Virtual Machines
Part 1: 54 years ago
It’s 1964 …

The Beatles appear on the Ed Sullivan show

- IBM wants a multiuser time-sharing system

- TSS project
  - large, monolithic system
  - lots of people working on it
  - for years
  - total, complete flop

- CMS
  - single-user time-sharing system for IBM 360

- CP67
  - virtual machine monitor (VMM)
  - supports multiple virtual IBM 360s

- Put the two together …
  - a (working) multiuser time-sharing system
Virtual Machines

Applications
OSa
Virtual Machine

Applications
OSb
Virtual Machine

Applications
OSc
Virtual Machine

Virtual Machine Monitor

Hardware
Why?

• Structuring technique for a multi-user system
• OS debugging and testing
• Multiple OSes on one machine
• Adapt to hardware changes in software
• Server consolidation and service isolation
User vs. Privileged Mode

• Privileged mode
  – may run all instructions, access all registers
  – for example:
    - modify address translation for virtual memory
    - access and control I/O devices
    - mask and unmask interrupts
    - start and stop system clock

• User mode
  – may run only “innocuous” instructions
  – may access only normal registers
How?

• Approach 1
  – system has “normal” scheduler and virtual memory
  – its processes run in privileged mode
How?

• Approach 2
  – system has “normal” scheduler and virtual memory
  – its processes run an emulator of the real machine
How?

• Approach 3
  – system has “normal” scheduler and virtual memory
  – its processes execute user-mode code directly, but run the emulator when going into privileged mode
How?

• Approach 4
  – system has “normal” scheduler and virtual memory
  – its processes execute user-mode code directly, but emulate only privileged instructions
How?

Diagram showing the relationship between User and Privileged levels.
Requirements

• A virtual machine is an efficient, isolated duplicate of real machine
Sensitive Instructions

• Control-sensitive instructions
  – affect the allocation of resources available to the virtual machine
  – change processor mode without causing a trap

• Behavior-sensitive instructions
  – effect of execution depends upon location in real memory or on processor mode
Privileged Instructions

- Cause a fault in user mode
- Work fine in privileged mode
Theorem (!)

• For any conventional third-generation computer, a virtual machine monitor may be constructed if the set of sensitive instructions for that computer is a subset of the set of privileged instructions.
IBM 360
The (Real) 360 Architecture

- Two execution modes
  - supervisor and problem (user)
  - all sensitive instructions are privileged instructions
- Memory is protectable: 2k-byte granularity
- All interrupt vectors and the clock are in first 512 bytes of memory
- I/O done via channel programs in memory, initiated with privileged instructions
- Dynamic address translation (virtual memory) added for Model 67
Real Interrupts and Traps

handler address
handler address
handler address
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handler address
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(handler addresses repeated 11 times)
Virtual Interrupts and Traps

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## Actions on Real 360

<table>
<thead>
<tr>
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<th>User mode</th>
<th>Privileged mode</th>
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<tbody>
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<td>non-sensitive instruction</td>
<td>executes fine</td>
<td>executes fine</td>
</tr>
<tr>
<td>errant instruction</td>
<td>traps to kernel</td>
<td>traps to kernel</td>
</tr>
<tr>
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</tr>
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## Actions on Virtual 360

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<td>traps to VMM; VMM verifies and emulates/translates access</td>
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Quiz

Can a VMM (supporting other virtual machines) run on a virtual machine?

a) yes, no problem
b) it requires some changes to a VMM for it to run on a virtual machine
c) no, can’t be done
Virtual Devices?

• Terminals
  – connecting (real) people
• Networks
  – didn’t exist in the 60s
  – (how did virtual machines communicate?)
• Disk drives
  – CP67 supported “mini disks”
  – extended at Brown into “segment system”
• Interval timer
  – virtual or real?
Coping

• Invent new devices
  – recognized by VMM as not real, but referring to additional functionality
    - e.g., mini disks
• Provide new VM facilities not present on real machine
  – e.g., Brown segment system
  – special instructions on VM to request service from VMM
    - sort of like system calls (supervisor calls on 360), but ...
      • hypervisor calls
        – 360 had an extra, unused privileged instruction
        – the diagnose instruction