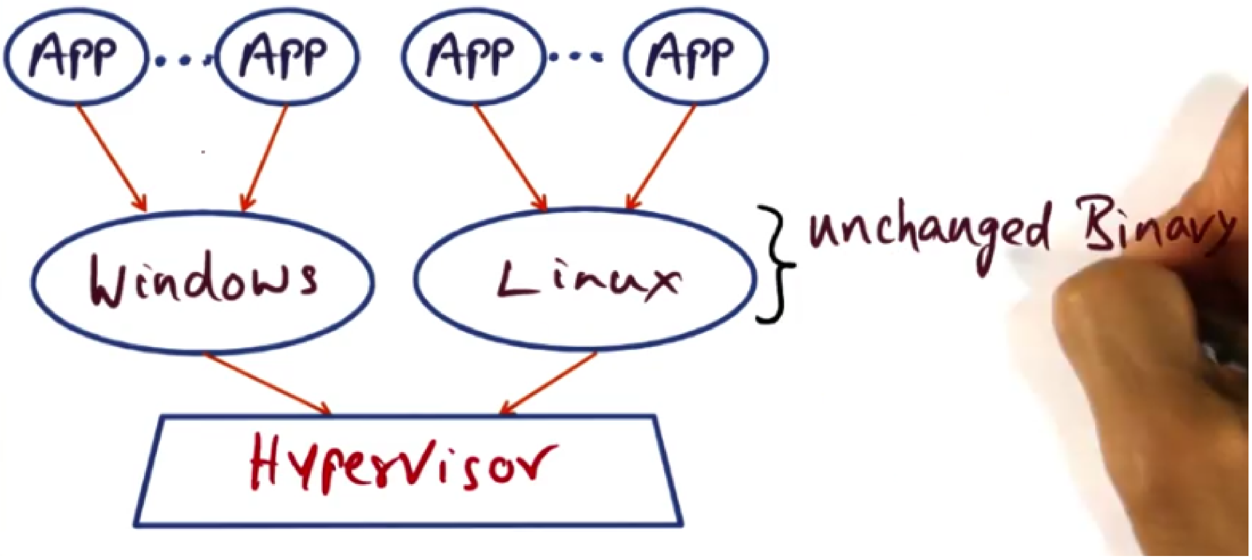
Virtualization

Virtualization Introduction

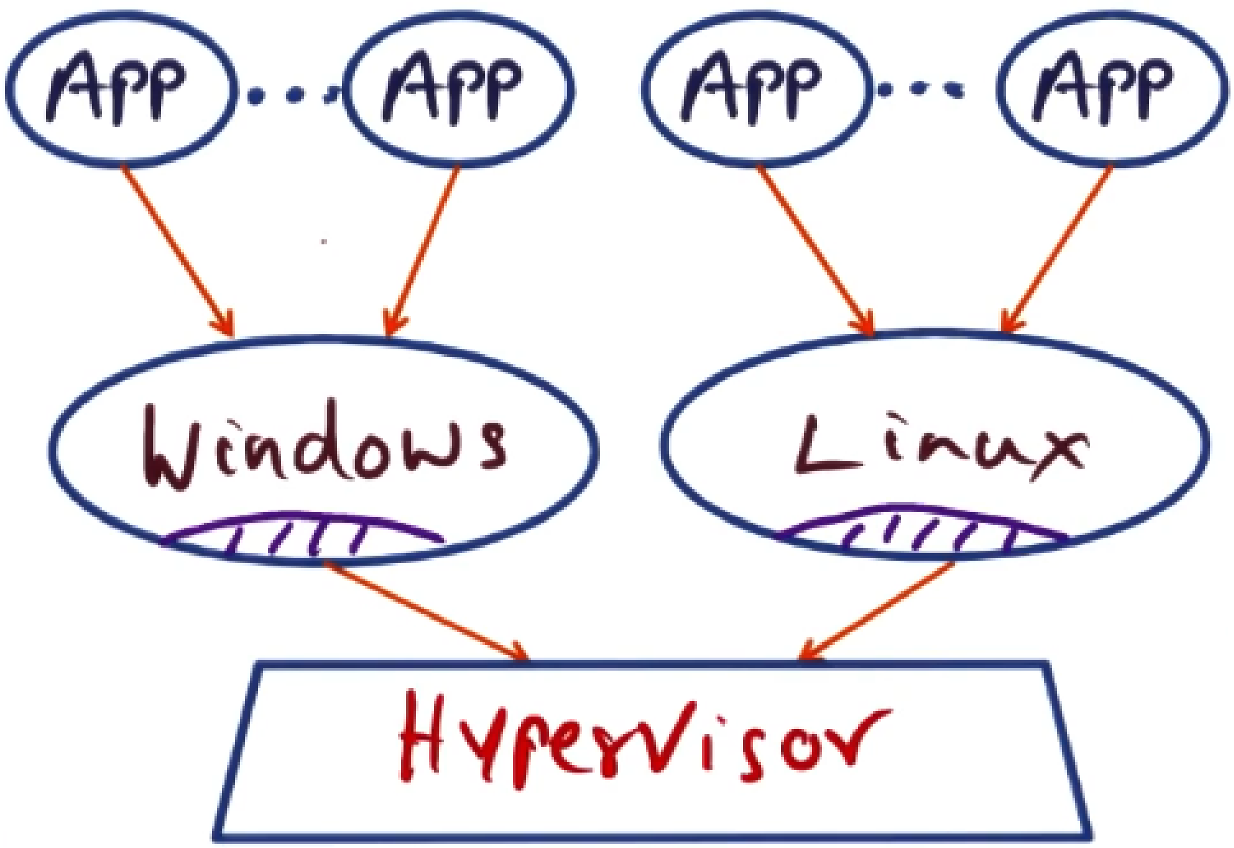
1. Virtualization Examples
    - Memory systems
    - Data centers
    - JVM
    - VirtualBox
    - IBM VM/370
    - Google Glass
    - Cloud computing
    - Dalvik
    - VMWare Workstation
    - The movie "Inception"
2. Platform Virtualization: Instead of running on actual hardware, can we run on virtual hardware without loss of performance?
3. 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
4. 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
5. 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
6. 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

7. 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



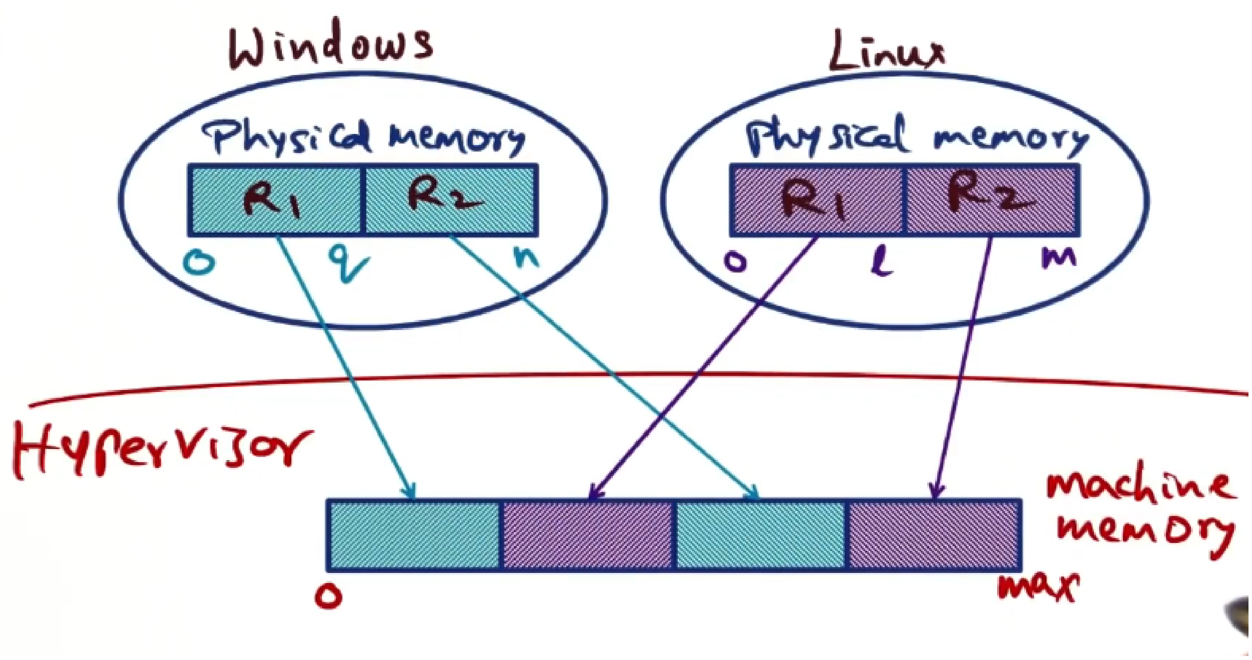
Para Virtualization

8. Big picture
    - Virtualize harware
        - Memory hierarchy
        - CPU
        - Devices
    - Effect data and control between guests and hypervisor

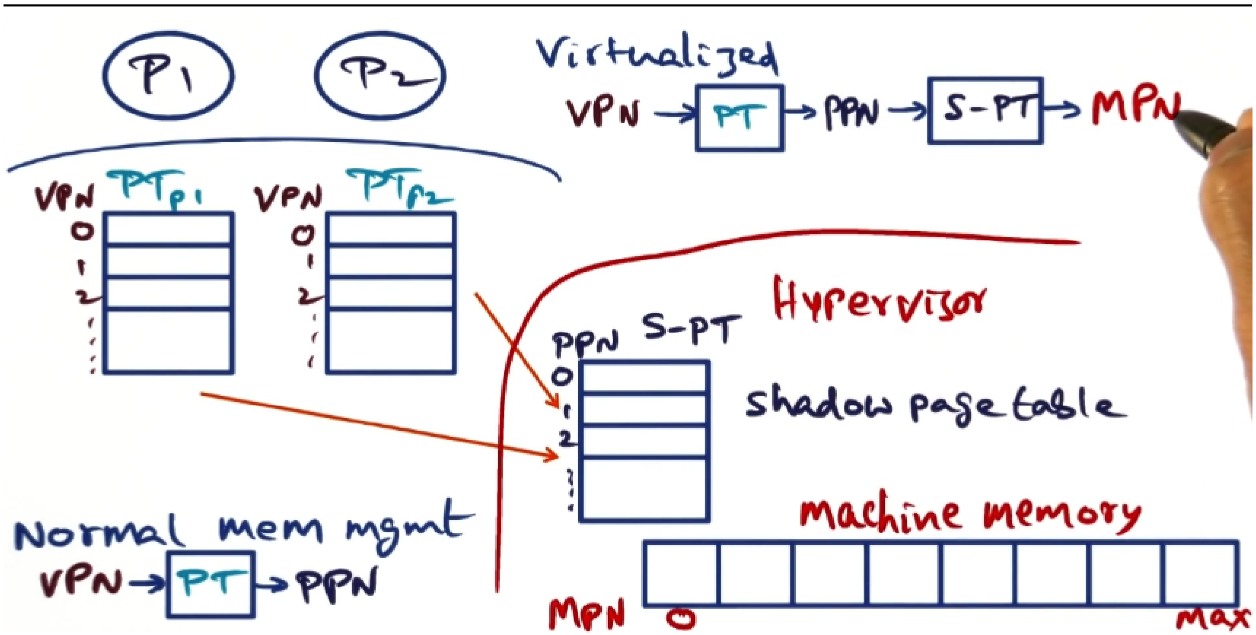
Memory Virtualization

1. 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
        - 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)



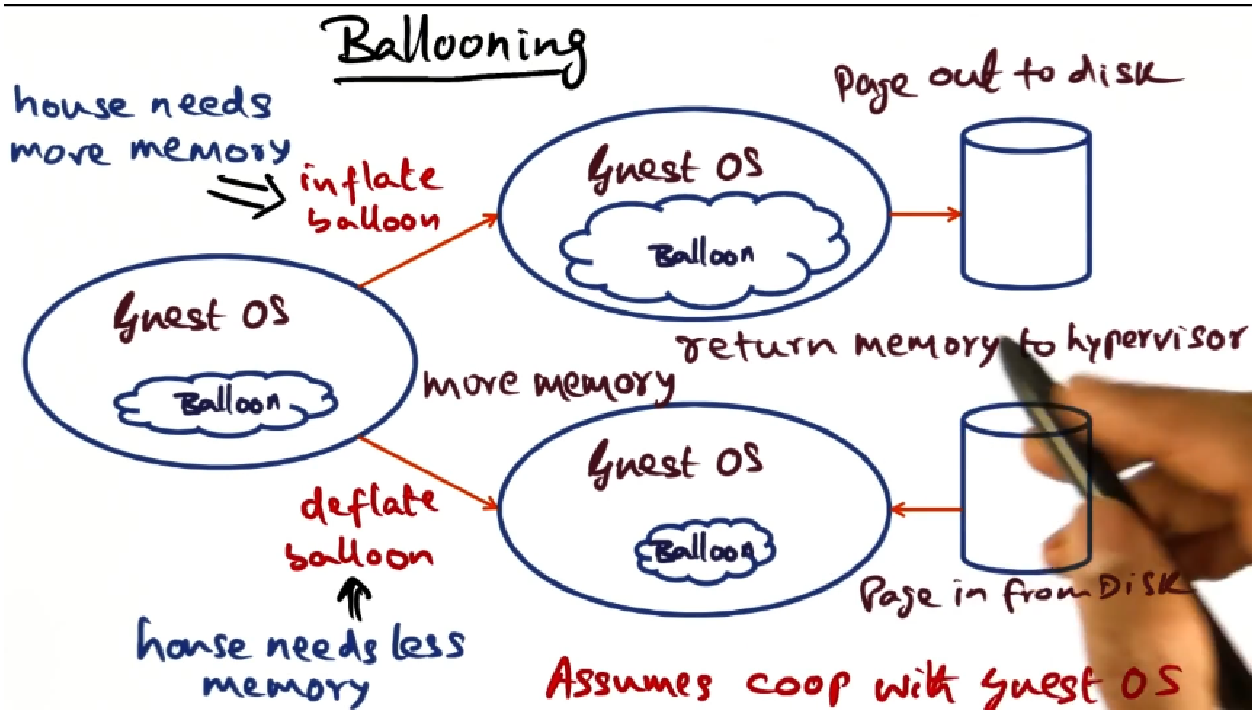
Memory Manager (Macro view)



Memory Manager (Micro view)

2. 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
3. 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
4. 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)
5. 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
6. 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

7. 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)
8. 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
9. 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; 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

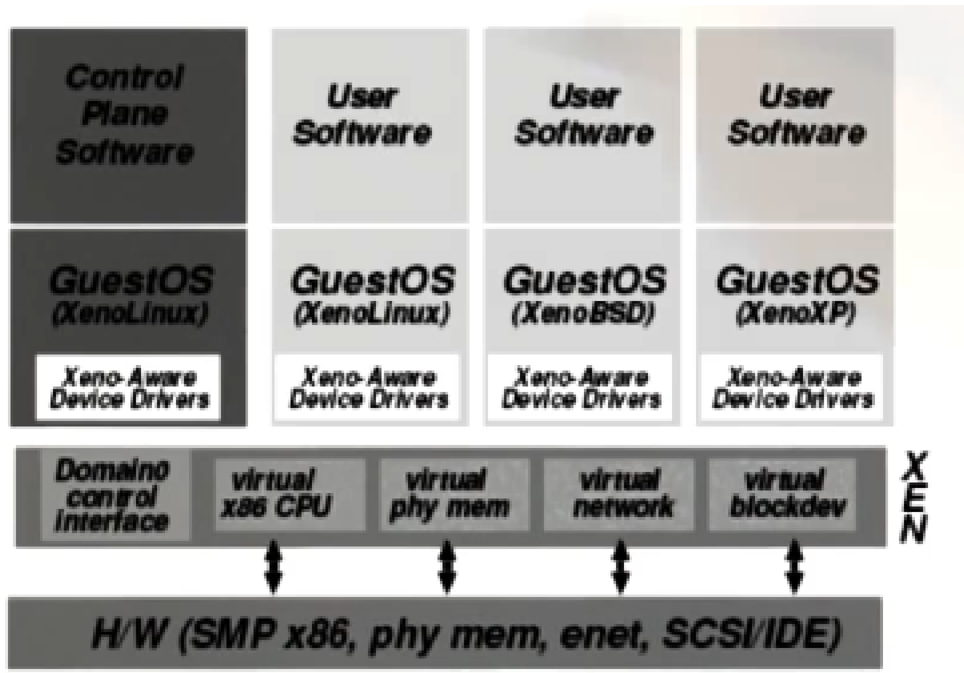
1. CPU Virtualization Introduction
   - Provide the illusion of owning the CPU (not aware of other guests)
     - Provided by hypervisor at OS granularity
   - Handle program discontinuities
2. CPU Virtualization
   - Guest OS is already multiplexing CPU across processes, hypervisor needs to multiplex 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
3. 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

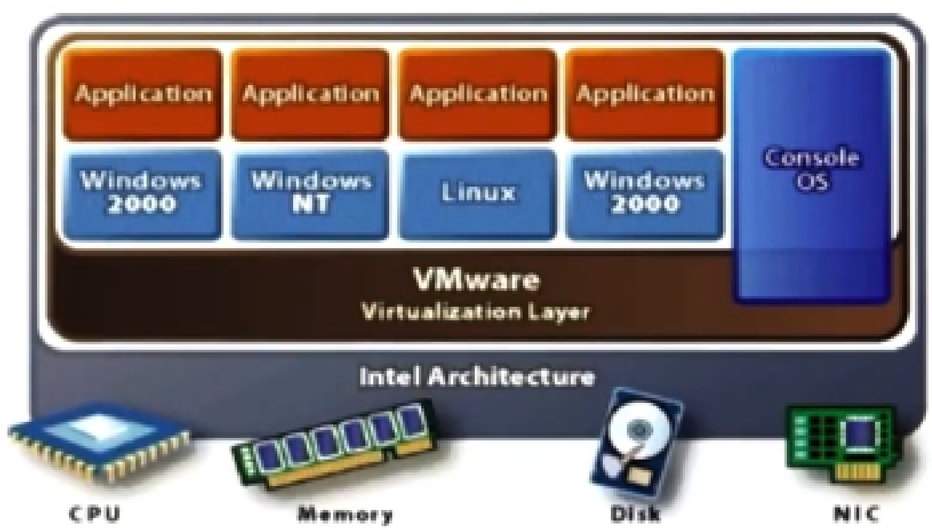
1. Full Virtualization
   - Guest OS thinks it owns devices; communication is handled through "trap and emulate" instructions to hypervisor
     - Hypervisor must determine the legality of the I/O operation
2. Para Virtualization
   - More opportunity for innovation
   - Interrupts go to hypervisor, transferred as events to guest OS
   - Hypervisor defines "hypercalls" (i.e., page table updates)
   - Hypervisor includes shared buffers to avoid multiple copying of data
3. 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)

4. 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
5. 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
6. 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)
7. Measuring Time
    - Resources shared by many clients; need a mechanism to bill them
        - CPU usage
        - Memory usage
        - Storage usage
        - Network usage
8. 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)