Virtual Machines

CMPU 334 – Operating Systems
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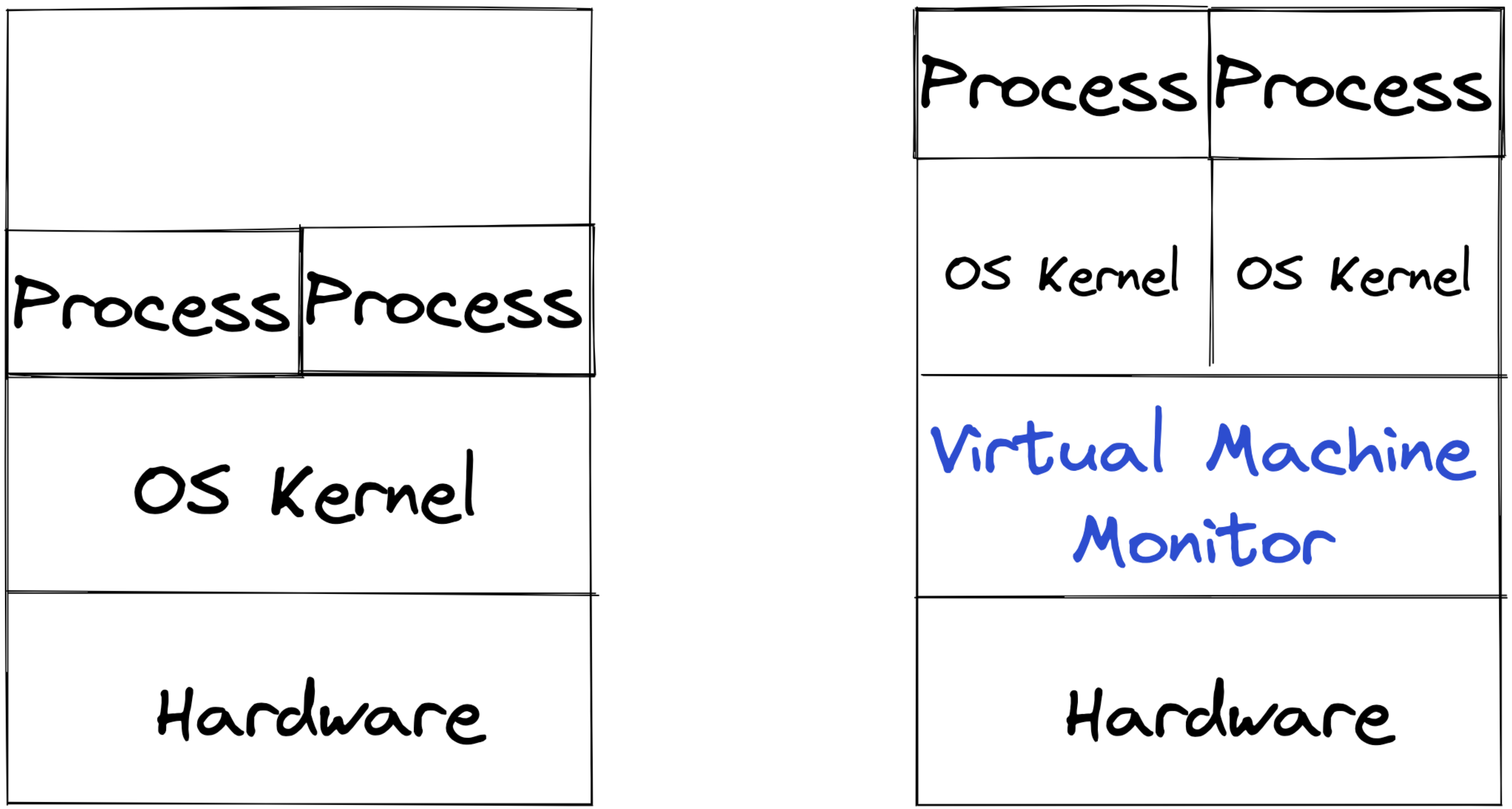
Layers and Abstraction



Virtual Machine Monitor (VMM)

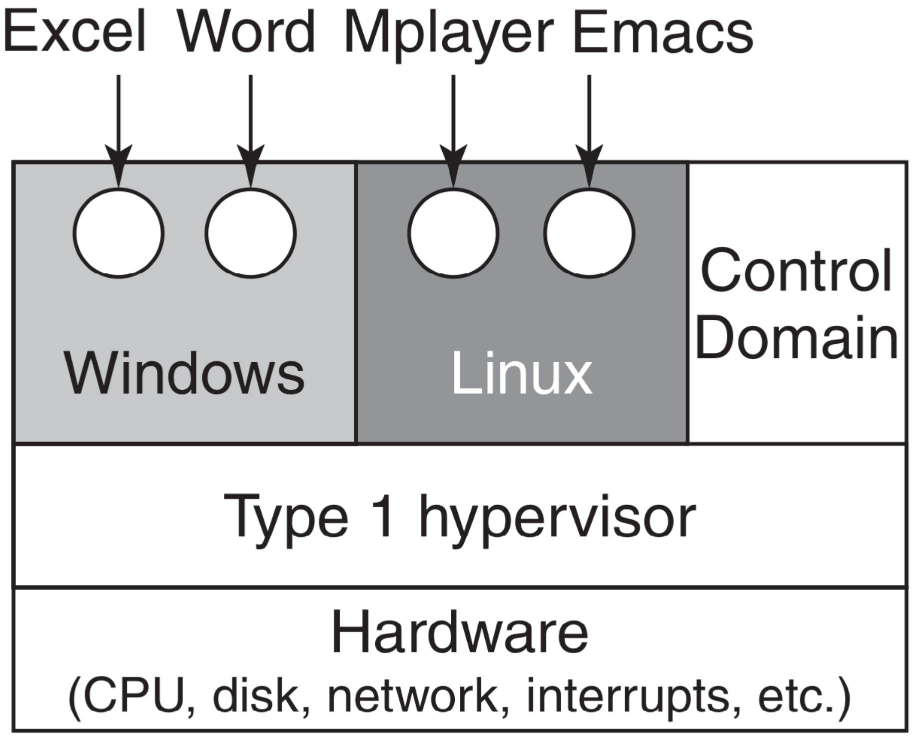
- Also called a hypervisor

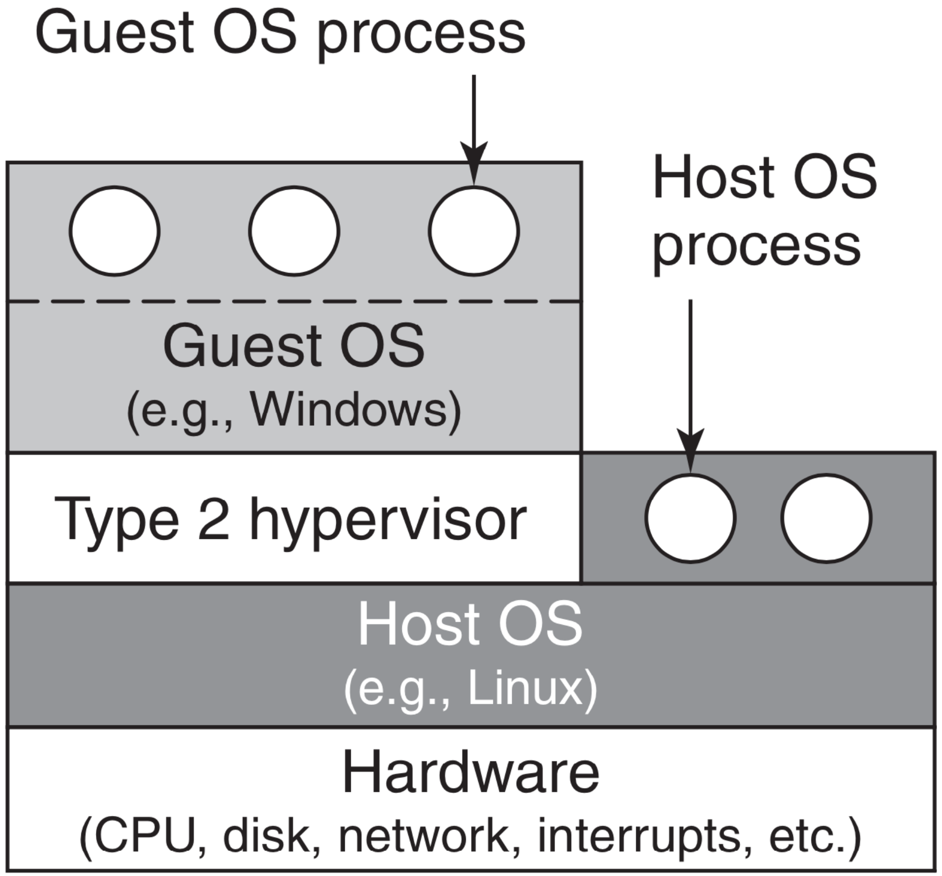
- Provides a virtualized version of the hardware to each running OS
  - OS thinks it has direct control of the hardware
  - An illusion provided by the VMM

- VMM is really the one in charge
  - Must multiplex running multiple OSes on the hardware

- Think of the VMM as an Operating System for OSes

Type 1 and Type 2 Hypervisors





Motivation for VMMs

- Server consolidation
  - Different services with different Oses
  - If these machines are lightly loaded, it makes sense to consolidate to one machine
  - Can suspend, snapshot, and migrate VMs

- Testing and debugging
  - Easily test and deploy on multiple platforms

- Isolation
  - If one VM is compromised or crashes, sandboxing will prevent it from effecting the other VMs

VMM History

- Original concepts date back to the 1970’s
  - IBM used VMs on their mainframe systems

- Did not gain traction for PCs until the 90’s
  - x86 architecture presented challenges to efficient virtualization
    - Current x86 processes have virtualization extensions
  - Research group out of Stanford came out with Disco
    - Went on to found VMware
    - First virtualization solution in 1999

VMM Requirements

- **Safety**: the hypervisor should have full control of the hardware
- **Fidelity**: the behavior of a program on a virtual machine should be identical to that of the same program running on bare metal
- **Efficiency**: much of the code in the virtual machine should run without intervention by the hypervisor
  - An extension of Limited Direct Execution used for processes

Virtualizing the CPU

- When the VMM wishes to “boot” a new OS, jump to the starting address of the OS kernel

- When the VMM wants to switch between OSes, the VMM must perform a **machine switch**
  - Similar to a context switch
  - Save the state of the OS (PC, registers, and any privileged hardware state)
  - Restore the state of the next OS to run

Trap and Emulate (mechanism)

- What happens when the OS tries to perform a **privileged operation**?
  - VMM must remain in control of hardware resources, so it can't allow the OS run those instructions directly
  - E.g., the kernel now runs in **user mode** instead of kernel mode

- A privileged instruction by the OS causes a trap into the VMM
  - The VMM can emulate that operation on behalf of the OS
  - VMM retains control but OS still thinks it is in control

Handling an OS syscall

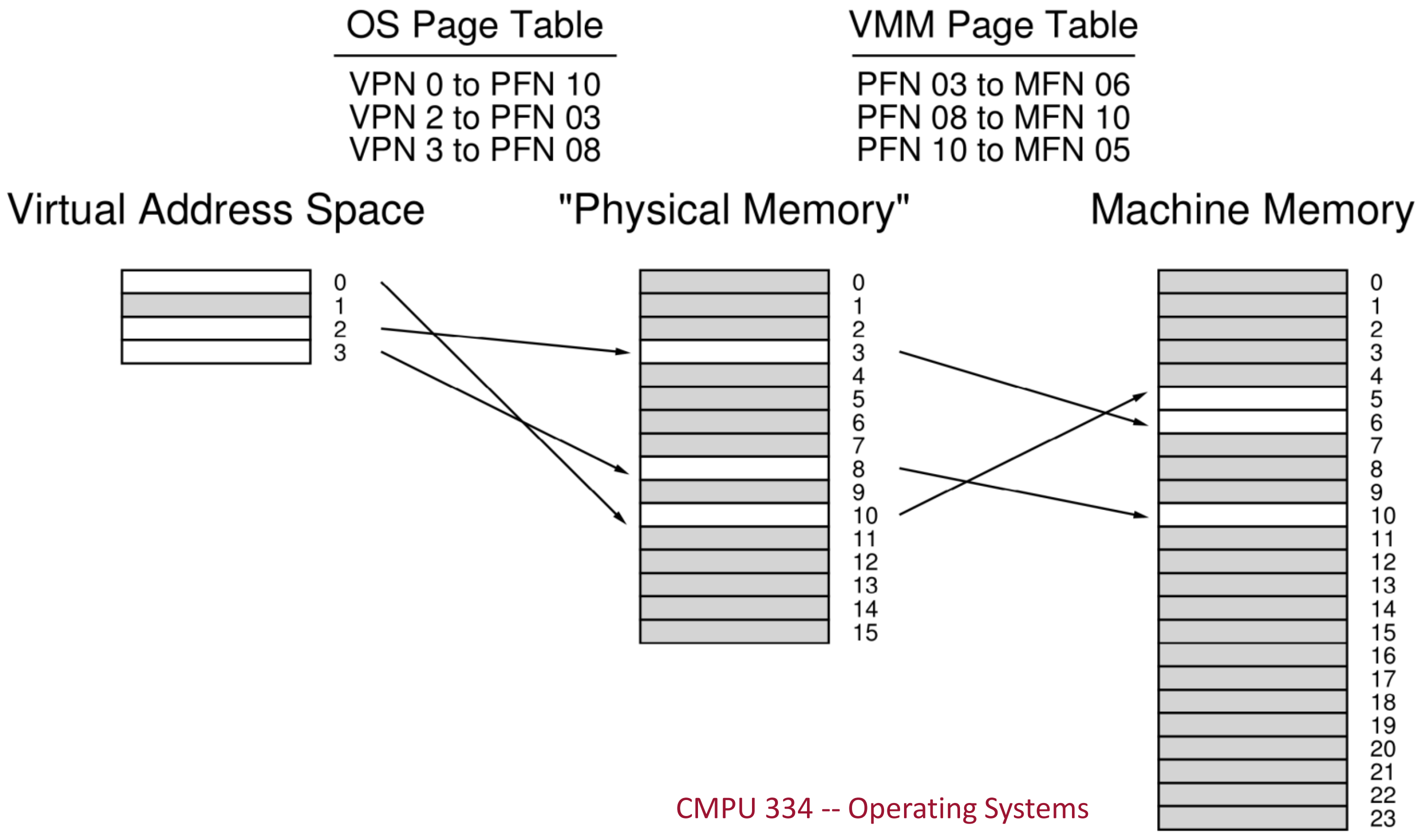
- In a non-virtualized environment
  - On OS boot, kernel installs trap handlers
  - User process calls privileged instruction as part of the syscall
    - `ecall` on RISC-V
    - Hardware transitions to kernel mode and jumps to the trap handler
- In a virtualized environment
  - OS is not in kernel mode
  - User process can’t trap into the kernel
  - It actually traps into the VMM
    - But VMM doesn’t know how to handle the trap
    - So VMM transfers control to the OS trap handler
    - VMM knows the right handler because OS tried to install the handlers at OS “boot” time

VM Memory Translation

- OS builds its own page tables
- Kernel loads a hardware register to point to the top-level page table
  - This is a privileged instruction, so trap into the VMM
- VMM creates a **shadow page table** to map to the actual physical pages used
  - Must also keep track of any changes to the OS page table
  - **Problem**: the OS can change a page table just by writing memory
- One possible solution: Mark the page table memory as read-only
  - When the OS tries to modify the table, a page fault will trap into the VM
  - This is expensive, 10s of thousands of cycles

Hardware Support for Nested Page Tables

- To reduce this cost hardware support is needed
  - Nested Page Tables (AMD)
  - EPT -- Extended Page Tables (Intel)



The Information Gap

- Even though the VMM is in charge, it knows very little about what the OS is doing or what it needs
  - This is an **information gap** between the VMM and the OS

- Examples
  - Idle loop
    - OS will idle if there is nothing else to do, but VMM still schedules it
  - Demand zeroing of pages
    - VMM zeros pages given to the OS for security
    - OS doesn’t know they have been zeroed, so OS will zero them again

Paravirtualization

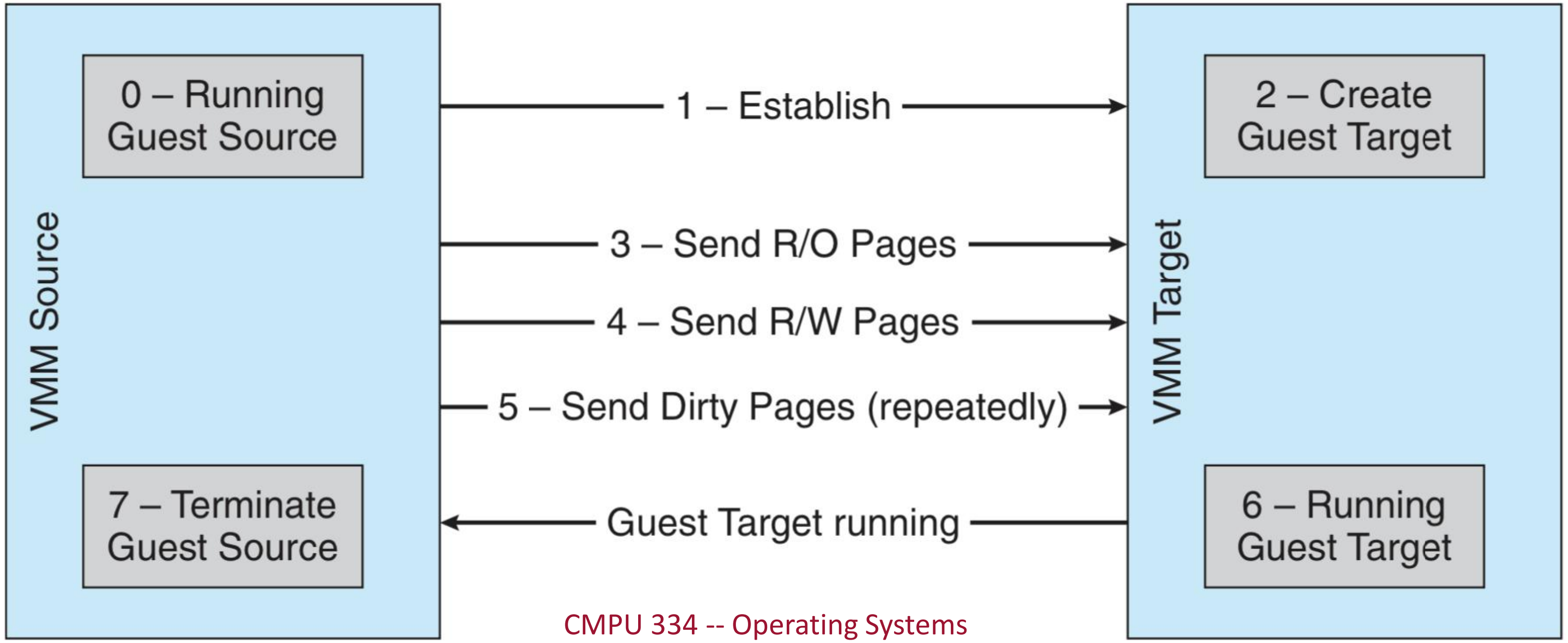
- To this point, we've assumed the OS does not know it not running directly on the hardware
- The VMM must go through hoops to maintain this illusion
- What modifications can we make to the OS to improve performance
  - Trap and emulate no longer needed
  - Make an explicit call on the VMM
    - Similar to how a process makes a syscall

I/O Virtualization

- OS will probe the hardware on boot to find out what I/O devices exist
  - Trap into the VMM
- VMM can report back the actual hardware that exists
  - But then OS will install device drivers for that hardware
    - When driver accesses device hardware, will trap into VMM
- Or report back generic canonical hardware
  - Paravirtualized drivers, e.g., virtio

Fun Virtualization Tricks

- Checkpointing (Snapshotting)
  - Write out state of VM as backup
  - Can boot directly to a running VM from a checkpoint
- Live Migration
  - Move a running system from one host to another



Summary

- Virtualization is here to stay
  - The basis for cloud computing

- VMMs extend the notion of limited direct execution
  - Set up the hardware to enable the VMM to interpose on key events such as traps
  - Control how machine resources are allocated while preserving the illusion that the OS in charge

- Similar to the virtualization that the OS does for processes
  - However, OSes were designed to have a clean interface (e.g., syscall)
  - VMMs interface is the hardware
  - Paravirtualization can make that interface a little cleaner (e.g., KVM)