**Administrivia**

- Guest lecture Thursday
  - Mark Lentczner (Google) on the Belay project
  - 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
  - Wednesday March 16, 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/cvd)
- 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.

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 machines 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 for many workloads
  - With tricks can have direct execution on CPU/MMU
- Isolation
  - Seemingly total data isolation between virtual machines
  - Use hardware protection
- Encapsulation
  - Virtual machines are not tied to physical machines
  - Checkpoint/Migration
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
    ```c
    if (OS == WinNT) ... 
    ```
- Solution: Use a VMM to run both WinNT and WinXP
  - Obvious for OS migration as well: Windows → Linux

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
- Resource management
  - Provide service-level agreements
- Heterogeneous environments
  - Linux, FreeBSD, Windows, etc.

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
    ```c
    1/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× 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?
  - One issue: Safety – How to get the CPU back? Or stop it from stepping on us? How about cli/halt?
  - Solution: Use protection mechanisms already in CPU
- Run virtual machine’s OS directly on CPU in unprivileged user mode
  - “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:
  - Give CPU an IDT that vectors back to VMM
  - Look up trap vector in VM’s “virtual” IDT
  - Push virtualized %cs, %esi, %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

Complete Machine Simulation

- Logical partitioning of servers
- OS backwards compatibility
- Virtualizing the CPU
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

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

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

Shadow PT issues

- Hardware only ever sees shadow 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 $P_T \rightarrow P_I$
  - VMM stores $P_I$ 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)

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: mov $\times cs, \times ax$
- Trap should be transparent to software in VM
  - Software in VM shouldn’t 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

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, …

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

- C source:
  ```
  int isPrime (int a){
      for (int i = 2; i < a; i++) {
          if (a % i == 0)
              return 0;
          }
      return 1;
  }
  ```

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 through 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 => 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

- Bracket ([. . . ]) 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
Hardware-assisted virtualization

- Both Intel and AMD now have hardware support
  - Different mechanisms, similar concepts
  - Will discuss AMD in this lecture (see [AMD Vol 2], Ch. 15)
  - For Intel details, see [Intel Vol 3b]
- VM-enabled CPUs support new guest mode
  - This is separate from kernel/user modes in bits 0–1 of %cs
  - Less privileged than host mode (where VMM runs)
  - Some sensitive instructions trap in guest mode (e.g., load %cr3)
  - Hardware keeps shadow state for many things (e.g., %eflags)
- Enter guest mode with vmrun instruction
  - Loads state from hardware-defined 1-KiB VMCB data structure
- Various events cause EXIT back to host mode
  - On EXIT, hardware saves state back to VMCB

Guest state saved in VMCB

- Saved guest state
  - Full segment registers (i.e., base, lim, attr, not just selectors)
  - Full GDTR, LDTR, IDTR, TR
  - Guest %cr3, %cr2, and other cr/dr registers
  - Guest %eip and %eflags (%rip & %rflags for 64-bit processors)
  - Guest %rax register
- Entering/exiting VMM more expensive than syscall
  - Have to save and restore large VM-state structure

Hardware vs. Software virtualization

- HW VM makes implementing VMM much easier
  - A voids implementing binary translation (BT)
- Hardware VM is better at entering/exiting kernel
  - E.g., Apache on Windows benchmark: one address space, lots of syscalls, hardware VM does better [Adams]
  - Apache on Linux w. many address spaces: lots of context switches, tracing faults, etc., Software faster [Adams]
- Fork with copy-on-write bad for both HW & BT
  - [Adams] reports fork benchmark where BT-based virtualization 37× and HW-based 106× slower than native!
- Newer CPUs support nested paging
  - Eliminates tracing faults (& simplifies implementation)
  - But dramatically increases cost of TLB misses—might be a wash

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 ⇒ 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

VMCB control bits

- Intercept vector specifies what ops should cause EXIT
  - One bit for each of %cr0–%cr15 to say trap on read
  - One bit for each of %cr0–%cr15 to say trap on write
  - 32 analogous bits for the debug registers (%dr0–%dr31)
  - 32 bits for whether to intercept exception vectors 0–31
  - Bits for various other events (e.g., NMI, SMI, ...)
  - Bit to intercept writes to sensitive bits of %cr0
  - 8 bits to intercept reads and writes of IDTR, GDTR, LDTR, TR
  - Bits to intercept rdts, rdpmc, pushf, popf, vmrun, hlt, invlpg, int, iret, in/out (to selected ports), ...
- EXIT code and reason (e.g., which inst. caused EXIT)
- Other control values
  - Pending virtual interrupt, event/exception injection

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 its 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 / (P(f + k(1 − f))).
    f = fraction of non-idle pages; k = “idle page cost” parameter.
  - Be conservative & overestimate f to respect priorities
    (f is max of slow, fast, and recent memory usage samples)