Virtual Machines

Today

- VM over time
- Implementation methods
- Hardware features supporting VM

Next time

- Midterm!

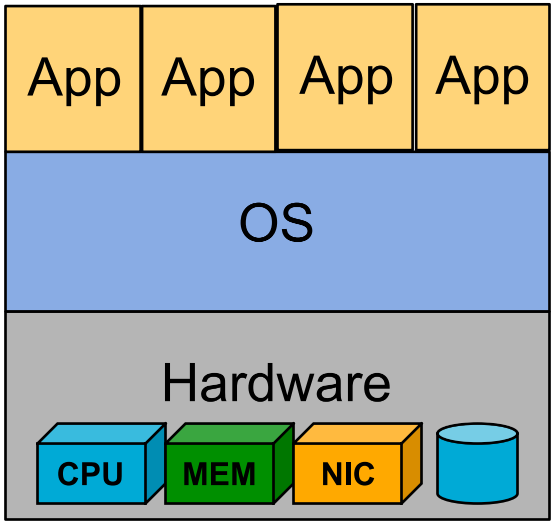
*Partially based on notes from C. Waldspurger, VMware, 2010

Types of virtualization

- Process virtualization
  - Language-level: Java, .NET, Smalltalk
  - OS-level: processes, Solaris Zones, BSD Jails
  - Cross-ISA emulation: Apple 68K-PPC-x86
- Device virtualization
  - Logical vs. physical: VLAN, VPN, LUN, RAID
- System virtualization
  - Xen, VMware Fusion, KVM, Palacios …

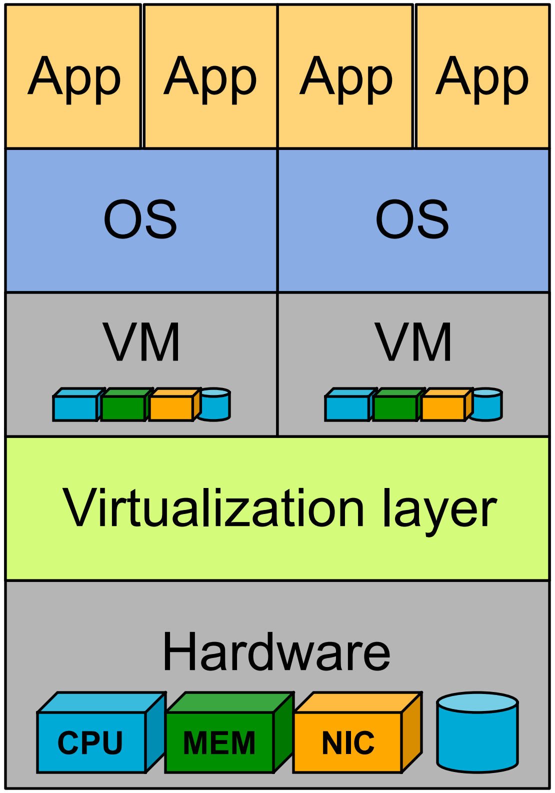
System virtualization starting point

- Physical hardware
  - Processors, memory, chipset, I/O devices, etc.
  - Resources often grossly underutilized
- Software
  - Tightly coupled to physical hardware
  - Single active OS instance
  - OS controls hardware



Adding a virtualization layer

- Software abstraction
  - Behaves like hardware
  - Encapsulates all OS and application state
- Virtualization layer
  - Extra level of indirection
  - Decouples hardware, OS
  - Enforces isolation
  - Multiplexes physical hardware across VMs



Virtual Machine Monitor

- Classic definition*

> … an efficient, isolated duplicate of the real machine. … the VMM provides an environment … essentially identical with the original machine; second, programs run in this environment show at worst only minor decreases in speed; and last, the VMM is in complete control of system resources.

- VMM properties
  - Fidelity – SW on the VMM executes identically to its execution on HW, other than timing effects
  - Performance – HW runs most of the instructions w/o the VMM involvement
  - Safety and isolation – VMM manages all HW resources

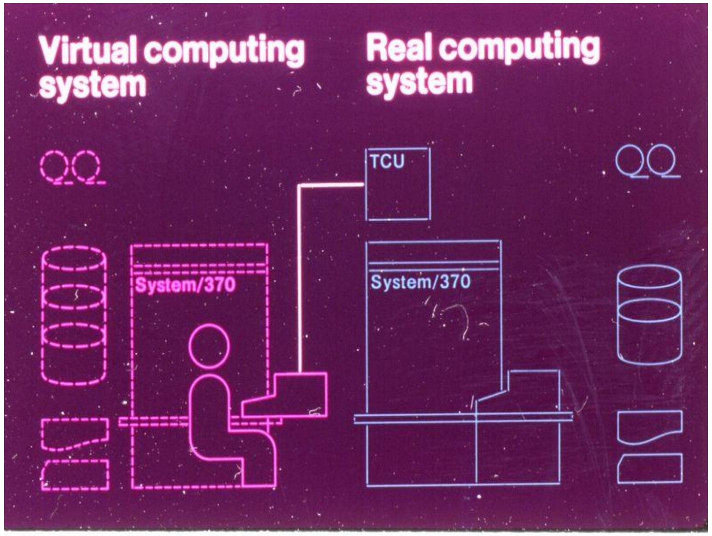
*Popek, G. J.; Goldberg, R. P. "Formal requirements for virtualizable third generation architectures". Communications of the ACM, July 1974.

Virtualization applications

- Server consolidation
  - Convert underutilized servers to VMs, saving cost
  - Increasingly used for virtual desktops
- Simplified management
  - Datacenter provisioning and monitoring
  - Dynamic load balancing
- Improved availability
  - Automatic restart
  - Fault tolerance
  - Disaster recovery
- Test and development

Classic virtualization

- Classical VMM
  - IBM mainframes:
    IBM S/360, IBM VM/370
  - Co-designed proprietary hardware, OS, VMM
  - “Trap and emulate” model
- Applications
  - Timeshare several single-user OS instances on expensive hardware
  - Compatibility



From IBM VM/370 product announcement, *ca*. 1972

Modern virtualization renaissance

- Recent proliferation of VMs
  - Considered exotic mainframe technology in 90s
  - Now pervasive in datacenters and clouds
  - Huge commercial success (partly lead by Rosenblum's VMware)

- Why?
  - Introduction on commodity x86 hardware
  - Ability to "do more with less" saves $$$
  - Innovative new capabilities
  - Extremely versatile technology

Virtualization’s building blocks

- Processor virtualization
  - Trap and Emulate
  - Binary Translation
- Memory virtualization
- I/O virtualization

Virtualizing the CPU

- Running a virtual machine
  - Limited direct execution – remember processes?
  - Wishing to boot a new VM, jump to the first address and go …
- To switch between two VMs, a machine switch
  - Like a processes switch, but using a Virtual CPU
  - VCPU – the sate of the CPU as the guest machine believes it to be; a VCPU per guest (~PCB)
  - The VM loaded can be either within the OS or within a process running on that OS
- *Easy right?*

Virtualizing the CPU

- What if the OS or running app tries to perform a privileged instruction?
  - E.g., update the TLB in a software managed TLB
  - The OS cannot be allowed to do it, the VM must intercept it
  - Consider `open(path, flags, mode)` in FreeBSD

```
push dword mode
push dword flags
push dword path
mov eax, 5
push eax
int 80h
```

Process	Hardware	OS
1.Execute instruction (add, load, etc) 2.System call: trap to OS		
	3.Switch to kernel mode; jump to trap handler	
		4.In kernel mode; handle syscall; return from trap
	5.Switch to user mode; return to user code	
6.Resume execution		

Trap and Emulate

- Trap and emulate
  - Kernel in guest attempts a privileged instruction, traps to VMM
  - VMM emulates the requested action, updates VCPU, and returns control to VM

Process	OS	VMM
1.System call: trap to OS		
		2.Process trapped, call OS trap handler (at reduce privilege)
	3.OS trap handler; decode, trap and execute syscall; return from trap	
		4.OS tried to return from trap; do real return
5.Resume execution		

Trap and emulate

- How does the VMM know where the trap handler is?
  - The OS tried to installed them at boot time, a privilege instruction, and the VMM took notes
- Trap costs may be high
- VMM consumes a privilege level
  - In Rosenblum’s Disco they used a MIPS supervisor mode
    - Access additional memory but not privilege instructions
    - Additional memory is enough for the OS to keep its data
  - Without it, need to virtualize protection levels, use page tables and TLBs to protect OS data structs

Binary translation

- Not all architectures support trap and emulate, i.e. are
- *Strictly virtualizable*
  - A processor is strictly virtualizable if, when executed in a lesser privileged mode:
    - All instructions that access privileged state trap
    - All instructions either trap or execute identically
  - x86 was not strictly virtualizable ☹ – example problem instruction – “pop flags” or `popf`
    - In privilege mode, popf may change system flags such as IF, which controls interrupt delivery
    - For a deprivileged guest, we need the kernel to trap so that the VMM can emulate the virtual IF
    - *But all user-mode popf simply suppresses attempts to modify IF*

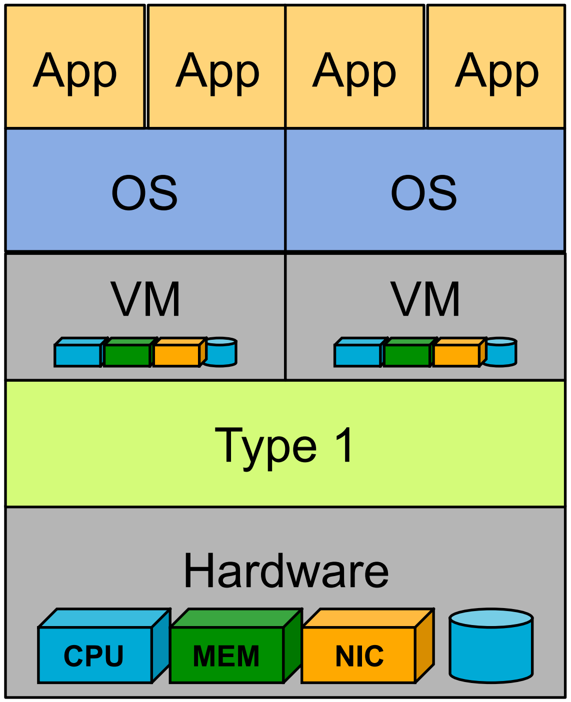
Binary translation

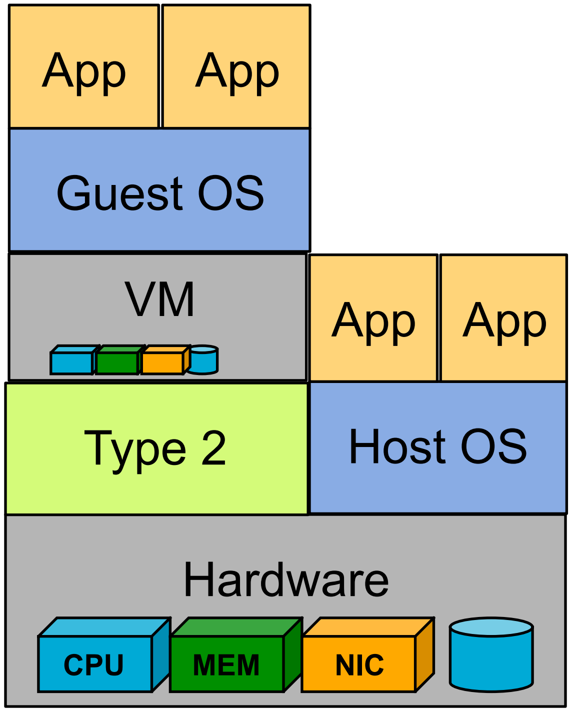
- Simple form – fidelity and safety, but bad performance
- Dynamically translate potentially dangerous instructions (non-virtualizable) into safe ones
  - VMM inspects next block of instr (up to a control transfer)
  - Translate each instr and cache translation, jump to start of the translated block and run with VCPU state on HW

- Issues with binary translation
  - Translation cache management
  - PC synchronization on interrupts
  - Self-modifying code
    - Notified on writes to translated guest code
  - Protecting VMM from guest

Type 1 and 2 hypervisors

Virtualization method	Type 1	Type 2
Without HW support	ESX Server 1.0	VMware Workstation 1
Paravirtualization	Xen 1.0	
With HW support	vSphere, Xen, Palacios	VMware Fusion, KVM
Process virtualization		Wine





Virtualization’s building blocks

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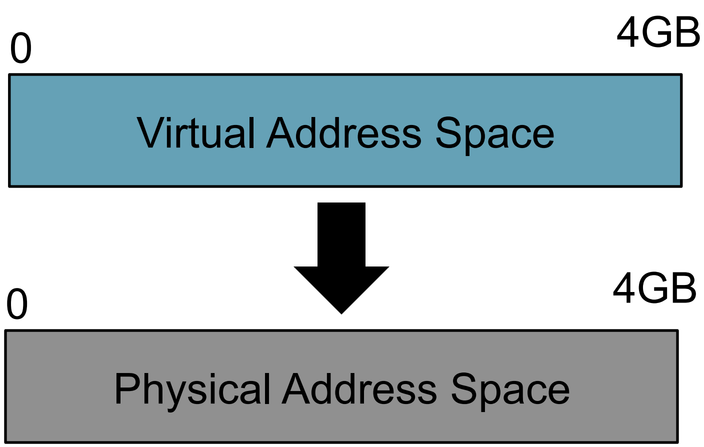
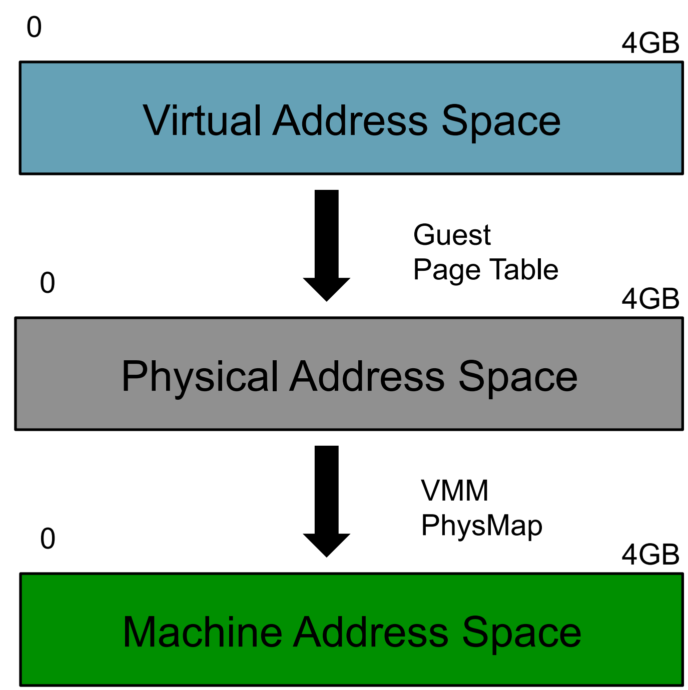
- I/O virtualization

Virtualizing memory

- Add another level of indirection too for memory too
- Physical memory is now a virtualization on top of "machine memory"
  - Each OS maps virtual-to-physical addresses via its per-process page table
  - VMM maps physical mappings to underlying machines via its per-OS page tables





Traditional address spaces

- Consider address translation with a software-managed TLB

Process	**OS**
1.Load from memory; TLB miss: trap to OS	
	2.OS TLB miss handler; extract VPN from VA; do page table lookup; if present and valid, get PFN, update TLB; return from trap
3.Resume execution; instruction is retried, results in TLB hit	

TLB miss flow with virtualization

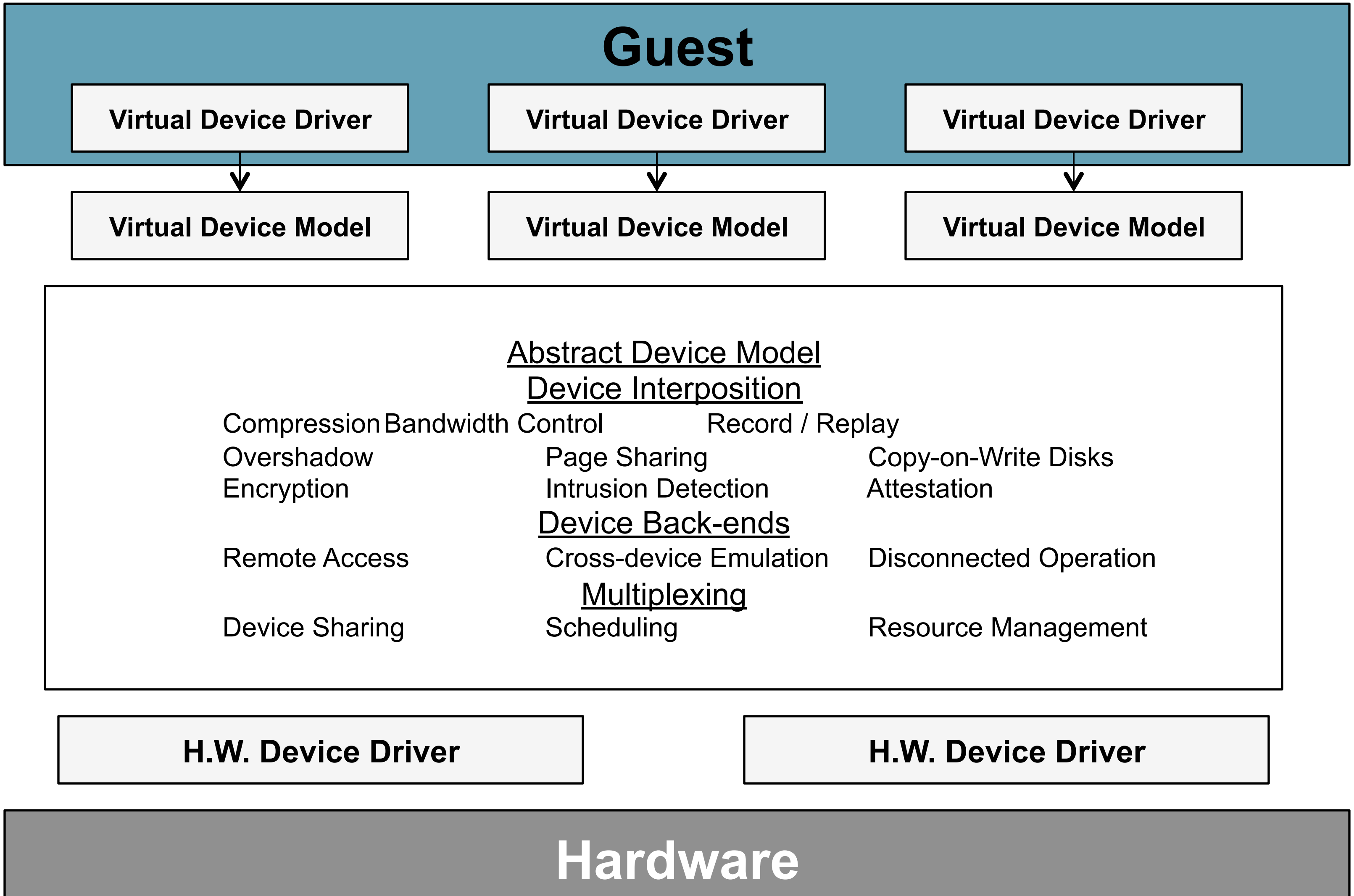
- With a VMM, upon a miss TLB is not the OS TLB miss handler that runs but the VMM's

Process	OS	VMM
1.Load from memory; TLB miss: trap to OS		
		2.VMM TLB miss handler; call into OS TLB handler (reducing privilege)
	3.OS TLB miss handler; extract VPN from VA; do page table lookup; if present and valid, get PFN, update TLB	
		4.Trap handler; unprivileged code trying to update TLB; OS is trying to install VPN-PFN mapping; Update TLB instead with VPN-to-MFN (privileged); Jump back to OS (reducing privilege)
	5.Return from trap	
6.Resume execution; instruction is retried, results in TLB hit		

Issues with virtualized memory

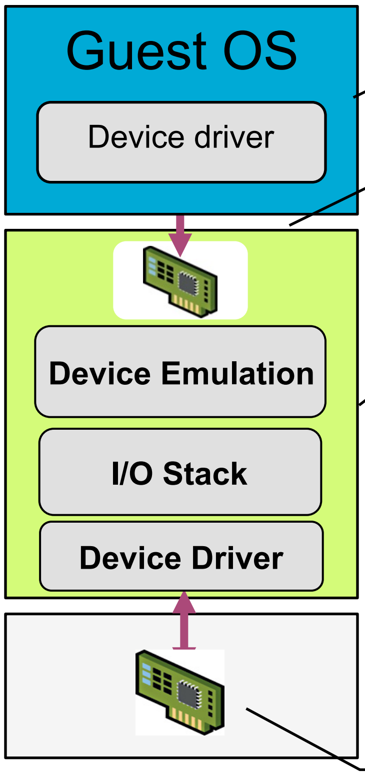
- Positives
  - Simplifies monitor design
- TLB misses significantly more expensive
  - In Disco they added a software TLB to reduce this cost
- With a hardware-managed TLB
  - HW walks the TLB and updates it as needed
  - The VMM must monitor changes the OS makes to each page table and keep a shadow page table that instead maps the virtual address of each process to the VMM's desired machine pages
  - The VMM installs a process' shadow table when the OS tries to install the process' OS-level page table

I/O Virtualization



I/O Virtualization implementations

Virtualized I/O



VMware ESX

Guest device driver

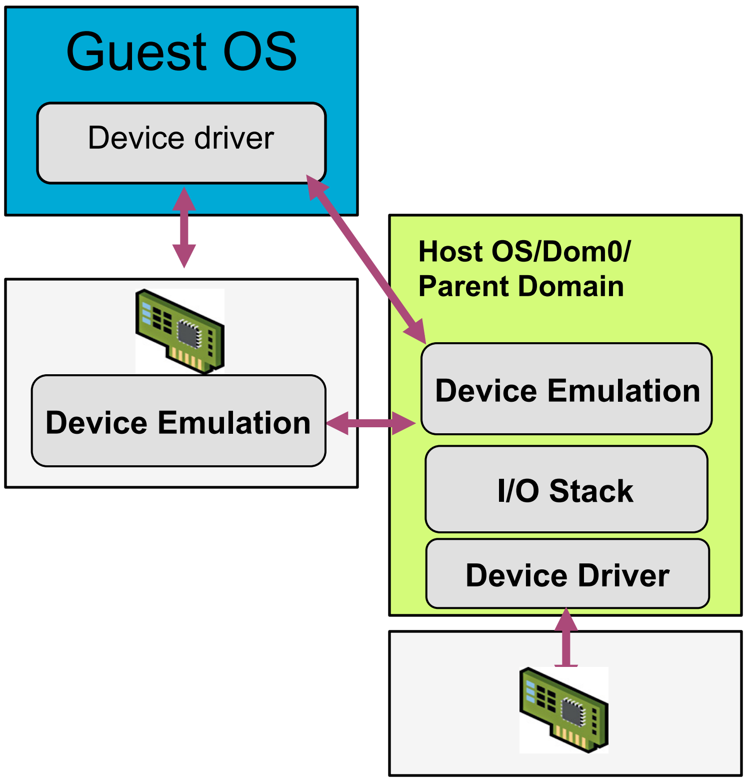
Virtual device

Virtualization layer
- Emulates the virtual device
- Remaps guest and real I/O addresses
- Multiplexes and drives the physical device
- I/O features

Real device
- May be different from virtual

I/O Virtualization implementations

Virtualized I/O: Hosted or Split

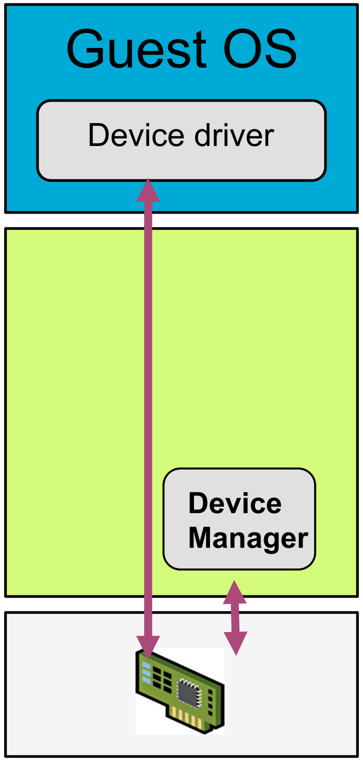


VMware Workstation, VMware Server, Xen, Microsoft Hyper-V, Virtual Server

- Only Domain0, created at boot, has direct access
  - Can also create/terminate domains, control scheduling parameters, physical memory allocation, ..
- All others domains access through virtual device
- Information is pass between domains through shared-memory, asynchronous buffer-descriptor rings

I/O Virtualization implementations

Passthrough I/O



VMware ESX (FPT)

- Fast but inflexible
- How to handle
  - Discontinuous physical memory
  - Read-only physical memory (COW)
  - Paged out physical memory
  - VM migration
  - …

Summary

- Virtualization
  – Not a new concept but technological improvements brought a renaissance and many new usages
  – Interested? Take EECS 441 – much of it focused on Linux kernel development
- Second half of the quarter
  – The power and danger of concurrency
  – I/O and persistent storage