CS 318 Principles of Operating Systems

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Lecture 20: Virtual Machine Monitors

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In-class Quiz 5 for Lecture 9 on Thursday (11/18)

So Far...

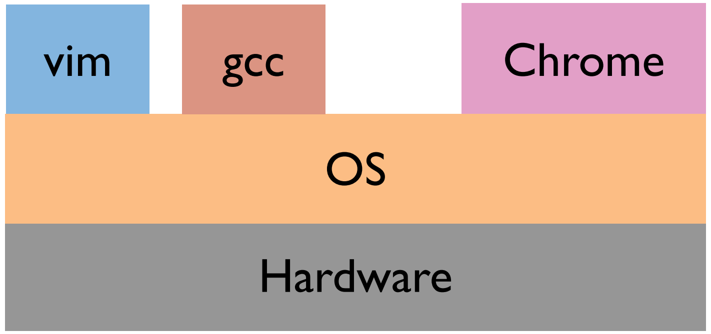
We've covered the three fundamental concepts in OS

- Concurrency
- Virtualization
- Persistency

✅ **A major milestone of the course**

Remaining lectures are slightly advanced (but important) OS topics

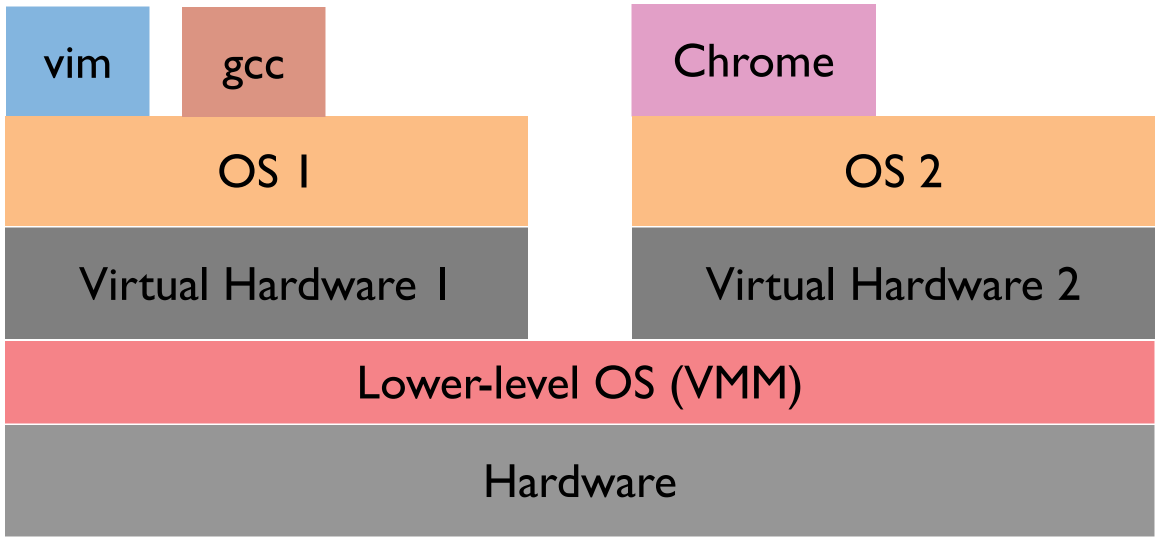
Review: What Is An OS



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

What If…



The process abstraction looked just like hardware?

How Do Process Abstraction & H/W Differ

Process

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

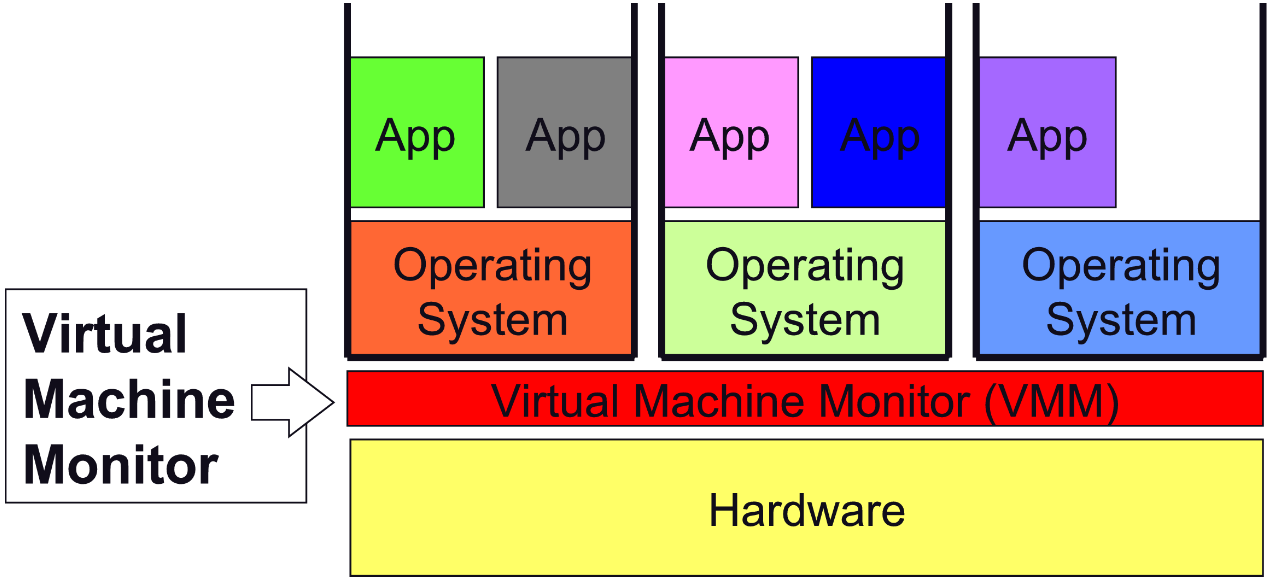
Hardware

- 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

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
  - Run multiple instances of an OS or different OSes simultaneously on the same physical machine



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]

VMMs Today

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
    - If Intel and AMD add it to their chips, you know it's serious…
- Academia: lots of related projects and papers

Why Would You Do Such a Crazy Thing?

Software compatibility

- VMMs can run pretty much all software

Resource utilization

- Machines today are powerful, want to multiplex their hardware

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…

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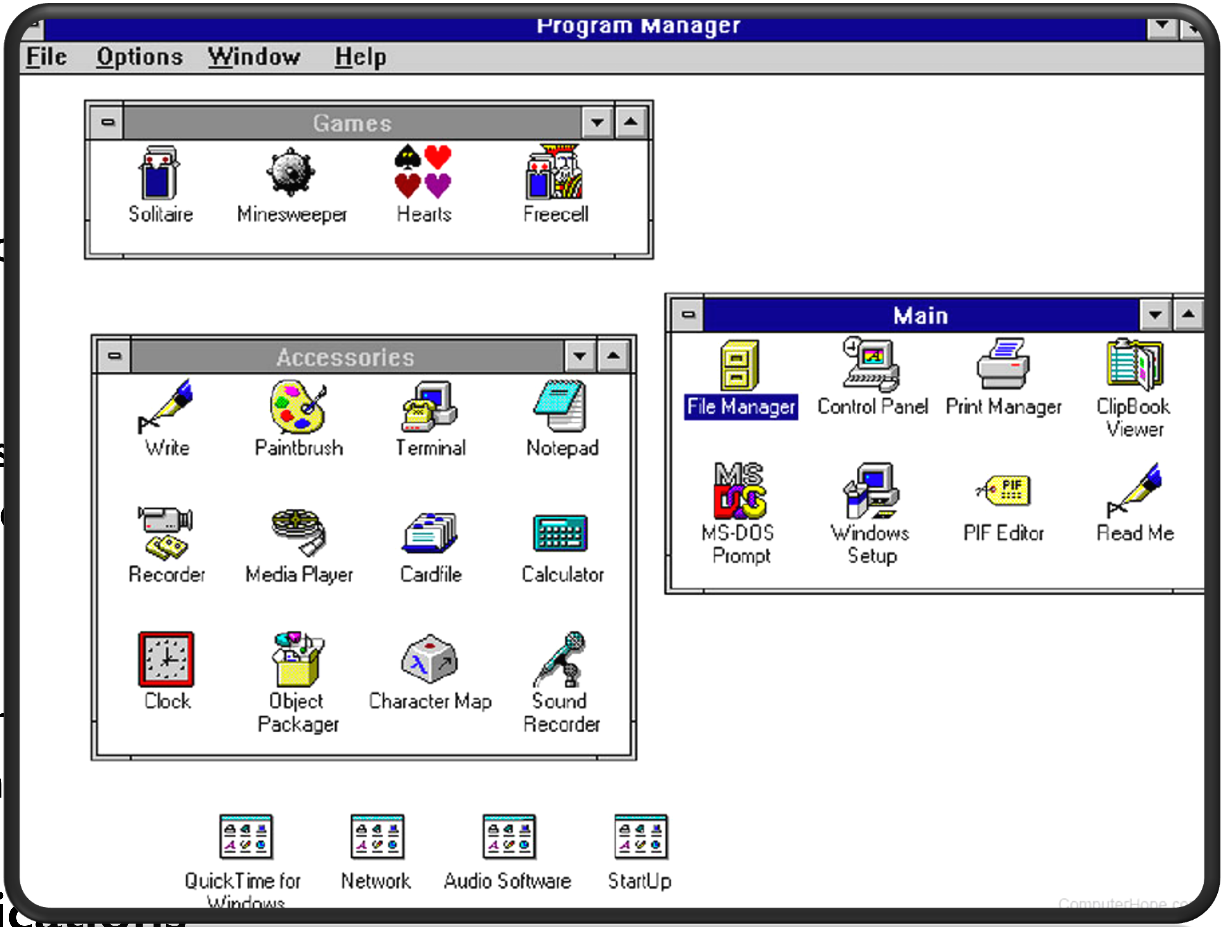


Many other cool applications

- Debugging, emulation, security, speculation, fault tolerance…

OS Backwards Compatibility

Backward compatibility is bane of new Oses

- Huge effort required to innovate but not break

Security considerations may make it impossible

- Choice: Close security hole and break apps or be insecure

Example: Windows XP is end of life

- Eventually hardware running WinXP will die
- What to do with legacy WinXP applications?
- Not all applications will run on later Windows
- Given the # of WinXP applications, practically any OS change will break something

```
if (OS == WinXP) ...
```

Solution: Use a VMM to run both WinXP and Win10

- Obvious for OS migration as well: Windows → Linux

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

- Printer server doesn't take down Exchange server
- Compromise of one VM can't get at data of others

Resource management

- Provide service-level agreements

Heterogeneous environments

- Linux, FreeBSD, Windows, etc.

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
- VMware (early):
  - CPU-intensive apps: 2-10% overhead
  - 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

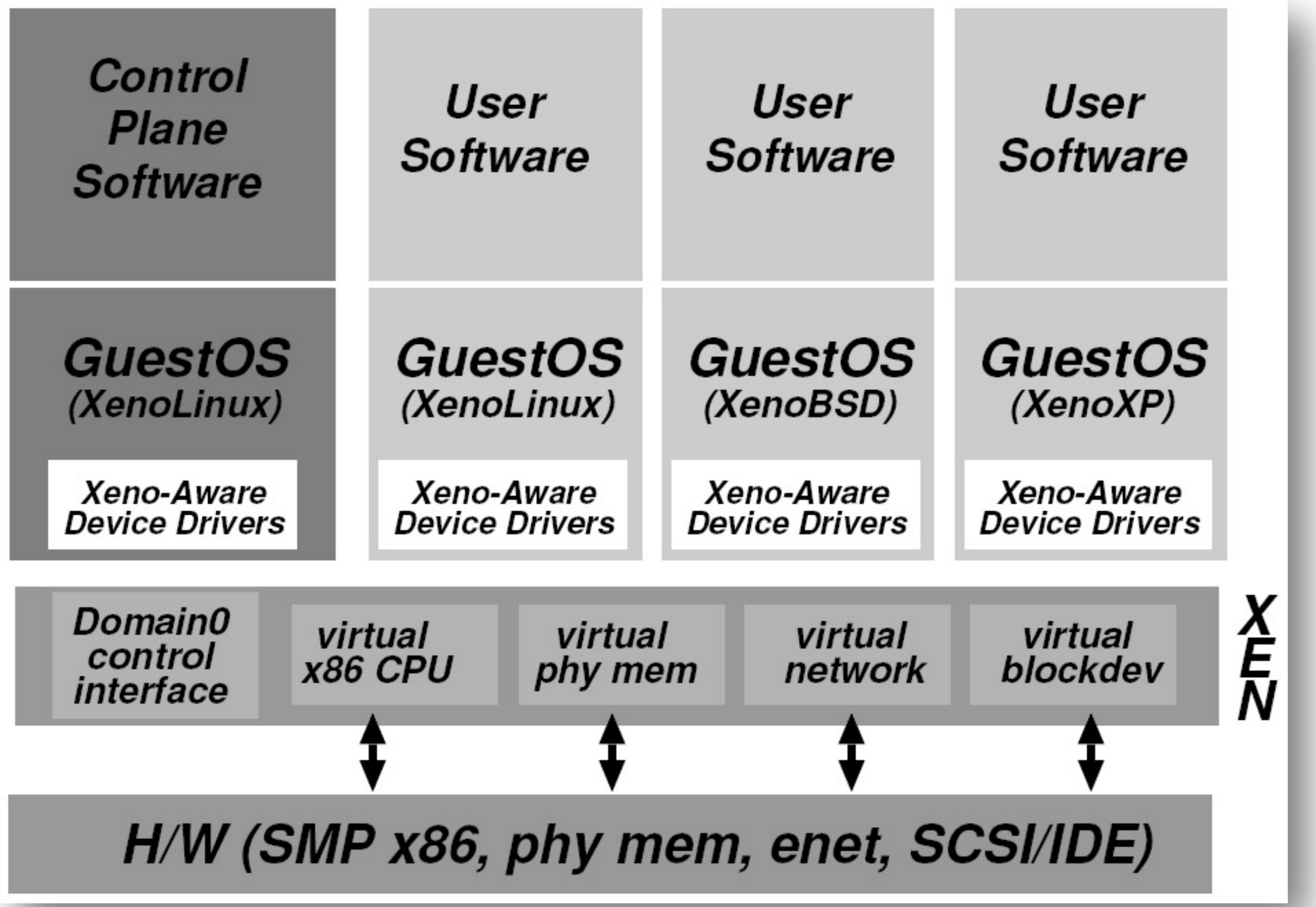
- VMM runs at privilege, VMs (domains) run unprivileged
- Trusted OS (Linux) runs in own domain (Domain0)
  - Use Domain0 to manage system, operate devices, etc.

Most recent version of Xen does not require OS mods

- Because of Intel/AMD hardware support

Commercialized via XenSource, but also open source

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

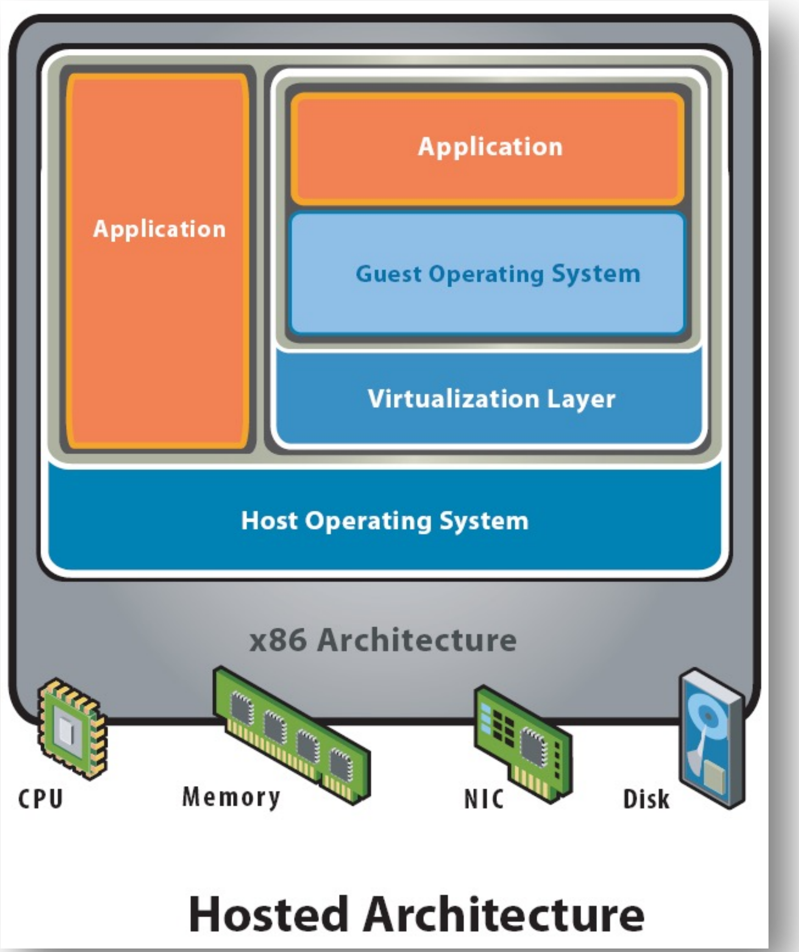
VMware ESX server uses hypervisor model

- Similar to Xen, but no guest domain/OS

VMware uses software virtualization

- Dynamic binary rewriting translates code executed in VM
  - Most instructions translated identically, e.g., `movl`
  - Rewrite privileged instructions with emulation code (may trap), e.g., `popf`
- 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
- Events (exceptions and interrupts)
- Memory
- I/O devices

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

- Yes and no
- Approaches will be similar to what we do with OSes
  - Simpler in functionality, though (VMM much smaller than OS)
- But implements a different abstraction
  - Hardware interface vs. OS interface

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

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 and 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

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
- Makes some assumptions about architecture: processor is "virtualizable"

Virtualizable Processor

Sensitive instructions access low-level machine states

Virtualizable CPU: all sensitive instructions are privileged

For many years, x86 chips were *not* virtualizable

- On the Pentium chip, 17 instructions were not virtualizable
- Example: `push` instruction pushes a register value onto the top of the stack
  - `%cs` register contains (among other things) 2 bits representing the current privilege level
  - A guest OS in Ring 1 could push `%cs` and see that the privilege level isn't Ring 0!
  - To be virtualizable, `push` should cause a trap when invoked from Ring 1, allowing the VMM to push a fake `%cs` value which indicates that the guest OS is running in Ring 0

Virtualizable Processor

For many years, x86 chips were *not* virtualizable

- On the Pentium chip, 17 instructions were not virtualizable
- Example: **`push`** instruction pushes a register value onto the top of the stack
- Another example: **`pushf/popf`** read/write the **`%eflags`**
  - Bit 9 of **`%eflags`** enables interrupts
  - In Ring 0, **`popf`** can set bit 9, but in Ring 1, CPU silently ignores **`popf`**!
  - To be virtualizable, **`pushf/popf`** should cause traps in Ring 1 so that the VMM can detect when guest OS wants to changes its interrupt level

Virtualizing Traps

What happens when an interrupt or trap occurs

- Like normal kernels: we trap into the monitor

What if the interrupt or trap should go to guest OS?

- Example: Page fault, illegal instruction, system call, interrupt
- Re-start the guest OS execution simulating the trap

x86 example:

- Give CPU an IDT that vectors back to VMM
- Look up trap vector in VM's "virtual" IDT
  - How does VMM know this?
- Push virtualized `%cs, %eip, %eflags`, on stack
- Switch to virtualized privileged mode

Virtualizing Memory

OSes assume they have full control over memory

- Managing it: OS assumes it owns it all
- Mapping it: OS assumes it can map any virtual page to any physical page

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 Solution: Direct Mapping

VMM uses the page tables that a guest OS creates

- These page tables are used directly by hardware MMU

Page tables work the same as before, but OS is constrained to only map to the physical pages it owns

VMM validates all updates to page tables by guest OS

- OS can read page tables without modification
- But VMM needs to check all PTE writes to ensure that the virtual-to-physical mapping is valid
  - That the OS "owns" the physical page being used in the PTE
- Modify OS to hypervisor call into VMM when updating PTEs

Works fine if you can modify the OS (used in Xen paravirtualization)

If you can't…

Second Approach: 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 you know and love
  - Standard 2^{32} or 2^{64} address space

Translation: VM's Guest VA → VM's Guest PA → 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

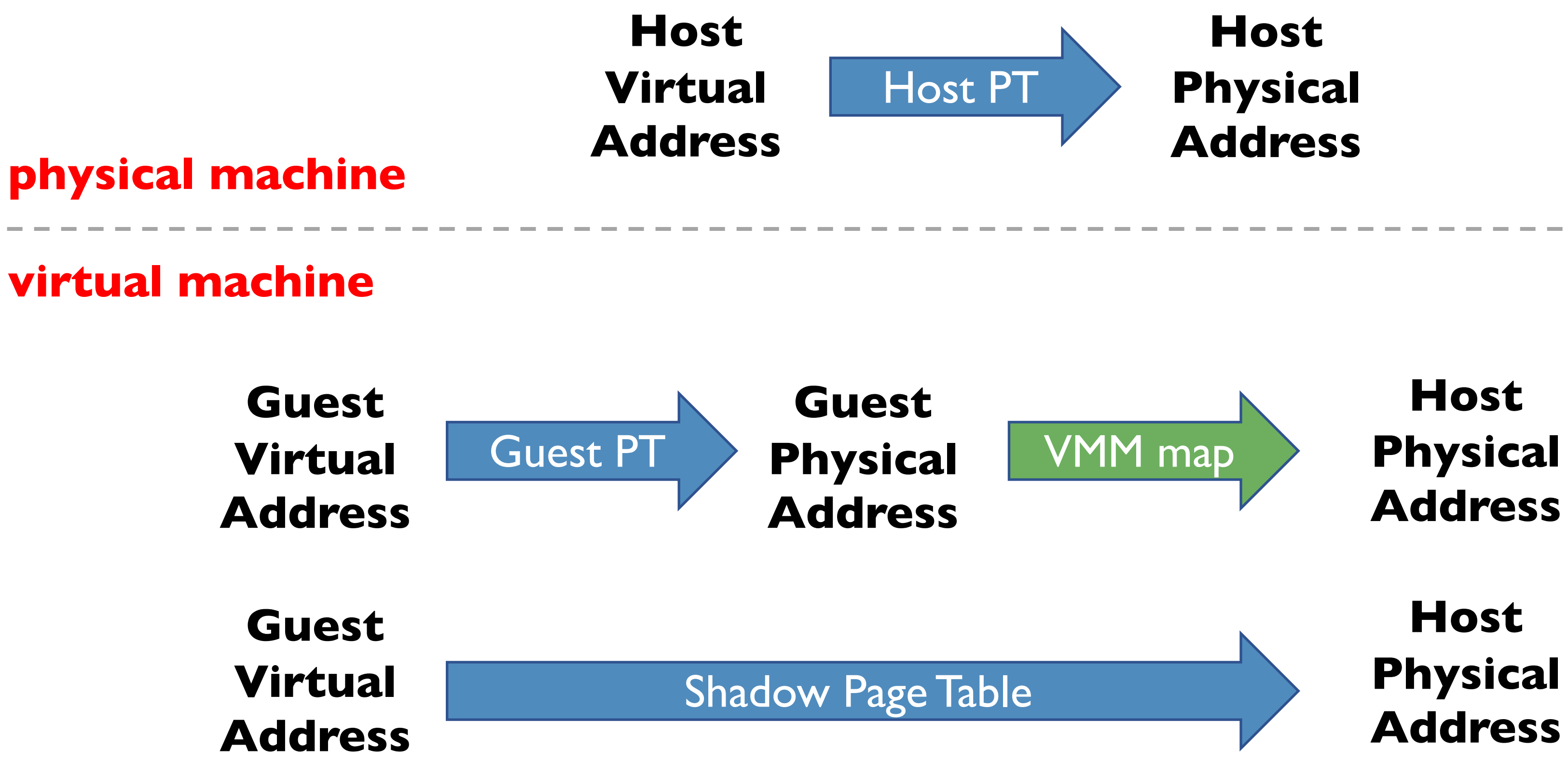
VMM creates and manages page tables that map virtual pages directly to machine pages

- These tables are loaded into the MMU on a context switch
- VMM page tables are the shadow page tables

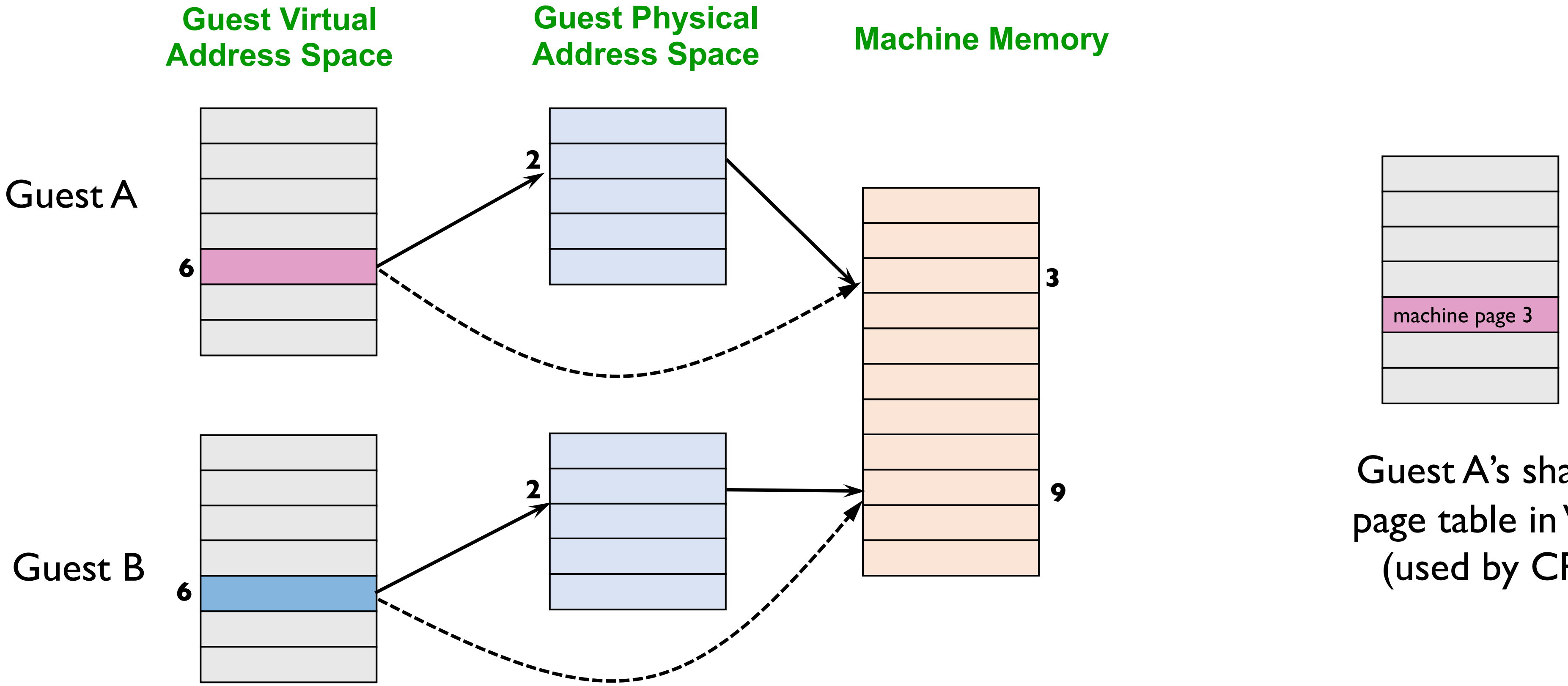
VMM needs to keep its V→M tables consistent with changes made by OS to its V→ P tables

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

Memory Mapping Summary



Shadow Page Table Example



Guest A's shadow page table in VMM (used by CPU)

More on Shadow Page Table

Shadow page tables are essentially a cache

VMM is responsible for maintaining the consistency

Two kinds of page faults

- *True page faults* when page not in VM's guest page table
- *Hidden page faults* when just misses in shadow page table

On a page fault, VMM must:

- Lookup guest VPN → guest PPN in guest's page table
- Determine where guest PPN is in host physical memory
- Insert guest VPN → host PPN mapping in shadow page table

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)

Identify identical physical pages (e.g., all zeroes)

- Map those pages copy-on-write across VMs

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

Make `in/out` trap into VMM

Use tracing for memory-mapped I/O

Run simulation of I/O device

- Interrupt – Tell CPU simulator to generate interrupt
- DMA – Copy data to/from physical memory of virtual machine

Virtualizing I/O: Three Models

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

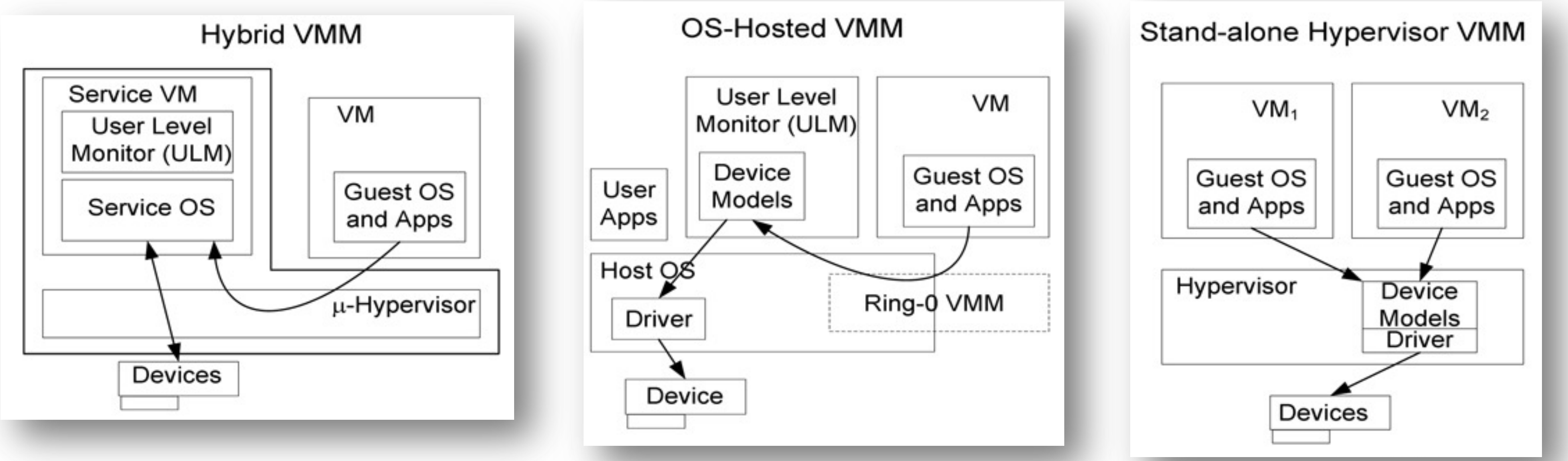
- Define generic devices with simple interface
  - Virtual disk, virtual NIC, etc.
- Ring buffer of control descriptors, pass pages back and forth
- Handoff to trusted domain running OS with real drivers

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)

Virtualized I/O Models



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

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

These CPUs support new execution mode: guest mode

- This is separate from kernel/user modes in bits 0–1 of `%cs`
- Less privileged than host mode (where VMM runs)
- Direct execution of guest OS code, including privileged insts
- Some sensitive instructions trap in guest mode (e.g., load `%cr3`)
- Hardware keeps shadow state for many things (e.g., `%eflags`)

Guest mode

Enter and exit guest mode

- New instruction `vmenter` enters guest mode, runs VM code
- When VM traps, CPU executes new `vmexit` instruction
- Enters VMM, which emulates operation
- Virtual machine control block (VMCB)
  - Controls what operations trap, records info to handle traps in VMM
- `vmenter` loads state from hardware-defined 1-KiB VMCB data structure
- On EXIT, hardware saves state back to VMCB

Guest State Saved in VMCB

Saved guest state

- Full segment registers (i.e., base, lim, attr, not just selectors)
- Full GDTR, LDTR, IDTR, TR
- Guest %cr3, %cr2, and other cr/dr registers
- Guest %eip and %eflags
- Guest %rax register

Entering/exiting VMM more expensive than syscall

- Have to save and restore large VM-state structure

Hardware Support (2)

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
- No need to trap to VMM when OS updates its page tables
- 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 Device Exclusion Vector (DEV) (c.f. Xen memory paravirtualization)
- Intel VT-d: IOMMU – address translation support for DMA

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

- Virtualize CPU, Memory, I/O

Lesson: Never underestimate the power of indirection