# Computer Security

05. Confinement

Paul Krzyzanowski
Rutgers University
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## Last Time

- *chroot*
- FreeBSD Jails
- Linux namespaces, capabilities, and control groups
  - – Control groups
    - Allow processes to be grouped together – control resources for the group
  - – Capabilities
    - Limit what root can do for a process & its children
  - – Namespaces
    - Restrict what a process can see & who it can interact with: PIDs, User IDs, mount points, IPC, network



## Containers



## What's the main problem?

- Installing software packages can be a pain
  - – Dependencies
- Running multiple packages on one system can be a pain
  - – Updating a package can update a library or utility another uses
    - Causing something else to break
  - – No isolation among packages
    - Something goes awry in one service impacts another
- Migrating services to another system is a pain
  - – Re-deploy & reconfigure



## How did we address these problems?

- Sysadmin effort
  - – Service downtime, frustration, redeployment
- Run every service on a separate system
  - – Mail server, database, web server, app server, …
  - – Expensive! … and overkill
- Deploy virtual machines
  - – Kind of like running services on separate systems
  - – Each service gets its own instance of the OS and all supporting software
  - – Heavyweight approach
    - Time share between operating systems



## What are containers?

Containers: created to package & distribute software

- – Focus on services, not end-user apps
- – Software systems usually require a bunch of stuff:
  - Libraries, multiple applications, configuration tools, …
- – Container = image containing the application environment
  - Can be installed and run on any system

Key insight:
*Encapsulate software, configuration, & dependencies into one package*



## A container feels like a VM

- Separate
  - Process space, network interface, network configuration, libraries, …
  - Limited root powers
- But:
  - All containers on a system share the same OS & kernel modules



## How are containers built?

- **Control groups**
  - Meters & limits on resource use
    - Memory, disk (I/O bandwidth), CPU (set %), network (traffic priority)
- **Namespaces**
  - Isolates what processes can see & access
  - Process IDs, host name, mounted file systems, users, IPC
  - Network interface, routing tables, sockets
- **Capabilities**
  - Keep root access but restrict what it can do
- **Copy on write file system**
  - Instantly create new containers without copying the entire package
  - Storage system tracks changes
- **AppArmor**
  - Pathname-based mandatory access controls
  - Confines programs to a set of listed files & capabilities



## Initially … Docker

- First super-popular container
- Designed to provide Platform-as-a-Service capabilities
  - Combined Linux cgroups & namespaces into a single easy-to-use package
  - Enabled applications to be deployed consistently anywhere as one package
- Docker Image
  - Package containing applications & supporting libraries & files
  - Can be deployed on many environments
- Make deployment easy
  - Git-like commands: docker push, docker commit, ...
  - Make it easy to reuse image and track changes
  - Download updates instead of entire images
- Keep Docker images immutable (read-only)
  - Run containers by creating a writable layer to temporarily store runtime changes



## Later Docker additions

- Docker Hub: cloud based repository for docker images
- Docker Swarm: deploy multiple containers as one abstraction



## Container Orchestration

- We wanted to manage containers across systems
- Multiple efforts
  - Marathon/Apache Mesos (2014), Kubernetes (2015), Nomad, Docker Swarm, …
- Google designed Kubernetes for container orchestration
  - Google invented Linux control groups
  - Standard deployment interface
  - Scale rapidly (e.g., Pokemon Go)
  - Open source (unlike Docker Swarm)



## Container orchestration

- Kubernetes orchestration
  - Handle multiple containers and start each one at the right time
  - Handle storage
  - Deal with hardware and container failure
  - Add remove containers in response to demand
  - Integrates with the Docker engine, which runs the actual container



## Containers & Security

Primary goal was software distribution, not security

- Makes moving & running a collection of software simple
  - E.g., Docker Container Format
- Everything at Google is deployed & runs in a container
  - Over 2 billion containers started per week (2014)
  - lmctfy ("*Let Me Contain That For You*")
    - Google's old container tool – similar to Docker and LXC (Linux Containers)
  - Then Kubernetes to manage multiple containers & their storage



## Containers & Security

- But there are security benefits
  - **Containers use namespaces, control groups, & capabilities**
    - Restricted capabilities by default
    - Isolation among containers
  - **Containers are usually minimal and application-specific**
    - Just a few processes
    - Minimal software & libraries
    - Fewer things to attack
  - **They separate policy from enforcement**
  - **Execution environments are reproducible**
    - Easy to inspect how a container is defined
    - Can be tested in multiple environments
  - **Watchdog-based restarting**: helps with availability
  - Containers help with **comprehension errors**
    - Decent default security without learning much
    - Also ability to enable other security modules



## Security Concerns

- **Kernel exploits**
  - All containers share the same kernel
- **Denial of service attacks**
  - If one container can monopolize a resource, others suffer
- **Privilege escalation**
  - Shouldn't happen with capabilities ... But there might be bugs
- **Origin integrity**
  - Where is the container from and has it been tampered?



## Sandboxes



## The sandbox

**sand•box**, 'san(d)-"bäks, *noun*. Date: 1688 : a box or receptacle containing loose sand: as **a:** a shaker for sprinkling sand on wet ink **b:** a box that contains sand for children to play in

- A restricted area where code can play in
- Allow users to download and execute untrusted applications with limited risk
- Restrictions can be placed on what an application is allowed to do in its sandbox
- Untrusted applications can execute in a trusted environment

*Jails & containers are a form of sandboxing*
*… but we want to focus on giving users the ability to run apps*

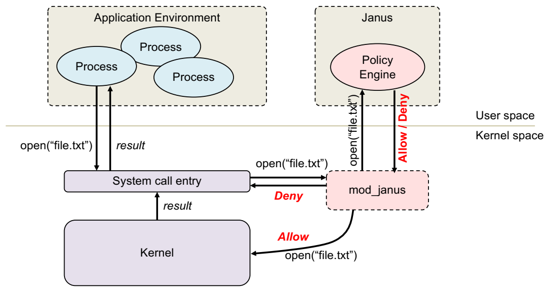


## System Call Interposition

- System calls interface with resources
  - An application must use system calls to access any resources, initiate attacks … and cause any damage
    - Modify/access files/devices: *creat, open, read, write, unlink, chown, chgrp, chmod, …*
    - Access the network: *socket, bind, connect, send, recv*
- **Interposition**
  - Intercept & inspect an app's system calls

## Example: Janus

App sandboxing tool implemented as a loadable kernel module






## Example: Janus

- Policy file defines allowable files and network operations
- Dedicated policy per process
  - Policy engine reads policy file
  - Forks
  - Child process *execs* application
  - All accesses to resources are screened by Janus
- System call entry points contain *hooks*
  - Redirect control to `mod_Janus`
  - Module tells the user-level Janus process that a system call has been requested
    - Process is blocked
    - Janus process queries the module for details about the call
    - Makes a policy decision



## Implementation Challenge

Janus has to mirror the state of the operating system!

- If process forks, the Janus monitor must fork
- Keep track of the network protocol
  - socket, bind, connect, read/write, shutdown
- Does not know if certain operations failed
- Gets tricky if file descriptors are duplicated
- Remember filename parsing?
  - We have to figure out the whole dot-dot (..) thing!
  - Have to keep track of changes to the current directory too
- App namespace can change if the process does a *chroot*
- What if file descriptors are passed via Unix domain sockets?
  - *sendmsg, recvmsg*
- Race conditions: **TOCTTOU**



## Web plug-ins

- External binaries that add capabilities to a browser
- Loaded when content for them is embedded in a page
- Examples: Adobe Flash, Adobe Reader, Java



## Chromium Native Client (NaCl)

chrome

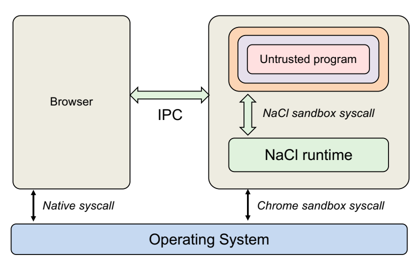
- Designed for
  - Safe execution of platform-independent untrusted native code in a browser
  - Compute-intensive applications
  - Interactive applications that use resources of a client
- Two types of code: **trusted** & **untrusted**
  - **Untrusted** has to run in a sandbox
  - Pepper Plugin API (PPAPI): portability for 2D/3D graphics & audio
- Untrusted native code
  - Built using NaCl SDK or any compiler that follows alignment rules and instruction restrictions
    - GNU-based toolchain, custom versions of gcc/binutils/gdb, libraries
    - 32-bit x86 support
  - NaCl statically verifies the code to check for use of privileged instructions



## Chromium Native Client (NaCl)

Two sandboxes

- Outer sandbox: restricts capabilities using system call interposition
- Inner sandbox: uses x86 segmentation to isolate memory among apps





## Java Language

- Type-safe & easy to use
  - Memory management and range checking
- Designed for an interpreted environment: JVM
- No direct access to system calls



## Java Sandbox

1. Bytecode verifier: verifies Java bytecode before it is run
   - Disallow pointer arithmetic
   - Automatic garbage collection
   - Array bounds checking
   - Null reference checking
2. Class loader: determines if an object is allowed to add classes
   - Ensures key parts of the runtime environment are not overwritten
   - Runtime data areas (stacks, bytecodes, heap) are randomly laid out
3. Security manager: enforces *protection domain*
   - Defines the boundaries of the sandbox (file, net, native, etc. access)
   - Consulted before any access to a resource is allowed



## JVM Security

- Complex process
- ~20 years of bugs … hope the big ones have been found!
- Buffer overflows found in the C support library
  - C support library buggy in general
- Generally, the JVM is considered insecure
  - But Java in general is pretty secure
    - Array bounds checking, memory management
    - Security manager with access controls
  - Use of native methods allows you to bypass security checks



## OS-Level Sandboxes

**Example: the Apple Sandbox**

- Create a list of rules that is consulted to see if an operation is permitted
- Components:
  - Set of libraries for initializing/configuring policies per process
  - Server for kernel logging
  - Kernel extension using the TrustedBSD API for enforcing individual policies
  - Kernel support extension providing regular expression matching for policy enforcement
- sandbox-exec command & sandbox_init function
  - sandbox-exec: calls *sandbox_init()* before *fork()* and *exec()*
  - `sandbox_init(kSBXProfileNoWrite, SANDBOX_NAMED, errbuf);`



## Apple sandbox setup & operation

*sandbox_init*:
- Convert human-readable policies into a binary format for the kernel
- Policies passed to the kernel to the TrustedBSD subsystem
- TrustedBSD subsystem passes rules to the kernel extension
- Kernel extension installs sandbox profile rules for the current process

Operation: intercept system calls
- System calls hooked by the TrustedBSD layer will pass through **`Sandbox.kext`** for policy enforcement
- The extension will consult the list of rules for the current process
- Some rules require pattern matching (e.g., filename pattern)



## Apple sandbox policies

Some pre-written profiles:
- Prohibit TCP/IP networking
- Prohibit all networking
- Prohibit file system writes
- Restrict writes to specific locations (e.g., /var/tmp)
- Perform only computation: minimal OS services



## Virtual Machines



## Virtual CPUs (sort of)

*What time-sharing operating systems give us*

- Each process feels like it has its own CPU & memory
  - But cannot execute privileged CPU instructions (e.g., modify the MMU or the interval timer, halt the processor, access I/O)
- Illusion created by OS preemption, scheduler, and MMU
- User software has to "ask the OS" to do system-related functions
- Containers, BSD Jails, namespaces give us operating system-level virtualization



## Process Virtual Machines

CPU interpreter running as a process

- Pseudo-machine with interpreted instructions
  - 1966: O-code for BCPL
  - 1973: P-code for Pascal
  - 1995: Java Virtual Machine (JIT compilation added)
  - 2002: Microsoft .NET CLR (pre-compilation)
  - 2003: QEMU (dynamic binary translation)
  - 2008: Dalvik VM for Android
  - 2014: Android Runtime (ART) – ahead of time compilation
- Advantage: run anywhere, sandboxing capability
- No ability to even pretend to access the system hardware
  - Just function calls to access system functions
  - Or "generic" hardware



## Machine Virtualization



## Machine Virtualization

Normally all hardware and I/O managed by one operating system

Machine virtualization

- Abstract (virtualize) control of hardware and I/O from the OS
- Partition a physical computer to act like several real machines
  - Manipulate memory mappings
  - Set system timers
  - Access devices
- Migrate an entire OS & its applications from one machine to another

1972: IBM System 370

- Allow kernel developers to share a computer



## Why are VMs popular?

- Wasteful to dedicate a computer to each service
  - Mail, print server, web server, file server, database
- If these services run on a separate computer
  - Configure the OS just for that service
  - Attacks and privilege escalation won't hurt other services

## Hypervisor

- Hypervisor: Program in charge of virtualization
  - Aka Virtual Machine Monitor
  - Provides the illusion that the OS has full access to the hardware
  - Arbitrates access to physical resources
  - Presents a set of virtual device interfaces to each host



## Machine Virtualization

An OS is just a bunch of code!

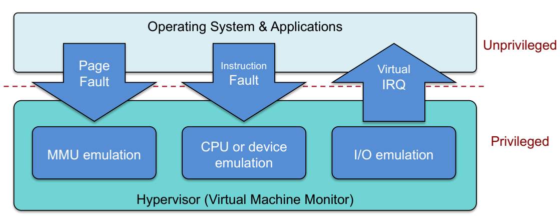
- Privileged vs. unprivileged instructions

- If regular applications execute privileged instructions, they trap
- Operating systems are allowed to execute privileged instructions
- If running kernel code, the VMM catches the trap and emulates the instruction
  - Trap & Emulate



## Hypervisor

Application or Guest OS runs until:
- Privileged instruction traps
- System interrupts
- Exceptions (page faults)
- Explicit call: VMCALL (Intel) or VMMCALL (AMD)





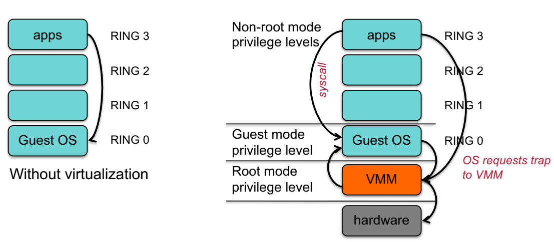

## Intel & ARM Didn't Make VM Easy

- Intel/AMD systems prior to Core 2 Duo (2006) did not support trapping privileged instructions
- Most ARM architectures also did not trap on certain privileged instructions
  - Hardware support added in Cortex-A15 (ARMv7 Virtualization Extension): 2011
- Two approaches
  - Binary translation (BT)
    - Scan instruction stream on the fly (when page is loaded) and replace privileged instructions with instructions that work with the virtual hardware (VMware approach)
  - Paravirtualization
    - Don't use non-virtualizable instructions (Xen approach)
    - Invoke hypervisor calls explicitly



## Hardware support for virtualization

Root mode (Intel example)
- Layer of execution more privileged than the kernel






## Architectural Support

- Intel Virtual Technology
- AMD Opteron

**Guest mode execution**: can run privileged instructions directly
- E.g., a system call does not need to go to the VM
- Certain privileged instructions are intercepted as VM exits to the VMM
- Exceptions, faults, and external interrupts are intercepted as VM exits
- Virtualized exceptions/faults are injected as VM entries



## CPU Architectural Support

- Setup
  - Turn VM support on/off
  - Configure what controls VM exits
  - Processor state
    - Saved & restored in guest & host areas
- VM Entry: go from hypervisor to VM
  - Load state from guest area
- VM Exit
  - VM-exit information contains cause of exit
  - Processor state saved in guest area
  - Processor state loaded from host area

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## Two Approaches to Running VMs

1. Native VM (hypervisor model)
2. Hosted VM

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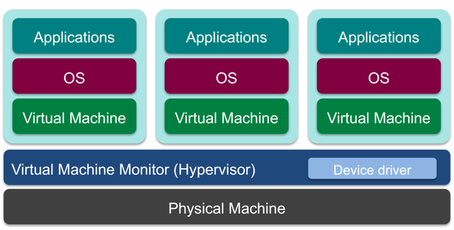
## Native Virtual Machine

Example: VMware ESX

Native VM (or *Type 1* or *Bare Metal*)
- No primary OS
- Hypervisor is in charge of access to the devices and scheduling
- OS runs in "kernel mode" but does not run with full privileges

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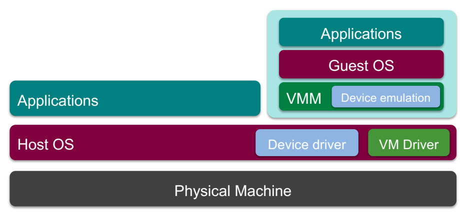
## Hosted Virtual Machine

Example: VMware Workstation

Hosted VM
- VMM runs without special privileges
- Primary OS responsible for access to the raw machine
  - Lets you use all the drivers available for that primary OS
- Guest operating systems run under a VMM
- VMM invoked by host OS
  - Serves as a proxy to the host OS for access to devices

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## Security Assumptions

- Attacks & malware can target the guest OS & apps
- Malware cannot escape from the infected VM
  - Cannot infect the host OS
  - Cannot infect the VMM
  - Cannot infect other VMs on the same computer

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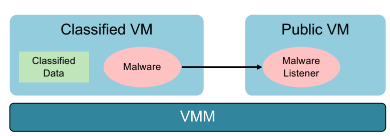
## Covert Channels

**Covert channel**
- Secret communication channel between components that are not allowed to communicate

**Side channel attack**
- Communication using some aspect of a system's behavior




1. Malware can perform CPU-intensive task at specific times
2. Listener can do CPU-intensive tasks and measure completion times

This allows malware to send a bit pattern:

*malware working = 1 = slowdown on listener*

Depends on scheduler but there are other mechanisms too… like memory access

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The end