W4118: virtual machines

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Virtual machines (VM)
Why virtual machines?

- Manage big machines
  - Multiplex CPUs/memory/devices at VM granularity
  - E.g., Amazon EC2

- Multiple OS on one machine
  - E.g., use Windows on Linux OS

- Isolate faults/break-ins
  - One VM is compromised/crashes, others OK

- Kernel development
  - Like QEMU, but faster

- OS granularity checkpoint/record/replay
Usual VM goals

- **Accurate**
  - Guest can’t distinguish VM from real computer

- **Isolated**
  - Guest can’t escape VM

- **Fast**

- **Some VM implementations require guest kernel modifications**
  - E.g., Xen
Virtual machine lineage

- **1960s**: IBM used VMs to share mainframe
  - VM/370, today's z/VM
  - Still in use!

- **1990s**: VMWare re-popularized VMs for x86
  - VMWare ESX servers
  - VMWare work station
  - ...
Virtual machine structures

```
<table>
<thead>
<tr>
<th>User programs</th>
<th>&quot;guest&quot;</th>
</tr>
</thead>
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<tr>
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<td></td>
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VMM responsibilities

- Time-share CPU among guests

- Space-share memory among guests

- Simulate disk, network, and other devices
  - Often multiplex on host devices
Naive approach: simulation

- Interpret each guest instruction
- Maintain each VM state purely in software
- Problem: too slow!
2\textsuperscript{nd} approach: trap-and-emulate

- Execute guest instructions on real CPU when possible
  - \textit{E.g.}, \texttt{addl \%eax, \%ebx}

- Run guest OS in unprivileged mode

- Privileged instructions trap, and VMM emulates
  - \textit{E.g.}, \texttt{movl \%eax, \%cr3}

- VMM hides real machine state from guests
  - \textit{E.g.}, virtual \%cr3 set by guest, real \%cr3 set by VMM,
  - More: page table, privilege level, interrupt flag, …
Trap-and-emulate: tricky on x86

- Not all instructions that should be emulated cause traps
- Instructions have different effects depending on privilege mode
- Instructions reading privileged state don’t trap
- Page table modifications don’t trap
- Trap them all \(\Rightarrow\) slow
Real x86 state to hide & protect

- **CPL** (low bits of CS) = 3, but guest expects 0

- **Physical memory**: guest expects 0..PHYSTOP, VMM maps to one slice of physical memory

- **Page tables**: don’t map to physical addresses expected by guest OS
  - Shadow page table

- **%cr3**: points to shadow page table
Real x86 state to hide & protect (cont.)

- **GDT**: guest OS descriptors have DPL = 3, but guest expects 0

- **GDTR**: points to shadow GDT table

- **IDT descriptors**: traps go to VMM, not guest

- **IDTR**: points to shadow IDT table

- **IF in EFLAGS**: guest expects 0 after `cli`

- ...
Virtualize physical memory

- **Guest wants**
  - Physical address starts at PA = 0
  - Use “all” physical memory

- **VMM must**
  - Space-share all physical memory among guests
  - Protect one guest’s memory from another

- **Idea:**
  - Claim DRAM smaller than real DRAM
  - Ensuring paging is enabled
  - Rewrite guest’s PTEs to map to real PA?
  - Copy guest’s PTEs to shadow page table and map copied PTEs to real PA
Example: VMM allocates a guest 0x1000000-0x2000000
Handling page table modifications

- VMM must make shadow page table entries (PTEs) consistent with guest PTEs

- PTE loading: copy guest PTEs to shadow PTEs on context switch

- PTE tracing: when guest modifies guest PTEs, modify shadow PTEs as well
PTE loading

- Naïve approach: on guest %cr3 write, copy all gueste PTEs
  - Problem: slow context switch

- Another approach: start with minimum mappings (just the PTEs of VMM), and copy on demand on “hidden” page faults
  - Problem: too many page faults

- Approach used in VMware: reuse populated shadow PTEs
PTE tracing

- Approach I: mark the memory region holding guest PTES as readonly, and copy updates to shadow PTEs on page faults
  - Problem: too many page faults

- Approach II: binary translate code that writes to shadow PTEs to call out to VMM
  - Faster than traps
Do all instructions that read/write sensitive state cause traps at CPL = 3?

- `pushw %cs`: reveals CPL = 3, not 0
- `sgdt`: reveals real GDTR
- `sidt`: reveals real IDTR
- `pushfl`: reveals IF flag
- `popfl`: if CPL = 3, do not set IF flag (no trap)
- `iret`: no privilege mode change so won’t restore SS/ESP
3rd approach: binary translation

- **Simplified idea**
  - Replace non-trapping instructions that read/write sensitive state with trap instruction
    - `int3`: triggers a break point exception. Shortest instruction (1 byte), doesn’t change code size/layout
  - Keep track of original instruction
  - VMM emulate original instruction in trap

- **Problems:** how does the rewriter find all code?
  - Or where the instruction boundaries are,
  - Or whether bytes are code or data ...
Dynamic binary translation

- Idea: disassemble code only as executed, since jump instructions reveal where code is

- When VMM first loads guest kernel, translate from entry (fixed) up to first jump
  - Replace bad instructions with equivalent instructions on virtual states
  - Replace “jmp X” with “movl X, %eax; jmp translator;”

- In translator, look where the jump goes
  - Repeat above steps

- Keep track of what we’ve translated to avoid re-translate
  - Store translated code in code cache (original ➔ translated mapping)
Binary translation example

Entry:
pushl %ebp
popfl
jnz x
x:
  ...
jmp y

Entry’:
pushl %ebp
vm->IF = ...
popfl
movl x, %eax
jnz translator

x’:
  ...
movl y, %eax
jmp translator
4th approach: hardware support

- Simplified implementation of VMM

- Hardware maintains per-guest virtual state
  - CPL, EFLAGS, idtr, etc

- Hardware knows it is in “guest mode”
  - Instructions directly modify virtual state
  - Avoids many traps to VMM
Hardware support details

- Hardware basically adds a new privilege level
  - VMM mode, CPL=0, CPL=3
  - Guest-mode, CPL=0 is not fully privileged

- No traps on system calls; hardware handles CPL transition

- Hardware supports two page tables: guest page table and VMM’s page table
  - Virtual address \(\rightarrow\) guest physical address
  - Guest physical address \(\rightarrow\) host physical address