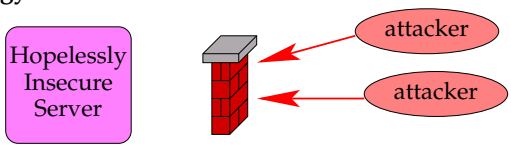
Administrivia

- **Guest lecture Thursday**
  - Amit Singh (Google): Real-world Operating Systems
  - Please attend lecture if at all possible
- **Last project due Thursday**
  - No extensions unless *all* non-SCPD group members at lecture
  - If staff grants you extension, means only if you attend lecture
  - We will have a more stringent enforcement mechanism
- **Final Exam**
  - Thursday March 18, 12:15-3:15pm
  - Open book, covers all 19 lectures
    (possibly including topics already on the midterm)
- **Televised final review session Friday**
  - Bring questions on lecture material

Confining code with legacy OSes

- **Often want to confine code on legacy OSes**
- **Analogy: Firewalls**



  - Your machine runs hopelessly insecure software
  - Can't fix it—no source or too complicated
  - *Can* reason about network traffic
- **Similarly block unrusted code within a machine**
  - By limiting what it can interact with

Using chroot

- `chroot (char *dir)` **"changes root directory"**
  - Kernel stores root directory of each process
  - File name "/" now refers to `dir`
  - Accessing "`..`" in `dir` now returns `dir`
- **Need root privs to call chroot**
  - But subsequently can drop privileges
- **Ideally "Chrooted process" wouldn't affect parts of the system outside of** `dir`
  - Even process still running as root shouldn't escape chroot
- **In reality, many ways to cause damage outside** `dir`

Escaping chroot

- **Re-chroot to a lower directory, then chroot . .**
  - Each process has one root directory, so chrooting to a new directory can put you above your new root
- **Create devices that let you access raw disk**
- **Send signals to or ptrace non-chrooted processes**
- **Create setuid program for non-chrooted proc. to run**
- **Bind privileged ports, mess with clock, reboot, etc.**
- **Problem: chroot was not originally intended for security**
  - FreeBSD jail, Linux vserver have tried to address problems

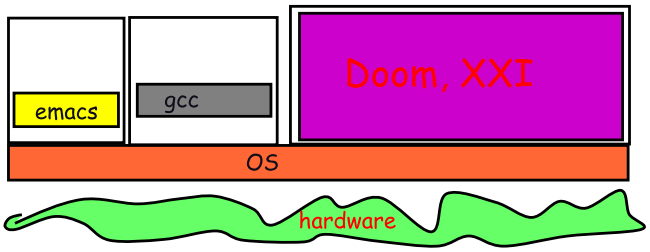
System call interposition

- **Why not use *ptrace* or other debugging facilities to control untrusted programs?**
- **Almost any "damage" must result from system call**
  - delete files → unlink
  - overwrite files → open/write
  - attack over network → socket/bind/connect/send/recv
  - leak private data → open/read/socket/connect/write . . .
- **So enforce policy by allowing/disallowing each syscall**
  - Theoretically much more fine-grained than chroot
  - Plus don't need to be root to do it
- **Q: Why is this not a panacea?**

Limitations of syscall interposition

- **Hard to know exact implications of a system call**
  - Too much context not available outside of kernel
    (e.g., what does this file descriptor number mean?)
  - Context-dependent (e.g., `/proc/self/cwd`)
- **Indirect paths to resources**
  - File descriptor passing, core dumps, "unhelpful processes"
- **Race conditions**
  - Remember difficulty of eliminating TOCCTOU bugs?
  - Now imagine malicious application deliberately doing this
  - Symlinks, directory renames (so "`..`" changes), . . .
- **See [Garfinkel] for a more detailed discussion**

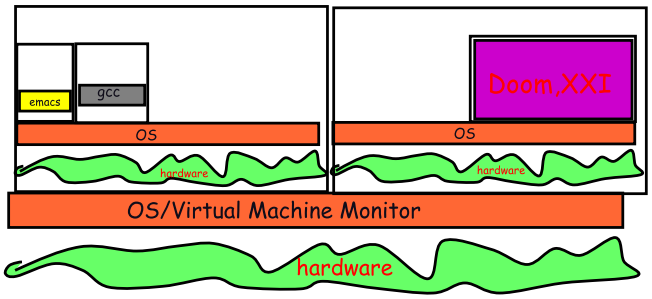
Review: What is an OS



- **OS is software between applications and reality**
  - Abstracts hardware and makes portable
  - Makes finite into (near) infinite
  - Provides protection

What if…

- **The process abstraction looked just like hardware?**



How is a process different from HW?

Process

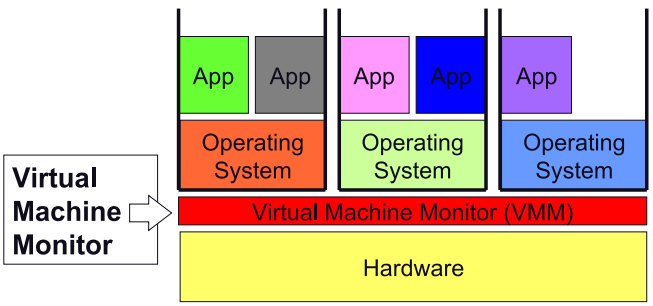
- CPU – Non-Privileged registers and instructions.
- Memory – Virtual memory.
- Exceptions – signals, errors.
- I/O – File System, Directory, Files, raw devices.

Hardware

- CPU – All registers and instructions.
- Memory – Both virtual and physical memory, memory management, TLB/page tables, etc.
- Exceptions – Trap architecture, interrupts, etc.
- I/O – I/O devices accessed using programmed I/O, DMA, interrupts.

Virtual Machine Monitor

- **Thin layer of software that virtualizes the hardware**
  - Exports a virtual machine abstraction that looks like the hardware



Old idea from the 1960s

- **See [Goldberg] from 1974**
- **IBM VM/370 – A VMM for IBM mainframe**
  - Multiplex multiple OS environments on expensive hardware
  - Desirable when few machine around
- **Interest died out in the 1980s and 1990s**
  - Hardware got cheap
  - Compare Windows NT vs. *N* DOS machines
- **Interesting again today**
  - Different problems today – software management
  - VMM attributes still relevant

VMM benefits

- **Software compatibility**
  - Runs pretty much all software
  - Trick: Make virtual hardware match real hardware
- **Can get Low overheads/High performance**
  - Near "raw" machine performance
  - Direct execution of CPU/MMU
- **Isolation**
  - Seemingly total data isolation between virtual machines
  - Use hardware protection
- **Encapsulation**
  - Virtual machines are not tied to physical machines
  - Checkpoint/Migration

Different thought about OSes

- **Installing software on hardware is broken**
  - Tight coupling of OS and applications to hardware creates management problems
- **Want to subdivide OS:**
  - Hardware drivers
  - Hardware management
  - System support software
- **Turn OSes into normal software that can be managed**

OS backwards compatibility

- **Backward compatibility is bane of new OSes**
  - Huge effort require to innovate but not break
- **Security considerations may make it impossible**
  - Choice: Close security hole and break apps or be insecure
- **Example: Not all WinNT applications run on WinXP or XP on Vista**
  - In spite of a huge compatibility effort
  - Given the number of applications that ran on WinNT, practically any change would break something

    `if (OS == WinNT) ...`
- **Solution: Use a VMM to run both WinNT and WinXP**
  - Obvious for OS migration as well: Windows → Linux

Isolation & Multi-level security

- **Traditional tension: Security vs. Usability**
  - Secure systems tend not to be that usable
  - Flexible systems are not that secure
- **Additional information assurance requirement**
  - Data cannot flow between networks of different classification
- **Solution: Run two VMs:**
  - Classified VM
  - Internet VM
- **Use isolation property to isolate two VMs**
  - VMM has control of the information flow between machines
  - Declassifier mechanism
- **Note: Bad idea w. today's VMMs, not secure enough**

Logical partitioning of servers

- **Run multiple servers on same box (e.g., Amazon EC2)**
  - Ability to give away less than one machine
    Modern CPUs more powerful than most services need
  - 0.10U rack space machine – less power, cooling, space, etc.
  - Server consolidation trend: N machines → 1 real machine
- **Isolation of environments**
  - Printer server doesn't take down Exchange server
  - Compromise of one VM can't get at data of others[a]
- **Resource management**
  - Provide service-level agreements
- **Heterogeneous environments**
  - Linux, FreeBSD, Windows, etc.

[a] though in practice not so simple because of side-channel attacks [Ristenpart]

Example: VMMs for IDS

- **Problem Area: Intrusion Detection Systems (IDS)**
- **Trade-offs**
  - Host-based IDS (HIDS):
    - \+ Good visibility to catch intruder
    - – Weak isolation from intruder disabling/masking IDS
  - Network-based IDS (NIDS):
    - \+ Good isolation from attack from intruder
    - – Weak visibility can allow intruder to slip by unnoticed
- **Would like visibility of HIDS with isolation of NIDS**
  - Idea: Do it in the virtual machine monitor

VMM-based IDS

- **Strong isolation**
  - VMM isolate software in VM from VMM
  - Comprise OS in VM can't disable IDS in VMM
- **Introspection – Peer inside at software running in VM**
  - VMM can see: Physical memory, registers, I/O device state, etc.
  - Signature scan of memory
    Look through physical memory for patterns or signs of break-in
- **Interposition – Modify VM abstraction to enhance security**
  - Memory Access Enforcer (Interpose on page protection)
  - NIC Access Enforcer (Interpose on virtual network device)

Collective Project [Chandra]

- **Distributed system where all software runs in VMs**
  - Research with Prof. Monica Lam and students
  - Technology transfer to `moka5.com`
- **Virtual Appliance abstraction**
  - x86 virtual machine
  - Target specialized environment (e.g. program development)
  - Store in a centralized persistent storage repository
  - Cached on the machine where virtual appliances run
- **Target benefits**
  - System administration: Centralize and amortize administration of a virtual appliance
  - Mobility: Computing environment follows user around

Complete Machine Simulation

- **Simplest VMM approach, used by bochs**
- **Build a simulation of all the hardware.**
  - CPU – A loop that fetches each instruction, decodes it, simulates its effect on the machine state
  - Memory – Physical memory is just an array, simulate the MMU on all memory accesses
  - I/O – Simulate I/O devices, programmed I/O, DMA, interrupts
- **Problem: Too slow!**
  - 100x slowdown makes it not too useful
  - CPU/Memory – 100x CPU/MMU simulation
  - I/O Device – $< 2\times$ slowdown.
- **Need faster ways of emulating CPU/MMU**

Virtualizing the CPU

- **Observations: Most instructions are the same regardless of processor privileged level**
  - Example: `incl %eax`
- **Why not just give instructions to CPU to execute?**
  - Safety – How going to get CPU back? Or stop it from stepping on us? How about `cli/halt`?
  - Answer: Use protection mechanism
- **Run virtual machine's OS directly on CPU at non-privileged level**
  - "Trap and emulate" approach
  - Most instructions just work
  - Privileged instructions trap into monitor and run simulator on instruction
  - Makes some assumptions about architecture

Virtualizing traps

- **What happens when an interrupt or trap occurs**
  - Like normal kernels: we trap into the monitor
- **What if the interrupt or trap should go to guest OS?**
  - Example: Page fault, illegal instruction, system call, interrupt
  - Re-start the guest OS simulating the trap
- **x86 example:**
  - Lookup trap vector in VM's IDT
  - Push virtualized `cs`, `eip`, `eflags`, on stack
  - Switch to virtualized privileged mode

Virtualizing memory

- **Basic MMU functionality:**
  - OS manages physical memory (0...MAX_MEM)
  - OS sets up page tables mapping VA→PA
  - CPU accesses to VA should go to PA (Paging off: PA=VA)
  - Used for every instruction fetch, load, or store
- **Need to implement a virtual "physical memory"**
  - Logically need additional level of indirection
  - VM's VA → VM's PA → machine address
  - Note "physical memory" no longer mans hardware bits – machine memory is hardware bits
- **Trick: Use hardware MMU to simulate virtual MMU**
  - Can be folded into page tables: VA→machine address

Shadow page tables

- **Monitor keeps *shadow* of VM's page table**
  - Shadow PT is map from VA → machine address
- **Treat shadow page tables as a cache**
  - Have *true page faults* when a page not in VM's page table
  - Have *hidden page faults* when just misses in shadow page table
- **On a page fault, VMM must:**
  - Lookup VPN → PPN in VM's (guest OS's) page table
  - Determine where PPN is in machine memory (MPN)
  - Insert VPN→MPN mapping in shadow page table
  - Note: Monitor can demand-page the virtual machine
- **Uses hardware protection**
  - Monitor never maps itself into VM's page table
  - Never maps other VMs's memory in VM's page table

Shadow PT issues

- **Hardware only ever sees shadow page page table**
  - Guest OS only sees it's own VM page table, never shadow PT
- **Consider the following**
  - OS has a page table T mapping $V_U \rightarrow P_U$
  - T itself resides at physical address P_T
  - Another page table maps $V_T \rightarrow P_T$
  - VMM stores P_U in machine address M_U and P_T in M_T
- **What can VMM put in shadow page table?**
  - Safe to map $V_U \rightarrow M_U$ or $V_T \rightarrow M_T$
- **Not safe to map both simultaneously!**
  - If OS writes to P_T, may make $V_U \rightarrow M_U$ in shadow PT incorrect
  - If OS reads/writes V_U, may require accessed/dirty bits to be changed in P_T (hardware can only change shadow PT)

Tracing

- **VMM needs to get control on some memory accesses**
- **Guest OS changes VM page table**
  - OS *should* use `invlpg` instruction, which would trap to VMM – but in practice many/most OSes are sloppy about this
  - Must invalidate stale mapping in shadow page table
- **Guest OS accesses page when VM PT accessible**
  - Accessed/dirty bits in VM PT will no longer be correct
  - Must make VM PT inaccessible in shadow PT
- **Solution: *Tracing***
  - To track page access, make VPN(s) invalid in shadow PT
  - If guest OS accesses page, will trap to VMM w. page fault
  - VMM can emulate the result of memory access & restart guest OS, just as an OS restarts a process after a page fault

Tracing vs. hidden faults

- **Suppose VMM never allowed access to VM PTs?**
  - Every PTE access would incur the cost of a tracing fault
  - Very expensive when OS changes lots of PTEs
- **Suppose OS allowed access to *most* page tables (except very recently accessed regions)**
  - Now lots of hidden faults when accessing new region
  - Plus overhead to pre-compute accessed/dirty bits from shadow page tables when switching between VMs
- **Makes for complex trade-offs**
  - But adaptive binary translation (later) can make this better

I/O device virtualization

- **Type of communication:**
  - Special instruction – `in/out`
  - Memory mapped I/O (PIO)
  - Interrupts
  - DMA
- **Virtualization**
  - Make `in/out` and PIO trap into monitor
  - Run simulation of I/O device
- **Simulation:**
  - Interrupt – Tell CPU simulator to generate interrupt
  - DMA – Copy data to/from physical memory of virtual machine

CPU virtualization requirements

- **Need protection levels to run VMs and monitors**
- **All unsafe/privileged operations should trap**
  - Example: disable interrupt, access I/O dev, ...
  - x86 problem: `popfl` (different semantics in different rings)
- **Privilege level should not be visible to software**
  - Software shouldn't be able to query and find out it's in a VM
  - x86 problem: `movw %cs, %ax`
- **Trap should be transparent to software in VM**
  - Software in VM should be able to tell if instruction trapped
  - x86 problem: traps can destroy machine state (E.g., if internal segment register was out of sync with GDT)
- **See [Goldberg] for a discussion**
  - Lost art with modern hardware

Binary translation

- **Cannot directly execute guest OS kernel code on x86**
  - Can maybe execute most user code directly
  - But how to get good performance on kernel code?
- **VMware solution: binary translation**
  - Don't run slow instruction-by-instruction emulator
  - Instead, translate guest kernel code into code that runs in fully-privileged monitor mode[a]
- **Challenges:**
  - Don't know the difference between code and data (guest OS might include self-modifying code)
  - Translated code may not be the same size as original
  - Prevent translated code from messing with VMM memory
  - Performance, performance, performance, ...

[a] actually CPL 1, so that the VMM has its own exception stack

VMware binary translator

- **VMware translates kernel dynamically (like a JIT)**
  - Start at guest `eip`
  - Accumulate up to 12 instructions until next control transfer
  - Translate into binary code that can run in VMM context
- **Most instructions translated identically**
  - E.g., regular `movl` instructions
- **Use segmentation to protect VMM memory**
  - VMM located in high virtual addresses
  - Segment registers "truncated" to block access to high VAs
  - `gs` segment not truncated; use it to access VMM data
  - Any guest use of `gs` (rare) can't be identically translated

Details/examples from [Adams & Agesen]

Control transfer

- **All branches/jumps require indirection**
- **Original:**

```
isPrime: mov %ecx, %edi ; %ecx = %edi (a)
         mov %esi, $2   ; i = 2
         cmp %esi, %ecx ; is i >= a?
         jge prime      ; jump if yes
```

- **Translated:**

```
isPrime': mov %ecx, %edi    ; IDENT
          mov %esi, $2
          cmp %esi, %ecx
          jge [takenAddr] ; JCC
          jmp [fallthrAddr]
```

- **Brackets ([...]) indicate *continuations***
  - First time jumped to, target untranslated; translate on demand
  - Then fix up continuation to branch to translated code
  - Can elide `[fallthrAddr]` if fallthrough next translated

Non-identically translated code

- **PC-relative branches & Direct control flow**
  - Just compensate for output address of translator on target
  - Insignificant overhead
- **Indirect control flow**
  - E.g., jump though register (function pointer) or `ret`
  - Can't assume code is "normal" (e.g., must faithfully `ret` even if stack doesn't have return address)
  - Look up target address in hash table to see if already translated
  - "Single-digit percentage" overhead
- **Privileged instructions**
  - Appropriately modify VMM state
  - E.g., `cli` $\Longrightarrow$ `vcpu.flags.IF = 0`
  - Can be faster than original!

Adaptive binary translation

- **One remaining source of overhead is tracing faults**
  - E.g., when modifying page table or descriptor table
- **Idea: Use binary translation to speed up**
  - E.g., translate write of PTE into write of guest & shadow PTE
  - Translate PTE read to get accessed & dirty bits from shadow
- **Problem: Which instructions to translate?**
- **Solution: "innocent until proven guilty" model**
  - Initially always translate as much code identically as possible
  - Track number of tracing faults caused by an instruction
  - If high number, re-translate to non-identical code
  - May call out to interpreter, or just jump to new code

ESX mem. mgmt. [Waldspurger]

- **Virtual machines see virtualized physical memory**
  - Can let VMs use more "physical" memory than in machine
- **How to apportion memory between machines?**
- **VMware ESX has three parameters per VM:**
  - min – Don't bother running w/o this much machine memory
  - max – Amount of "physical" memory VM OS thinks exists
  - share – How much mem. to give VM relative to other VMs
- **Straw man: Allocate based on share, use LRU paging**
  - OS already uses LRU $\Rightarrow$ double paging
  - OS will re-cycle whatever "physical" page VMM just paged out
  - So better to do random eviction
- **Next: 3 cool memory management tricks**

Reclaiming pages

- **Idea: Have guest OS return memory to VMM**
  - Then VMM doesn't have to page memory to disk
- **Normally OS just uses all available memory**
  - But some memory much more important than other memory
  - E.g., buffer cache may contain old, clean buffers; OS won't discard if doesn't need memory...but VMM may need memory
- **ESX trick: Baloon driver**
  - Special pseudo-device driver in supported guest OS kernels
  - Communicates with VMM through special interface
  - When VMM needs memory, allocates many pages in guest OS
  - Baloon driver tells VMM to re-cycle it's private pages

Sharing pages across VMs

- **Often run many VMs with same OS, programs**
  - Will result in many machine pages containing same data
- **Idea: Use 1 machine page for all copies of phys. page**
- **Keep big hash table mapping:** Hash(contents)→info
  - If machine page mapped once, info is VM/PPN where mapped. In that case, Hash is only a hint, as page may have changed
  - If machine page mapped copy-on-write as multiple physical pages, info is just reference count
- **Scan OS pages randomly to populate hash table**
- **Always try sharing a page before paging it out**

Idle memory tax

- **Need machine page? What VM to take it from?**
- **Normal proportional share scheme**
  - Reclaim from VM with lowest "shares-to-pages" (S/P) ratio
  - If A & B both have $S = 1$, reclaim from larger VM
  - If A has twice B's share, can use twice the machine memory
- **High-priority VMs might get more mem. than needed**
- **Solution: Idle-memory tax**
  - Use statistical sampling to determine a VM's % idle memory (randomly invalidate pages & count the number faulted back)
  - Instead of S/P, reclaim from VM w. lowest $S/\left(P(f + k(1 - f))\right)$. f = fraction of non-idle pages; k = "idle page cost" paremeter.
  - Be conservative & overestimate f to respect priorities (f is max of slow, fast, and recent memory usage samples)

Final thoughts

- **You are all now operating systems experts**
- **Use this knowledge to build better applications**
  - Sometimes need to coax right behavior out of kernel
  - Should be much easier now that you know what's going on
- **Syscall interface can be an *innovation barrier***
  - Much harder to change kernel than user code
  - Other barriers include standardized net. protocols, servers
  - Get these wrong and many people will suffer
- **Some of you will go on to design interfaces that many people are later subjected to**
  - Strive to achieve both simplicity and flexibility for users

How to learn more about OSes

- **Take CS240 – Advanced Topics in Operating Systems**
  - Class will bring you up to speed on OS research
  - Read & discuss 18–25 research papers
  - By the end, should be ready to do OS research
- **Get involved in research!**
- **Lot's of interesting OS work at Stanford**
  - Rosenblum – launched the virtual machine resurgence
  - Lam – collective system, software for mobile devices
  - Levis – seminal work on sensor nets & power management
  - Engler – tools to find OS bugs automatically
  - Boneh/Mitchell – lots of practical OS security work
  - Mazières – done multiple new OSes, FSes, and distributed systems. Applying OS ideas to browser, language security.