

Administrivia

- Project 4 due Friday
- Final exam review section Friday
- Extra office hours next week—refresh web page this weekend
- Don't forget to use the Lectures+Exams tag on edstem
- Final exam next Wednesday 3/20, 3:30pm-6:30pm
 - Will post location to web site and edstem

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Outline

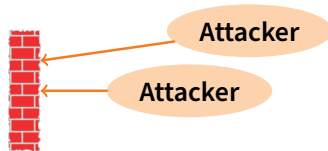
- 1 Confining code with legacy OSes
- 2 Virtual machines
- 3 Implementing virtual machines
- 4 Binary translation
- 5 Hardware-assisted virtualization
- 6 Memory management optimizations

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Confining code with legacy OSes

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

Hopelessly
Insecure
Server



- 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

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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`

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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 always change current directory
 - So re-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?

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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 always change current directory
 - So re-chrooting to a lower directory puts you above your new root (Can re-chroot to real system root)
- 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

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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/rcv
 - 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?

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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

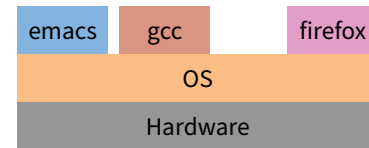
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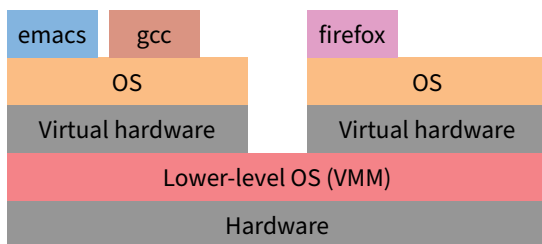
Review: What is an OS



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

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What if...



- The process abstraction looked just like hardware?

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How do process abstraction & HW differ?

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.

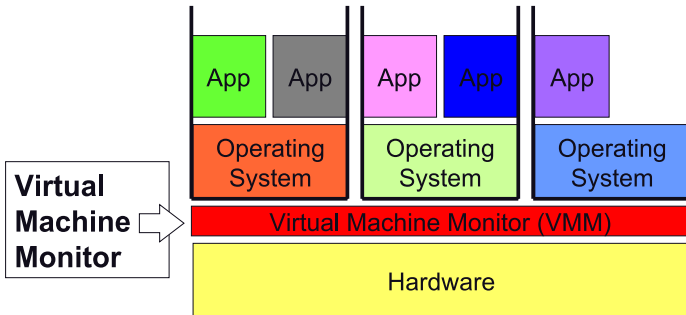
Trap architecture, interrupts

I/O devices accessed using programmed I/O, DMA, interrupts

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Virtual Machine Monitor

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



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

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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 and/or right hardware can have direct execution on CPU/MMU
- **Isolation**
 - *Seemingly* total data isolation between virtual machines (complicated by side-channel attacks like Spectre)
 - Leverage hardware memory protection mechanisms
- **Encapsulation**
 - Virtual machines are not tied to physical machines
 - Checkpoint/migration

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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 (still 0.52% today)
 - 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

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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 others¹
- **Resource management**
 - Provide service-level agreements
- **Heterogeneous environments**
 - Linux, FreeBSD, Windows, etc.

¹In practice not so simple because of side channels [\[Ristenpart\]](#) [\[Meltdown\]](#)

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- 3 **Implementing virtual machines**
- 4 Binary translation
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- 6 Memory management optimizations

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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 – $< 2\times$ slowdown.
 - 100x slowdown makes it not too useful
- Need faster ways of emulating CPU/MMU

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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

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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

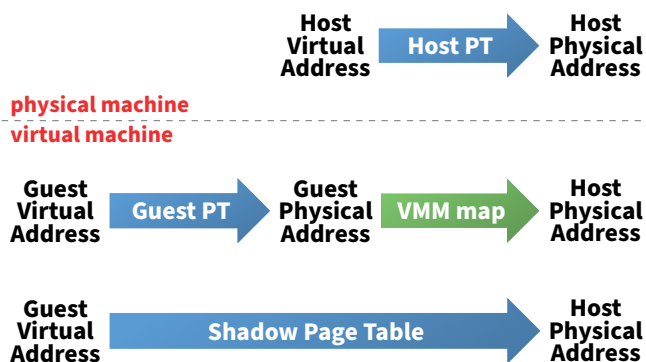
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Virtualizing memory

- Basic MMU functionality:
 - OS manages physical memory (0...MAX_MEM)
 - OS sets up page tables mapping VA \rightarrow PA
 - CPU accesses to VA should go to PA (if 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 *Guest VA* \rightarrow VM's *Guest PA* \rightarrow *Host PA*
 - Note “Guest physical” memory no longer means hardware bits
 - Hardware is host physical memory (a.k.a. machine memory)
- Trick: Use hardware MMU to simulate virtual MMU
 - Point hardware at *shadow page table*
 - Directly maps Guest VA \rightarrow Host PA

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Memory mapping summary



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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 \rightarrow guest PPN in guest's page table
 - If true page fault, emulate page fault in guest OS
 - Otherwise, determine where guest PPN is in host physical memory
 - Insert guest VPN \rightarrow host PPN mapping in shadow page table
 - Note: VMM can demand-page the virtual machine
- Uses hardware protection

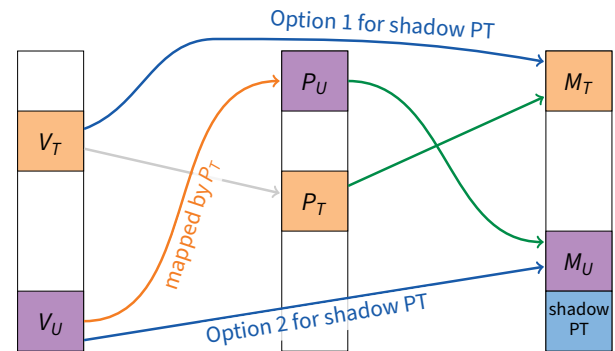
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Shadow PT issues

- **Hardware only ever sees shadow page table**
 - Guest OS only sees it's own VM page table, never shadow PT
- **Consider the following**
 - 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, $V_T = P_T + \text{PHYS_BASE}$)
 - 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)

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Illustration



- **Option 1:** Page table accessible at V_T , but changes won't be reflected in shadow PT or TLB; access to V_U dangerous
- **Option 2:** V_U accessible, but hardware sets accessed/dirty bits only in shadow PT, not in guest PT at P_T/M_T

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Tracing

- **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

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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 PT as page tables preemptively made valid in shadow PT
- **Makes for complex trade-offs**
 - But adaptive binary translation (later) can make this better

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I/O device virtualization

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

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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: different semantics in different rings (e.g., `popf1`)
- **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 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 safely²
- **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, ...

²actually CPL 1 rather than 0, so that the VMM has its own exception stack

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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]

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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;
}
```

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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
         ...
```
- **Translated:**

```
isPrime': mov %edi, %ecx # IDENT
          mov $2, %esi
          cmp %ecx, %esi
          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

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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` \implies `vcpu.flags.IF = 0`
 - Can be faster than original!

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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

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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

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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 `rdtsc`, `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

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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

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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 guest physical memory than exists host
- **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 \implies 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**

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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

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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) \rightarrow 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**

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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**
 - Tax idle memory at $0 \leq \tau \leq 1$ so "cost" of idle page is $k = 1/(1 - \tau)$
 - 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)

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