Administrivia

- Last project due Friday
- Final exam by email Wednesday, March 18th, 3:30pm-6:30pm
  - Likely ASCII-only exam to be submitted on AFS
  - SCPD students do not need an exam monitor
  - SCPD only can start up to 24 hours later
  - Please monitor class list and stanford mail for details

- Exam content
  - Open notes (except textbook), exam may require web searches
  - Covers all lectures including topics already on the midterm
  - Make sure you understand all answers to midterm before final

- Final review session Friday (zoom only)
- Pre-exam office hours for me 2pm-4pm Monday (talky only)

Outline

1. Confining code with legacy OSes
2. Virtual machines
3. Implementing virtual machines
4. Binary translation
5. Hardware-assisted virtualization
6. Memory management optimizations

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
- Can we similarly block untrusted code within a machine
  - Have OS limit what the code 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 privileges 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 in process structure
  - Implementation special-cases / (always) & . . in root directory
  - chroot does not allow changing current directory
  - So chrooting to a lower directory puts you above your new root
    (Can re-chroot to real system root)
- What else can you do as root in a chrooted process?
  - Create devices that let you access raw disk
  - Send signals to or ptrace non-chrooted processes
  - Create setuid program for non-chrooted processes to run
  - Bind privileged ports, mess with clock, reboot, etc.
  - Problem: chroot was not originally intended for security
    - FreeBSD jail attempts to address the problems
    - Also, Linux cgroups, namespaces allow containers
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

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Review: What is an OS

- OS is software between applications and hardware/external reality
  - Abstracts hardware to makes applications portable
  - Makes finite resources (memory, # CPU cores) appear much larger
  - Protects processes and users from one another

What if...

- The process abstraction looked just like hardware?

Process

Non-privileged registers and instructions

Virtual memory

Errors, signals

File system, directories, files, raw devices

Hardware

All registers and instructions

Both virtual and physical memory, MMU functions, TLB/page tables, etc.

Trap architecture, interrupts

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
  - Just put a window machine on every desktop
- Today, VMs are used everywhere
  - Used to solve different problems (software management)
  - But VMM attributes more relevant now than ever

**VMM benefits**

- Software compatibility
  - VMMs can run pretty much all software
- 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
  - Leverage hardware memory protection mechanisms
- 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: Windows XP is end of life
  - 4.59% machines ran 2001 Windows XP in 2018
  - XP support ended in 2019, eventually XP-capable hardware will die
  - What to do with legacy WinXP applications?
  - Not all applications will run on later Windows
  - Given the number of WinXP applications, practically any OS change will break something
  - If (OS == WinXP) ...
- Solution: Use a VMM to run both WinXP and Win10
  - Obvious for OS migration as well: Windows → Linux

**Logical partitioning of servers**

- Run multiple servers on same box (e.g., Amazon EC2)
  - Modern CPUs more powerful than most services need
  - VMs let you give away less than one machine
  - Server consolidation trend: $N$ machines → 1 real machine
  - 0.10U rack space machine – less power, cooling, space, etc.
- 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.

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1 In practice not so simple because of side channels [Ristenpart] [Meltdown]
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!
  - CPU/Memory – 100x CPU/MMU simulation
  - I/O Device – < 2x slowdown.
  - 100x slowdown makes it not too useful
- 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, %eip, %eflags, on stack
  - Switch to virtualized privileged mode

Memory mapping summary

<table>
<thead>
<tr>
<th>Virtual Address</th>
<th>Physical Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guest PPN (Guest PT)</td>
<td>Host PPN (Host PT)</td>
</tr>
<tr>
<td>Shadow Page Table</td>
<td>Host Physical Address</td>
</tr>
</tbody>
</table>

Shadow page tables

- VMM responsible for maintaining shadow PT
  - And for maintaining its consistency (including TLB flushes)
- Shadow page tables are a cache
  - Have true page faults when page not in VM’s guest page table
  - Have hidden page faults when just misses in shadow page table
- On a page fault, VMM must:
  - Lookup guest VPN → guest PPN in guest’s page table
  - Determine where guest PPN is in host physical memory
  - Insert guest VPN → host PPN mapping in shadow page table
  - Note: Monitor can demand-page the virtual machine
- Uses hardware protection
Shadow PT issues
- **Hardware only ever sees shadow page table**
  - Guest OS only sees its own VM page table, never shadow PT
- **Consider the following**
  - Guest OS has a page table \( T \) mapping \( V_U \rightarrow P_U \)
  - \( T \) itself resides at guest physical address \( P_T \)
  - Another guest page table entry maps \( V_T \rightarrow P_T \)
    (e.g., in Pintos, \( V_T = P_T + \text{PHYS}\_\text{BASE} \))
  - VMM stores \( P_U \) in host physical address \( M_U \) and \( P_T \) in \( M_T \)
- **What can VMM put in shadow page table?**
  - Safe to map user page \( (V_U \rightarrow M_U) \) or page table \( (V_T \rightarrow M_T) \)
- **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)

VMM needs to get control on some memory accesses
- Guest OS changes previously used mapping in its PT
  - Must intercept to invalidate stale mappings in shadow PT, TLB
  - Note: OS should use `invlpg` instruction, which would trap to VMM – but in practice many/most OSes are sloppy about this
- Guest OS accesses page when its VM PT is accessible
  - Accessed/dirty bits in VM PT may no longer be correct
  - Must intercept to fix up VM PT (or make VM PT inaccessible)
  - **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
- **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 PT as page tables preemptively made valid in shadow PT
- **Makes for complex trade-offs**
  - But adaptive binary translation (later) can make this better

Tracing vs. hidden faults
- **Need protection levels to run VMs and monitors**
- **All unsafe/privileged operations should trap**
  - Example: disable interrupt, access I/O dev, ...
  - x86 problem: `popf` (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 %cs, %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**
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### 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?
- **Original VMware solution: binary translation**
  - Don’t run slow instruction-by-instruction emulator
  - Instead, translate guest kernel code into code that runs in fully-privileged kernel mode, but acts safely\(^2\)
- **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, ...

\(^2\)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 %edi, %ecx # %ecx = %edi (a)
  mov $2, %esi   # i = 2
  cmp %ecx, %esi # is i >= a?
  jge [takenAddr] # JCC
  jmp [fallthrAddr]
  ```

  **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 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 \(\Rightarrow\) vcpu.flags.IF = 0
  - Can be faster than original!

Details/examples from [Adams & Agesen]

### Non-identically translated code

- **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
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 read of PTE 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

Hardware-assisted virtualization

- Both Intel and AMD now have hardware support
  - Different mechanisms, similar concepts
  - This lecture covers AMD (see [AMD Vol 2], Ch. 15)
    - For Intel details, see [Intel Vol 3c]
- 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, %cs, and other cr/dr registers
  - Guest %eip and %eflags (%eip & %eflags for 64-bit processors)
  - Guest %rax register
- Entering/exiting VMM more expensive than syscall
  - Have to save and restore large VM-state structure

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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–%dr15)
  - 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 rdmsr, rdtsc, 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

Hardware vs. Software virtualization

- HW VM makes implementing VMM much easier
  - Avoids 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!
- Today, CPUs support nested paging (a.k.a. EPT on intel)
  - Eliminates shadow PT & tracing faults, simplifies VMM
  - Guests can now manipulate %cr3 w/o VM EXIT
  - But dramatically increases cost of TLB misses
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ESX memory management [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 guest physical memory VM OS thinks exists
  - share – How much memory 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

Reclaiming pages

- 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
- Idea: Have guest OS return memory to VMM
  - Then VMM doesn’t have to page memory to disk
- ESX trick: Balloon 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
  - Balloon 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 host physical pages containing same data
- Idea: Use 1 host physical page for all copies of guest physical
  page (in any virtual machine)
- Keep big hash table mapping: Hash(contents) → info
  - If host physical 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 memory 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 with 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)