Virtual Machines

COS 316: Principles of Computer System Design

Amit Levy & Wyatt Lloyd

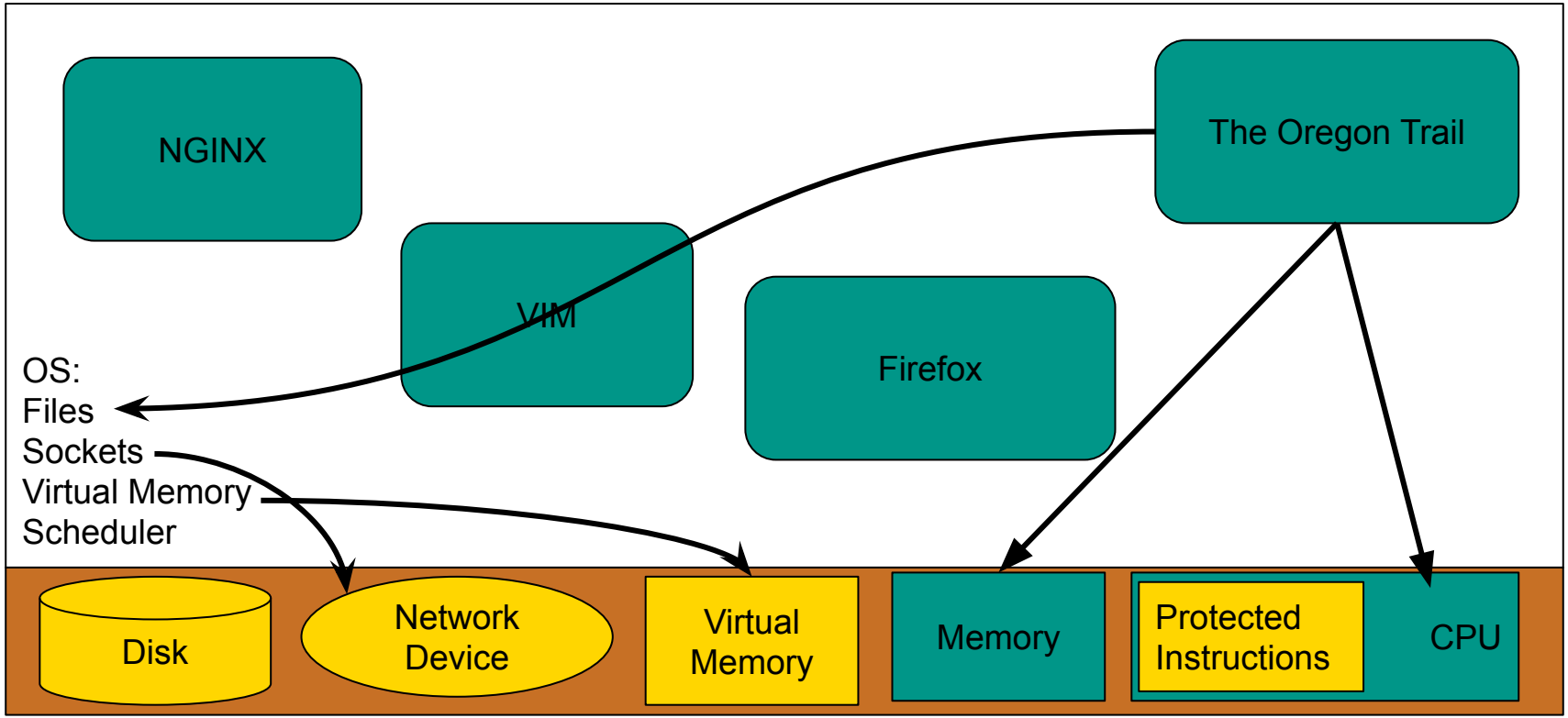
Layering: When it works we get

- Modularity
  - Application developer and ethernet developer can work independently
- Portability
  - The narrow waist of IP
- Hide complexity with abstraction
  - Simple applications on top of TCP
- Re-use
  - Many transport protocols on to of IP

Layering and Its Discontents

- How layering can *fail* and why abstraction can sometimes be *bad*
  - Poor choices of abstraction
  - Too much abstraction
- When to “pop open the hood”?
- Important, ubiquitous systems sometimes an accident of history

Traditional Operating System



Operating Systems Have *Thick* Abstractions

UNIX File System

- Files divide disk into non-contiguous chunks.
- File system layers need to interpose between applications and disk

Sockets

- Use transport-layer specific abstractions
  - E.g., allocate by tuple of (destination address, destination port, source port)
- Networking subsystem routes each packet, allocates new sockets

Big abstractions & multicore

The year is [some year in the 1990s]...

CPUs have ***1 core***

Operating systems are ***monolithic*** and ***centralized***

But...

Single-core CPU acceleration is slowing…

Your next computer will have ***many cores***

Scalability: Disco (1997)

> “Extensive modifications to the operating system are required to efficiently support scalable machines.”

> “[W]e examine the problem of extending modern operating systems to run efficiently on large-scale shared-memory multiprocessors without a large implementation effort. [...] We use virtual machines to run multiple commodity operating systems on a scalable multiprocessor.”

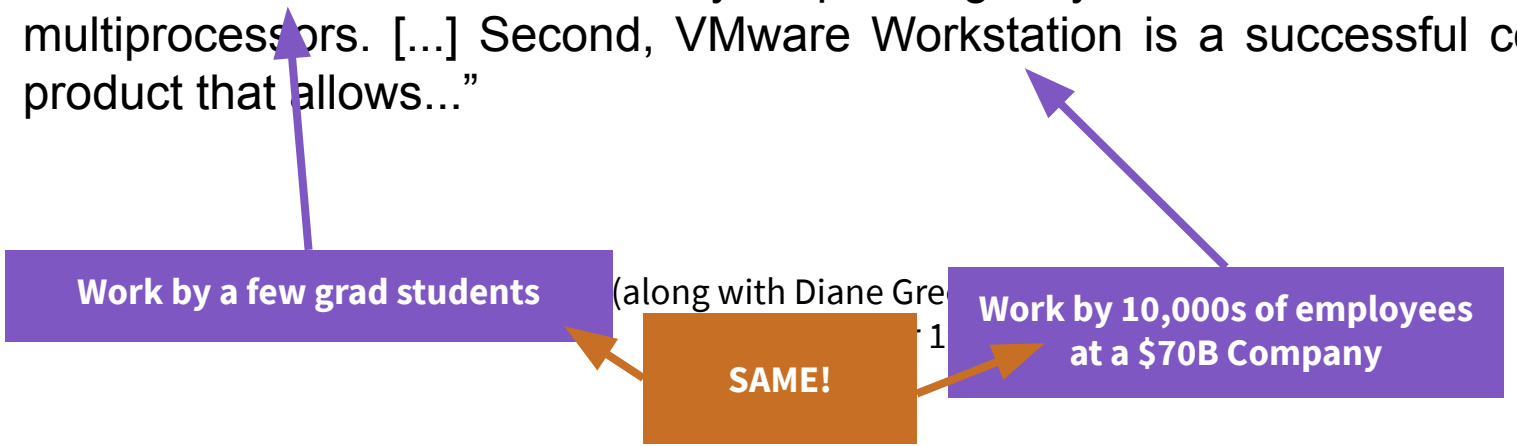
“Disco: Running Commodity Operating Systems on Scalable Multiprocessors”
Edouard Bugnion, Scott Devine, Kinshuk Govil, and Mendel Rosenblum

Ed, Scott & Mendel (along with Diane Green) founded VMWare a year later in October 1998

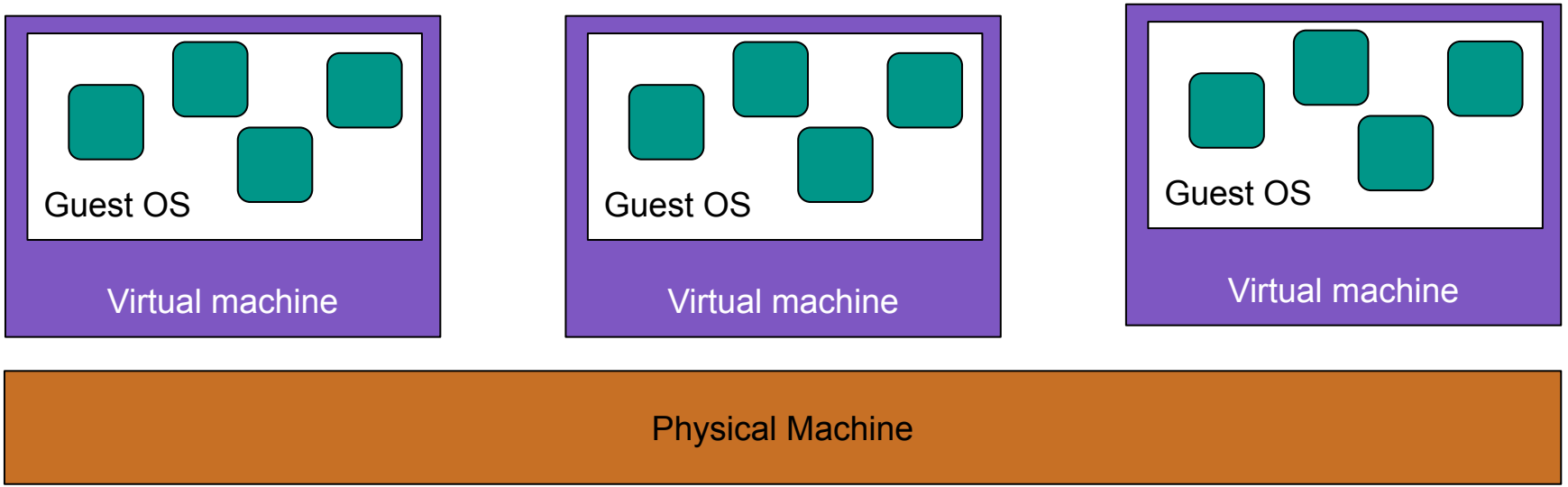
Scalability: Disco (1997)

From Edouard Bugnion's job talk at EPFL in 2014:

"First, Disco ran commodity operating systems on scalable MIPS multiprocessors. [...] Second, VMware Workstation is a successful commercial product that allows..."



Virtual Machines



Virtualization

presents a physical machine as though many guest OSs had exclusive access

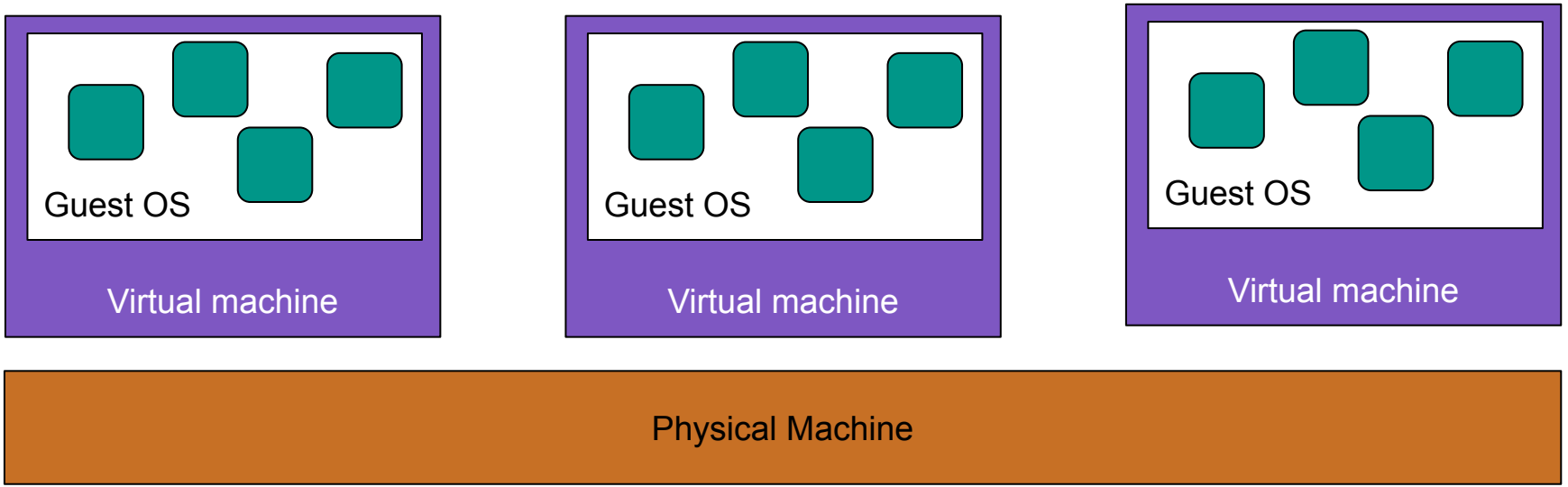
Isn’t a VMM just an Operating System?

- Yes!
- No: API is hardware resources (disk, network card), not abstract interfaces (file system, socket)

Virtual Machines vs. Processes

	Virtual Machine Interface	**Process Interface**
Network	Network device (ethernet, WiFi, etc…)	TCP & UDP sockets
Storage	Block device	File System
Compute	CPU	Unprivileged subset of CPU (x86/ARM/RISC-V...)
Memory	Virtual & physical memory addresses	Virtual addresses only

Virtual Machines



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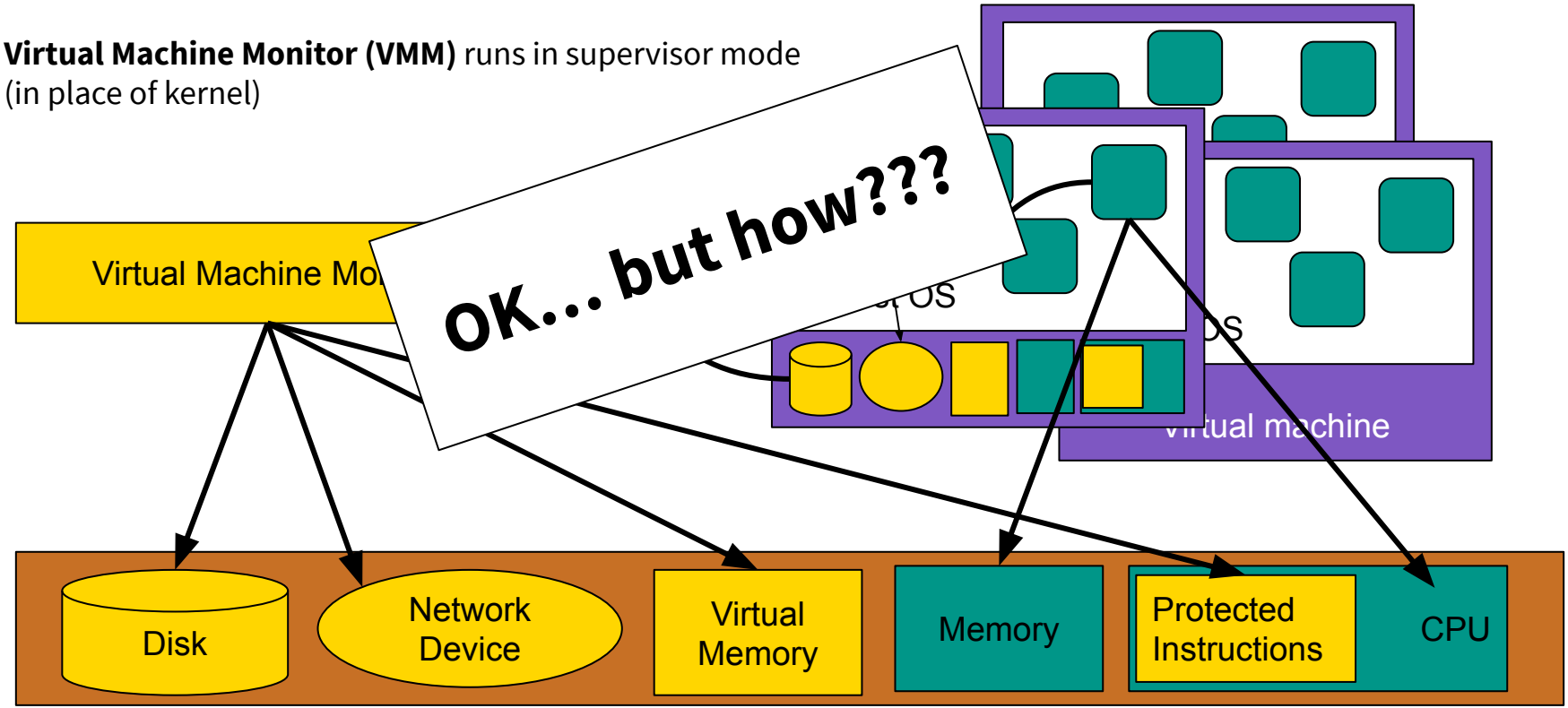
But How??

Virtual Machines

Virtual Machine Monitor (VMM) runs in supervisor mode
(in place of kernel)



Trap-and-Emulate: System Calls

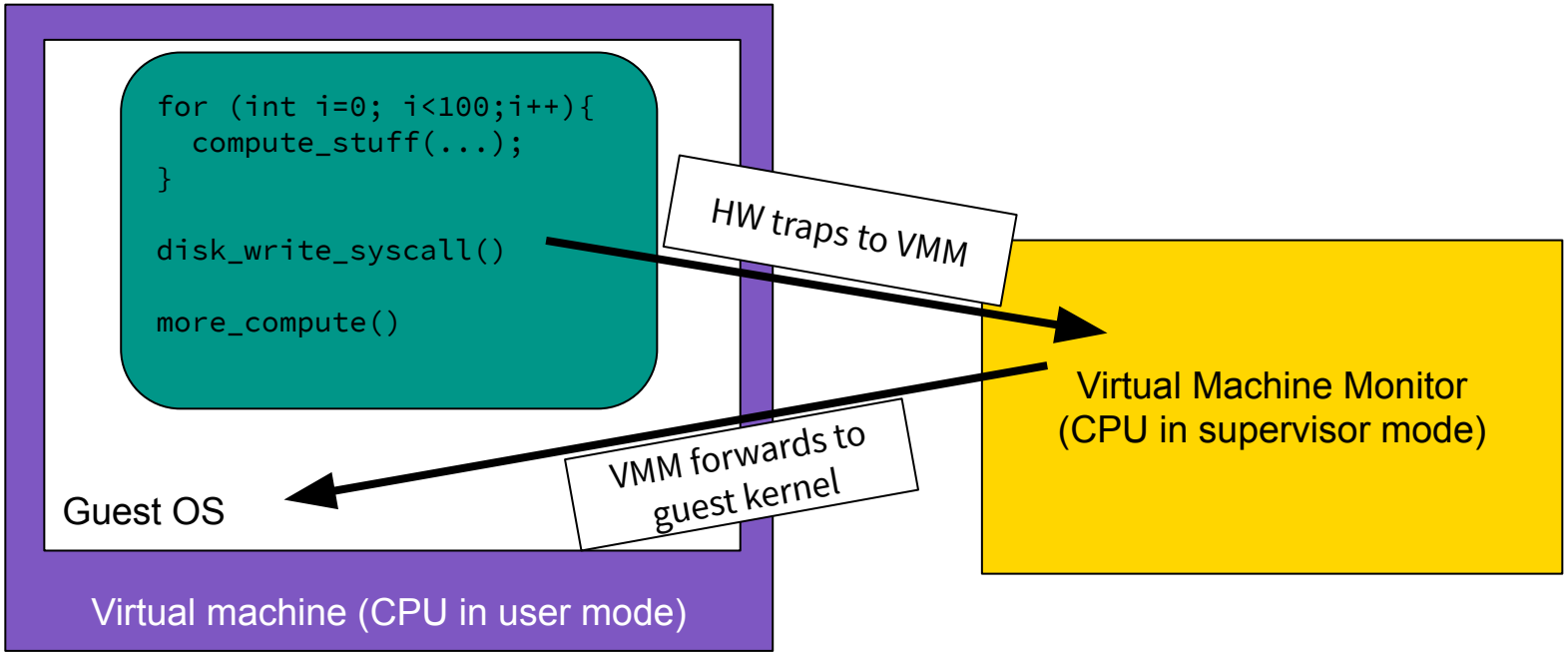
Assumes typical separation of applications and operating systems:

1. Applications interact with hardware by issuing system calls
2. System calls trapped by hardware which switches to OS context
3. OS uses *protected instructions* to access hardware directly

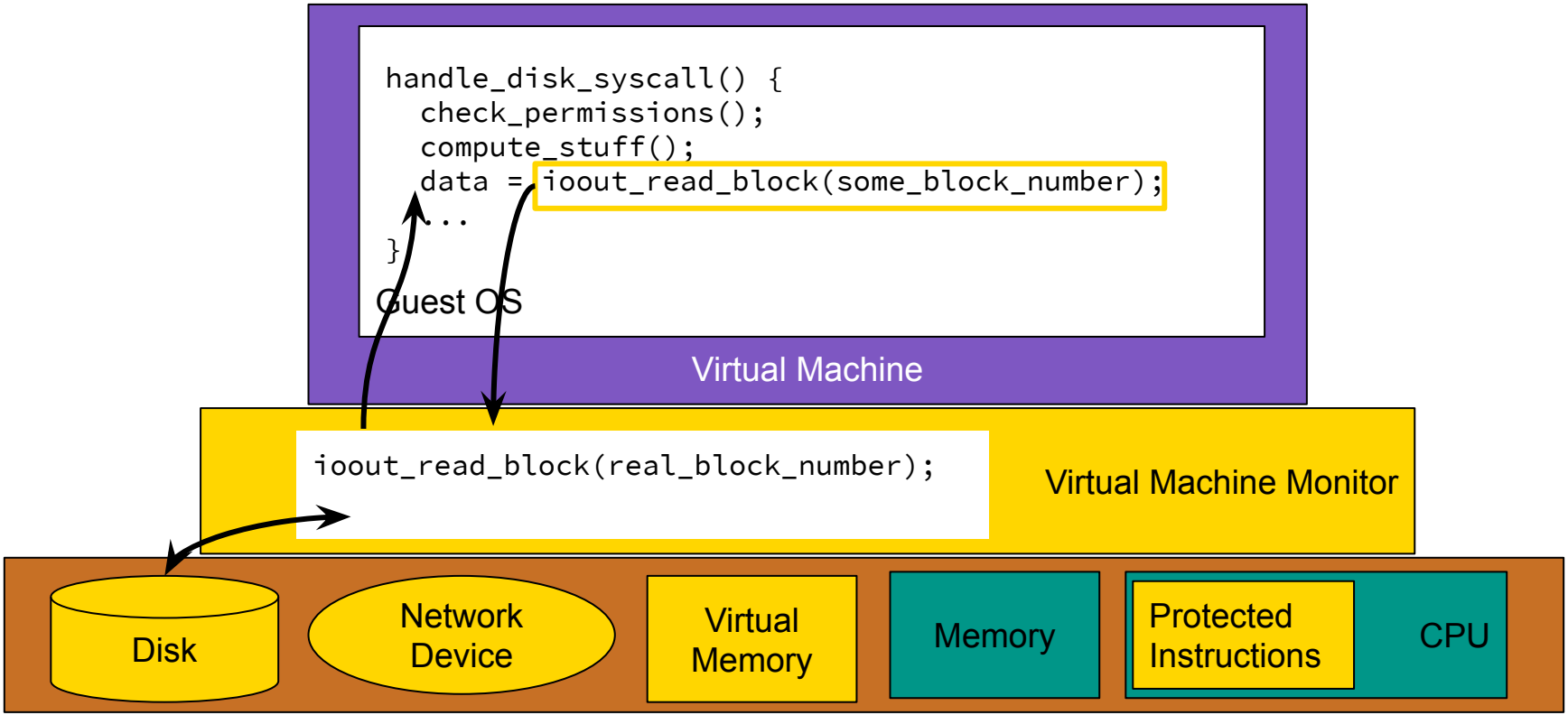
Virtual Machine Monitor “routes” system calls to appropriate guest OS

OS, running in process mode, causes trap through hardware on *protected instruction*

Trap-and-Emulate: System Calls



Trap-and-Emulate: I/O



What if we *can't* trap-and-emulate?

x86 didn't fault when some protected instructions were executed by user programs.

E.g. setting interrupt flags with Pop-Flags (POPFL) instruction silently fails

- Binary translation
  - Before running VM code for the first time, translate it to replace with explicit calls to VMM
  - Disco & early VMWare
- Para-virtualization
  - Modify guest OSs to detect if they are running inside a VM and use different instructions
  - Xen (2003) & most VMMs since
- Modify the hardware
  - Intel VT-X, APICV, VT-d, SR-IOV, GVT-d, and on and on… starting 2005

Flexibility: VMWare Workstation, Parallels

1999-~2006

Use virtual machines alongside physical machines

Run Windows apps on Linux, and Linux apps on Windows

Cloud Computing: Amazon EC2

“Before the advent of Amazon EC2, you had to buy or rent sufficient servers to cover your present needs, and you also had to be able to anticipate [and] forecast [...] for enough hardware to accomodate*(sic)* [...] growth as well as bursts of traffic [...]

With Amazon EC2, you don’t need to acquire hardware in advance of your needs. Instead, you simply turn up the dial, spawning more virtual CPUs, as your processing needs grow.”

-Amazon EC2 Announcement, August 25th 2006 *Jeff Barr*

Did VMMs solve scalability?

- Yes! Can harness increasing number of cores to run more virtual machines!
- No: VMMs don’t help scale *individual* applications
- No: VMMs don’t mediate *sharing* between virtual machines

A decade later:
“An Analysis of Linux Scalability to Many Cores”
Silas Boyd-Wickizer, Austin T. Clements, Yandong Mao, Aleksey Pesterev, M. Frans Kaashoek, Robert Morris, and Nickolai Zeldovich

Careful adaptation of OS kernels broke the scalability barrier

Virtual Machine Conclusions

- Traditional *implementations* of OS abstractions poor fit for multicore
- Difficult to re-implement thick abstractions
- VMMs introduced a much simpler machine abstraction
  - Just run multiple OSs to “scale”
  - A decade to take advantage of increased density before OSs caught up
- Would we still build VMWare/EC2 today?