CSE 120
Principles of Operating Systems

Spring 2023

Lecture 18: Protection

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Administrivia

- Homework #4
  - Due today
- Project 3
  - Due June 10th – there will be no extensions
- Grades for Homework #3 are on Canvas
- Discussion section this week – Q&A

Administrivia Continued

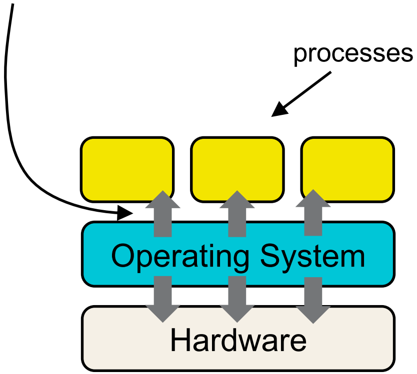
- Course Evaluation
  - New SET form
  - I really appreciate your feedback
  - Due Saturday June 10th at 8:00 AM
- Final Exam
  - Monday June 12th at 3:00 PM
  - We will review in class on 6/8
  - Extra office hour 1-2 pm on 6/8
  - See announcement on Canvas for details

Today's Outline

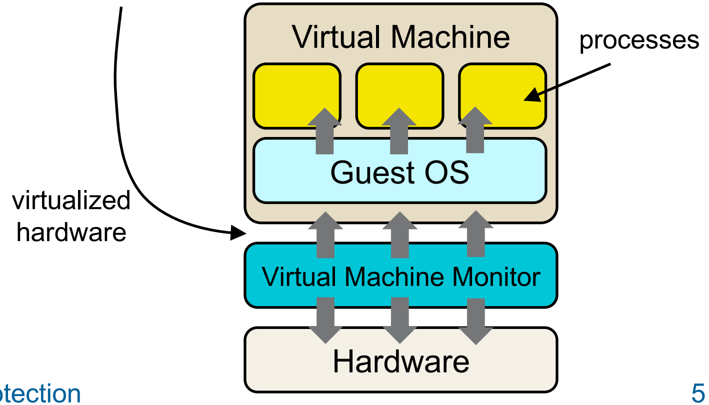
- Virtual machines (continued)
- Containers
- Protection

Processes vs. Virtual Machines

- Abstractions for processes:
  - Virtual memory
  - System calls
  - Most instructions in the ISA
  - Most registers

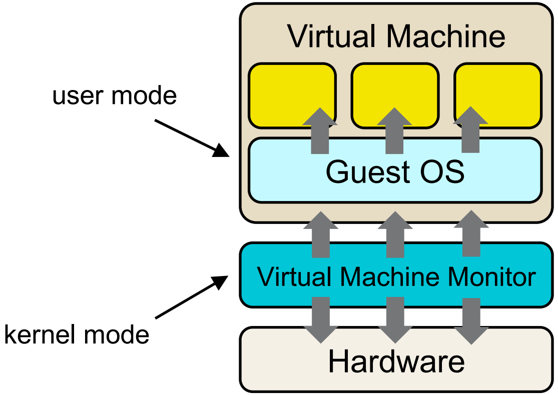


- Abstractions for virtual machines:
  - Physical memory
  - Interrupts
  - All instructions in the ISA
  - All registers
  - I/O devices



VMM Approach

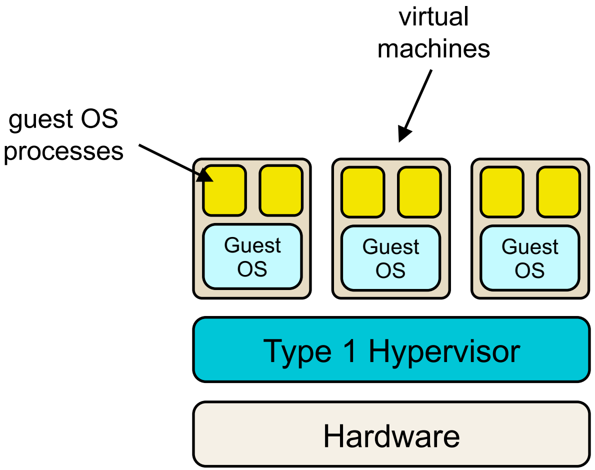
- Run the guest OS in user mode
  - Most instructions execute at regular CPU speed
- Run the VMM in kernel mode
- Anything “unusual” causes a trap to the VMM
- VMM has 2 options:
  - Call back into the guest OS for handling
  - Simulate the appropriate behavior with trap-and-emulate



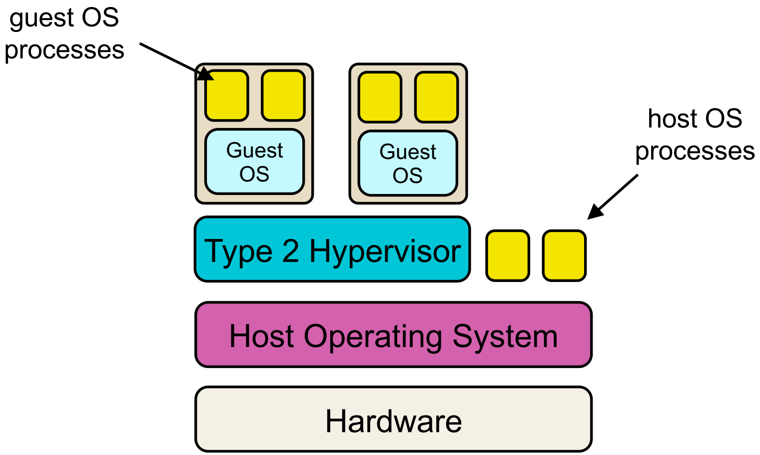
Virtualizing the x86 Architecture

- Paravirtualization
  - Change the guest OS to better cooperate with the VMM
- Binary translation
  - Run guest OS code under control of a binary translator
  - Rewrites privileged instructions with emulation at runtime (may trap to VMM)
- Hardware support
  - Intel and AMD added virtualization support in 2005 (Intel VT-x, AMD-V)

Type 1 and Type 2 Hypervisors



Type 1

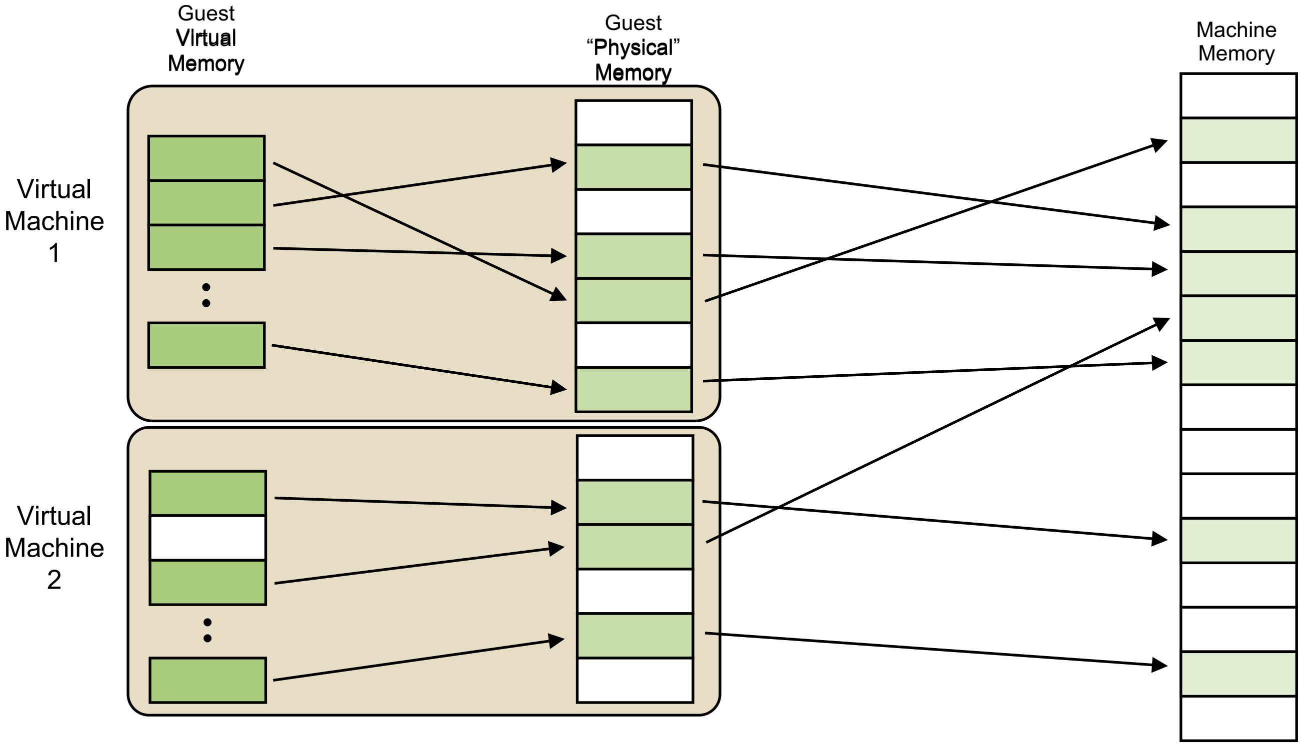


Type 2
(hosted hypervisor)

What Needs to be Virtualized?

- Events (exceptions and interrupts)
- CPU
- I/O devices
- Memory

Virtualizing Memory

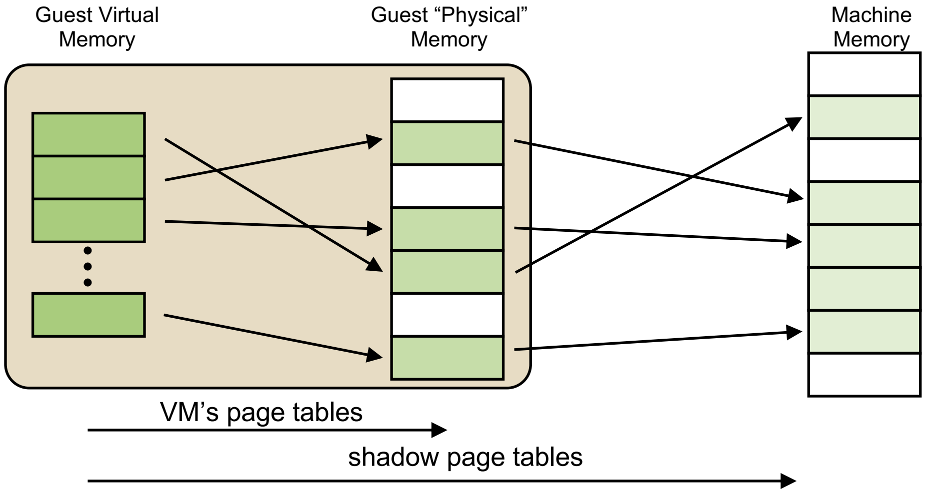


Virtualizing Memory

- Challenges:
  - VMM needs to assign hardware pages to VMs
  - Hardware-managed TLBs – hardware will walk page tables with no opportunity for the VMM to run

Shadow Page Tables

- One approach – shadow page tables
  - VMM maintains shadow page tables for each VM
  - Shadow page tables map from virtual pages in the VM to physical pages allocated by the VMM

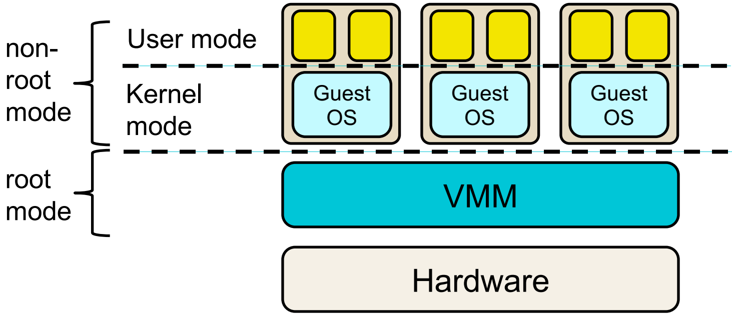


Shadow Page Tables

- MMU points to shadow page tables
- When VM tries to change MMU to point to a different page table:
  - Traps to VMM which updates MMU to point to the shadow page table
- Keeping shadow page tables in sync with guest page tables:
  - Mark pages of guest OS page table as read only
  - When guest OS updates page table, trap to VMM, VMM updates shadow page table
- VMM can also swap out pages and indicate this in the shadow page tables

Hardware Support for Virtualization

- Most modern CPUs provide virtualization support in CPUs in hardware
  - Intel VT-x, AMD-V, RISC-V H-extension
- Privileged instructions
  - New execution mode: non-root mode
  - Traps from VM processes go to the Guest OS
- Interrupts
  - Hardware delivers them directly to the right VM
- I/O
  - SR-IOV virtualizes I/O devices (e.g., NIC, storage device)
- Memory
  - Intel Extended Page Tables (EPT) virtualize page tables



Other Abstractions for Virtualization

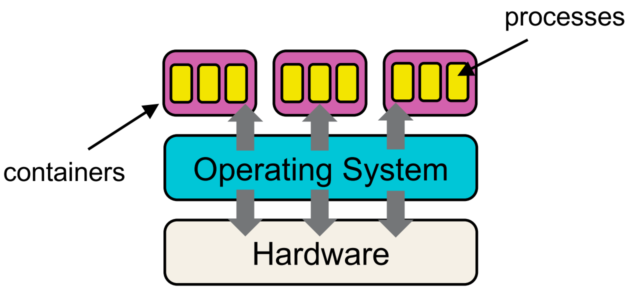
- Virtual machines
  - Types of Virtual Machine Monitors
    - Type I vs. type II
    - Full vs. para-virtualization
  - Virtualization components
    - Events
    - CPU
    - I/O devices
    - Memory
- Containers
  - Namespace isolation
  - Resource management

Virtualization Tradeoffs

https://en.wikipedia.org/w/index.php?curid=70663056

Container-Based OS Virtualization

- Containers virtualize OS abstractions
  - Manage isolated sets of OS objects (using namespaces)
  - Manage isolated sets of resources (using resource management)
- Lightweight virtualization
  - Containers on the same machine share an OS



Namespace Isolation

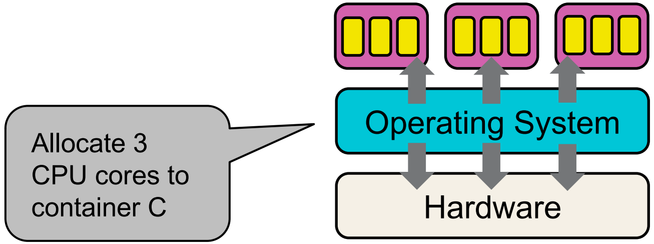
- Principle: if you cannot name it, you are isolated from it
  - Similar to virtual memory
- OS implements a collection of namespaces
  - Process IDs: processes
  - User IDs: users and groups
  - Network: IP address, network ports, routing, firewall
  - File system: files and directories
- Each namespace is completely independent
- Containers can use any mix of namespaces

Namespace Implementation

- OS implements everything as usual, but tags objects with the namespace that they belong to
  - A process has both a PID and a namespace identifier
- Mappings map container-local IDs to global perspective
  - OS tracks processes on global lists
  - OS maps from PID within a container to a process on the global list
- Filters restrict which objects are visible in a namespace
  - E.g., running `ps` in a namespace only shows processes in the namespace

Resource Management in Containers

- Goal: control resources assigned to containers
  - How much CPU, memory, disk, and network
- OS manages resources at a process granularity by default
- Containers manage resources among a set of processes
  - Which cores can be used, how much overall CPU utilization
  - How much memory (e.g., paging among processes in a group)
  - How much disk and network I/O
- In Linux: control groups (cgroups)



Today's Outline

- Virtual machines (continued)
- Containers
- Protection

Protection

- Protection: mechanisms that prevent accidental or intentional misuse of a system
- Three components:
  - Authentication – identify a responsible party behind each action
  - Authorization – determine which parties are allowed to perform which actions
  - Enforcement – control access using authentication and authorization

Protection Principles

- Permission rather than exclusion
  - Default is no access (will quickly discover if wrong)
- Check every access to every object
  - Including every instruction and memory reference
- Design is not secret
  - E.g., Linux is open source and that should not make it insecure
- Principle of least privilege
  - Only execute with the privileges you need (avoids mistakes)
- User interface to protection must be easy to use
  - If it is hard to use, users will find ways around it

Users

- Protection starts with the concept of a user
- Which user you are defines:
  - What programs you can run (execute)
  - Which files you can access and how (read, write)
- Cannot do anything on the system until you log in (authentication)
- Once you log in, everything you do on the system is performed under your user ID
  - Every process runs under a user ID
  - The user ID is the basis for protection checks

Root and Administrator

- The user "root" is special on Unix
  - It bypasses all protection checks in the kernel
  - Administrator is the equivalent on Windows
- Recall: principle of least privilege
- Running as root can be dangerous
  - A mistake (or exploit) can harm the system
  - This is why we create user accounts even if you have root access
    - Only run as root when you need to modify the system
  - If you have Administrator privileges on Windows, then you are effectively always running as root

sudo and su

- The sudo command runs a process with root privileges
  - Authenticate using the user’s password
  - User must be in the sudo group (/etc/group)
- The su command runs a shell with root privileges
  - Authenticate using the password for the root user
  - Effectively logging in as root
  - Less precise than sudo, more risky

Authorization

- Authorization: determines who is allowed to perform which actions
- More formally:
  - Subjects – who is performing the action (e.g., user)
  - Objects – what the action is being performed on (e.g., a file)
  - Actions – what the subject is allowed to do to the object
- Can a given subject perform a given action on a given object?

Objects

Subjects

	/one	/two	/three
Alice	rw	-	rw
Bob	w	-	r
Charlie	w	r	rw

Access Control Lists vs. Capability Lists

- Access control lists: organize by columns
  - For each object, maintain a list of which users are allowed to perform which actions
- Capability lists: organize by rows
  - For each subject, maintain a list of objects and their permitted actions

access control list

Objects

	/one	/two	/three
Alice	rw	-	rw
Bob	w	-	r
Charlie	w	r	rw

Subjects

capability list

Access Control Lists vs. Capability Lists

- Approaches differ only in how the table is “represented”
  - Different tradeoffs so we use them in different ways
- Capabilities are faster to check and easier to transfer
  - They are like keys, easy to hand off
  - Very fast to check
- ACLs are slower but easier to use
  - Slow to check compared to capabilities
  - Object-centric, easy to grant and revoke
  - Easier for users to express protection goals

access control list

Objects

Subjects

	/one	/two	/three
Alice	rw	-	rw
Bob	w	-	r
Charlie	w	r	rw

capability list

Operating Systems Use Both

- OSes use ACLs on objects in the file system
  - These are what users manipulate to express protection
- OSes use capabilities when checking access frequently
  - Checking every memory reference needs to be fast

File System Protection

- File systems implement a static protection system
  - Who can access files, directories, devices, etc.
  - How they are allowed to access it
- The mechanism used to represent file system permissions is the access control list
  - Recall: permission, not exclusion
- For each object (file), which users have access to the object, and what actions can they take?
  - Can be compact: Unix’s owner/group/other, read/write/execute
  - Can be flexible: an arbitrary list of user:rights entries

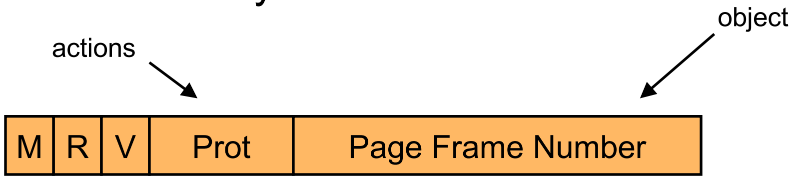
Checking File Permissions

- Recall: check every access
- For reading/writing a file, the OS needs to verify on every `read()/write()` that the process has permission to perform the syscall
- But, checking file permissions is expensive
  - Scanning ACLs on every read/write is slow
- How do we optimize the permissions check?
  - open syscall
- Use file descriptors as capabilities
  - The process passes this descriptor to every call to `read()/write()`
  - OS checks that the descriptor is valid and the action is allowed

Virtual Memory Protection

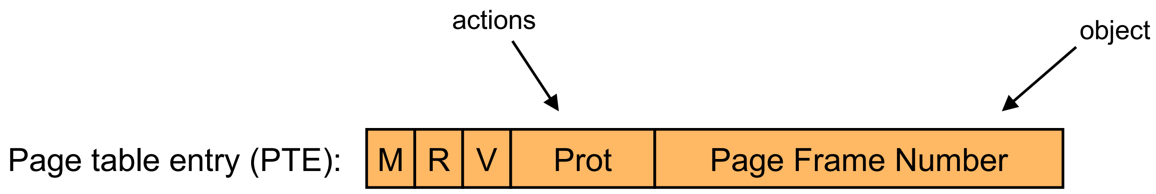
- The address space defines permissions for a process under execution
  - It is a dynamic representation of permissions
- The mechanism used to represent virtual memory protection is capabilities
- Page table entries are our VM capabilities
  - Every PTE refers to a page of memory
  - Specifies what the process is allowed to do with that page
- Recall: check every access
  - Every instruction execution and every load/store

Page table entry (PTE):



Origins of PTEs

- PTEs are capabilities
  - Where are they derived from?
- Loading a process and creating the address space
  - Code pages: set the PTE protection bits to read-only and execute
  - Data pages: set the PTE protection bits to read/write but not execute



For next class…

- Study for the final
- Come with questions!