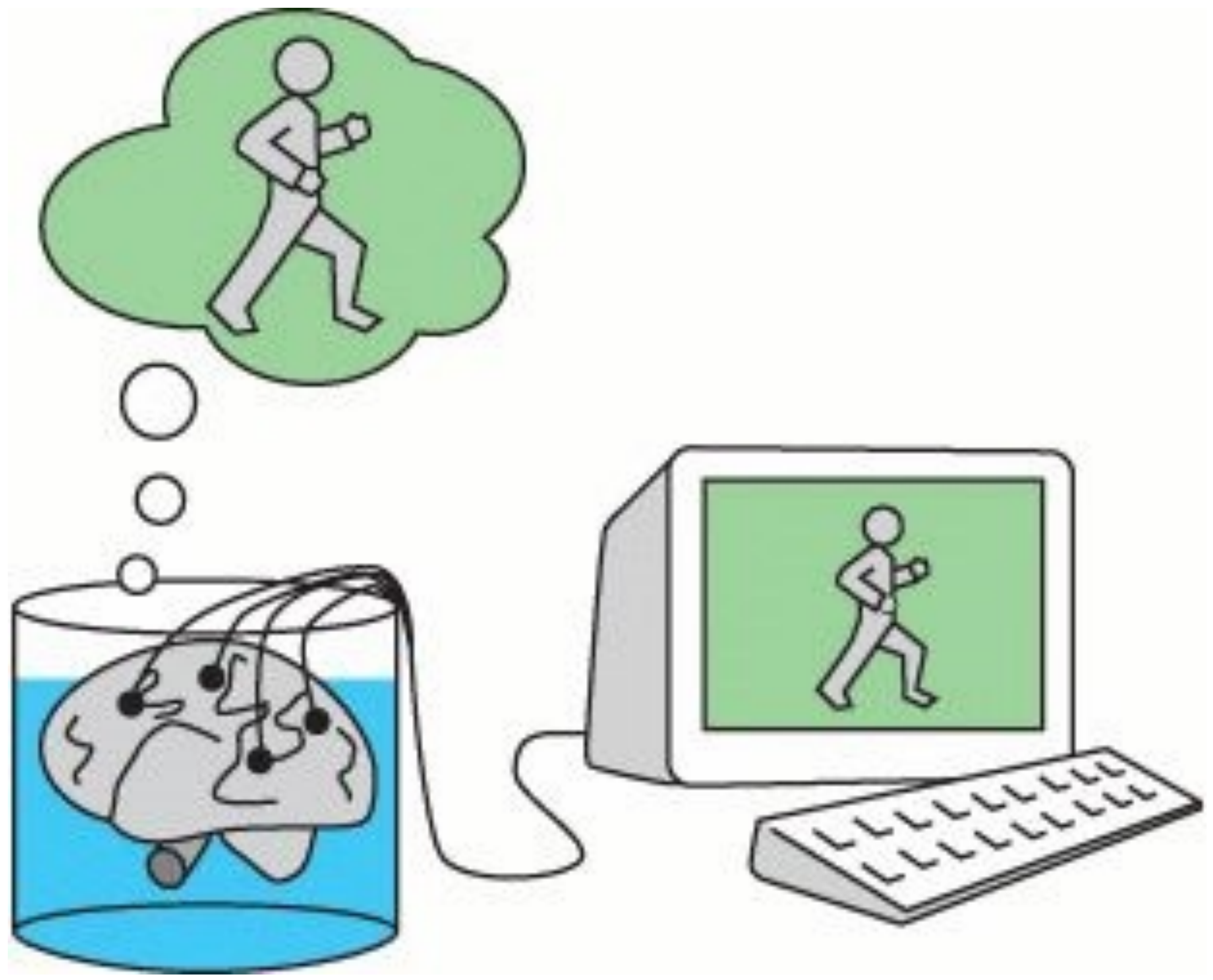
Prof. Chang Lou, UVA CS, Spring 2024

# Are we living in the real world, or a simulation?

# ARE WE LIVING IN A COMPUTER SIMULATION?

By Nick Bostrom

*I argue that at least one of the following propositions is true: (1) the human species is very likely to become extinct before reaching a 'posthuman' stage; (2) any posthuman civilization is extremely unlikely to run a significant number of simulations of its evolutionary history (or variations thereof); (3) we are almost certainly living in a computer simulation. It follows that the belief that there is a significant chance that we shall one day become posthumans who run ancestor-simulations is false, unless we are currently living in a simulation. I discuss some consequences of this result.*



# INTRODUCTION

– If the answer is yes, is there a way to tell?

– Hope you can get some insights from today's lecture :)

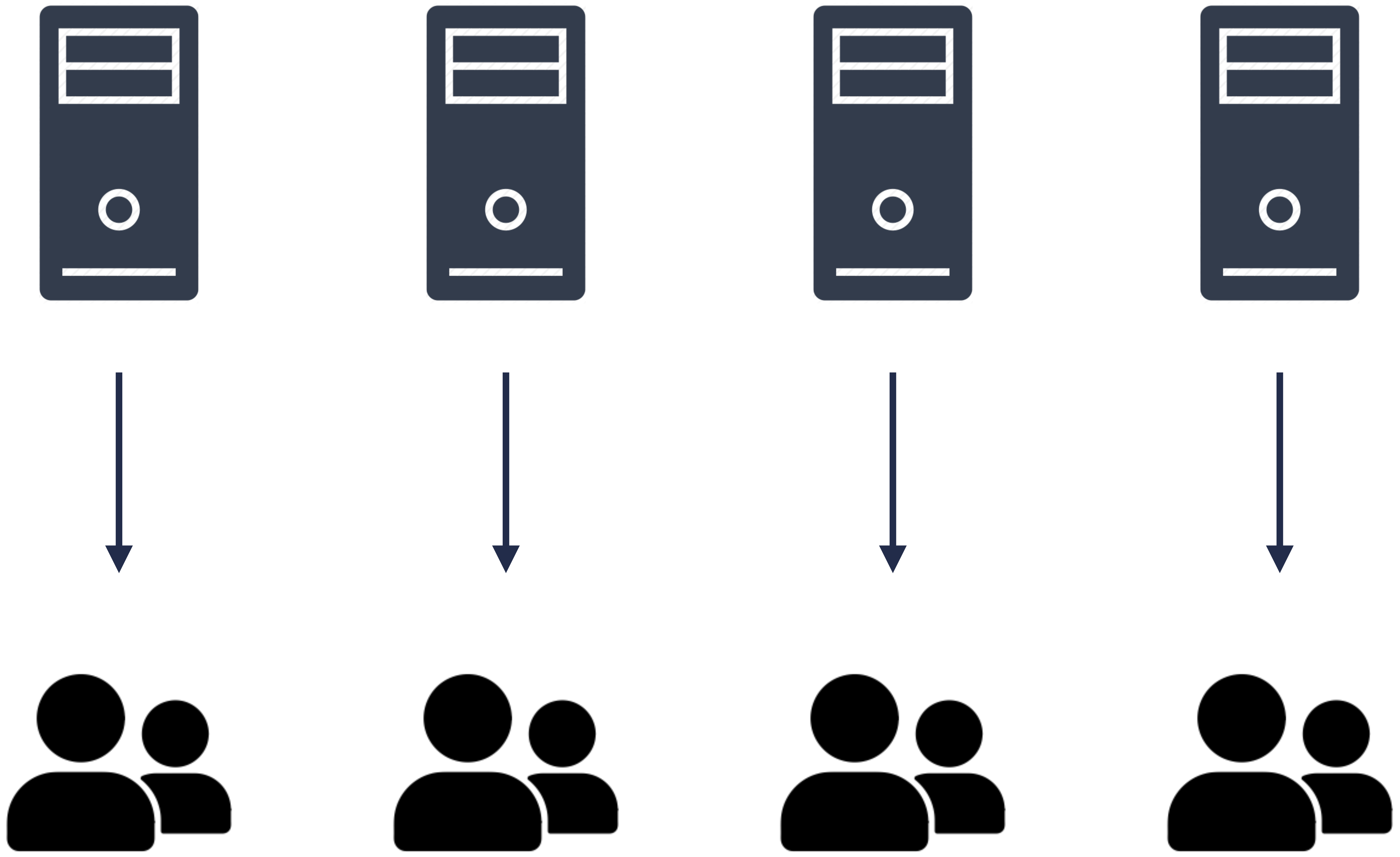
# AGENDA

– Motivation

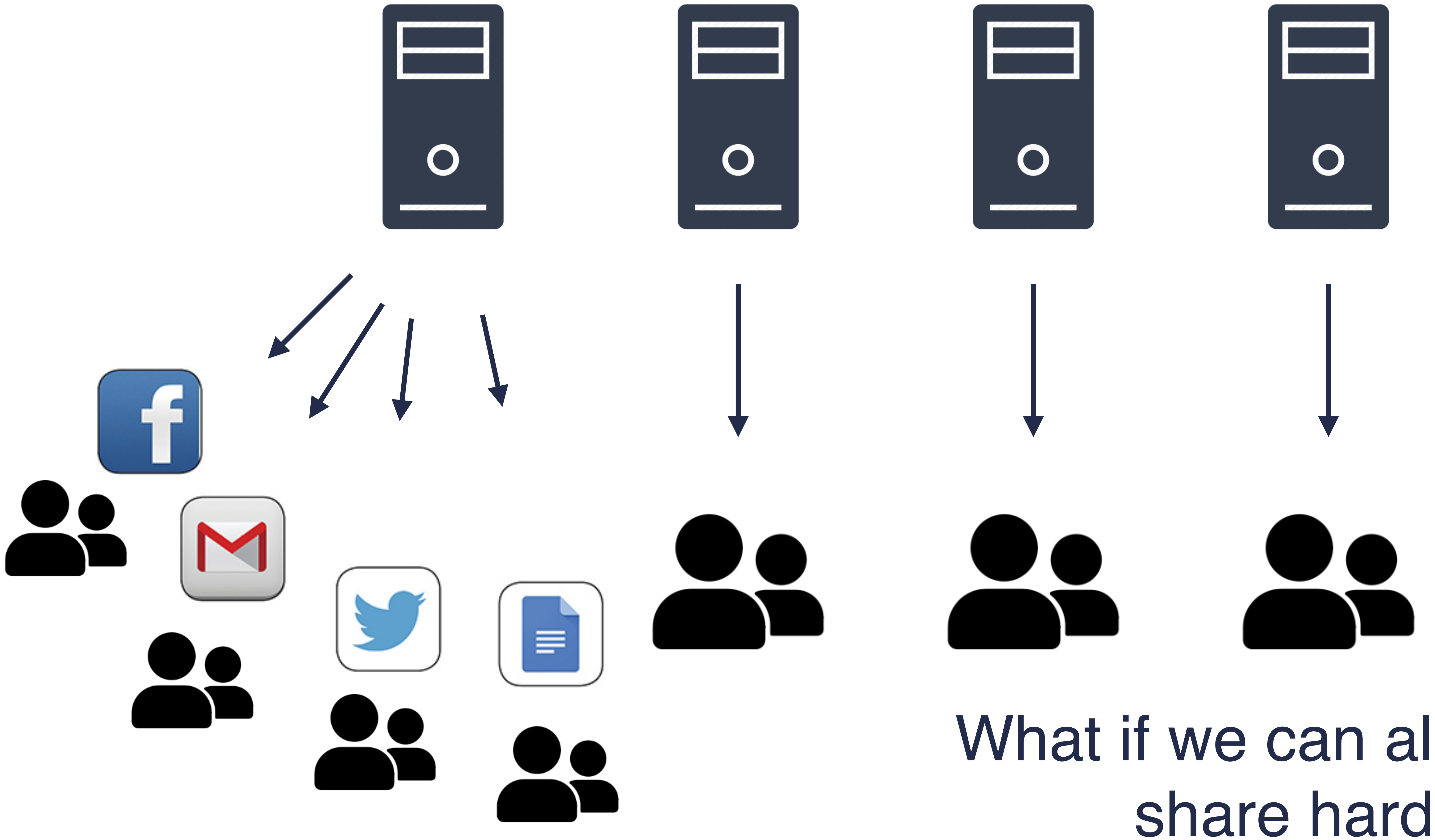
– Techniques
  – Virtual machines
  – Containers

*This lecture's slides are heavily based on Prof. Ryan Huang's OS course at UMich

# Why cloud computing needs virtualization?



Efficiency?



What if we can allow different customers share hardware resources?

# VIRTUALIZATION: BENEFITS

- Resource efficiency
  - Maximum use of the physical hardware’s computing capacity.
- Easier management
  - Automated IT service management workflows.
- Minimal downtime
  - Failover and migration.
- Faster provisioning

# VIRTUALIZATION: BENEFITS (CONTD.)

- Software compatibility
  - VMMs can run pretty much all software
- Isolation
  - Seemingly total data isolation between virtual machines
  - Leverage hardware memory protection mechanisms
- Encapsulation
  - Virtual machines are not tied to physical machines
  - Checkpoint/migration
- Many other cool applications
  - Debugging, emulation, security, speculation, fault tolerance…

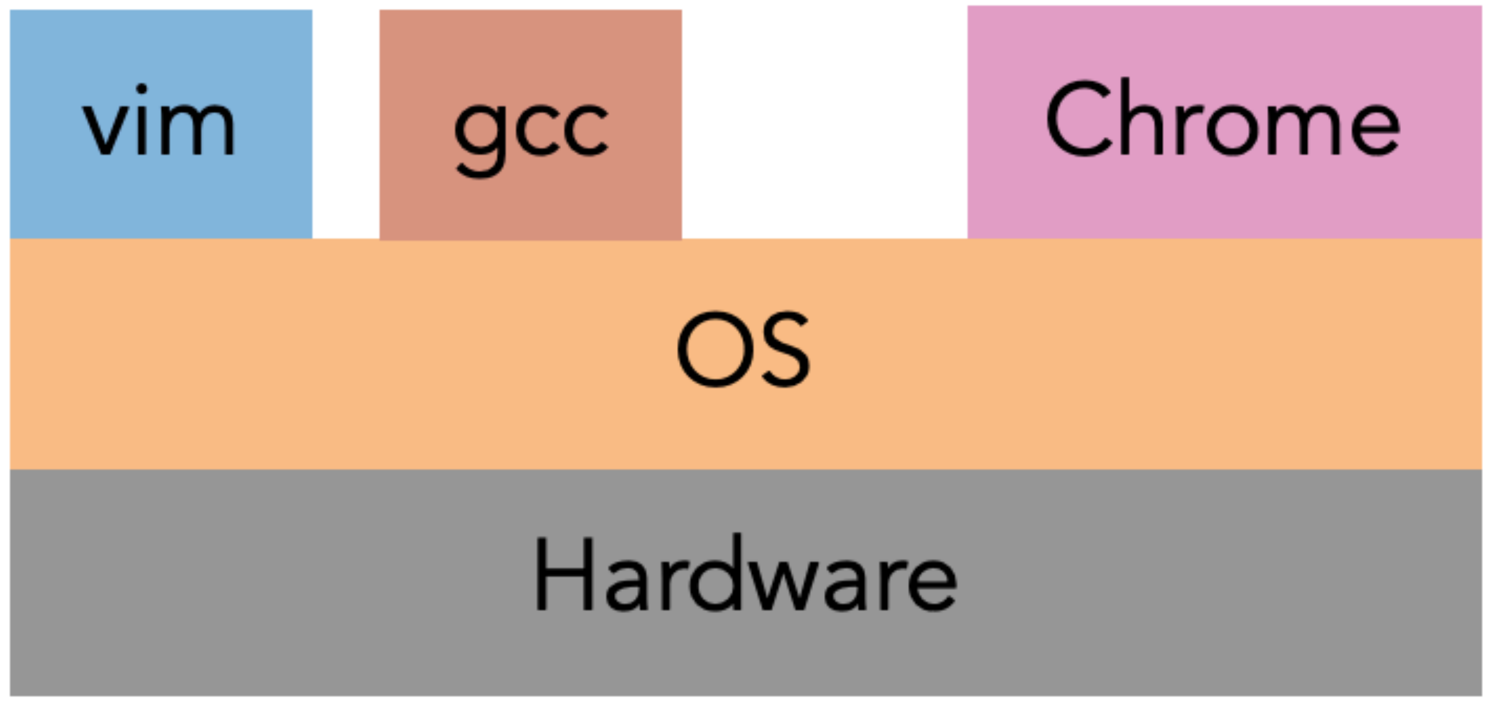
# OLD IDEA FROM THE 1970S

- IBM VM/370 – A VMM for IBM mainframe
  - Multiplex multiple OS environments on expensive hardware
  - Desirable when few machines around
- Interest died out in the 1980s and 1990s
  - Hardware got cheap
  - Compare Windows NT vs. N DOS machines
- Revived by the Disco [SOSP '97] work
  - Led by Mendel Rosenblum, later lead to the foundation of VMware
- Another important work Xen [SOSP '03]

# How to implement virtualization?

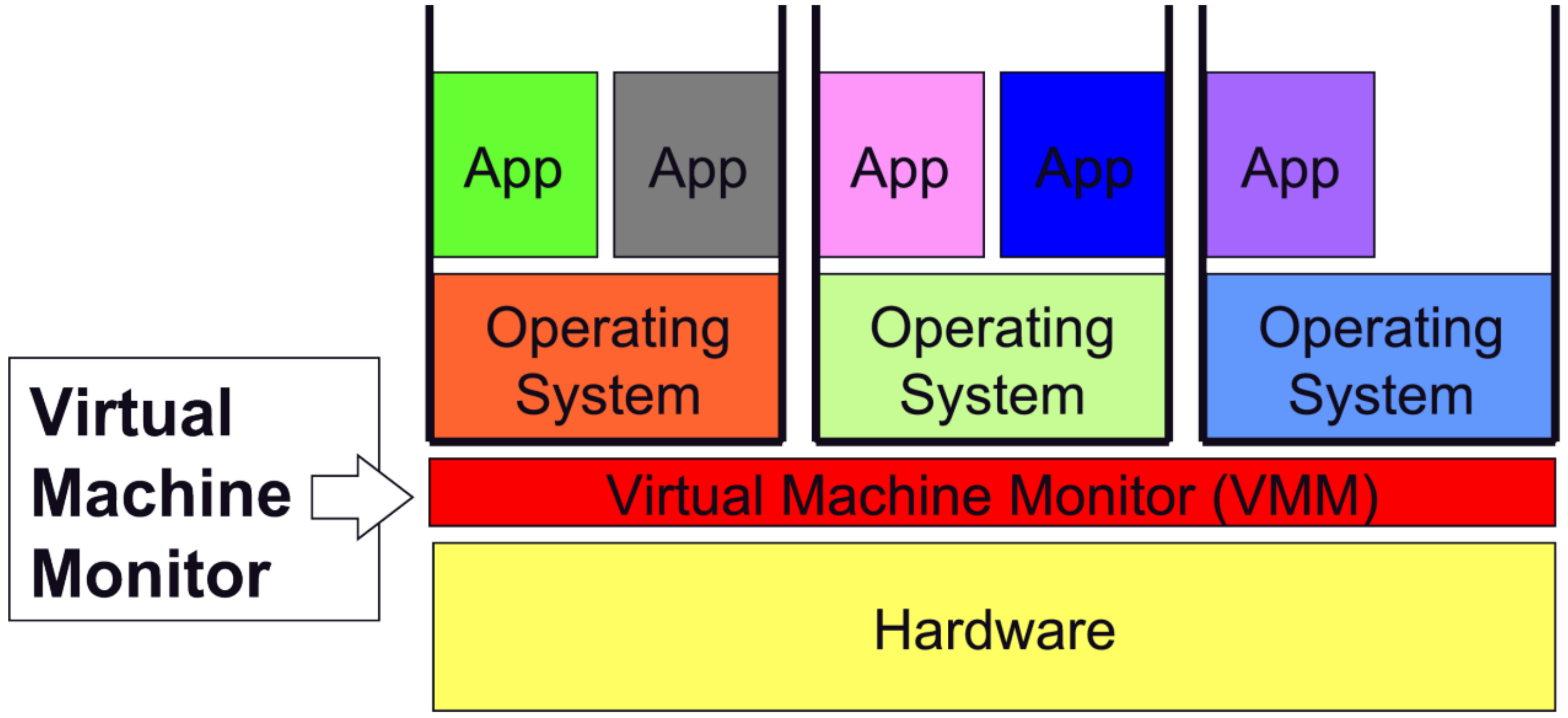
# BACKGROUND: OS

- OS is software between applications and hardware
  - Abstracts hardware to makes applications portable
  - Makes finite resources (memory, # CPU cores) appear much larger
  - Protects processes and users from one another



# VIRTUAL MACHINE

- Thin layer of software that virtualizes the hardware
  - Exports a virtual machine abstraction that looks like the hardware
  - Provides the illusion that software has full control over the hardware
  - Run multiple instances of an OS or different OSes simultaneously on the same physical machine



# VMMS TODAY

- VMs are used everywhere
  - Popularized by cloud computing
  - Used to solve different problems
- VMMs are a hot topic in industry and academia
  - Industry commitment
    - Software: VMware, Xen,…
    - Hardware: Intel VT, AMD-V
  - Academia: lots of related projects and papers

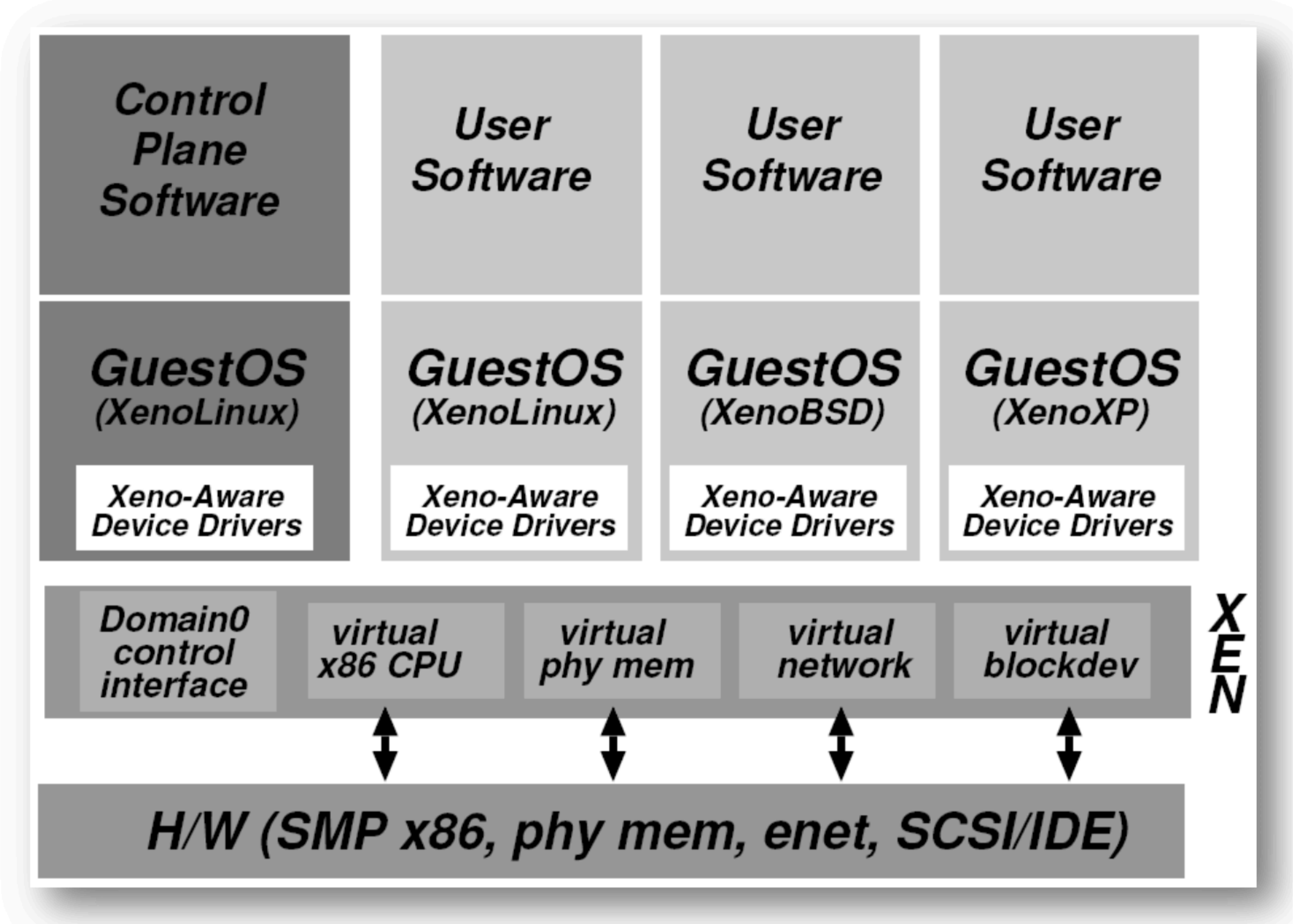
# IMPLEMENTING VMMS - REQUIREMENTS

- Fidelity
  - OSes and applications work the same without modification
  - (although we may modify the OS a bit)
- Isolation
  - VMM protects resources and VMs from each other
- Performance
  - VMM is another layer of software…and therefore overhead
  - As with OS, want to minimize this overhead
  - CPU-intensive apps: 2-10% overhead (early)
  - I/O-intensive apps: 25-60% overhead (much better today)

# VMM CASE STUDY 1: XEN

– Early versions use "paravirtualization"
  – Fancy word for "we have to modify & recompile the OS"
  – Since you're modifying the OS, make life easy for yourself
  – Create a VMM interface to minimize porting and overhead
– Xen hypervisor (VMM) implements interface
  – VMM runs at privilege, VMs (domains) run unprivileged
  – Trusted OS (Linux) runs in own domain (Domain0)
– Most recent version of Xen does not require OS mods
  – Because of Intel/AMD hardware support
– Commercialized via XenSource, but also open source

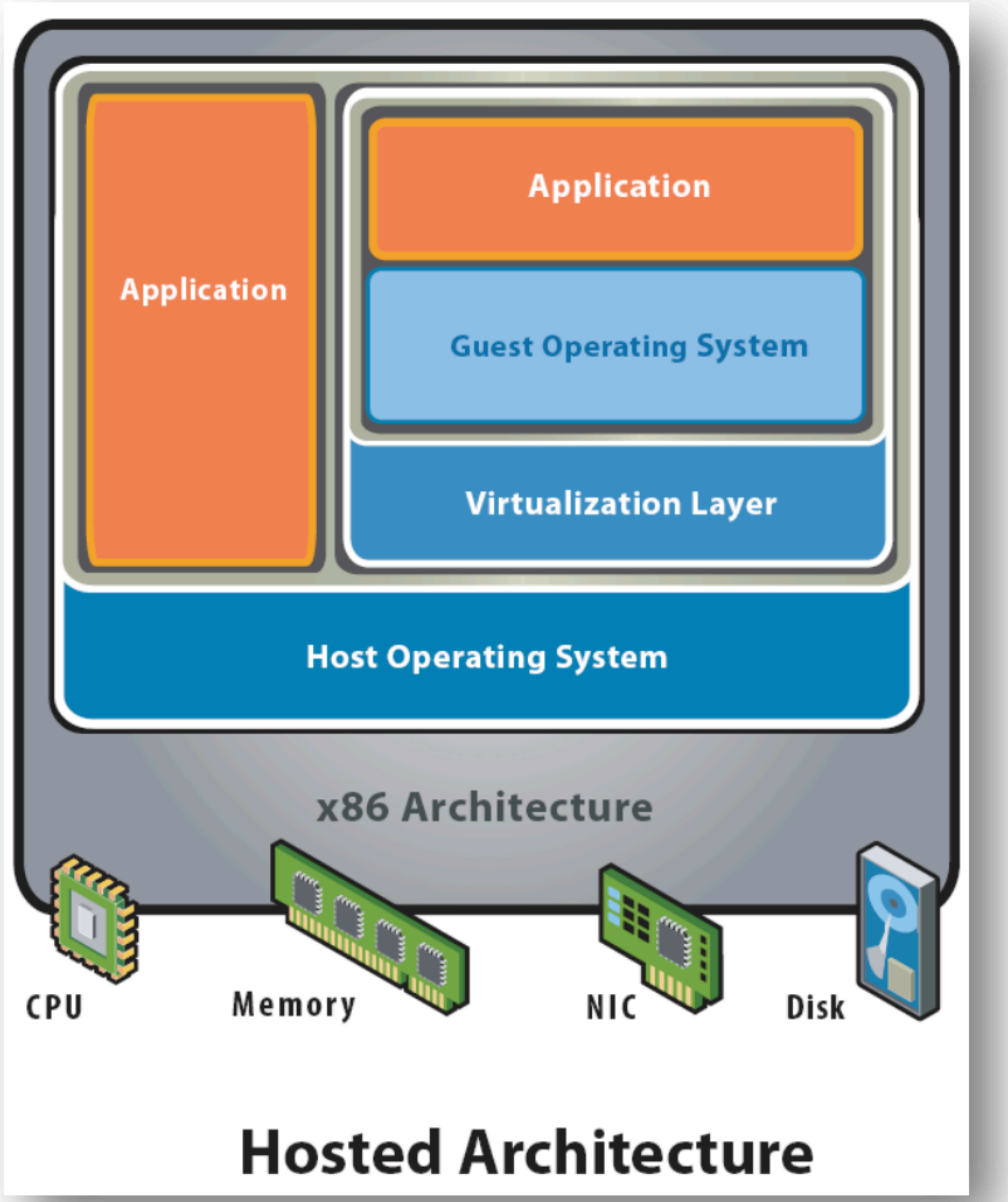
# XEN ARCHITECTURE



# VMM CASE STUDY 2: VMWARE

- VMware workstation uses hosted model
  - VMM runs unprivileged, installed on base OS (+ driver)
  - Relies upon base OS for device functionality
- VMware ESX server uses hypervisor model
  - Similar to Xen, but no guest domain/OS
- VMware uses software virtualization
  - Dynamic binary rewriting translates code executed in VM
  - Think JIT compilation for JVM, but full binary x86 -> IR code -> safe subset of x86
  - Incurs overhead, but can be well-tuned (small % hit)

# VMWARE HOSTED ARCHITECTURE



# WHAT NEEDS TO BE VIRTUALIZED?

- Exactly what you would expect
  - CPU, Memory, I/O devices, Events (exceptions and interrupts)

- How to do it?

# APPROACH 1: COMPLETE MACHINE SIMULATION

- Simplest VMM approach, used by bochs
- Run the VMM as a regular user application atop a host OS
- Application simulates all the hardware (i.e., a simulator)
  - CPU – A loop that fetches each instruction, decodes it, simulates its effect

```
while (1) {
  curr_instr = fetch(virtHw.PC); virtHw.PC += 4;
  switch (curr_instr) {
    case ADD:
      int sum = virtHw.regs[curr_instr.reg0] +
        virtHw.regs[curr_instr.reg1];
    virtHw.regs[curr_instr.reg0] = sum;
    break;
    case SUB: //...
```

  - Memory – Memory is just an array, simulate the MMU on all memory accesses
  - I/O – Simulate I/O devices, programmed I/O, DMA, interrupts

# APPROACH 1: COMPLETE MACHINE SIMULATION

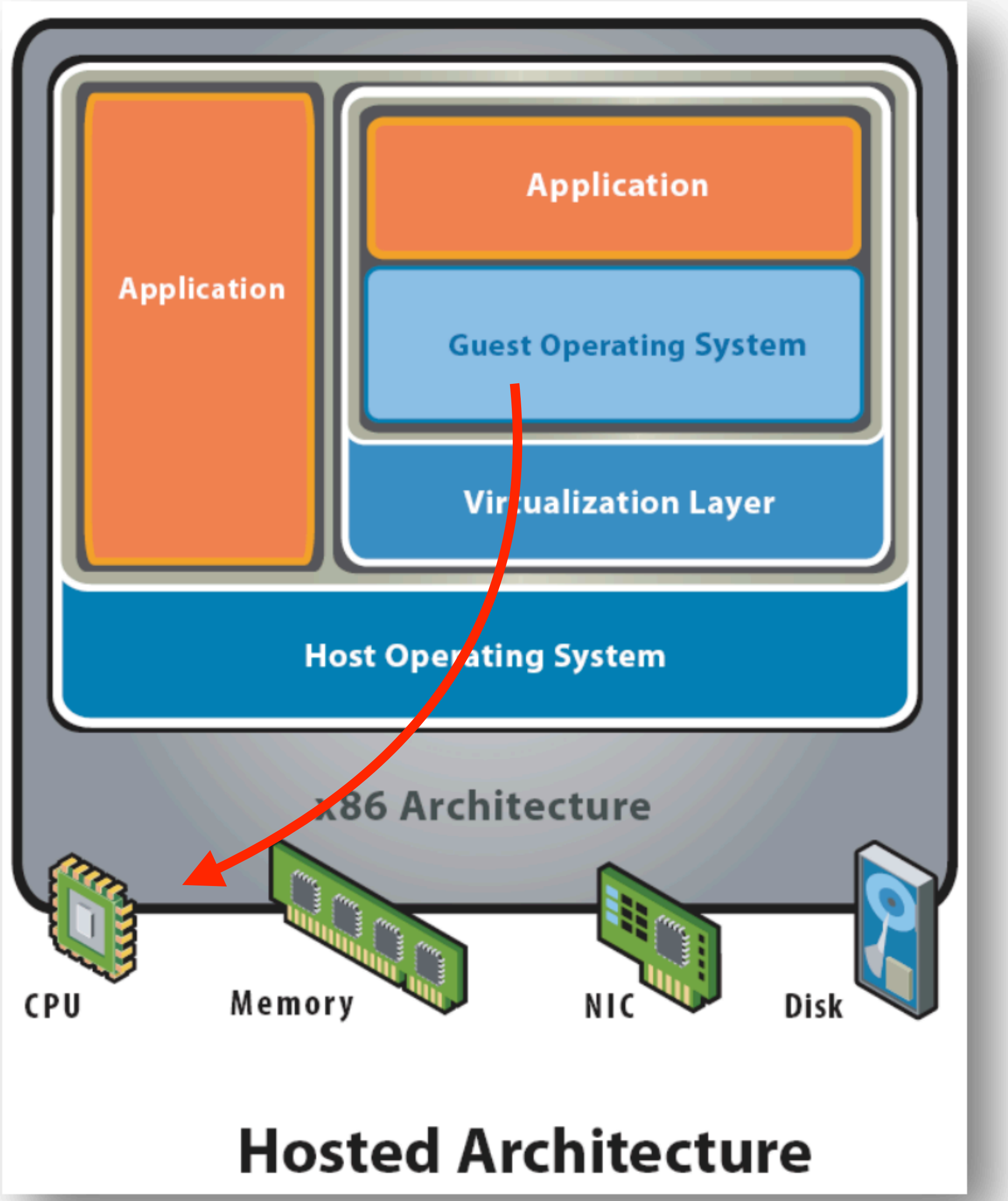

This 8-bit processor built in Minecraft can run its own games I PCWorld

# APPROACH 1: COMPLETE MACHINE SIMULATION

- Simplest VMM approach, used by bochs
- Run the VMM as a regular user application atop a host OS
- Application simulates all the hardware (i.e., a simulator)
- Problem?
- Too slow!
  - CPU/Memory – 100x CPU/MMU simulation
  - I/O Device – < 2× slowdown.
  - 100× slowdown makes it not too useful
- Need faster ways of emulating CPU/MMU

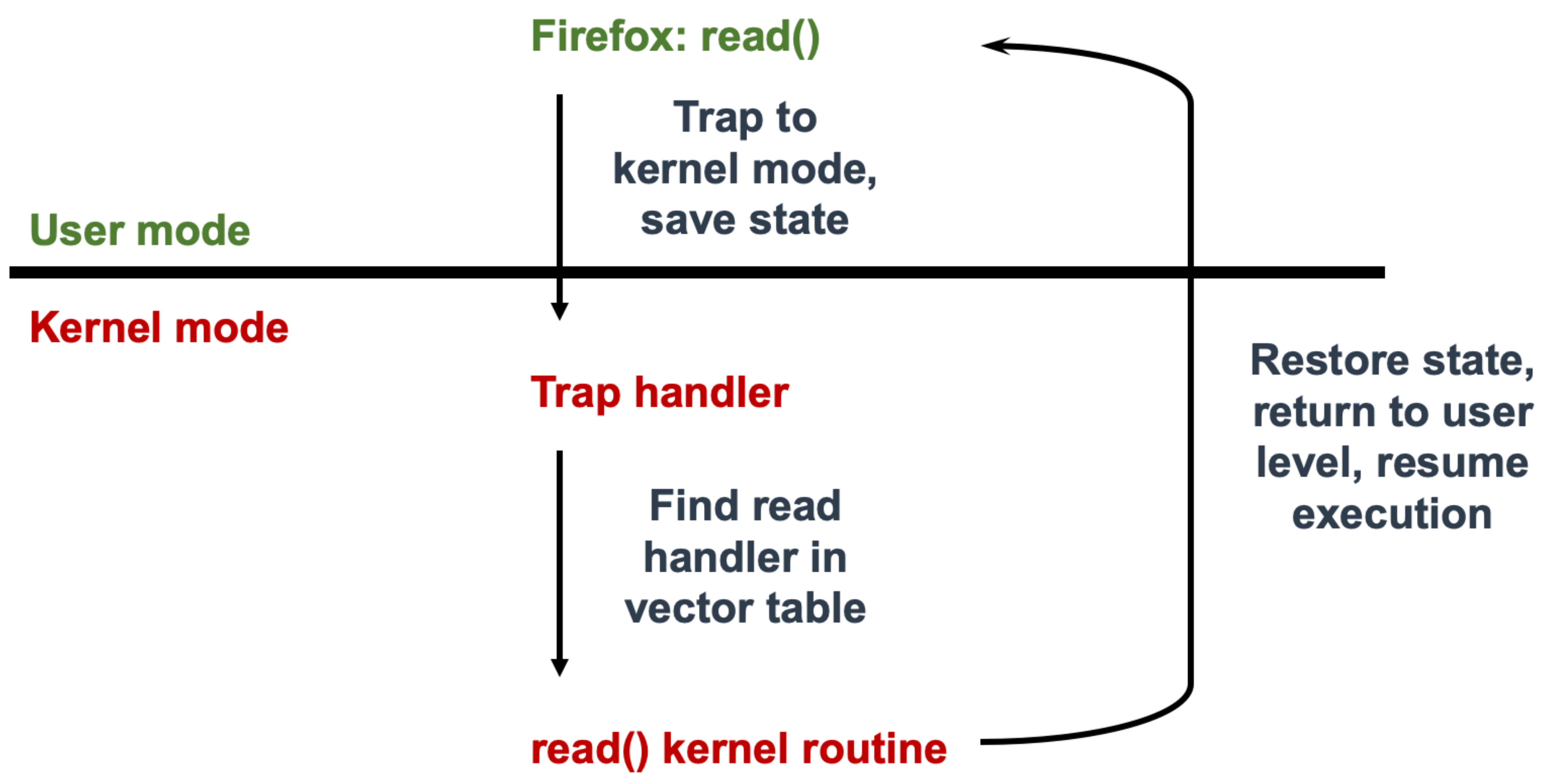
# APPROACH 2: DIRECT EXECUTION W/ TRAP & EMULATE

- Observations: Most instructions are the same regardless of processor privileged level
  - Example: incl %eax
- Why not just give instructions to CPU to execute?
  - One issue: Safety – How to get the CPU back? Or stop it from stepping on us? How about cli/halt?
  - Solution: Use protection mechanisms already in CPU



# BACKGROUND: DUAL-MODE OPERATION IN CPU

- User mode
  - Limited privileges
  - Only those granted by the operating system kernel
- Kernel mode
  - Execution with the full privileges of the hardware
  - Read/write to any memory, access I/O device, read/write disk sector, send/read packet



# APPROACH 2: DIRECT EXECUTION W/ TRAP & EMULATE

- Run virtual machine's OS directly on CPU in unprivileged user mode
  - "Trap and emulate" approach
  - Most instructions just work
  - Privileged instructions trap into monitor and run simulator on instruction

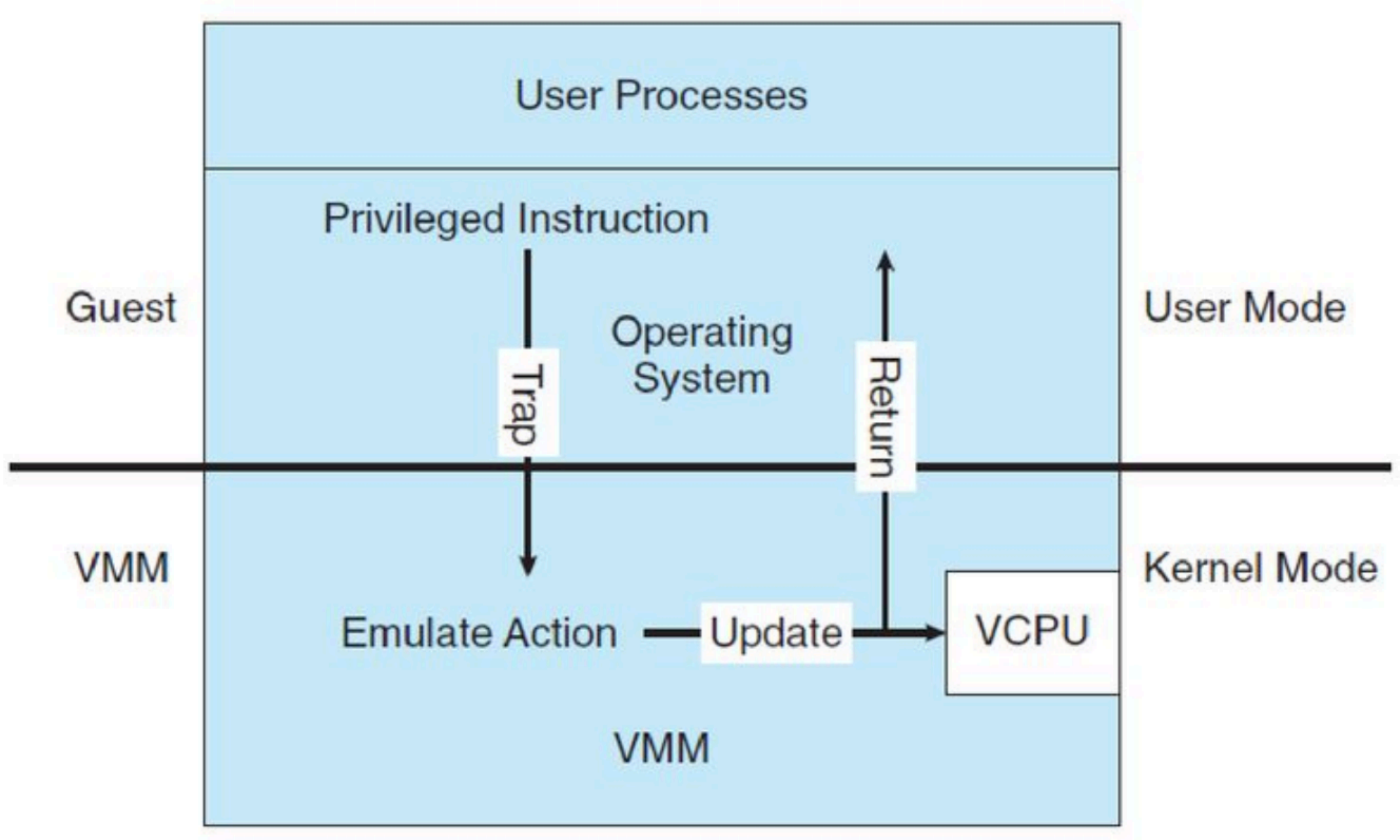
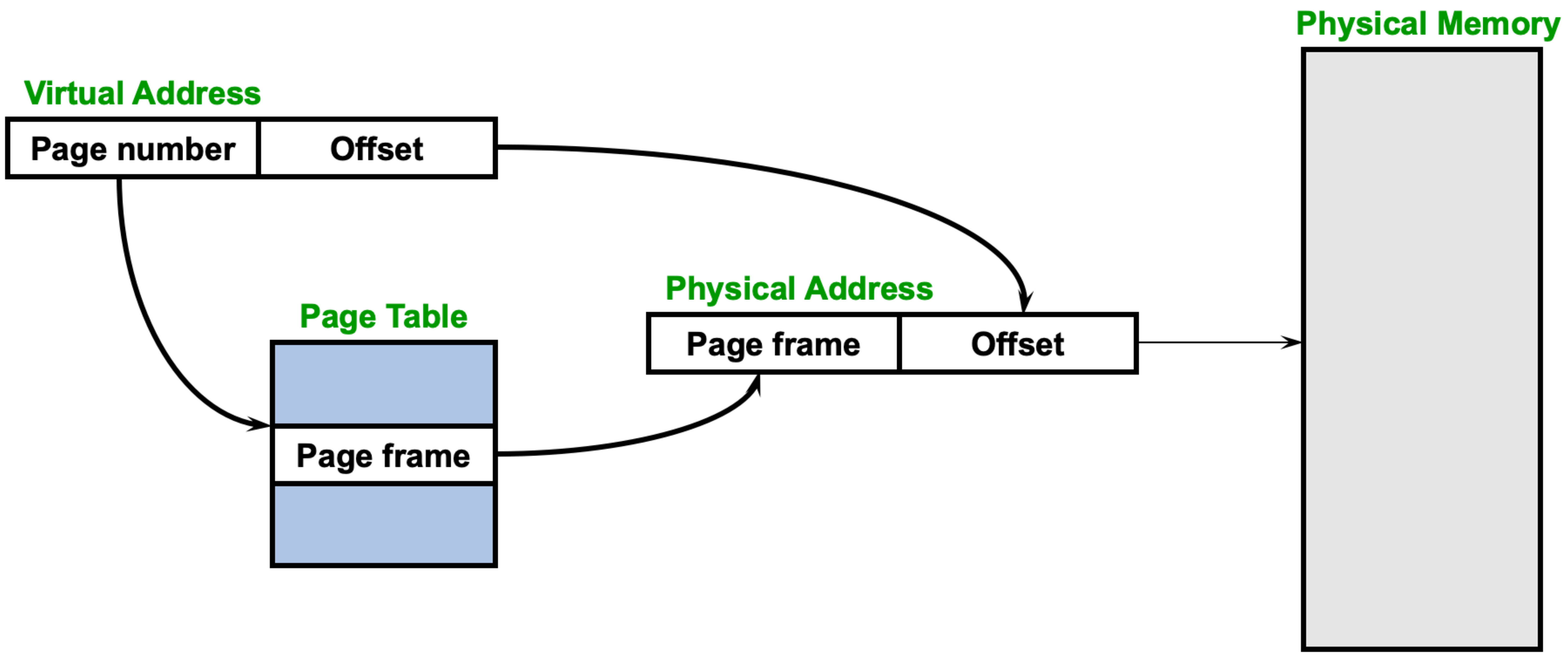
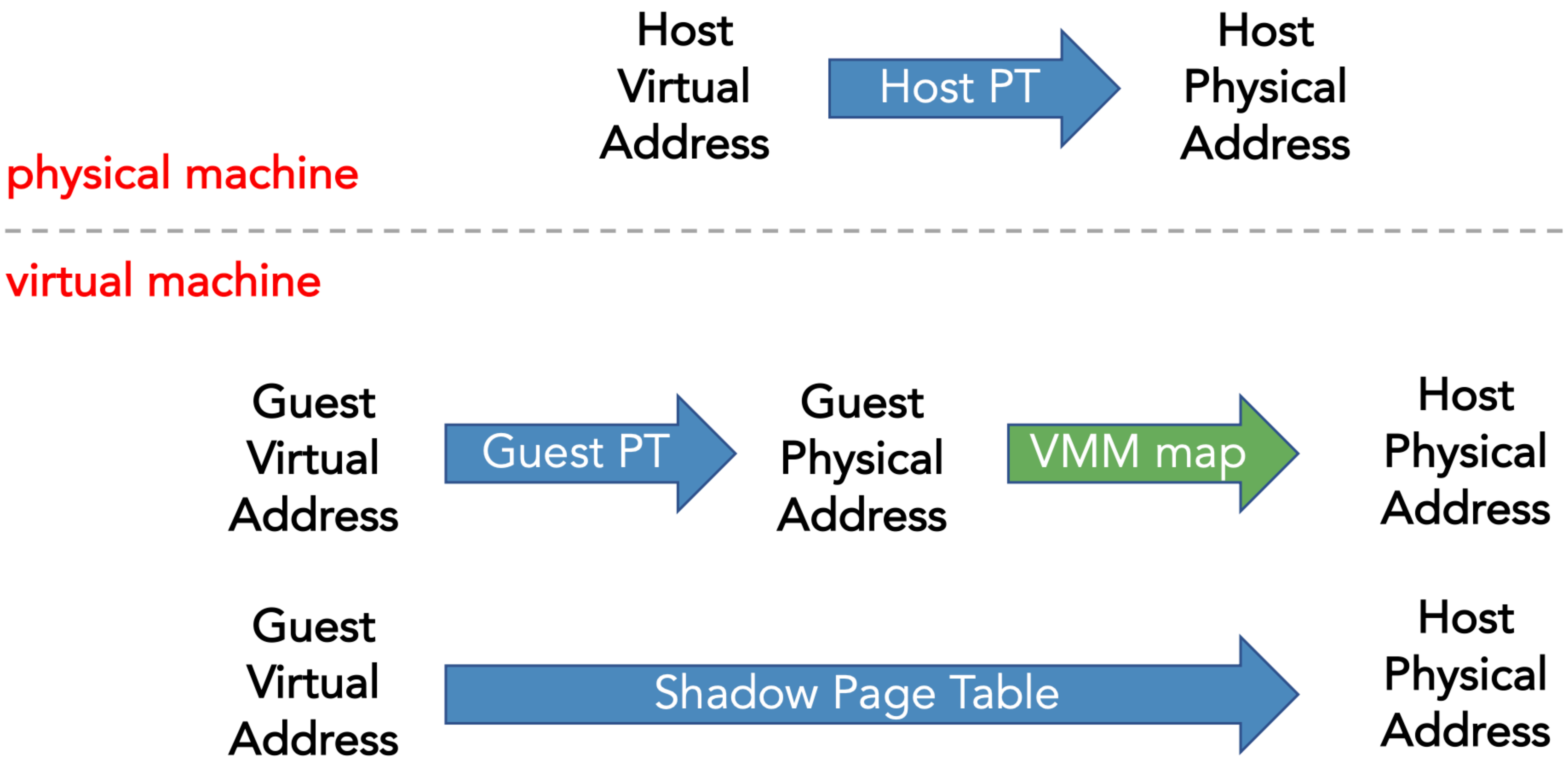



**Figure 16.2** Trap-and-emulate virtualization implementation.

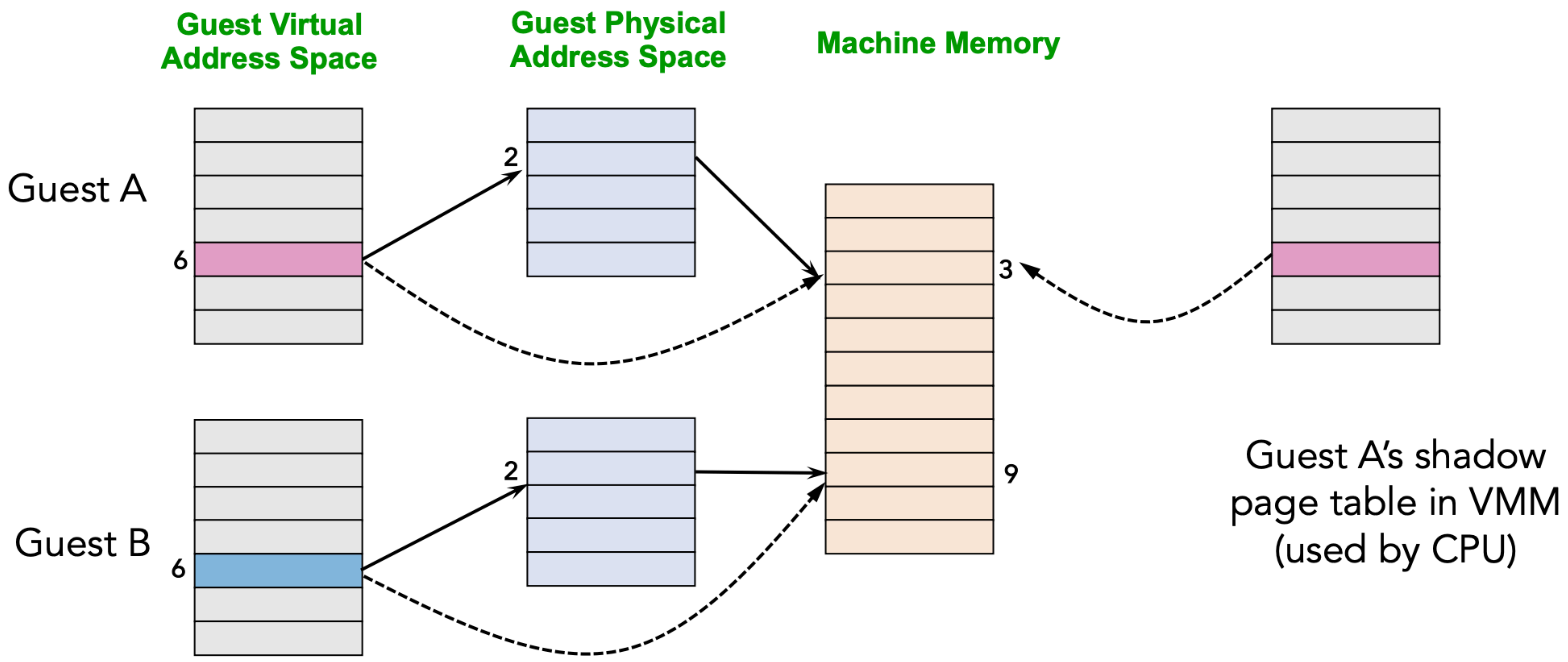
# BACKGROUND: PAGE TABLE



# VIRTUALIZING MEMORY



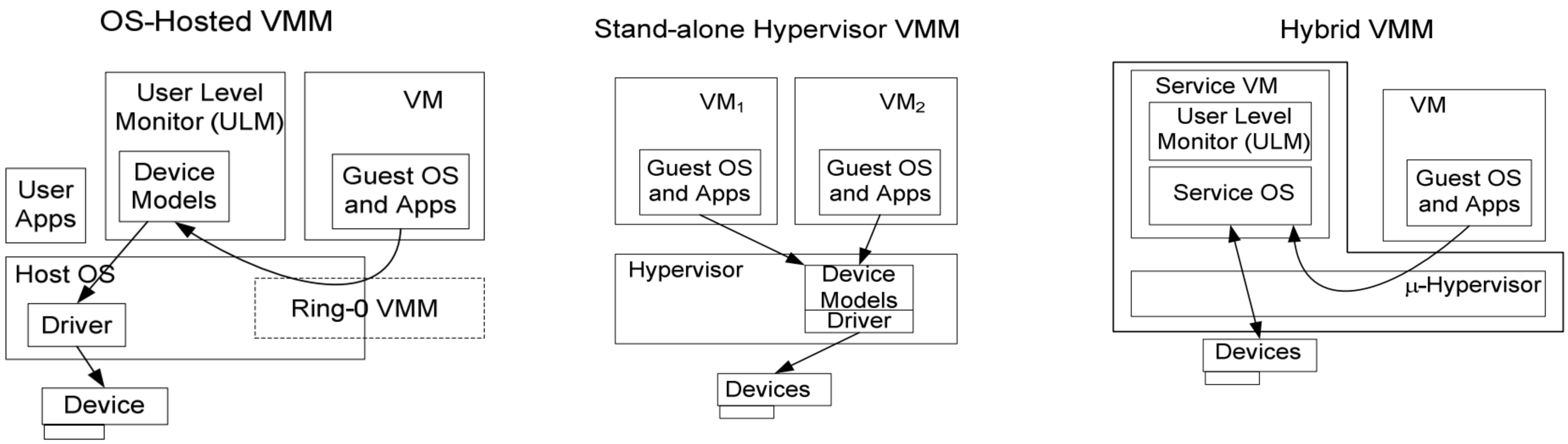
# VIRTUALIZING MEMORY



# VIRTUALIZING I/O: THREE MODES

- Xen: modify OS to use low-level I/O interface (**hybrid**)
  - Define generic devices with simple interface: Virtual disk, virtual NIC, etc.
  - Ring buffer of control descriptors, pass pages back and forth
  - Handoff to trusted domain running OS with real drivers
- VMware: VMM supports generic devices (**hosted**)
  - E.g., AMD Lance chipset/PCNet Ethernet device
  - Load driver into OS in VM, OS uses it normally
  - Driver knows about VMM, cooperates to pass the buck to a real device driver (e.g., on underlying host OS)
- VMware ESX Server: drivers run in VMM (**hypervisor**)

# VIRTUALIZING I/O: THREE MODES

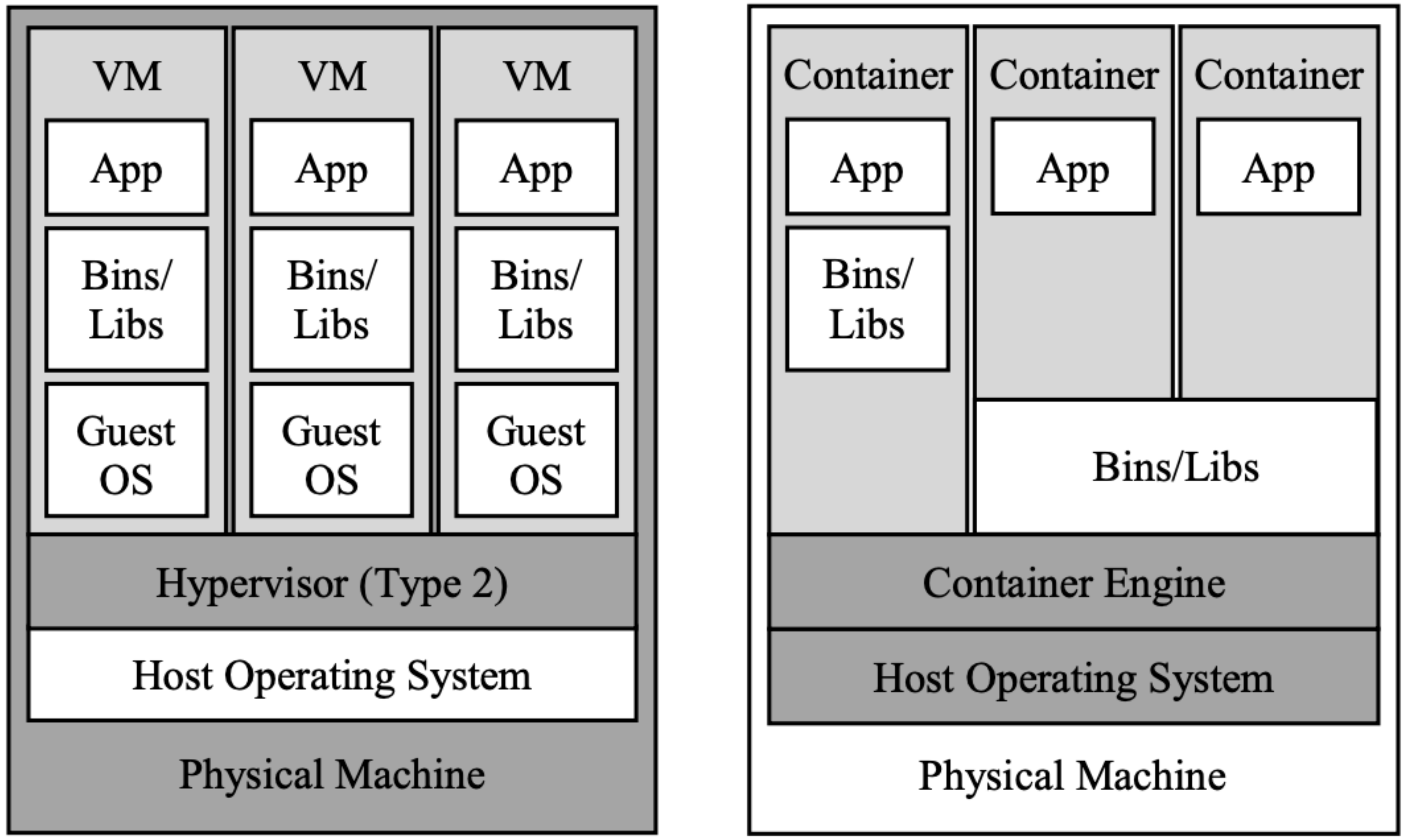



Abramson et al., "Intel Virtualization Technology for Directed I/O", Intel Technology Journal, 10(3) 2006

# Containers

# CONTAINERS

https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7921010




(a) Hypervisor-based virtual service.

(b) Container-based virtual service.

# DIFFERENCES BETWEEN VMMS AND CONTAINERS

"Virtualization vs Containerization to support PaaS", VMware

| Parameter |
|---|
| Guest OS |
| Communi-cation |
| Security |
| Performance |
| Isolation |
| Startup time |
| Storage |

# DIFFERENCES BETWEEN VMMS AND CONTAINERS

"Virtualization vs Containerization to support PaaS", VMware

| Parameter | Virtual Machines | Containers |
|---|---|---|
| Guest OS | Each VM runs on virtual hardware and Kernel is loaded into in its own memory region | All the guests share same OS and Kernel. Kernel image is loaded into the physical memory |
| Communication | Will be through Ethernet Devices | Standard IPC mechanisms like Signals, pipes, sockets etc. |
| Security | Depends on the implementation of Hypervisor | Mandatory access control can be leveraged |
| Performance | Virtual Machines suffer from a small overhead as the Machine instructions are translated from Guest to Host OS. | Containers provide near native performance as compared to the underlying Host OS. |
| Isolation | Sharing libraries, files etc between guests and between guests hosts not possible. | Subdirectories can be transparently mounted and can be shared. |
| Startup time | VMs take a few mins to boot up | Containers can be booted up in a few secs as compared to VMs. |
| Storage | VMs take much more storage as the whole OS kernel and its associated programs have to be installed and run | Containers take lower amount of storage as the base OS is shared |

# DOCKER

- A software platform that allows you to build, test, and deploy applications quickly.
- Docker packages software into standardized units
  - including libraries, system tools, code, and runtime.
- Quickly deploy and scale applications into any environment

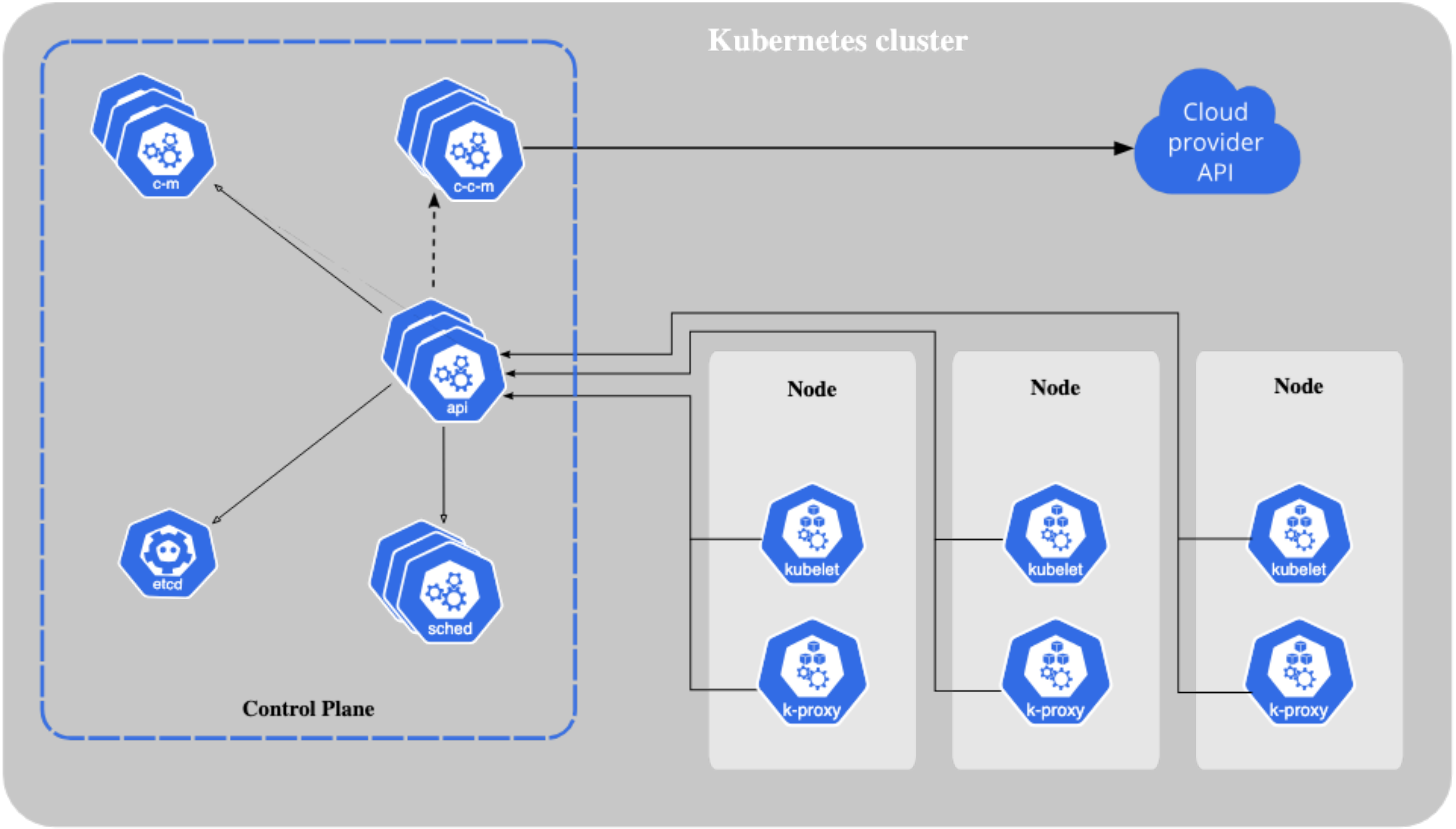
```
ARG CODE_VERSION=latest
FROM ubuntu:${CODE_VERSION}
COPY ./examplefile.txt /examplefile.txt
ENV MY_ENV_VARIABLE="example_value"
RUN apt-get update

# Mount a directory from the Docker volume
# Note: This is usually specified in the 'docker run' command.
VOLUME ["/myvolume"]

# Expose a port (22 for SSH)
EXPOSE 22
```

Example Docker file

# KUBERNETES (K8S)

- An open-source container orchestration system
- Inspired by Google's Borg cluster manager
- Widely deployed software systems in the world
- Features
  - Service discovery and load balancing
  - Storage orchestration
  - Automated rollouts and rollbacks
  - Self-healing
  - ...

# KUBERNETES (K8S)



## IS THERE A WAY TO TELL LIVING IN VIRTUALIZATION OR REALITY?

- For humans, maybe not
- For software, especially malware, yes
  - Scan registry entries specific to virtualization software
  - Monitor for specific processes or files that are typically part of virtualization software
  - Check firmware: known MAC addresses associated with virtual machines, check BIOS serial numbers
  - Run specialized instruction sets
- Some malware try to escape from VMs (*run, Neo!*)

# TAKEAWAYS

- VMMs multiplex virtual machines on hardware
- Implementing VMMs by virtualizing CPU, Memory, I/O
- Lesson: Never underestimate the power of **indirection**
- Next class: **Hacker Day**
  - fix bugs in lab 2a, 2b and implement lab 2c!

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