CS 370: OPERATING SYSTEMS
[VIRTUALIZATION]

Binary translation
Take code sequences
split them up into *blocks*
short sequences without a branch
tiny paths without logic forks

Swap out paths that are at risk
rewrite block, one at a time
swap out instructions
sensitive and privileged

Store this work
In a cache
Ready to use
Cause you'll need it soon

Shrideep Pallickara
Computer Science
Colorado State University

COMPUTER SCIENCE DEPARTMENT
COLORADO STATE UNIVERSITY

1

Frequently asked questions from the previous class survey

- Does the CS department use VMs?
- x86 ?
- Can there be a VM inside a VM?
- Does every VM get its own CPU core?
- How are the caches and physical memory divvied up across VMs?
- What happens when control sensitive instructions are executed in VMs?
- Is there concurrency (i.e., threads/processes running concurrently) within a VM?
- What do VPNs do?

COLORADO STATE UNIVERSITY | Professor: SHRIDEEP PALLICKARA COMPUTER SCIENCE DEPARTMENT | VIRTUALIZATION | L26.2

2

Topics covered in this lecture

- Techniques for efficient virtualization
  - Virtualizing the unvirtualizable
- Cost of virtualization
- Memory virtualization
- Virtual Appliances

3

Each sign signifies a sound, and to link sounds is to form words, and to link words is to construct worlds.
Cloud Cuckoo Land, Anthony Doerr

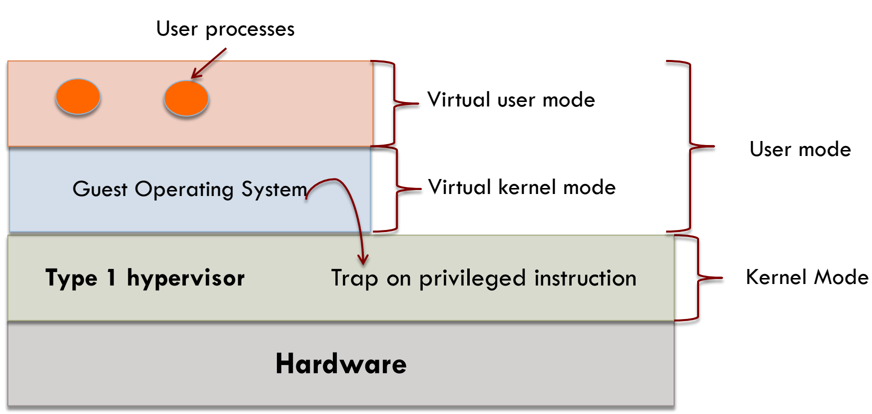
TECHNIQUES FOR EFFICIENT VIRTUALIZATION

4

Type-1 hypervisors

- Virtual machine runs as a user-process in user mode
  - Not allowed to execute sensitive instructions (in the Popek-Goldberg sense)
- But the virtual machine runs a Guest OS that **thinks** it is in kernel mode (although, of course, it is not)
  - **Virtual kernel mode**
- The virtual machine also runs user processes, which think they are in the user mode
  - And really are in user mode

Modes



Execution of kernel model instructions

- What if the Guest OS executes an instruction that is allowed only when the CPU is really in kernel mode?
  - On CPUs without VT (Intel: Virtualization Technology)?
    - Instruction fails and the OS crashes
- On CPUs with VT?
  - A trap to the hypervisor does occur
    - Hypervisor can inspect instruction to see if it was issued:
      - By Guest OS: Arrange for the instruction to be carried out
      - By user-process in that VM: Emulate what hardware would do when confronted with sensitive instruction executed in user-mode

7

8

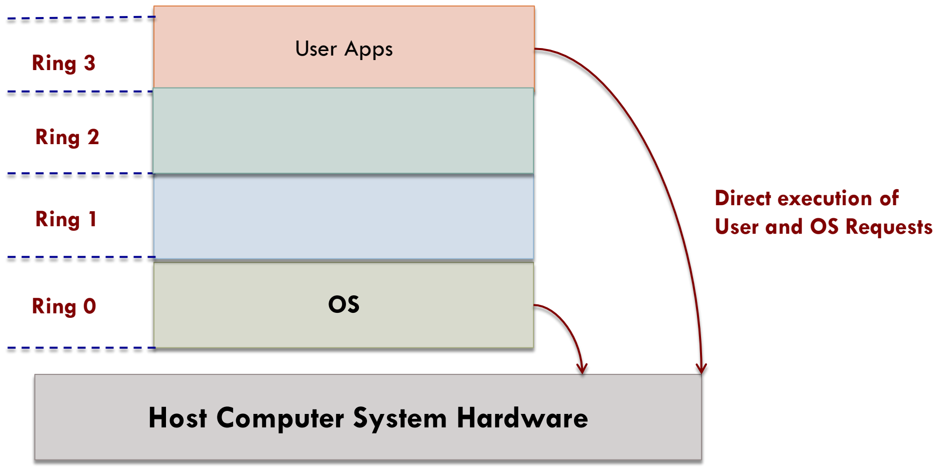
Virtualizing the x86 before VT (and AMD SVM)

- Virtualizing is straightforward when VT is available
- When it is not available?
  - Make clever use of:
    1. Binary translation
    2. Hardware features that did exist on the x86

Protection rings

- The x86 supported **4** protection modes (or **rings**)
- **Ring 3** is the least privileged
  - This is where normal processes execute
  - You cannot execute privileged instructions
- **Ring 0** is the most privileged
  - Allows execution of any instruction
  - In normal operation, the kernel runs here
- Other rings were *never used* by operating systems

x86 privilege level architecture without virtualization



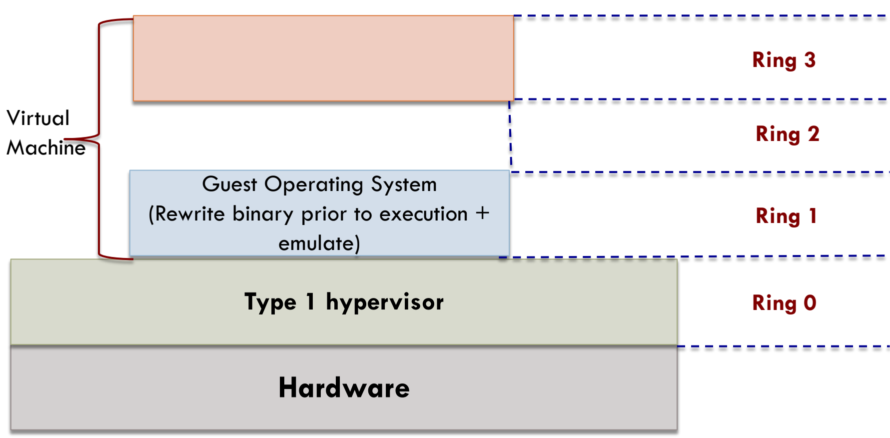
In other words, hypervisors had some room to play with

- Many solutions kept the hypervisor in kernel mode (ring 0)
- Applications in user mode (ring 3)
- Guest OS in a layer of intermediate privilege
  - Ring 1

How this allows virtualization …

- Kernel is privileged *relative* to user processes
  - Any attempt to access kernel memory from a user program leads to an access violation
- Guest OS' privileged instructions trap to the hypervisor
  - Hypervisor performs sanity checks and then performs instructions **on the guest's behalf**

Using the x86 rings prior to VT/SVM



But what about sensitive instructions in the guest OS' kernel code?

- The hypervisor makes sure that they no longer exist
  - Hypervisor rewrites code one **basic block** at a time
- Basic block
  - **Short, straight-line sequences** that end with a branch
  - Contain no jump, call, trap, return or other instructions that alter flow of control
    - Except for the very last instruction which does precisely that

Executing basic blocks

- Prior to executing a basic block, hypervisor **scans** it to see if there are sensitive instructions
  - If so, replace with call to hypervisor procedure that handles them

Dynamic translation and emulation sound very expensive

- But typically, are not
- Translated blocks are **cached**
  - So, no translation is needed in the future
- After basic block has completed executing, control is returned to hypervisor
  - Which locates block's successor
  - If successor has already been translated, it can be executed immediately

Binary translations

- Common to perform binary translation on all the guest OS code running in ring 1
- Replace even the privileged, sensitive instructions that could be made to trap
  - Traps can be expensive and binary translation leads to better performance

What about Type 2 hypervisors?

- Though type 2 hypervisors are conceptually different from type 1
  - They use, by and large, the same techniques
  - For e.g., VMware ESX Server (type 1, 2001) used exactly the same binary translation as the first VMware Workstation (type 2, 1999)

For faithful virtualization

- Guest OS should also be tricked into thinking it is the true and only king/queen of the mountain
  - Full control of all machine's resources
  - Access to entire address space (4GB on 32-bit machines)
- When the queen finds another king squatting in its address space?

Let's look at this 2 kings/queen problem

- In Linux, a user process has access to just 3 GB of the 4 GB address space [32-bit addressing]
  - 1 GB is reserved for the kernel
  - Any access to kernel memory leads to a trap
- We could take the trap and emulate appropriate actions
  - Expensive!

Type 2 hypervisors have a kernel module operating in ring 0

- Allows manipulation of hardware with privileged instructions
  - Allows the guest to have the full address space
- This is all well and good, but …
  - At some point hypervisor needs to clean up and restore original processor context

What if the guest is running and an interrupt arrives from an external device?

- Type 2 hypervisor depends on host's device drivers to handle the interrupt
- So, the hypervisor **reconfigures hardware** to to run the host OS system code
  - When the device driver runs, it finds everything just as it expected it to be
- Hypervisor behaves just like teenagers throwing a party when parents are away
  - It's OK to rearrange furniture completely, as long as they put it back as they found it before parents get home

World switch

- Going from a hardware configuration for the host kernel to a configuration for the guest OS

Why do hypervisors work even on unvirtualizable hardware?

- Sensitive instructions in the guest kernel are replaced by calls to procedures that **emulate** these instructions
- No sensitive instructions issued by the guest OS are ever executed directly by true hardware
  - Turned into calls to the hypervisor, which emulates them

COST OF VIRTUALIZATION

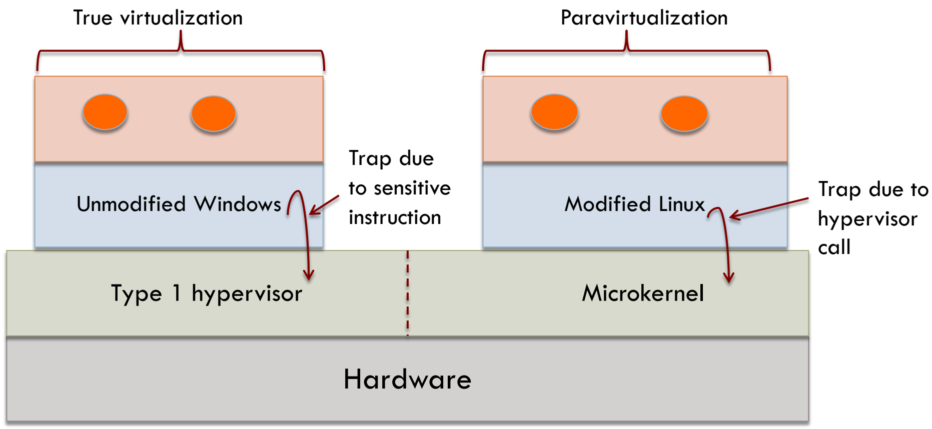
Cost of virtualization

- We expect CPUs with VT would greatly outperform software techniques
- Trap-and-emulate approach used by VT hardware generates a lot of traps … and these are expensive
  - **Ruin CPU caches, TLBs, and branch predictions**
- In contrast, when sensitive instructions are replaced by calls to hypervisor procedures
  - None of this context-switching overhead is incurred

Cost of virtualization

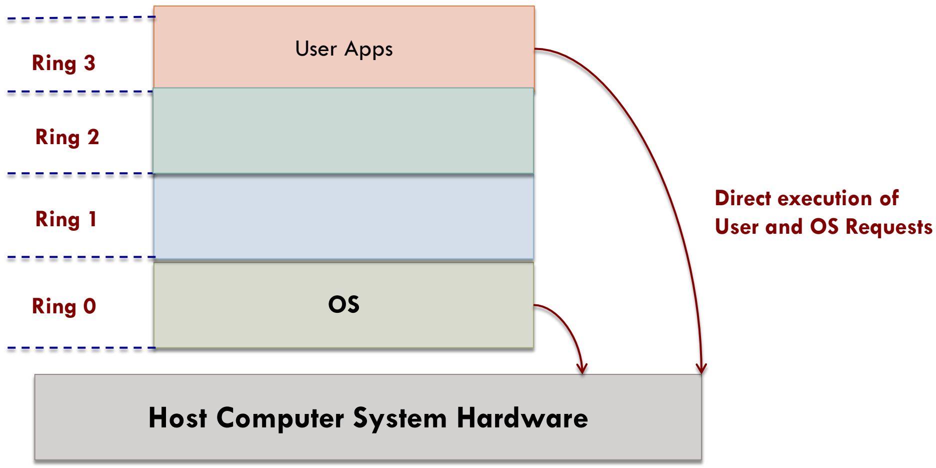
- Still … with modern VT hardware, usually the hardware beats the software

True virtualization & paravirtualization



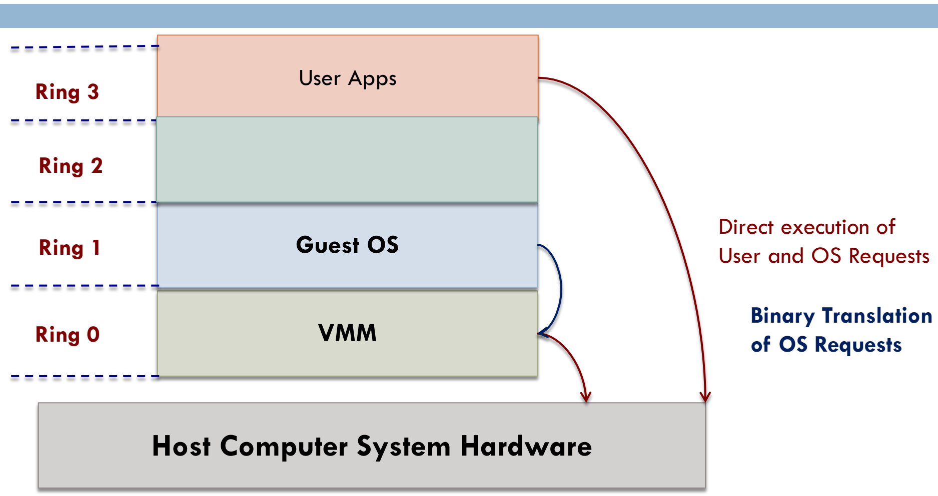
TO SUMMARIZE

x86 privilege level architecture without virtualization



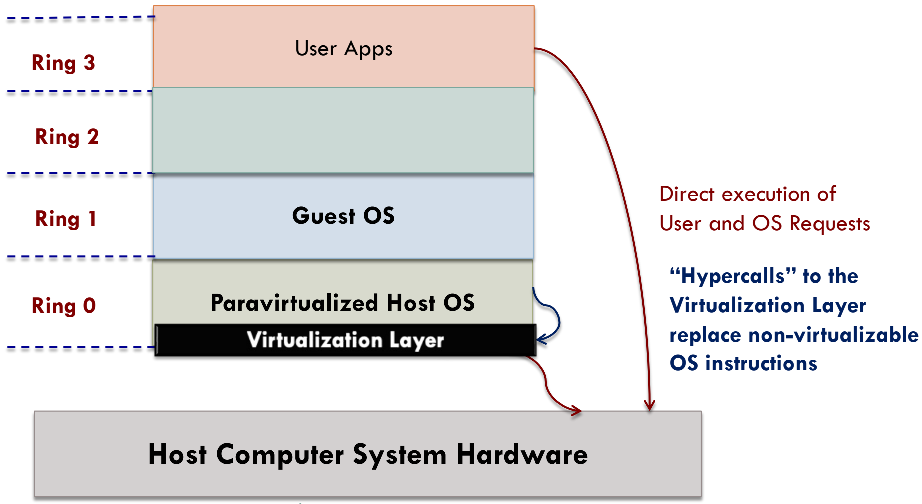
31

Full Virtualization: Binary translation approach to x86 virtualization



32

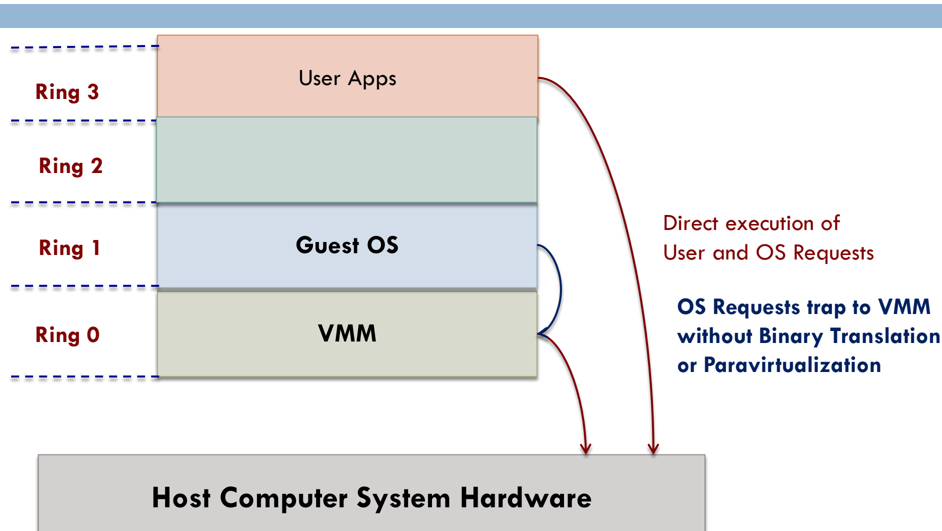
Paravirtualization approach to x86 virtualization



COLORADO STATE UNIVERSITY Professor: SHRIDEEP PALLICKARA COMPUTER SCIENCE DEPARTMENT VIRTUALIZATION L26.33

33

Hardware assisted virtualization



COLORADO STATE UNIVERSITY COMPUTER SCIENCE DEPARTMENT VIRTUALIZATION L26.34

34

Contrasting the virtualization approaches

	Full virtualization with Binary Translation	**Hardware Assisted Virtualization**	**OS Assisted Virtualization/ Paravirtualization**
Technique	Binary Translation and Direct Execution	Exit to Root Mode on privileged instructions	Hypercalls
Guest Modification/ Compatibility	Unmodified Guest OS Excellent compatibility	Unmodified Guest OS Excellent compatibility	GuestOS codified to issue Hypercalls so it can't run on native hardware. Compatibility is lacking

Tell all the truth but tell it slant —
Success in Circuit lies
Too bright for our infirm Delight
The Truth's superb surprise
As Lightning to the Children eased
With explanation kind
The Truth must dazzle gradually
Or every man be blind —

Tell all the truth but tell it slant, Emily Dickinson

MEMORY VIRTUALIZATION

All modern OS support virtual memory

- Basically **mapping** of virtual address space onto frames of physical memory
- Defined by (multilevel) page tables
- Mapping is set in motion by having the OS set a control register that points to the top-level page table
- Virtualization greatly complicates memory management

Scenario

- Guest OS decides to map its virtual pages 7, 4, and 3 onto physical frames 10, 11, and 12 respectively
- Builds page tables and sets hardware register to point to top level page table
  - Sensitive instruction that traps on a VT CPU
- We will look at type-1 but the problem is the same in type-2 and paravirtualization

What should the hypervisor do?

- Allocate physical frames 10, 11, and 12 to the VM
  - Setup page tables to map VM's virtual pages 7, 4, 3
- What if a second VM starts up and maps its virtual pages 4, 5, and 6 to physical frames 10, 11 and 12?
  - This VM loads a control register to point to its page tables
  - Hypervisor catches this trap

Choices for the hypervisor

- Cannot use the mapping from the 2nd VM because physical frames 10, 11, and 12 are already in use
- Find free frames, say 20, 21, and 22 and use them
  - But first, create new page tables mapping virtual pages 4, 5, and 6 of VM-2 onto 20, 21, and 22
- In general, for each VM, the hypervisor needs to create a **shadow page table**
  - Map virtual pages used by VM onto actual physical frames that the hypervisor gave it

Also …

- Every time the Guest OS changes its page tables?
  - The hypervisor must change the shadow page tables as well
- If the guest OS remaps virtual page 7 onto what it sees as physical frame 200
  - The hypervisor has to know about this change
- Trouble is that the guest OS can change its page tables by just writing into memory
  - No sensitive operations are required, so *the hypervisor does not even know about the change*
    - Certainly, cannot update shadow page tables used by actual hardware

Options

- Keep track of the top-level page table
  - There is a trap when the guest OS attempts to load register
  - Map the page tables it points to as read-only
    - If the guest OS tries to modify it, will cause a fault and give control to the hypervisor
      - Figure out what the guest OS is trying to do and update shadow tables accordingly
- Allow guest to add new mappings at will
  - Nothing changes in the shadow tables
  - When a new page is accessed, fault occurs and control reverts to hypervisor (can then add entries)

Hardware support for nested page tables

- Took AMD and Intel a few years to produce hardware to virtualize memory efficiently
- Support for **nested page tables** (AMD)
  - Intel calls this extended page tables (**EPT**)
- With EPT
  - Hypervisor still has the shadow page table, but CPU is able to handle intermediate levels in hardware
  - Hardware walks the EPT to to translate guest virtual address to guest physical address
    - Also, walks the EPT to find the host physical address **without software intervention**

Other issues

- **Overcommitment** of physical memory
  - 1 physical machine with 32 GB of memory will run 3 VMs each of which thinks there is 16 GB of memory
- **Deduplication**
  - Allow sharing of pages with the same content
    - E.g., Linux kernel

How can we take away memory pages safely from VMs?

- There is a trick known as **ballooning**
- Small balloon module loaded into each VM as a *psuedo device driver* that talks to hypervisor
- Balloon inflates at hypervisor's request by allocating more and more pinned pages
  - And deflates by deallocating these pages

How ballooning helps

- As balloon inflates
  - **Memory scarcity** in the guest OS increases
  - The guest OS responds by paging out what it believes are the least valuable pages
    - This is exactly what we need!
- As balloon deflates
  - More memory available for the guest to allocate

In other words

- Hypervisor tricks the guest OS into making tough decisions for it
- In politics this is known as passing the buck

VIRTUAL APPLIANCES

Installing application software

- VMs offer a solution to a problem that has long plagued users (especially open source)
  - **How to install application programs**
- Applications are dependent on numerous other applications and libraries
  - Which themselves depend on a host of software packages
- Plus, there are dependencies on particular versions of compilers, scripting languages, OS etc.

With VMs …

- Developer can carefully **construct** a virtual machine
  - Load it with required OS, compiler, libraries, and application code
  - **Freeze the entire unit** … ready to run
- Only the software developer has to understand the dependencies

What about customers?

- Customers get a complete package that actually works
  - Completely independent of which OS they are running and which other software, packages, and libraries they have
- These are "shrink-wrapped" virtual machines
  - **Virtual appliances**
- Amazon's EC2 cloud offers many pre-packaged virtual appliances
  - Software as a service

CLOUDS

Clouds

- Virtualization played a critical role in the dizzying rise of cloud computing
- Clouds
  - Public or private or federated
- Clouds offer different things
  - Bare metal
  - VMs of different sizes and capabilities
  - Appliances with software that is ready to use

5 characteristics of clouds: NIST

- **On-demand self-service**
  - No human interaction needed
- **Broad network access**
  - Resources available over the network
- **Resource pooling**
  - Resources pooled among multiple users
- **Rapid elasticity**
  - Acquire and release resources rapidly
- **Measured service**
  - Meters resource usage

LICENSING ISSUES

Licensing Issues

- Some software is licensed on a per-CPU basis
  - Especially, software for companies
  - When users buy a program they have the right to run it on just one CPU
    - What is a CPU anyway?
    - Can we run multiple VMs all running on the same physical hardware?
- Problem is even worse, when companies have licenses for N machines running the software
  - VMs come and go on demand

The contents of this slide-set are based on the following references

- *Andrew S Tanenbaum and Herbert Bos. Modern Operating Systems. 4th Edition, 2014. Prentice Hall. ISBN: 013359162X/ 978-0133591620. [Chapter 7]*
- *VMWare: Understanding Full Virtualization, Paravirtualization, and Hardware Assist.*
- *Avi Silberschatz, Peter Galvin, Greg Gagne. Operating Systems Concepts, 9th edition. John Wiley & Sons, Inc. ISBN-13: 978-1118063330.* [Chapter 9, 16]