CSE 451: Operating Systems
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Module 19
Virtual Machine Monitors

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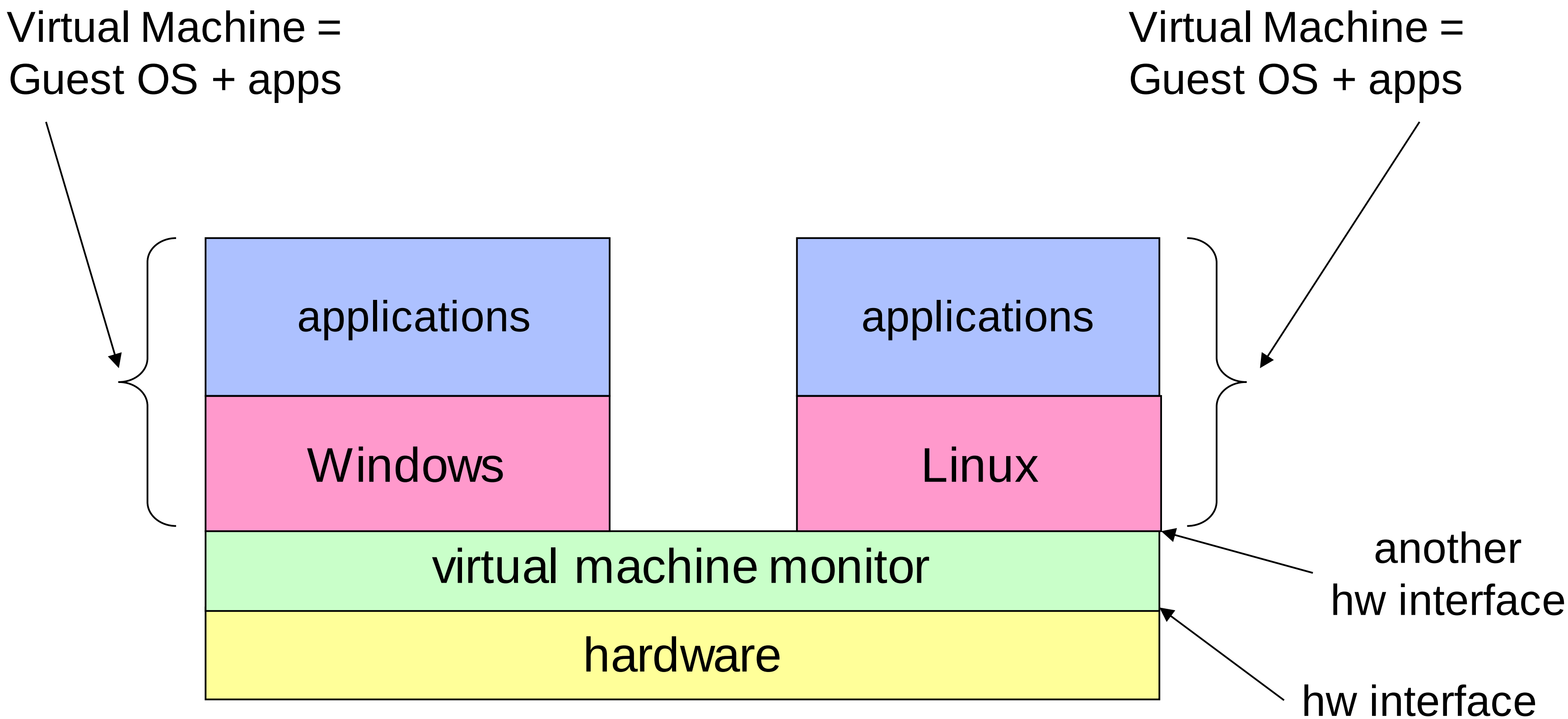
What do VMMs enable?

- Running multiple operating systems (called “guest OS’s”) and their applications on a single physical computer, as if each were running on its own private virtual computer

- Efficient – mostly direct execution, rather than simulation

- Contemporary examples
  - VMware
  - Microsoft’s VirtualPC / VirtualServer
  - Parallels (Mac)
  - Xen

VMM structure

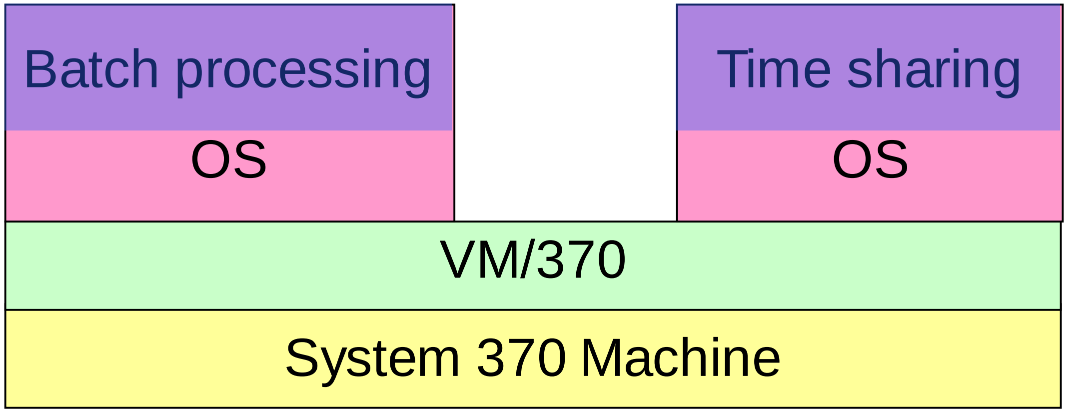


Basic ideas

- Guest OS runs in user mode
- When any kind of interrupt / exception / trap occurs, we'll end up in the VMM rather than the guest OS
- VMM simulates state changes that would have been made by the hardware, then restarts VM at the guest OS handler address
  - E.g., stuffs the saved PC where the architecture says it should be
- When the guest OS tries to execute a privileged instruction
  - VMM gets control, simulates effect of privileged instruction
    - VMM knows that guest OS was in virtual kernel mode so the attempted operation is OK

VMM History

- Conceived by IBM in the late 1960's
  - CP-40, CP-67, VM/360
- Sold continuously since then
- Used first for OS development and debugging, then for time sharing (multiple single-user OS's, plus a few single-job batch OS's), eventually for server consolidation



VMMs Today

- OS development and debugging
- Software compatibility testing
- Running software from another OS
  - or another OS version (newer or older than current)
- Virtual infrastructure for Internet services (server consolidation)
- Software system distribution
  - Distribute an entire, configured machine, rather than an app that needs configuring

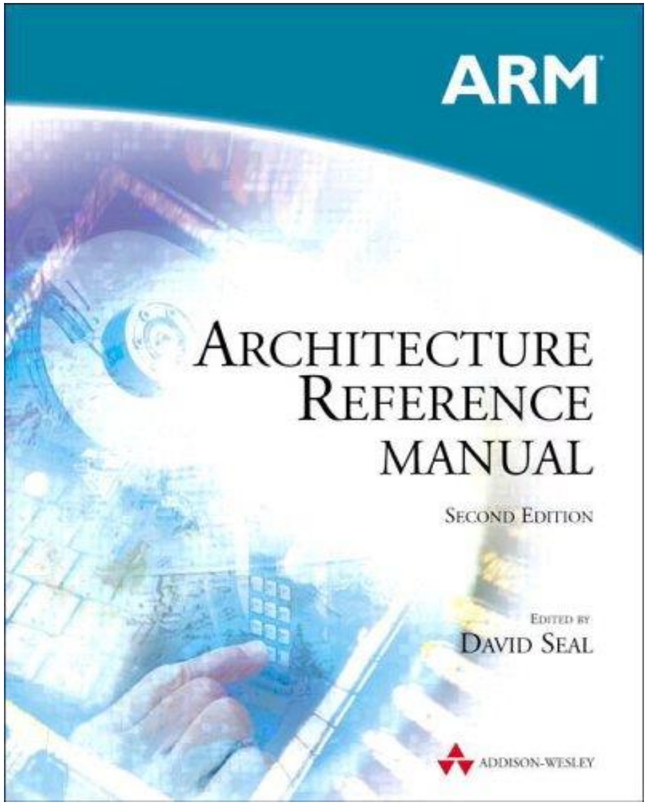
- Examples
  - Run Windows on your Mac, or MacOS on your PC
  - CSE Home virtual machine
  - Amazon's Elastic Compute Cloud (EC2)

Comparing the Unix and VMM APIs

	UNIX	VMM
Storage	File system	(virtual) disk
Networking	Sockets	(virtual) Ethernet
Memory	Virtual Memory	(virtual) Physical memory
Display	/dev/console	(virtual) Keyboard, display device

Possible Implementation Strategy: Complete machine emulation

- The VMM implements the complete hardware architecture as a software simulation



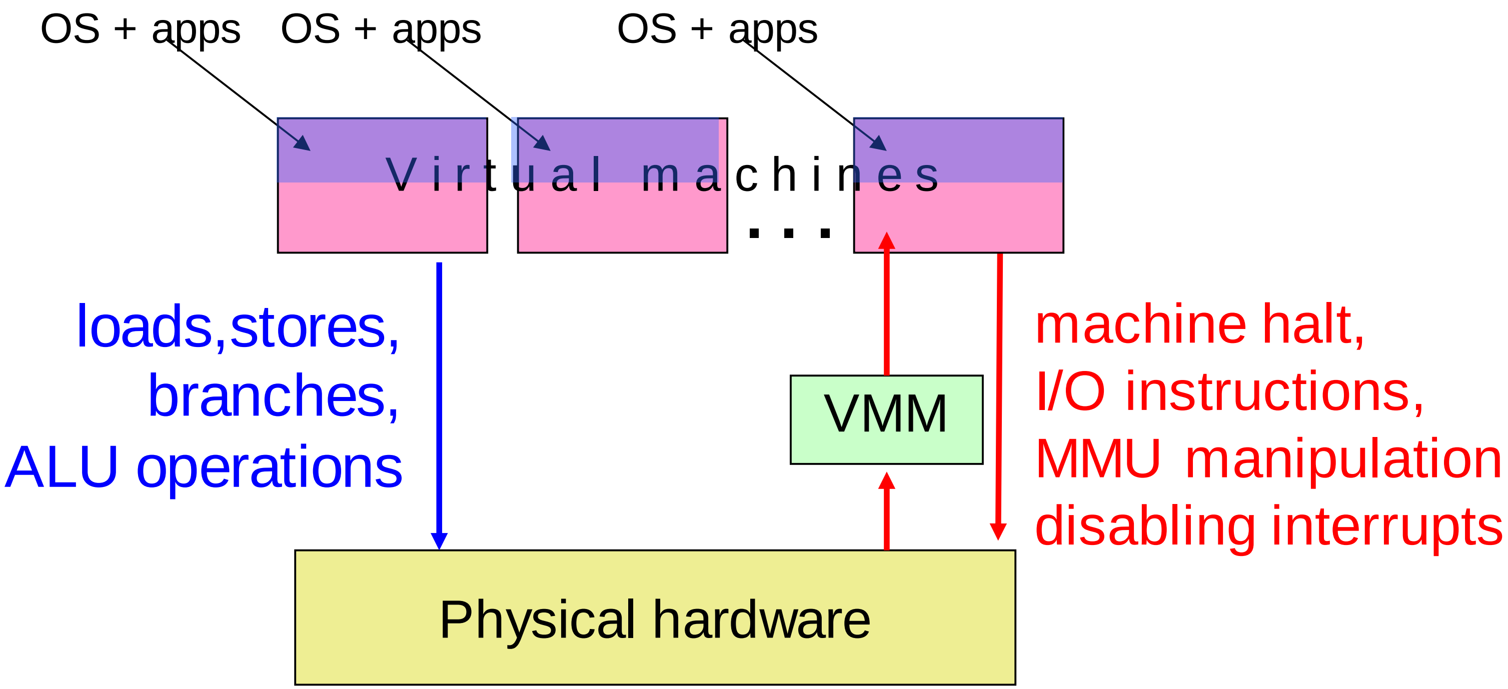

```
while(true) {
  Instruction instr = fetch();

  // emulate behavior in software
  instr.emulate();
}
```

Drawback: This is **really** slow

Practical alternative: VMM gets control on privileged instructions only

- Treat guest operating systems (and their apps) like an application
  - Guest apps run in user mode (mostly no problem…)
  - Guest OS runs in user mode (somewhat more of a problem…)
  - Most instructions execute natively on the CPU
  - Privileged instructions and traps transfer control to VMM, which reflects them back up to guest OS (after emulating virtual hw state changes)



Virtualizing the User/Kernel Boundary

- Both the guest OS **and** applications run in (physical) user-mode
- For each virtual machine, the VMM keeps a software mode bit:
  - During a system call, switch to “kernel” mode
  - On system call return, switch to “user” mode
- What does the VMM do if a VM executes a privileged instruction while in virtual user mode?
- What does the VMM do if a VM executes a privileged instruction while in virtual kernel mode?

Tracing Through a File System Read

Application	Guest OS	VMM	Hardware
read() syscall			
			trap detected
		trap handler; change VM to “kernel” mode	
	trap handler handle read syscall read from disk()		
			priv inst. detected
		trap handler; emulate I/O	

Questions, to clarify …

- What if the I/O could be handled from the buffer cache?

- Does the VMM handle a VM's I/O request synchronously?

- There are a zillion different types of disks (and networks and …) …
  Do the device drivers for these reside in the guest OS or in the VMM?

A possible "gotcha"

- All instructions that modify hardware state must be privileged (so that VMM can get control, modify the virtual hardware state for that guest, and not modify the physical hardware state)

- Example: Suppose the ERET instruction (return to a user process after handling an exception) is not privileged
  - ERET sets the PC to the saved PC, and sets CPU mode to user
  - There doesn't seem to be a reason to prevent user processes from doing this (even if there's no reason for them to want to)

Why would this be a problem for a VMM?

x86

- Conditions for an architecture to be virtualizable were defined in 1974

- x86 architecture did not satisfy these conditions!
  - Many reasons, but most of them stem from instructions that have different behavior in user mode and kernel mode, and that don't trap when executed in user mode

- Approach: binary re-writing
  - When a code page is loaded, scan it, looking for offending instructions
  - Patch these to cause a fault
  - Remember the instruction that used to be there

Other approaches

- Hardware: Both Intel (VT-x) and AMD (AMD-V) have developed virtualization extensions to the architecture (starting ~2006)
- Paravirtualization: Export a slight modification of the hardware; port the OS to this new hardware

Memory

- VMM’s also utilize memory protection (in addition to privileged instructions) to do their job
- Have not described how memory is virtualized by a VMM, creating “virtual physical memory” for the guest OS’s
- Approach involves the VMM futzing with the page tables of the guest OS’s

Trust Issues

Problem:

- Who can you trust?
- OS protects processes from each other
  - OS is “trusted” since *you’re running it on your hardware*
  - You don’t worry about OS snooping your data
- But in the cloud, Amazon (or Microsoft or Google) are running your operating systems in *their* VMM
  - VMs are ”just” user mode processes
  - VMM “naturally” isolates them
  - But, the VMM can look into the guest OS/process!

How You Can Trust The VMM

Solution:

- Tricky hardware!
- Keep all data encrypted
  - On disk, no problem.
  - In memory, sure… but...
  - How does the processor read/write/execute?
- Intel SGX/MEE processor / memory controller
  - RAM is encrypted!
  - Special instructions to tell processor where the encrypted regions are
  - *Processor decrypts pages into hidden caches and executes from there*

- A. Baumann, M. Peinado, and G. Hunt, “Shielding Applications from an Untrusted Cloud with Haven,” Sep. 2014.