W4118: virtual machines

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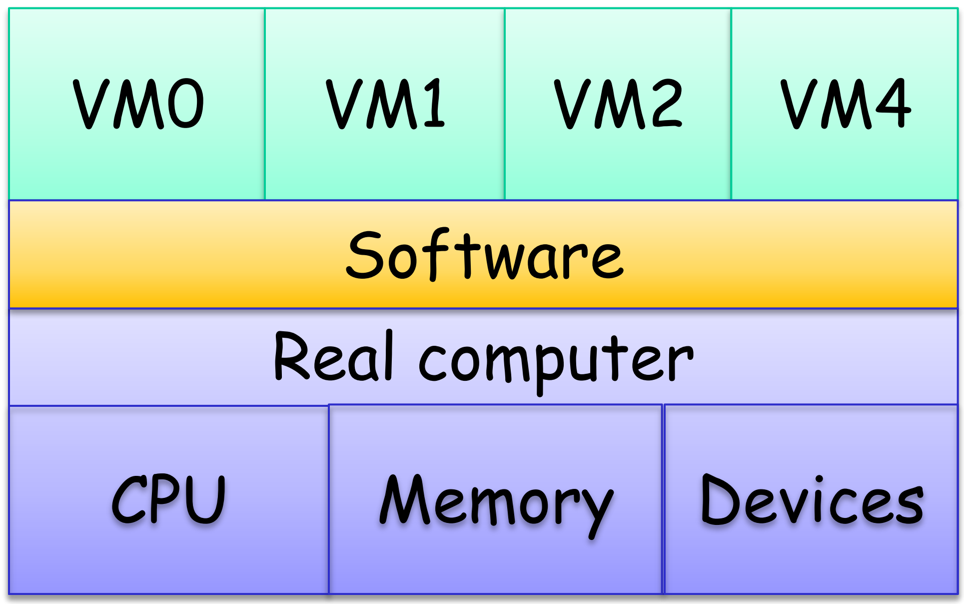
References: Modern Operating Systems (3rd edition), Operating Systems Concepts (8th edition), previous W4118, and OS at MIT, Stanford, and UWisc

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

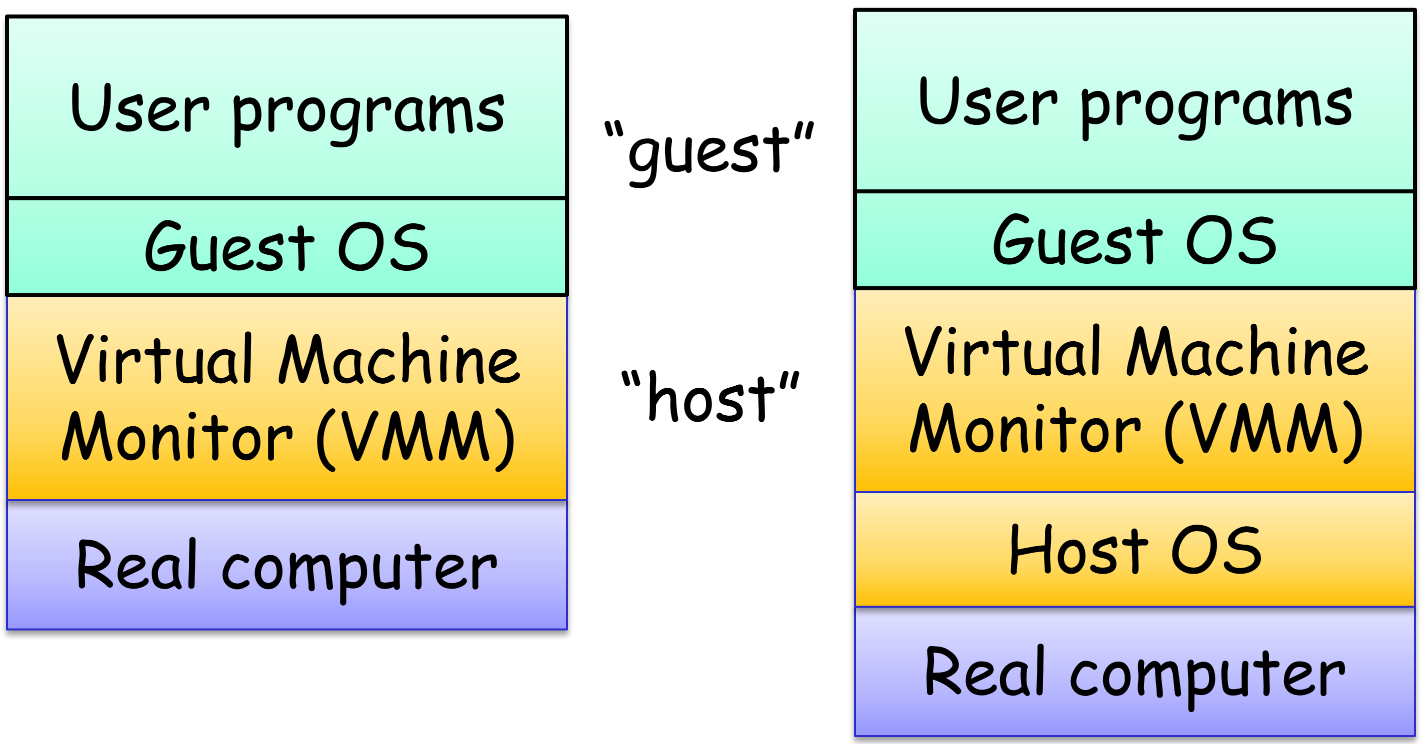
Usual VM goals

- 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



VMM responsibilities

- Time-share CPU among guests
- Space-share memory among guests
- Simulate disk, network, and other devices
  - Often multiplex on host devices

Naïve approach: simulation

```
int32_t regs[8];
#define REG_EAX 1;
#define REG_EBX 2;
#define REG_ECX 3;
...
int32_t eip;
int16_t segregs[4];
...
```

```
for (;;) {
        read_instruction();
        switch (decode_instruction_opcode()) {
        case OPCODE_ADD:
                int src = decode_src_reg();
                int dst = decode_dst_reg();
                regs[dst] = regs[dst] + regs[src];
                break;
        case OPCODE_SUB:
                int src = decode_src_reg();
                int dst = decode_dst_reg();
                regs[dst] = regs[dst] - regs[src];
                break;
        ...
        }
        eip += instruction_length;
}
```

- Interpret each guest instruction
- Maintain each VM state purely in software
- Problem: too slow!

2^{nd} approach: trap-and-emulate

- Execute guest instructions on real CPU when possible
  - E.g., addl %eax, %ebx
- Run guest OS in unprivileged mode
- Privileged instructions trap, and VMM emulates
  - E.g., movl %eax, %cr3
- VMM hides real machine state from guests
  - 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 → 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 table: 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

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, no trap
- iret: no privilge 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
```

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
  - 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 "hidden " 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

4^{th} 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 → guest physical address
  - Guest physical address → host physical address