Virtualization

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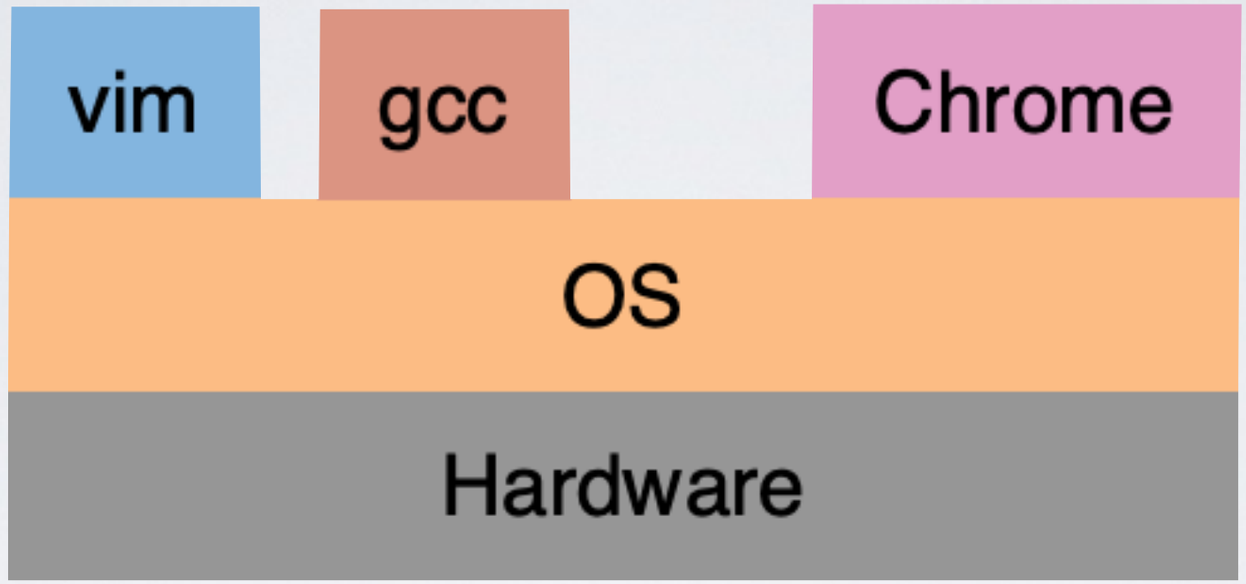
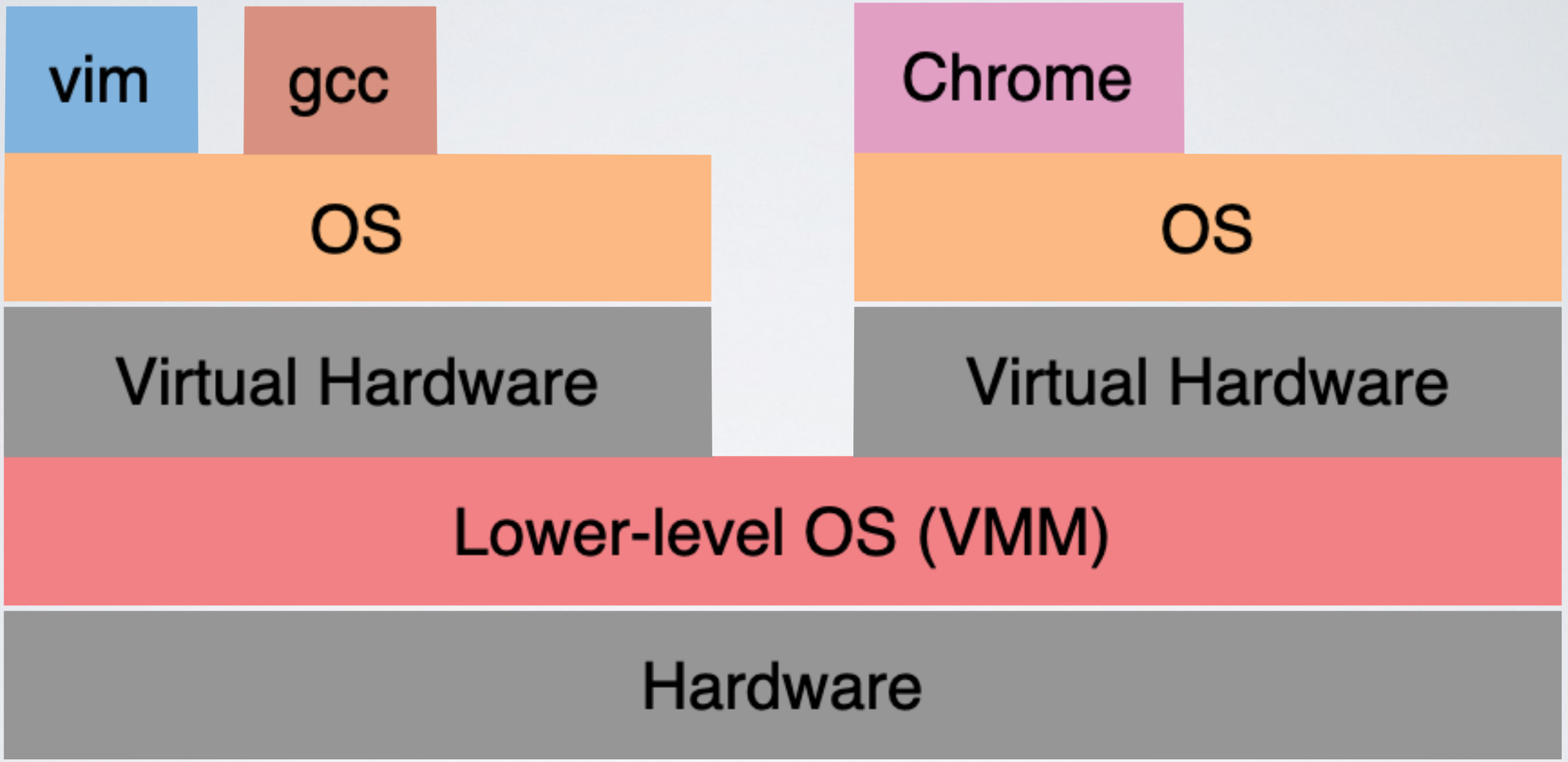
(recap) What is an OS?



OS is a software between applications and hardware

- Abstracts hardware to makes applications portable
- Makes finite resources (memory, # CPU cores) appear much larger and fully dedicated to running one application
- Protects processes and users from one another

What if…



➡ The process abstraction looked just like hardware?

How do process abstraction & hardware differ

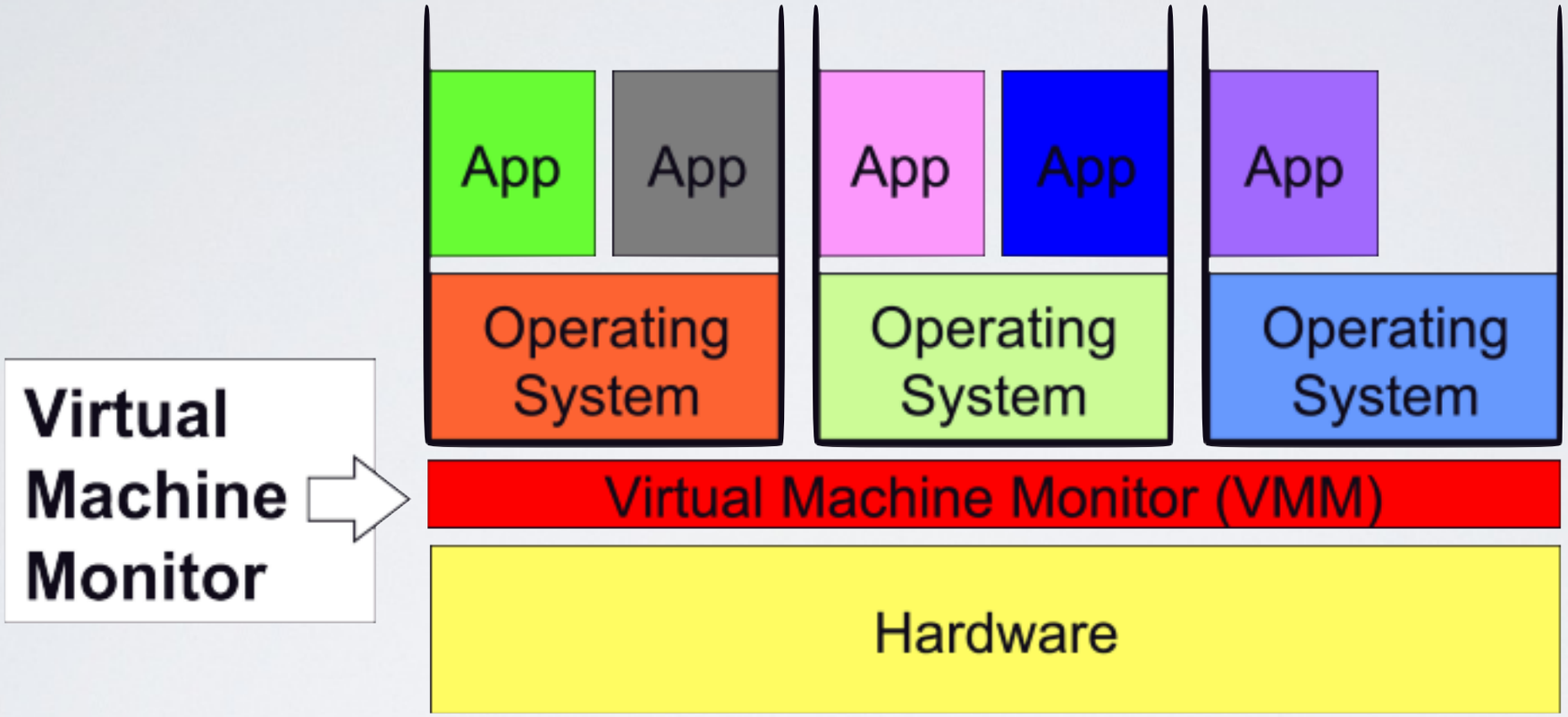
Process

- Non-privileged registers and instructions
- Virtual memory
- Errors and signals
- File systems, directories, files, raw devices

Hardware

- All registers and instructions
- Both virtual and physical memory, MMU functions, TLB/page tables ...
- Trap, interrupts
- I/O devices accessed through programmed I/O, DMA, interrupts

VMM - Virtual Machine Monitor



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

➡ **The Virtual Machine Monitor (a.k.a Hypervisor)**
runs multiple OSes simultaneously on the same physical machine

Motivations

Old idea from the 70s

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 80s and 90s

- Hardware got cheap
- The era of the personal computer (Windows)

➡ Revived by the Disco work
led by *Mendel Rosenblum*, later lead to the foundation of *VMware*

➡ Another important work *Xen*

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, VirtualBox, ...*
  Hardware : *Intel VT, AMD-V*
- Academia - lots of related projects and papers

Why would you do such a crazy thing?

- **Software compatibility**
  VMMs can run pretty much all software (since they can pretty much all OSes)

- **Resource utilization**
  Machines today are powerful, want to multiplex their hardware

- **Isolation**
  Seemingly total data isolation between virtual machines

- **Encapsulation**
  Virtual machines are not tied to physical machines

- **Many other cool applications**
  Debugging, emulation, security, fault tolerance…

OS backwards compatibility

Backward compatibility is bane of new OSes as it requires huge efforts to innovate but not break

➡ Security considerations may make it impossible in practice

Logical partitioning of servers

Run multiple servers on same box (e.g. Amazon EC2)

- Modern CPUs more powerful than most services need: e.g., only 10% utilization
- VMs let you give away less than one machine for running a service
- Server consolidation: N machines → 1 real machine
- Consolidation leads to cost savings (less power, cooling, management, etc.)

Isolation of environments

- Safety - printer server failure doesn't take down Exchange server
- Security - compromise of one VM cannot get at data of others

Resource management

- Provide service-level agreements

Heterogeneous environments

- Linux, FreeBSD, Windows, etc.

Implementation

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 (that needs to be minimized)

What needs to be virtualized?

Exactly what you would expect

- CPU
- Events (hardware and software interrupts)
- Memory
- I/O devices

Isn't this just duplicating OS functionality in a VMM?

- (yes) approaches will be similar to what we do with OSes
  simpler in functionality, though (VMM much smaller than OS)
- (and no) but implements a different abstraction
  hardware interface vs. OS interface

Approach 1 : complete machine simulation

➡ Simplest VMM approach, used by B*ochs*

Build a simulation of all the hardware

- CPU – a loop that fetches each instruction, decodes it, simulates its effect on the machine state (no direct execution)
- Memory – physical memory is just an array, simulate the MMU on all memory accesses
- I/O – simulate I/O devices, programmed I/O, DMA, interrupts

◉ Too slow!

- CPU/Memory – **100x slowdown**
- I/O Device – 2x slowdown

➡ Need faster ways of emulating CPU/MMU

Approach 2 : virtualizing the CPU/MMU

➡ Observations - most instructions are the same regardless of processor privileged level e.g. `incl %eax`

Why not just give instructions to CPU to execute?

- Problem - safety
  How to prevent privilege instructions from interfering with hypervisor and other OSes?
- Solution - use protection mechanisms already in CPU

➡ "Trap and emulate" approach

- run virtual machine's OS directly on CPU in unprivileged user mode
- privileged instructions trap into monitor and run simulator on instruction

Virtualizing interrupts

OS assumes to be in control of interrupts via the interrupt table

So what happens when an interrupt or trap occurs in a virtual environment?

➡ The VMM handles the interrupt (in kernel mode) using the "virtual" interrupt handler table of the running OS

✓ Some interrupt can be shadowed

Virtualizing memory

OS assumes to be in full control over memory via the page table

But VMM partitions memory among VMs

- VMM needs to assign hardware pages to VMs
- VMM needs to control mappings for isolation
  - Cannot allow an OS to map a virtual page to any hardware page
  - OS can only map to a hardware page given to it by the VMM

Hardware-managed TLBs make this difficult

- When the TLB misses, the hardware automatically walks the page tables in memory
- As a result, VMM needs to control access by OS to page tables

One way - direct mapping

➡ VMM uses the page tables that a guest OS creates (direct mapping by MMU)

VMM validates all updates to page tables by guest OS

- OS can read page tables without modification
- but VMM needs to check all page table entry writes to ensure that the virtual-to-physical mapping is valid

◉ Requires to modify the OS to patch updated to the page table (used in *Xen* paravirtualization)

Another way - level of indirection

Three abstractions of memory

- Machine - actual hardware memory (16 GB of DRAM)
- Physical - abstraction of hardware memory managed by OS
  If a VMM allocates 512 MB to a VM, the OS thinks the computer has 512 MB of contiguous physical memory (underlying machine memory may be discontiguous)
- Virtual - virtual address spaces (similar to virtual memory)
  standard 2^{32} or 2^{64} address space

➡ Translation - from **VM's Guest VA** to **VM's Guest PA** to **Host PA**
in each VM, OS creates and manages page tables for its virtual address spaces without modification but these page tables are not used by the MMU hardware

Shadow page tables

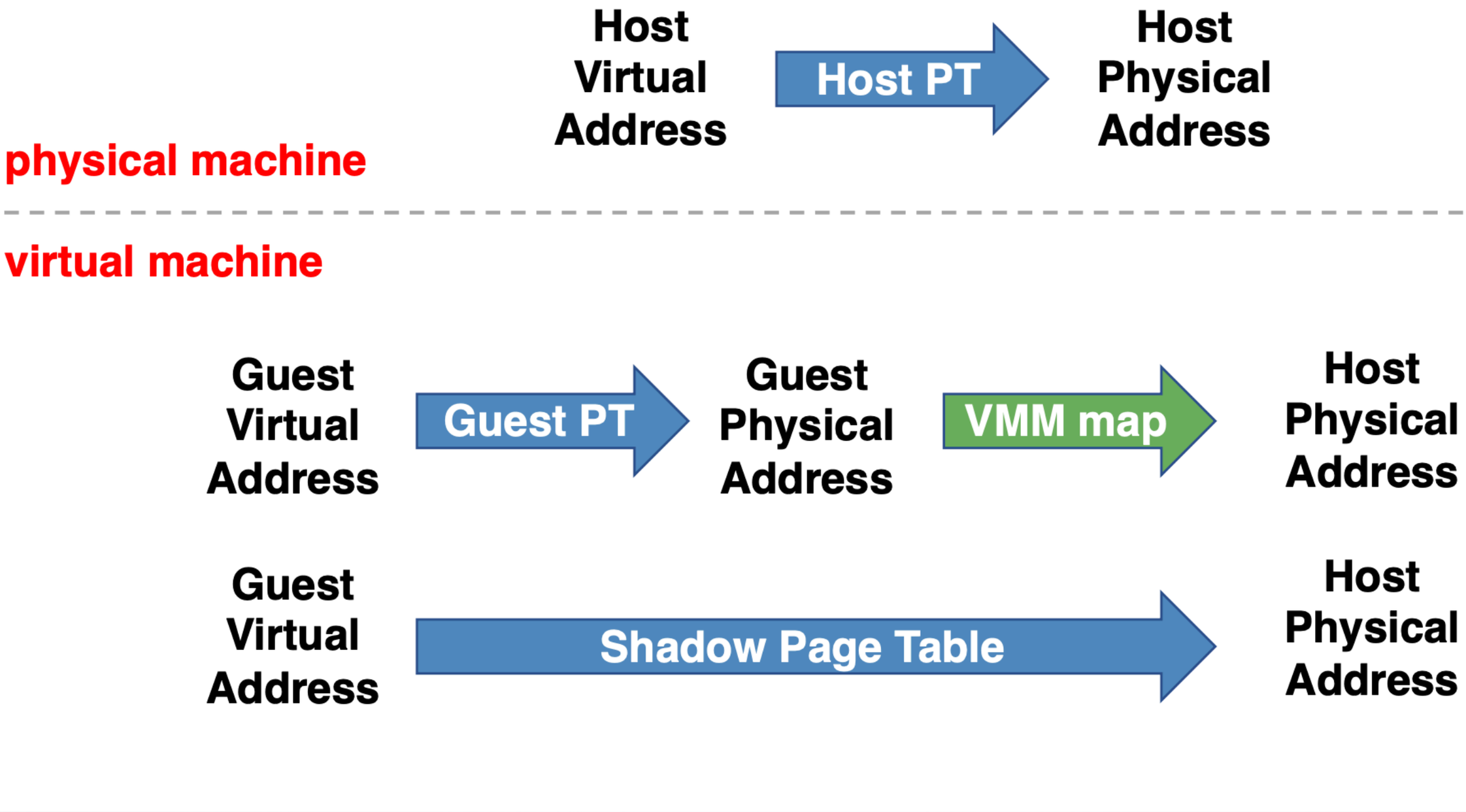
VMM creates and manages page tables that map virtual pages directly to machine page
these tables are loaded into the MMU on a context switch

➡ VMM page tables are the shadow page tables

VMM needs to keep its virtual to machine tables consistent with changes made by OS to its virtual to physical tables

- VMM maps OS page tables as read-only (i.e., write-protected)
- When OS writes to page tables, trap to VMM
- Memory tracing : VMM applies write to shadow table and OS table and returns
- Memory-mapped devices must be protected for both read- and write- protected

Memory mapping summary



Memory Allocation

VMMs tend to have simple hardware memory allocation policies

- Static - VM gets 512 MB of hardware memory for life
- No dynamic adjustment based on load
  OSes not designed to handle changes in physical memory
- No swapping to disk

More sophistication - overcommit with balloon driver

- Balloon driver runs inside OS to consume hardware pages
  steals from virtual memory and file buffer cache (balloon grows)
- Gives hardware pages to other VMs (those balloons shrink)

Virtualizing I/O

OSes can no longer interact directly with I/O devices

Types of communication

- Special instruction – in/out
- Memory-mapped I/O
- Interrupts
- DMA

1. Make in/out trap into VMM and use tracing for memory-mapped I/O
2. Run simulation of I/O device
   - Interrupt – tell CPU simulator to generate interrupt
   - DMA – copy data to/from physical memory of virtual machine

Hardware Support

Intel and AMD implement virtualization support in their recent x86 chips (Intel VT-x, AMD-V)

- Goal is to fully virtualize architecture
- Transparent trap-and-emulate approach now feasible
- Echoes hardware support originally implemented by IBM

Execution model

- New execution mode - guest mode
  Direct execution of guest OS code, including some privileged instructions
- Virtual machine control block (VMCB)
  controls what operations trap, records info to handle traps in VMM
- New instruction `vmenter` enters guest mode, runs VM code
- When VM traps, CPU executes new `vmexit` instruction

Hardware Support

Memory

- Intel extended page tables (EPT), AMD nested page tables (NPT)
- Original page tables map virtual to (guest) physical pages
  managed by OS in VM, backwards-compatible
- New tables map physical to machine pages
  managed by VMM
- Tagged TLB w/ virtual process identifiers (VPIDs)
  tag VMs with VPID, no need to flush TLB on VM/VMM switch

I/O

- Constrain DMA operations only to page owned by specific VM
- AMD DEV -exclude pages (c.f. Xen memory paravirtualization)
- Intel VT-d IOMMU – address translation support for DMA

Virtualizing I/O - Three Models

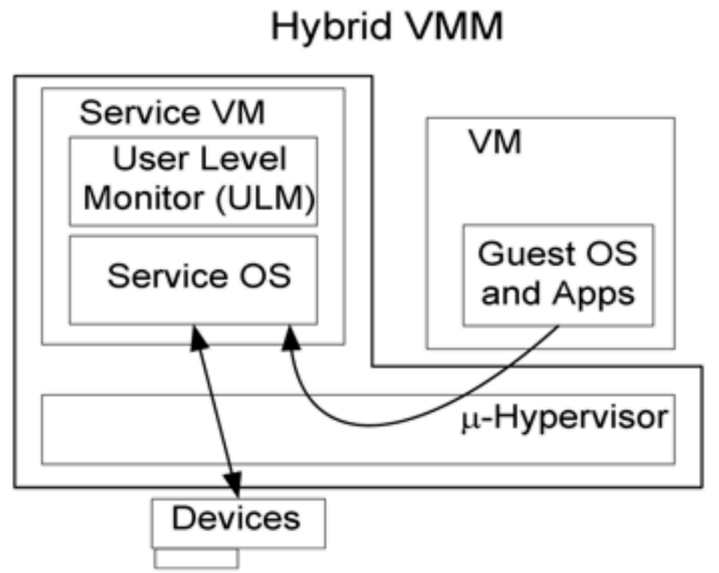
Xen : modify OS to use low-level I/O interface (hybrid)

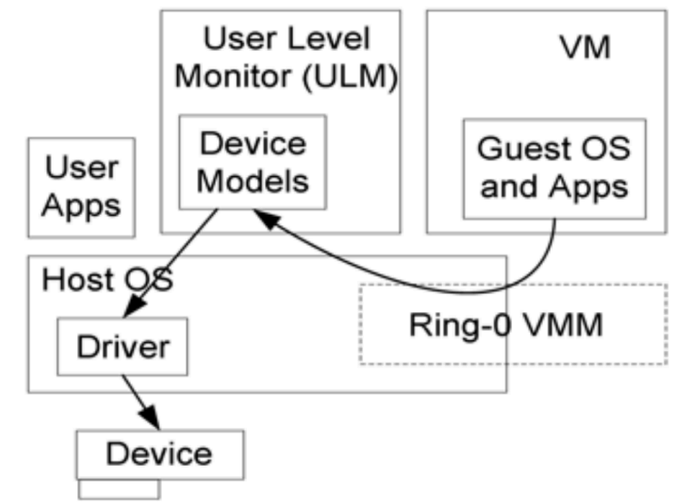
- Define generic devices with simple interface: virtual disk, virtual NIC, etc.
- Ring buffer of control descriptors, pass pages back and forth
- Handoff to trusted domain running OS with real drivers

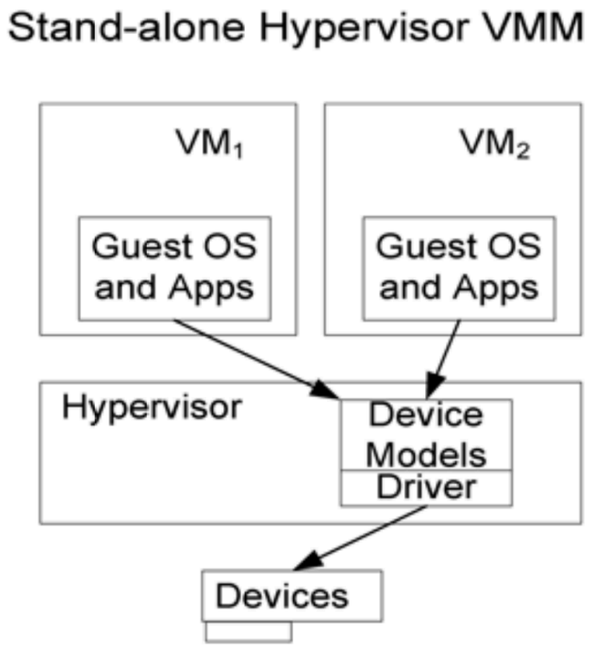
VMware : VMM supports generic devices (hosted)

- 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)

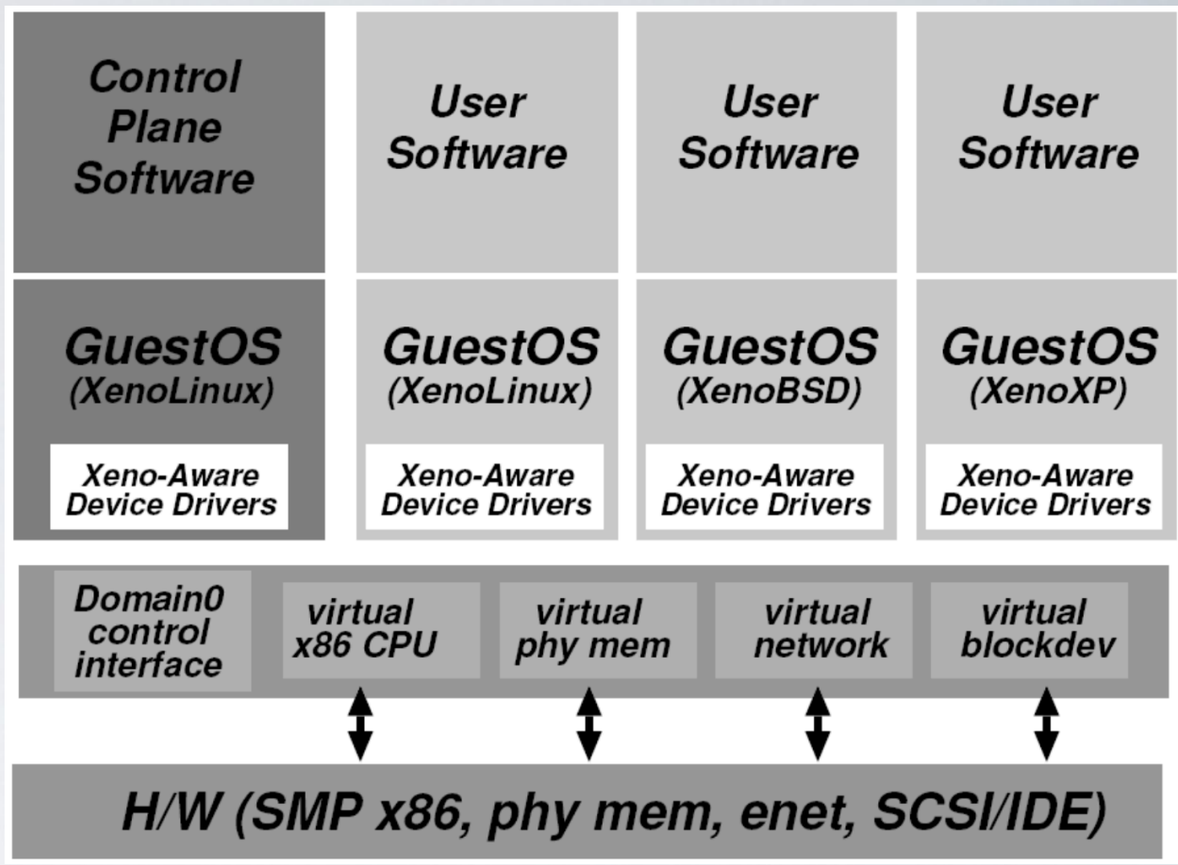
VMware ESX Server: drivers run in VMM (hypervisor)







VMM case study 1 - *Xen*



Early versions use "paravirtualization"

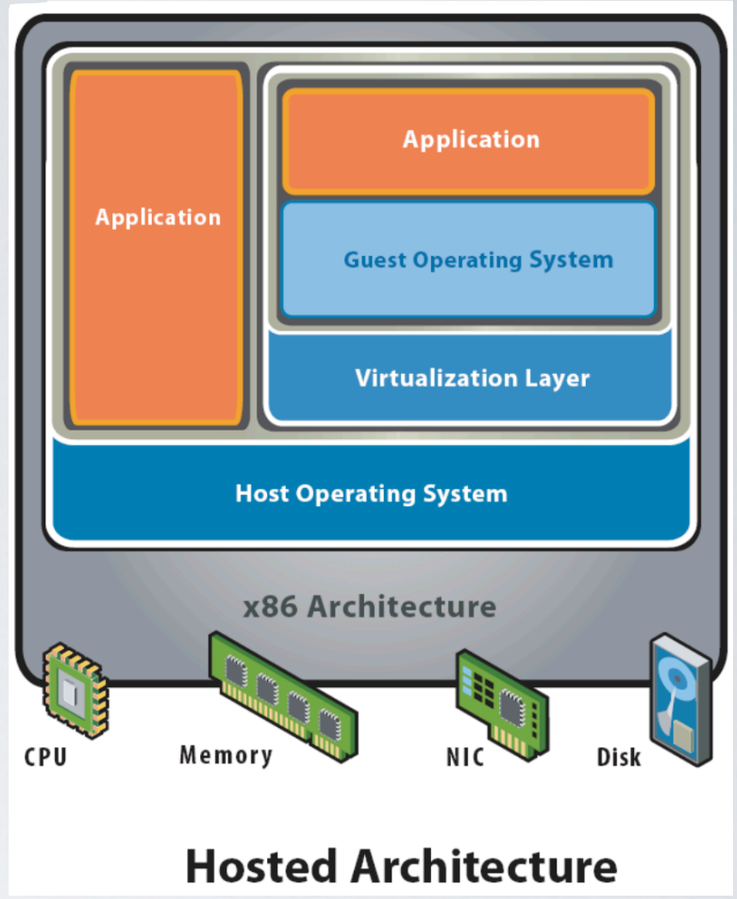
- Fancy word for "we have to modify & recompile the OS"
- Since you're modifying the OS, make life easy for yourself
- Create a VMM interface to minimize porting and overhead

Xen hypervisor (VMM) implements interface

- VMM runs at privilege, VMs (domains) run unprivileged
- Trusted OS (Linux) runs in own domain (Domain0)
  use Domain0 to manage system, operate devices, etc.

✓ Most recent version of Xen does not require OS mods because of Intel/AMD hardware support - commercialized via XenSource, but also open source

VMM case study 2 - *VMware*



VMware uses software virtualization

- Dynamic binary rewriting translates code executed in VM
  - Most instructions translated identically
  - Rewrite privileged instructions with emulation code (may trap)
- Think JIT compilation for JVM, but full binary x86 to IR code to safe subset of x86
- Incurs overhead, but can be well-tuned (small % hit)

✓ 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

Summary

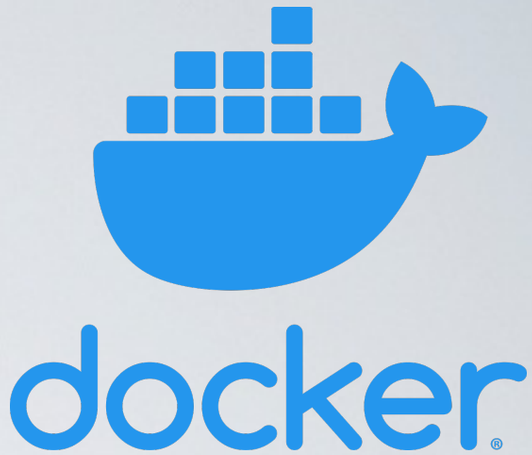
VMMs multiplex virtual machines on hardware

- Export the hardware interface
- Run OSes in VMs, apps in OSes unmodified
- Run different versions, kinds of OSes simultaneously

Implementing VMMs means virtualizing CPU, Memory, I/O

➡ Lesson: never underestimate the power of indirection

Another trend - containers



- Containers are not virtual OSes

➡ There are user applications running over the same OS kernel

Learn more about it

https://www.codementor.io/blog/docker-technology-5x1kilcbow

Acknowledgments

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