CSE 120
Principles of Operating Systems

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Lecture 13: Virtual Machine Monitors

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Virtual Machine Monitors

- Virtual Machine Monitors (VMMs) are a hot topic in industry and academia
  - Industry commitment
    - » Software: VMware, Xen, Microsoft Virtual PC
    - » Hardware: Intel VT, AMD-V
      - If Intel and AMD add it to their chips, you know it's serious…
  - Academia: lots of VMM-based projects and papers
- An old idea, actually: developed by IBM in 60s and 70s
- Today
  - What is it, what problems have to be solved, how to solve them
  - Survey some virtualization systems
  - Briefly outline cool things you can do with virtualization

What is a VMM?

- We have seen that an OS already virtualizes
  - Syscalls, processes, virtual memory, file system, sockets, etc.
  - Applications program to this interface
- A VMM virtualizes an entire physical machine
  - Interface supported is the hardware
    - » OS defines a higher-level interface
  - VMM provides the illusion that software has full control over the hardware (of course, VMM is in control)
  - VMM “applications” run in virtual machines (c.f., OS processes)
- Implications
  - You can boot an operating system in a virtual machine
  - Run multiple instances of an OS on same physical machine
  - Run different OSes simultaneously on the same machine
    - » Linux on Windows, Windows on Mac, etc.

Why in tarnation would you do such a crazy thing?

- Resource utilization
  - Machines today are powerful, want to multiplex their hardware
    - » e.g., ISP hosting can divvy up a physical machine to customers
  - Can migrate VMs from one machine to another without shutdown
- Software use and development
  - Can run multiple OSes simultaneously
    - » No need to dual boot
  - Can do system (e.g., OS) development at user-level
- Many other cool applications
  - Debugging, emulation, security, speculation, fault tolerance…
- Common theme is manipulating applications/services at the granularity of a machine
  - Specific version of OS, libraries, applications, etc., as package

VMM 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:
    - » CPU-intensive apps: 2-10% overhead
    - » I/O-intensive apps: 25-60% overhead (better today)

Rough VMM Model

- VMM runs with privilege
  - OS in VM runs at “lesser” privilege (think user-level)
  - VMM multiplexes resources among VMs
- Want to run OS code in a VM directly on CPU
  - Think in terms of making the OS a user-level process
  - What OS code can run directly, what will cause problems?
- Ideally, want privileged instructions to trap
  - Exception vectors to VMM, it emulates operation, returns
  - Nothing modified, running unprivileged is transparant
  - Known as trap-and-emulate
- Unfortunately on architectures like x86, not so easy

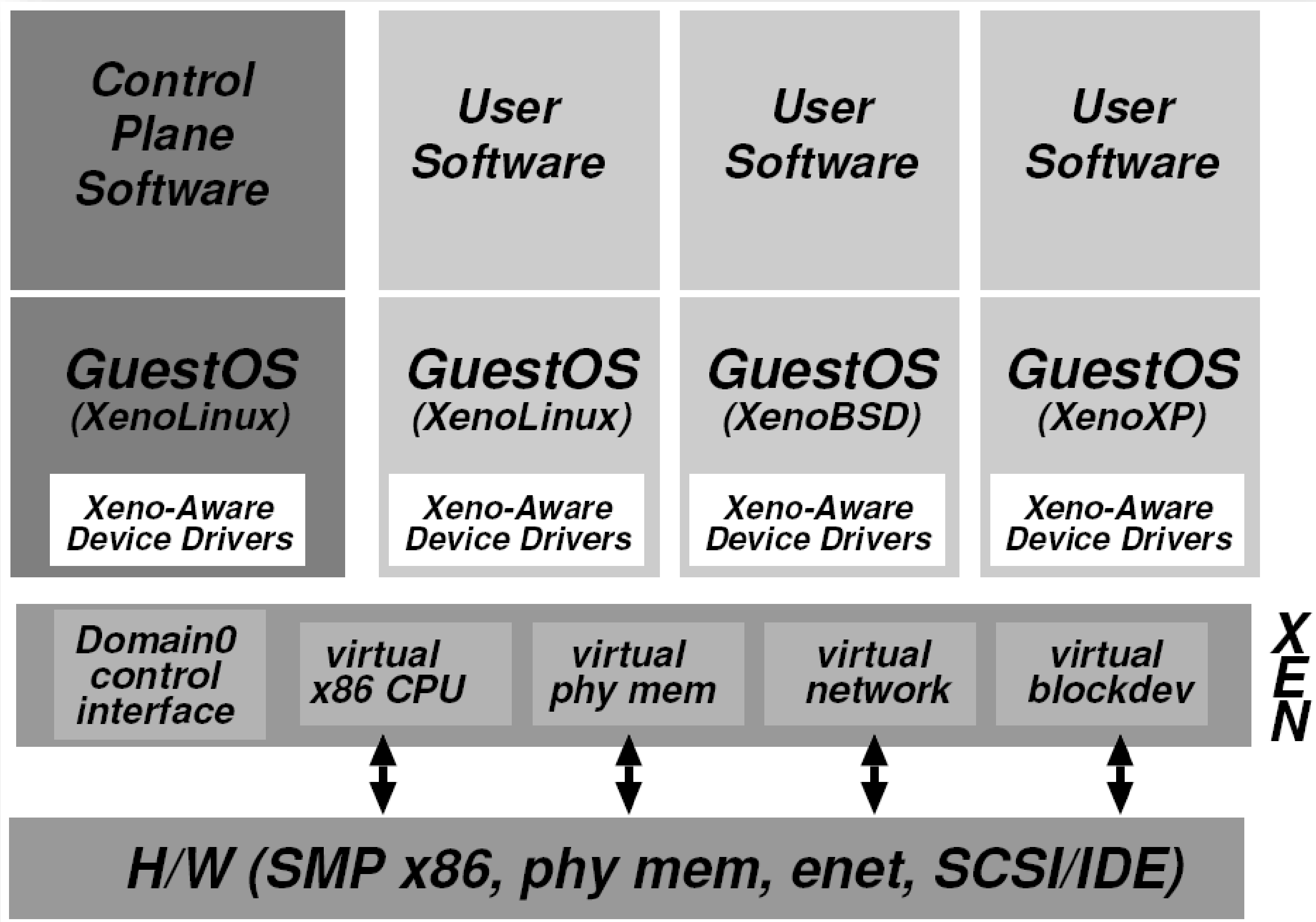
Virtualizing the x86

- Ease of virtualization influenced by the architecture
  - x86 is perhaps the last architecture you would choose
  - But it's what everyone uses, so…that's what we deal with
- Issues
  - Unvirtualizable events
    - » `popf` does not trap when it cannot modify system flags
  - Hardware-managed TLB
    - » VMM cannot easily interpose on a TLB miss (more in a bit)
  - Untagged TLB
    - » Have to flush on context switches (just a performance issue)
- Why Intel and AMD have added virtualization support

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

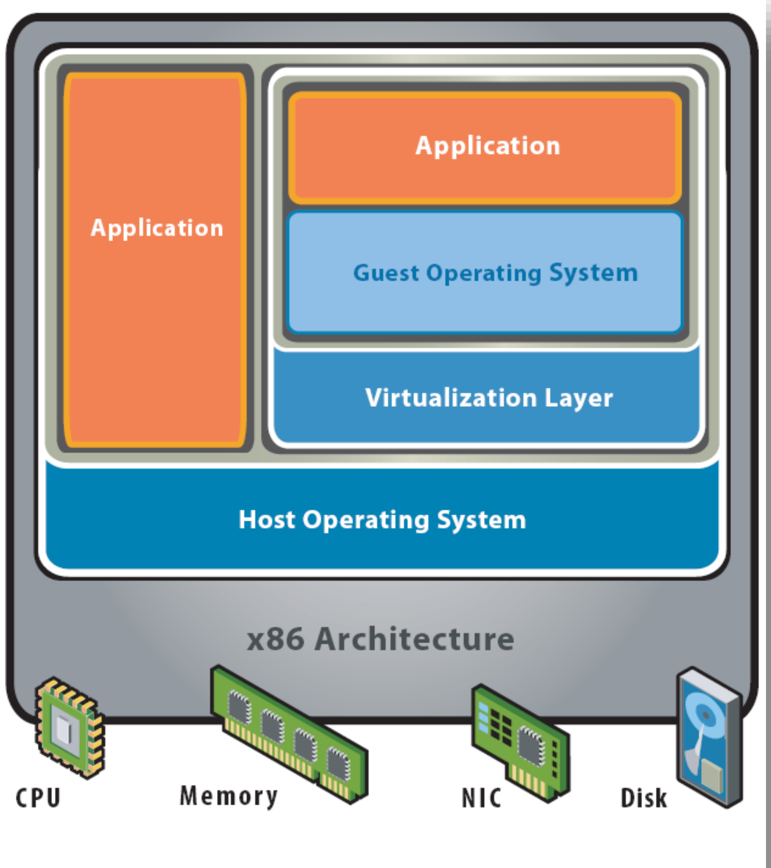
Xen Architecture



VMware

- VMware workstation uses hosted model
  - VMM runs unprivileged, installed on base OS
  - 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
    - » Rewrite privileged instructions with emulation code (may trap)
  - CPU only executes translated code
  - 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



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

Virtualizing Privileged Insts

- OSes can no longer successfully execute privileged instructions
  - Virtual memory registers, interrupts, I/O, halt, etc.
- For those instructions that cause an exception
  - Trap to VMM, take care of business, return to OS in VM
- For those that do not…
  - Xen: modify OS to hypervisor call into VMM
  - VMware: rewrite OS instructions to emulate or call into VMM

Virtualizing the CPU

- VMM needs to multiplex VMs on CPU
- How? Just as you would expect
  - Timeslice the VMs
  - Each VM will timeslice its OS/applications during its quantum
- Typically relatively simple scheduler
  - Round robin, work-conserving (give unused quantum to other VMs)

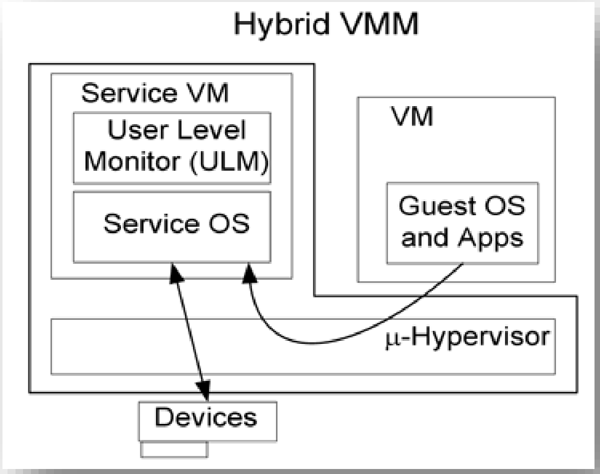
Virtualizing Events

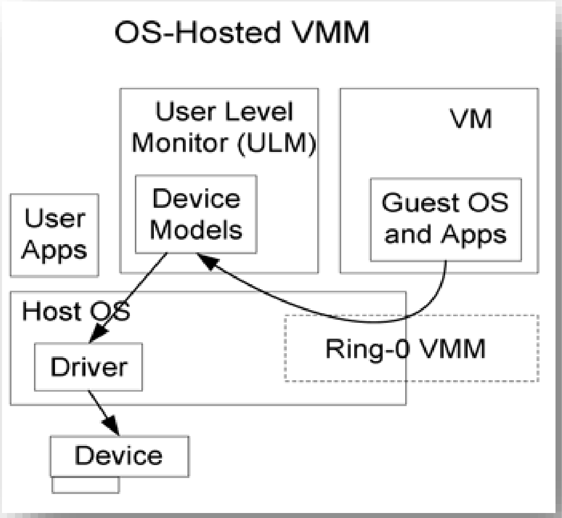
- VMM receives interrupts, exceptions
- Needs to vector to appropriate VM
  - Xen: modify OS to use virtual interrupt register, event queue
  - VMware: craft appropriate handler invocation, emulate event registers

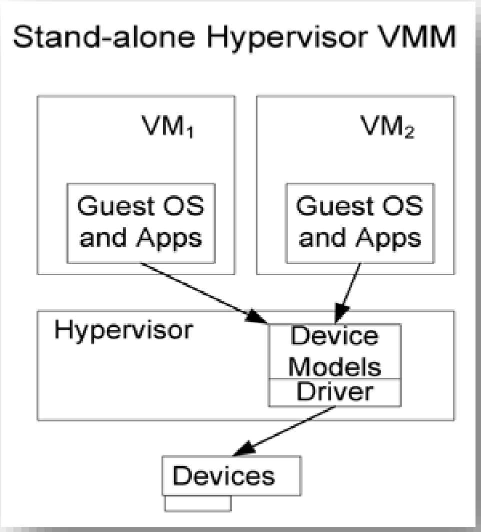
Virtualizing I/O

- OSes can no longer interact directly with I/O devices
- 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

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

Xen Paravirtualization

- Xen uses the page tables that an OS creates
  - These page tables are used directly by hardware MMU
- Xen validates all updates to page tables by OS
  - OS can read page tables without modification
  - But Xen 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 Xen when updating PTEs
    - Batch updates to reduce overhead
- Page tables work the same as before, but OS is constrained to only map to the physical pages it owns
- Works fine if you can modify the OS. If you can't…

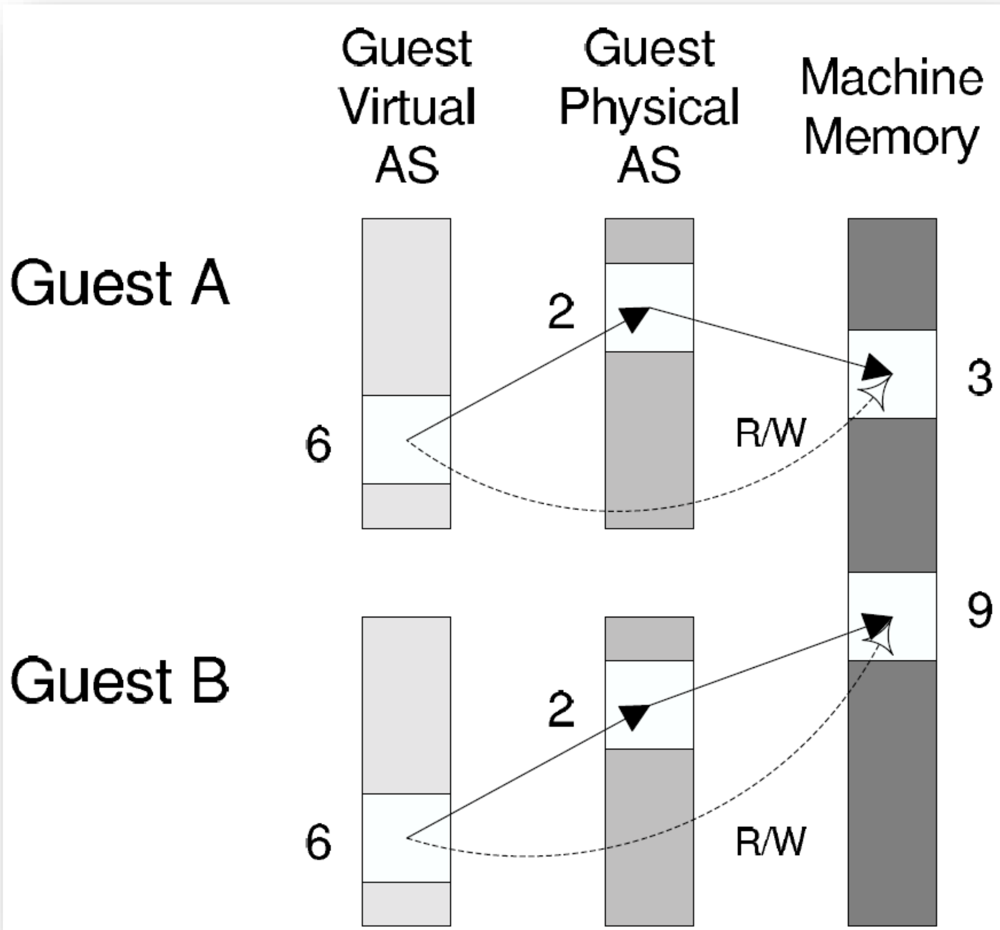
Shadow Page Tables

- 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} address space
- 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 (2)

- 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
  - When OS writes to page tables, trap to VMM
  - VMM applies write to shadow table and OS table, returns
  - Also known as memory tracing
  - Again, more overhead…

Shadow Page Tables (3)



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

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
- Execution model
  - New execution mode: guest mode
    - » Direct execution of guest OS code, including privileged insts
  - Virtual machine control block (VMCB)
    - » Controls what operations trap, records info to handle traps in VMM
  - New instruction `vmrun` enters guest mode, runs VM code
  - When VM traps, CPU executes new `exit` instruction
  - Enters VMM, which emulates operation

Hardware Support (2)

- Intel and AMD working on further hardware support
- 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
    - » No need to trap to VMM when OS updates its page tables
  - New tables map physical to machine pages
    - » Managed by VMM
  - 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 DEV: exclude pages (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
- Lesson: Never underestimate the power of indirection