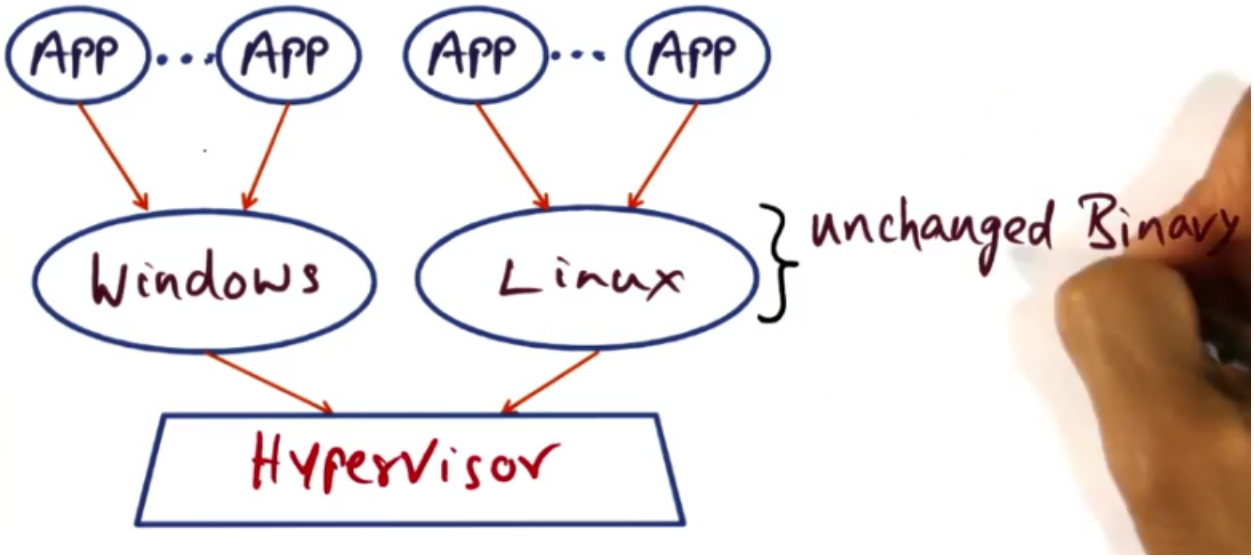
Virtualization

Virtualization Introduction

* Virtualization Examples
    1. Memory systems
    2. Data centers
    3. JVM
    4. VirtualBox
    5. IBM VM/370
    6. Google Glass
    7. Cloud computing
    8. Dalvik
    9. VMWare Workstation
    10. The movie "Inception"
* Platform Virtualization: Instead of running on actual hardware, can we run on virtual hardware without loss of performance?
* Utility Computing: Sharing hardware resources across different communities
    - This means different users can have different OS needs
    - Resource usage typically isn't constant and doesn't require 100% of system resources at a time
    - AWS, Microsoft Azure, GCP
    - Virtualization is the logical extension to the extensibility that was implemented by Exokernel, SPIN, and L3
        + Entire OS though, as opposed to individual services
* Hypervisors: Arbitrates resources across different client OS and protects them from one another
    - Running multiple OS on same hardware resources
    - Also called virtual machine managers (VMM)
    - Two types: Native (bare metal) and hosted
        + Native: Hypervisor running on hardware, guest OS runs on top of hypervisors
        + Hosted: Run on top of host OS as application process, not hardware
    - VMWare Workstation and VirtualBox are hosted hypervisors
    - Native hypervisors provide minimal interference with guest OS
* History of Virtualization
    - IBM VM 370: Provide illusion that the entire computer belonged to a single user, even though they were sharing it (70s)
    - Microkernels: Kernel provides minimal functionality, everything else sits on top of this microkernel (late 90s and 90s)
    - Extensibility of OS: Library OS running on top of minimal kernel (90s)
    - SIMOS: Basis for VMWare, idea of virtual OS (late 90s)
    - Xen and VMWare: Virtualization as we know today (early 2000s)
    - Today: Virtualization is used widely in data centers
* Full Virtualization: Leave the OS untouched so you can run an unchanged binary of the OS on top of the hypervisor
    - Guest OS will be running as a user-level process, not the same level of privelege as the OS would be if running on bare metal
    - Guest OS will be unaware that it doesn't have the same priveleges
        + Binary is unchanged
    - Trap and emulate: When a guest OS tries to execute a priveleged instruction, the hypervisor receives the trap and emulates the intended functionality
    - Some priveleged instructions may fail; guest OS will think it

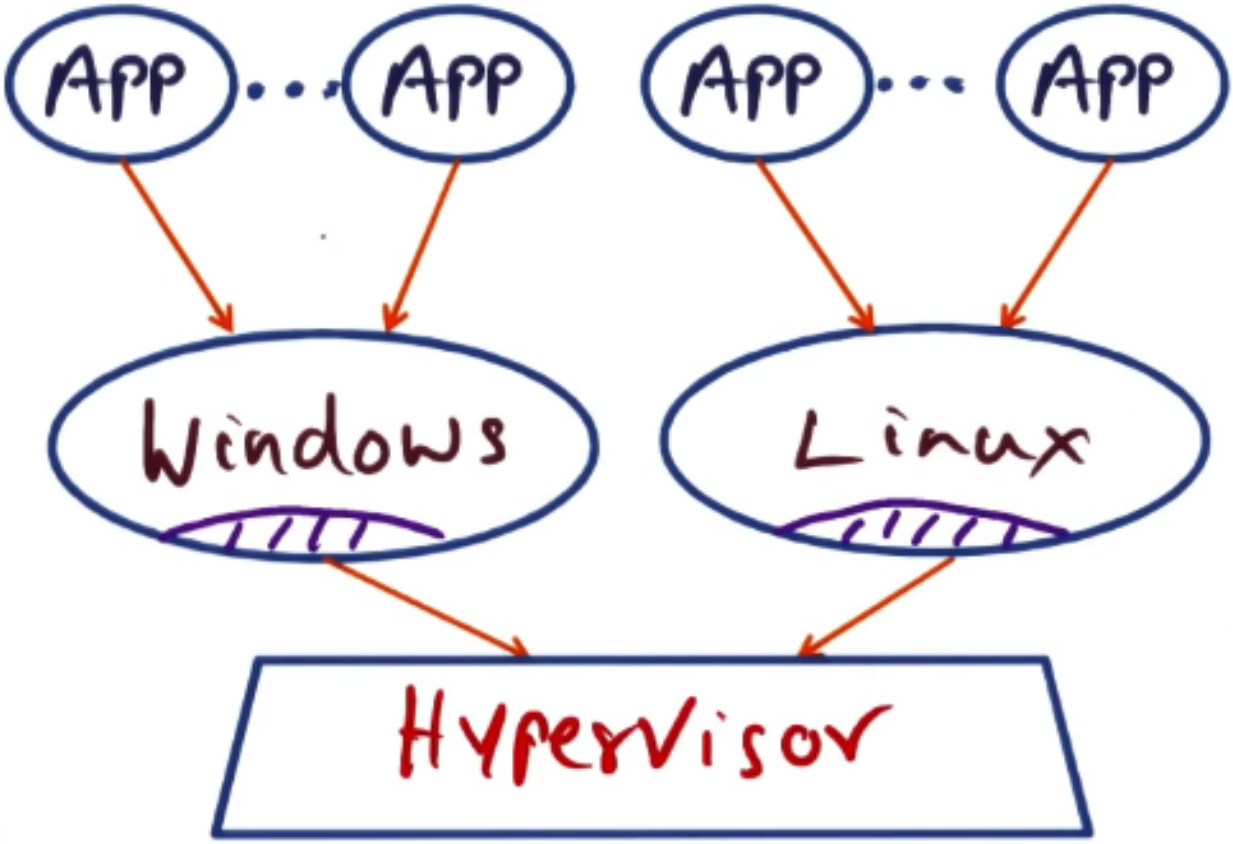
succeeded
    + Binary translation: Hypervisor looks for these instructions and ensures the instructions are dealt with carefully through binary editing strategies
- VMWare Workstation is an example of full virtualization



Full Virtualization

* Para Virtualization: Modify source of guest OS so they are aware they're running in a virtualization setting
    - Can introduce optimizations, such as giving guest OS access to hardware resources
    - Applications seem same interfaces an OS running on bare metal would provide
    - Not fully virtualized, only partially
    - Less than 2% of guest OS code needs to be modified
    - Xen architecture is an example of para virtualization
        + Showed this by proof of construction

Subsystem	Linux	XP
Architecture Independent	78	1299
Virtual Network Driver	484	0
Virtual Block Device Driver	1070	0
Xen Specific	1363	3321
Total	2995	4620
% Total Codebase	1.36	0.04



Para Virtualization

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* Big picture
    - Virtualize harware
        + Memory hierarchy
        + CPU
        + Devices
    - Effect data and control between guests and hypervisor
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Memory Virtualization

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* Memory Management and the Hypervisor
    - Hypervisor sits between guest OS and hardware
    - Each process (guest OS) is in its own protection domain
        + OS maintains separate page table for each process
    - Hypervisor isn't aware of the different processes running in each
    guest OS, so it doesn't know about their individual page tables
    - Guest OS assumes its physical memory is contiguous, but hypervisor
    does not provide this guarantee (not all memory can start at 0)
    - Normally, a virtual page number is mapped to a physical frame number
    through the page table
        + When virtualized, another level of indirection is required
        + Hypervisor tracks physical frame numbers of guest OS and how they
        are mapped to machine memory
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    + Physical page number to machine page number is kept in the "shadow
    page table"
- In a fully virtualized system, the shadow page table is kept by the
hypervisor
- In a para virtualized system, the shadow page table is kept by the
guest OS (could still be hypervisor though)
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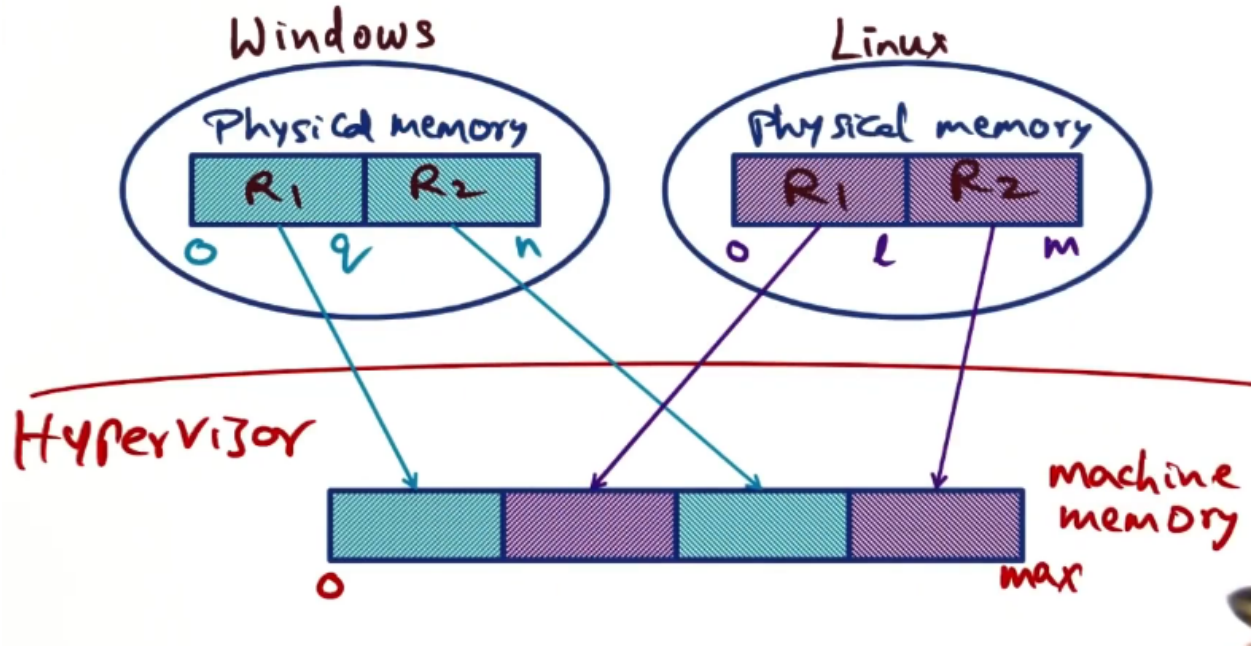
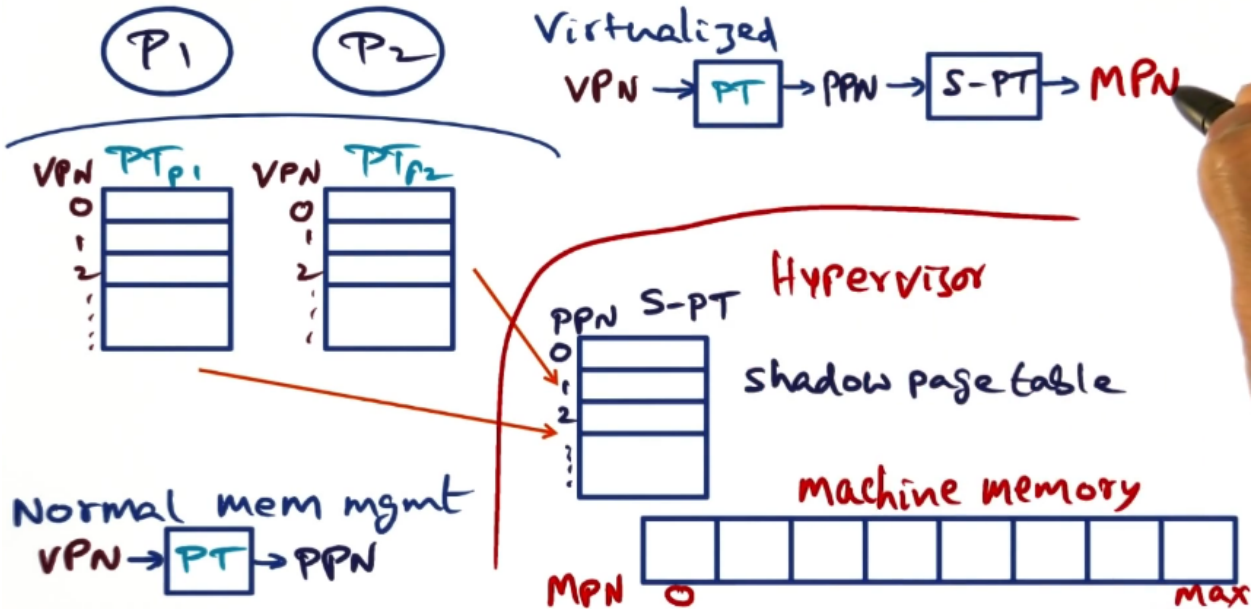
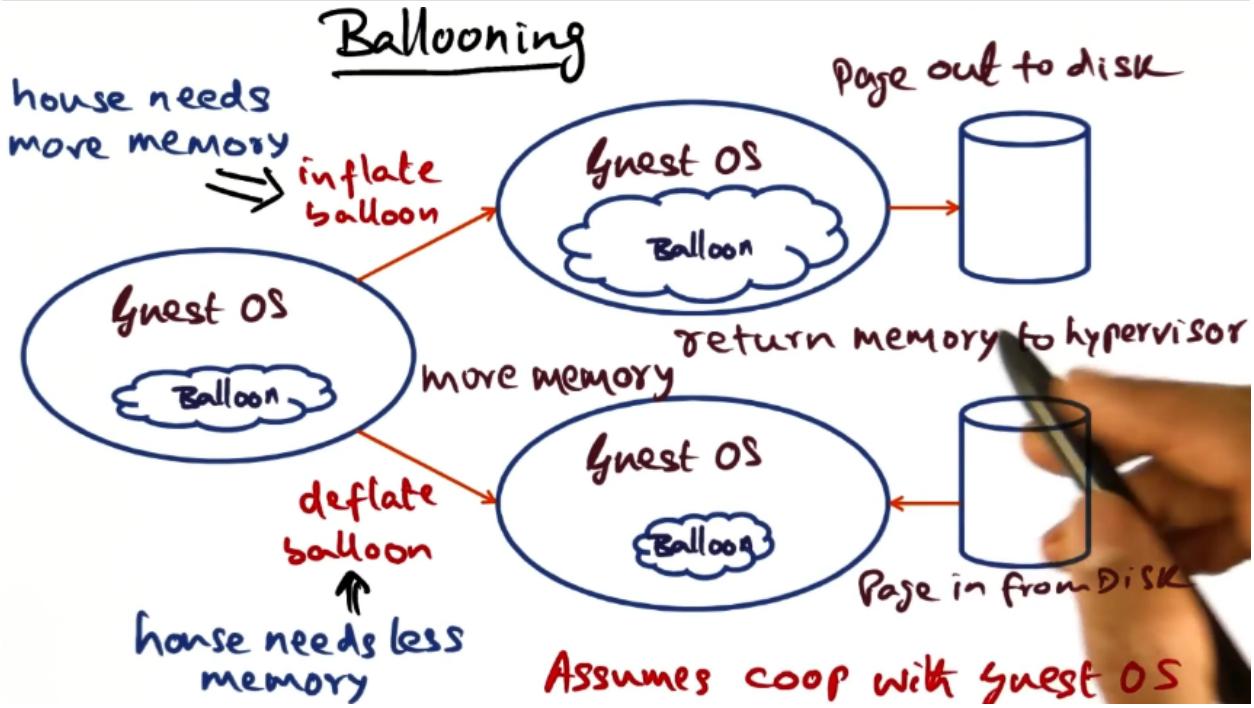


Memory Manager (Macro view)



Memory Manager (Micro view)

* Shadow Page Table
    - In many architectures (x86) CPU uses page table for address translation
        + Both TLB and page table are data structures used for address translation
    - This means the hardware page table is really the shadow page table
* Efficient Mapping (Full Virtualization)
    - Typically, the guest OS would map VPN -> PT -> PPN, then the hypervisor would map PPN -> SPT -> MPN
    - For efficiency, is there a way to eliminate the first level of indirection?
    - Any time guest OS tries to update page table/TLB, it causes a trap
        + Then, the hypervisor can update its shadow page table
        + This means it can all be done at once
        + Translations installed into TLB/hardware page table
        + Hypervisor can directly translate VPN to MPN through TLB and hardware page table
* Efficient Mapping (Para Virtualization)
    - Shift burden to guest OS
        + Maintain contiguous "physical memory"
        + Map to discontiguous hardware pages
    - Xen provides a set of "hypercalls" to tell the hypervisor about changes to the hardware page table
        + Create page table (on process initialization, allocate page frame)
        + Switch page table (on context switch)
        + Update page table (on page fault, VPN->PFN needs to change)
* Dynamically Increasing Memory
    - Hypervisor must be able to allocate machine memory to guest OS on demand
    - When on guest OS needs more memory, it issues a request to the hypervisor
        + Hypervisor can reclaim memory from another guest OS, but this can result in undefined behavior for the other guest
        + Can request that the other guest gives up some memory voluntarily
* Ballooning
    - Special device driver installed in every guest OS (even in fully virtualized system) called balloon
    - When the host needs more memory, it can "inflate" the balloon device driver, causing it to request memory from guest OS
        + If guest OS memory is full and balloon asks for more memory, it will page out memory to disk
        + Then, the excess memory claimed by the balloon is returned to the hypervisor
    - When the host no longer needs the memory, it can contact the balloon driver to "deflate"
        + This will release the pages in the guest OS and it will page in relevant pages from disk so its processes will have more resources
    - Assumes cooperation with guest OS
    - Analogous to airlines selling more seats than they have



Ballooning

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* Sharing Memory Across Virtual Machines
    - Desire to share memory between virtual machines to optimize usage if
    two guest OS's are using the same data
    - Can't affect integrity of the guest OS
    - If two guests are running the exact same process, we can set their
    page tables to point to the same physical memory location
        + Avoids duplications
        + Particularly true for core pages of a process (immutable)
    - On write, hypervisor can make a copy of the pages to prevent one guest
    from corrupting the memory of another (copy on write)
* VM Oblivious Page Sharing
    - Hypervisor keeps a hash table of the content of the machine pages
    - Creates a hash of the content and check the "hint frame" (hash table)
    to see if the content is already in memory
    - Doesn't guarantee that the contents are identical, just a hint
        + The page may have been updated since the hint frame was created
    - Once there's a match, we do a full comparison to guarantee that the
    pages are identical
    - Modify the physical page number to machine page number for guest
        + Update reference counter in hash table
        + Mark as "copy on write," meaning they can only share the frame as
        long as they're only reading from it
        + Frees up a machine page, but this is an expensive operation
    - Scanning pages is performed as a background activity of the server
    - Works in both fully virtualized and para virtualized settings
* Memory Allocation Policies
    - Pure share based approach: Resources given according to payment
        + Could lead to hoarding of resources (wasting)
    - Working-set based approach: If VM needs more resources, it gets them;
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when it no longer needs them, it frees them
- Dynamic idle-adjusted shares approach: Tax idle pages more than active pages
    + 0% means idle pages aren't reclaimed
    + 100% means all idle resources are reclaimed (use it or lose it)
    + Somewhere in between is ideal (50-75%); used by VMWare ESV server
- Reclaim most idle memory while simultaneously allowing for sudden increases in the working set

CPU and Device Virtualization

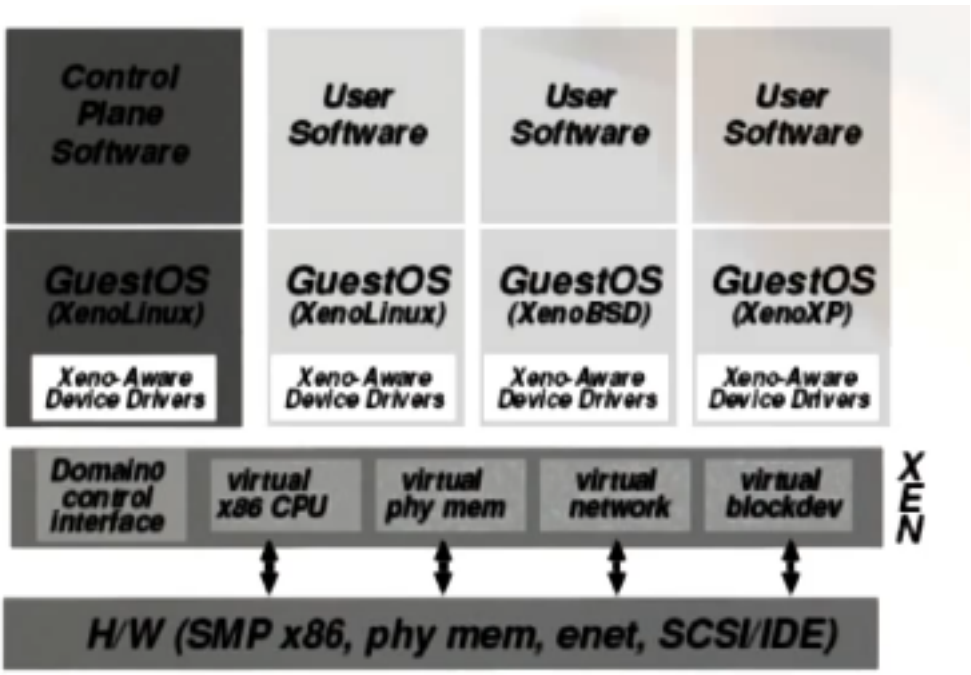
* CPU Virtualization Introduction
    - Provide the illusion of owning the CPU (not aware of other guests)
        + Provided by hypervisor at OS granularity
    - Handle program discontinuities
* CPU Virtualization
    - Guest OS is already multiplexing CPU across processes, hypervisor needs to multiplex CPU across OS's
        + Proportional share: Amount of CPU depends on agreement guest OS has with hypervisor
        + Fair share: Amount of CPU is equal for each guest OS
    - When an external interrupt occurs, hypervisor may need to steal cycles from currently running guest and give them back later
* Delivering Events to Guest OS (common to full and para)
    - While an OS is running, everything should be happening at hardware speeds (no overhead due to hypervisor)
    - However, interrupts, syscalls, exceptions, and page faults while require OS intervention
        + Hypervisor delivers events as software interrupts to guest OS
        + Handling some of these events may require priveleged access, but guest OS is running in user mode
        + Some priveleged instructions fail silently when executed at the user level instead of trapping (only issue in fully virtualized)
        + Hypervisor must be aware of what instructions these are in the guest OS to handle appropriately
        + Newer versions of Intel architecture provide support for virtualization
    - In a fully virtualized environment, communication between guest and hypervisor is implicit through traps
    - In a para virtualized environment, communication between guest and hypervisor is explicit through APIs

Device Virtualization

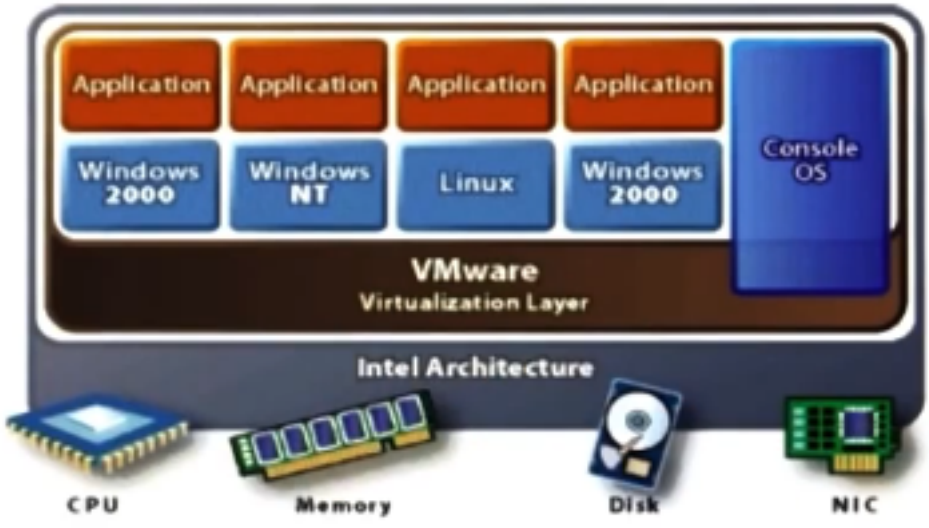
* Full Virtualization
    - Guest OS thinks it owns devices; communication is handled through "trap and emulate" instructions to hypervisor
        + Hypervisor must determine the legality of the I/O operation
* Para Virtualization
    - More opportunity for innovation
    - Interrupts go to hypervisor, transferred as events to guest OS
    - Hypervisor defines "hypercalls" (i.e., page table updates)
    - Hypervisor includes shared buffers to avoid multiple copying of data
* Control Transfer

    - Full virtualization
        + Implicit (traps) in guest OS transfer control to hypervisor
        + Software interrupts (events) in hypervisor transfer control to guest OS
    - Para virtualization
        + Explicit (hypercalls) in guest OS transfer control to hypervisor
        + Software interrupts (events) in hypervisor transfer control to guest OS
        + Guest has control via hypercalls on when event notifications are delivered (not possible in fully virtualized system)
* Data Transfer
    - Full virtualization
        + All implicit
    - Para virtualization
        + Explicit -> opportunity to innovate
        + When an interrupt occurs, hypervisor must demultiplex the data that is coming from the device to the domains quickly
        + Time issue: Which guest are CPU cycles "billed" to?
        + Space issue: How are buffers allocated and managed?
    - Xen's Asynchronous I/O rings
        + Data structure shared between guest and hypervisor for communication
        + I/O ring is a set of descriptors to I/O devices
        + Guest OS puts requests in the ring, hypervisor puts responses back
        + Guest OS has request producer pointer that Xen can read from
        + Hypervisor has request consumer pointer that is private to Xen
        + Hypervisor has response producer pointer that guest can read from
        + Guest OS has response consumer pointer that is private to guest
        + Requests/responses have a unique ID to identify them
        + All of this is done with pointer passing; fast
* Control and Data Transfer
    - Network transmit
        + Guest OS puts transmit request in transmit ring through hypercalls
        + Guest puts pointers to data buffers in request (no copying, page is pinned to prevent it from being paged out)
        + Xen uses round robin packet scheduler
    - Network receipt
        + Exchange received packet for guest OS page
        + No copying; Xen writes to the preallocated buffers
        + Xen can swap machine page for a page the guest already owns instead of using a preallocated buffer
* Disk I/O Virtualization
    - Every VM has a ring for disk I/O (private to each guest)
    - No copying into Xen
    - Request from competing domains may be reordered to make the I/O throughput more efficient
    - Xen provides a reorder barrier for guest OS semantics (disallows any reordering)
* Measuring Time
    - Resources shared by many clients; need a mechanism to bill them
        1. CPU usage
        2. Memory usage
        3. Storage usage
        4. Network usage
* Xen and Guests

- Difference from extensible OS
    + Focus on protection and flexibility
    + Not at the granularity of individual applications, but at the granularity of entire operating systems



Xen (Para Virtualized)



Xen (Para Virtualized)