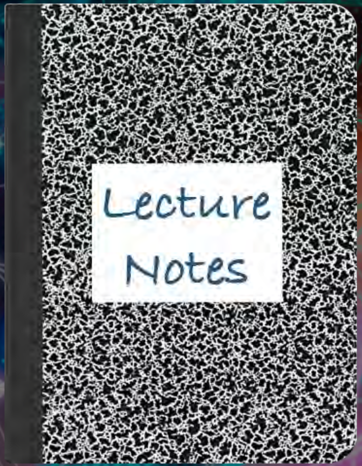
CS 419: Computer Security

Week 8: Containment



Paul Krzyzanowski

© 2025 Paul Krzyzanowski. No part of this content may be reproduced or reposted in whole or in part in any manner without the permission of the copyright owner.

Part 3

Containment

Compromised applications

- **Some services run as root**
- **What if an attacker compromises the app and gets root access?**
  - Create a new account
  - Install new programs
  - “Patch” existing programs (e.g., add back doors)
  - Modify configuration files or services
  - Add new startup scripts (launch agents, cron jobs, etc.)
  - Change resource limits
  - Change file permissions (or ignore them!)
  - Change the IP address of the system
- **Even without root, what if you run a malicious app – or exploit a path traversal bug?**
  - It has access to all your files
  - Can install new programs in your search path
  - Communicate on your behalf

Isn't access control good enough?

- **Limit damage via access control**
  - E.g., run services as a low-privilege user
  - Set proper read/write/search controls on files … or role-based policies
- **ACLs are based on users, not applications**
  - Processes run with the privilege of the user
  - Workaround: create a dummy user and run a setuid process with that user as the owner
  - Cannot set permissions for a process: "don't allow access to anything else"
  - At the mercy of default (other) permissions
- **We are responsible for setting the protections of every file on the system that could be accessed by an application**
  - And hope users don't change that
  - Or use more complex mandatory access control mechanisms … if available

Not high assurance

Containment: prepare for the worst

- **An application may be untrusted or compromised**

- **Limit an application to use a subset of the system's resources**
  - **Defense-in-depth** strategy: even if we have other protection mechanisms in place, create another layer of defense
- **Prevent a misbehaving application from harming the rest of the system**

Not just files

Other resources to protect

- **CPU time**
- **Amount of memory used: physical & virtual**
- **Disk space**
- **Network identity & access**
  - Each system has an IP address unique to the network
  - Compromised application can exploit address-based access control
    - E.g., log in to remote machines that think you're trusted
  - Intrusion detection systems can get confused

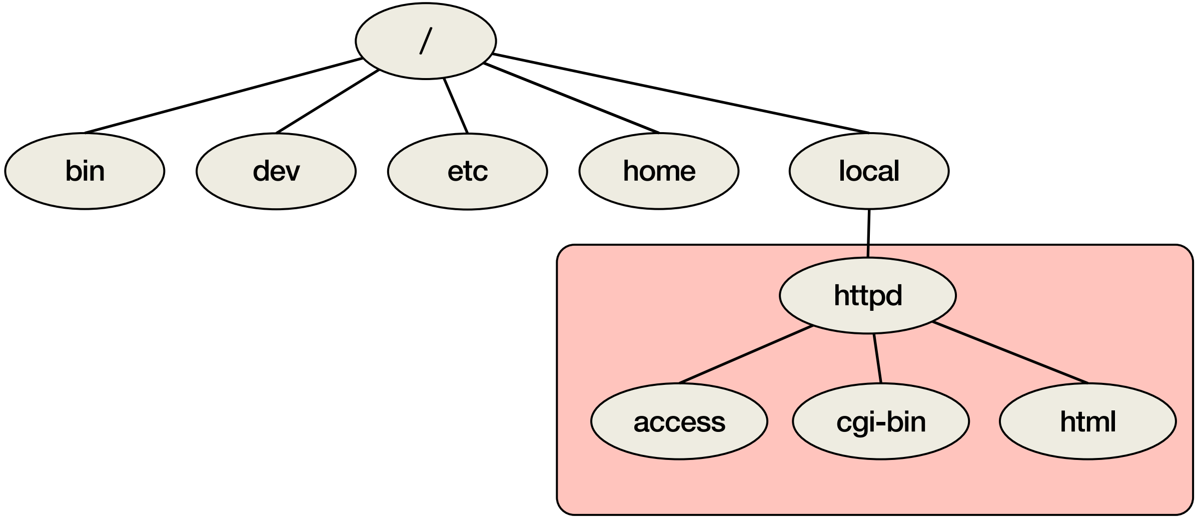
Application containment goals

- **Enforce security** – enable a broad set of access restrictions for an application
- **High assurance** – know it works
- **Simple setup** – minimize comprehension errors
- **General purpose** – works with any (most) applications

Origins: chroot & BSD Jails

chroot: the granddaddy of containment

- **Oldest containment mechanism (Unix v7 – 1982)**
  - chroot system call and chroot command
- **Make a subtree of the file system the root for a process**
- **Anything outside of that subtree doesn't exist**



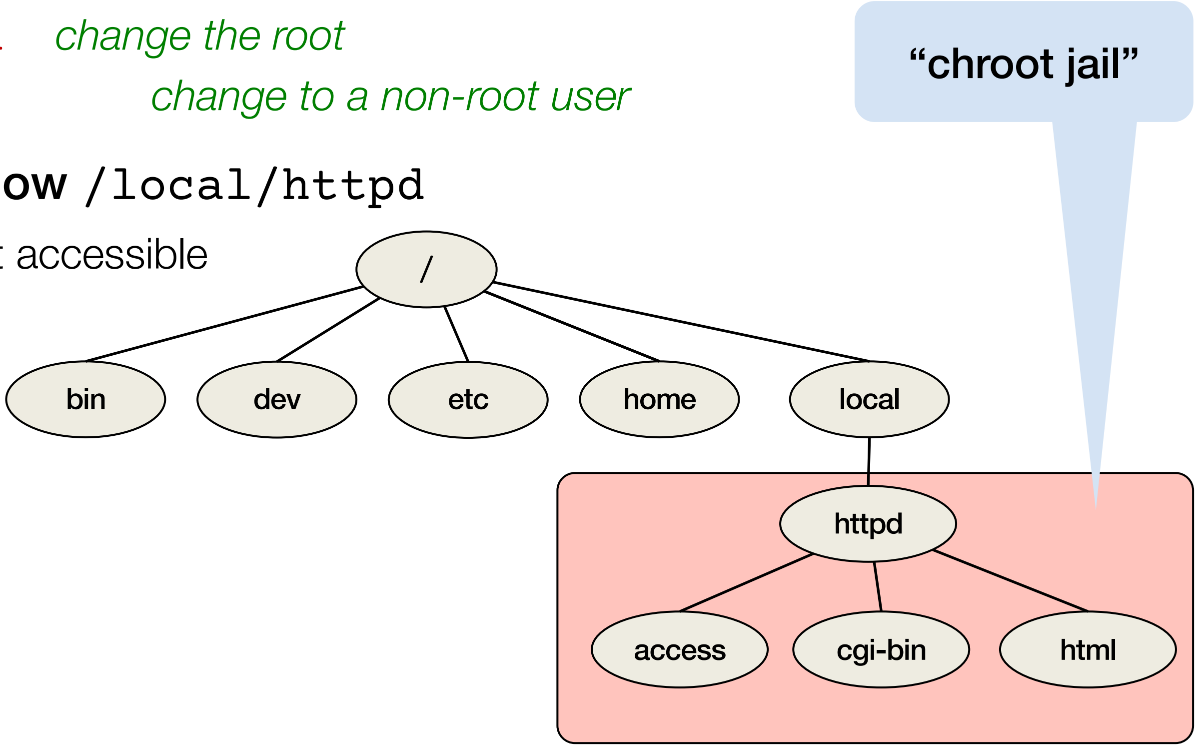
chroot: the granddaddy of containment

- **Only root can run *chroot***

  `chroot /local/httpd` *change the root*

  `su httpuser` *change to a non-root user*

- **The root directory is now `/local/httpd`**
  - Anything above it is not accessible



Jailkits

- **If programs within the jail need any utilities, they won't be visible**
  - They're outside the jail
  - Need to be copied
  - Ditto for shared libraries
- **Jailkit (https://olivier.sessink.nl/jailkit/)**
  - Set of utilities that build a chroot jail
  - Automatically assembles a collection of directories, files, & libraries
  - Place the **bare minimum** set of supporting commands & libraries
    - The fewer executables live in a jail, the less tools an attacker will have to use

jk_init	create a jail using a predefined configuration
jk_cp	copy files or devices into a jail
jk_chrootsh	places a user into a chroot jail upon login
jk_lsh	limited shell that allows the execution only of commands in its config file
…	

https://linux.die.net/man/8/jailkit

Problems?

Does not limit network access

Does not protect network identity

Applications are still vulnerable to root compromise

Normal users are not allowed to run chroot because they can get admin privileges

- Create a jail directory `mkdir /tmp/jail`
- Create a link to the su command `ln /bin/su /tmp/jail/su`
- Copy or link libraries & shell …
- Create an /etc directory `mkdir /tmp/jail/etc`
- Create password file(s) with a known password for root *`create passwd, shadow files`*
- Enter the jail `chroot /tmp/jail`
- Become root! `su`

  su will validate against the password file in the jail!

Escaping a chroot jail

If you can become root in a jail, you have access to *all* system calls

You can create devices within your jail

- On Linux/Unix/BSD, all non-network devices have filenames
- Even memory has a filename (/dev/mem)

- **Create a memory device (*mknod* system call)**
  - Change kernel data structures to remove your jail
- **Create a disk device to access the raw disk (also the *mknod* system call)**
  - Mount it within your jail and you have access to the whole file system
  - Get what you want, change the admin password, …
- **Send signals to kill other processes**
  (doesn't escape the jail but causes harm to others)
- **Reboot the system**

chroot summary

- **Only contains a process to a given subdirectory**
- **Imperfect solution**
  - Does not address access to system resources or the network
- **Useless against root**
  - Root can easily escape
- **Requires root access to set up**
  - Otherwise an attacker could get system-wide privileges
- **Setting up a working environment takes some work (or use jailkit)**

FreeBSD Jails (2000)

- **Enhancement to chroot**
- **Run via**

  `jail` *jail_path hostname ip_addr command*

- **Main ideas:**
  - Confine an application, just like *chroot*
  - Restrict what operations a process within a jail can perform, even if root

https://www.freebsd.org/doc/en/books/arch-handbook/jail.html

FreeBSD Jails: Differences from chroot

- **Network restrictions**
  - Jail has its own IP address
  - Can only bind to sockets with a specified IP address and authorized ports
- **Processes can only communicate with processes inside the jail**
  - No visibility into unjailed processes
- **Hierarchical: create jails within jails**
- **Root power is limited**
  - Cannot load kernel modules
  - Ability to disallow certain system calls
    - Raw sockets
    - Device creation
    - Modifying network configuration
    - Mounting/unmounting file systems
    - set_hostname

https://www.freebsd.org/doc/en/books/arch-handbook/jail.html

Problems

- **Coarse policies**
  - All-or-nothing access to parts of the file system
- **Does not prevent malicious apps from**
  - Accessing the network & other machines
  - Trying to crash the host OS
- **First true lightweight container model – but BSD Jails is a BSD-only solution**
- **Good for running things like DNS servers and web servers**
  - Not useful for user applications (like browsers) since these need access to things like user files

Linux Namespaces, Capabilities, & Control Groups

Linux **Namespaces**

- *chroot* only changed the root of the filesystem namespace
- Linux provides control over the following namespaces:

IPC	**System V IPC, POSIX message queues**	Objects created in an IPC namespace are visible to all other processes only in that namespace
Network	**Network devices, stacks, ports**	Isolates IP protocol stacks, IP routing tables, firewalls, socket port #s
Mount	**Mount points**	Mount points can be different in different processes – the file system root can be set for a process, just like chroot
PID	**Process IDs**	Different PID namespaces can have the same PID – child cannot see parent processes or other namespaces
User	**User & group IDs**	Per-namespace user/group IDs. You can be root in a namespace with restricted privileges
UTS	**Hostname and NIS domain name**	sethostname and setdomainname affect only the namespace

See namespaces(7)

Linux **Namespaces**

Unlike *chroot*, unprivileged users can create namespaces

unshare() – system call that dissociates parts of the process execution context

- Examples
  - Unshare IPC namespace, so it's separate from other processes
  - Unshare PID namespace, so the thread gets its own PID namespace for its children

clone() – system call to create a child process

- Like *fork()* but allows you to control what is shared with the parent
  - Open files, root of the file system, current working directory, IPC namespace, network namespace, memory, etc.

setns() – system call to associate a thread with a namespace

- A thread can associate itself with an existing namespace in /proc/[pid]/ns

Linux **Capabilities**

How do we restrict privileged operations?

UNIX systems distinguished *privileged* vs. *unprivileged* processes

Privileged = UID 0 = root ⇒ *kernel bypasses all permission checks*

- **With capabilities, privileges are assigned to a process and are *not* based on whether it's running as user ID 0 (root)**
- **A process running as root can be restricted to limited privileges**
  - E.g., no ability to set UID to root, no ability to mount filesystems
- **A process running as non-root can be granted limited privileges**
  - E.g., the ability to send an ICMP packet (ping message)

N.B.: These *capabilities* have nothing to do with *capability lists*

Linux **Capabilities**

Assign subsets of privileges to programs

- **Linux divides privileges into 38 distinct controls, including:**

CAP_CHOWN	make arbitrary changes to file owner and group IDs
CAP_DAC_OVERRIDE	bypass read/write/execute checks
CAP_KILL	bypass permission checks for sending signals
CAP_NET_ADMIN	network management operations
CAP_NET_RAW	allow RAW sockets
CAP_SETUID	arbitrary manipulation of process UIDs
CAP_SYS_CHROOT	enable chroot

- **These are per-thread attributes**
  – Can be set via the *prctl* system call

Linux **Capabilities** Example

Unprivileged processes cannot bind to network port #s below 1024

With capabilities, we can allow the command *`my_program`* to do this without having it run as root

```
sudo setcap 'cap_net_bind_service=+ep' my_program
```

- `cap_bind_service` **is the capability to bind to special ports**
- `+ep` **means:**
  - `e`: add the capability to the *Effective* set (what the process can currently do)
  - `p`: add the capability to the *Permitted* set (the maximum capabilities the process is allowed to enable)
  - Without being in the permitted set, a capability can't be used, and without being in the effective set, it isn't currently used.

Linux **Control Groups** (cgroups)

Limit the amount of resources a process tree can use

- **CPU, memory, block device I/O, network**
  - E.g., a process tree can use at most 25% of the CPU
  - Limit # of processes within a group
  - Help with denial-of-service attacks

- **Interface =** `cgroups` **file system:** `/sys/fs/cgroup`

Namespaces + cgroups + capabilities
= lightweight process virtualization

A group of processes can have the illusion that they are running on their own Linux system, isolated from other processes in the system

Vulnerabilities

Bugs have been found

- User namespace: unprivileged user was able to get full privileges

But **comprehension** is a bigger problem

- **Namespaces do not prohibit a process from making privileged system calls**
  - They control resources that those calls can manage
  - The system will see only the resources that belong to that namespace
- **Capabilities grant non-root users increased access to privileged operations**
  - Design concept: instead of dropping privileges from root, provide limited elevation to non-root users
- **A real root process with its admin capability removed can restore it**
  - If it creates a user namespace, the capability is restored to the root user in that namespace – although limited in function

Summary

- ***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 privileged operations a process & its children can perform
  - Namespaces
    - Restrict what a process can see & who it can interact with:
      PIDs, User IDs, mount points, IPC, network

Containment via Containers

Motivation for containers

- **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 virtual machine

- **It gives you the illusion of separate**
  - Set of apps
  - Process space
  - Network interface
  - Network configuration
  - Libraries, …
- **But limited root powers**
- **And …**
  - 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**
  - Restrict privileges on a per-process basis
- **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

Docker

- **First super-popular container**
  - LXC (Linux Containers) were the first
- **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**

Not Just Linux

Microsoft introduced Containers in Windows Server 2016 with support for Docker

- **Windows Server Containers**
  - Assumes trusted applications
  - Misconfiguration or design flaws may permit an app to escape its container
- **Hyper-V Containers**
  - Each has its own copy of the Windows kernel & dedicated memory
  - Same level of isolation as in virtual machines
  - Essentially a VM that can be coordinated via Docker
  - Less efficient in startup time & more resource intensive
  - Designed for hostile applications to run on the same host

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

- Handle multiple containers and start each one at the right time
- Handle storage
- Deal with hardware and container failure: automatic start & migration
- Integrates with the Docker engine
- Scale rapidly by adding/removing containers based on demand (e.g., Pokemon Go)
- Open source

Why were containers created?

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

But containers have 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 re-starting: 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
- **Privileges & escaping the container**
  - Privileged containers map uid 0 (root) to the host's uid 0 (root)

    Prevention of escape is based on MAC (apparmor), capabilities & namespace configuration
  - Unprivileged containers map uid 0 to an unprivileged user outside the container

    No possibility of root escalation
- **Users in multiple containers may share the same real ID**
  - If users map to the same parent ID, they share all the limits of that ID
  - A user in one container can perform a DoS attack on another user

Security Concerns

- **Denial of service attacks**
  - Untrusted users may launch attacks within containers
  - If one container can monopolize a resource, others suffer
- **Network spoofing**
  - A process in a container may be allowed to transmit raw ethernet packets and spoof any service
- **Origin integrity**
  - Where is the container from and has it been tampered?

Containment via 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 (and BSD Jails) give us operating system-level virtualization**
  – A group of processes may be isolated from others, with their own view of the filesystem, network stack, and restricted admin access

Process Virtual Machines

CPU interpreter running as a process

- **Pseudo-machine with interpreted instructions**
  - 1966: O-code for BCPL
  - 1973: P-code for Pascal
  - 1991: Python Virtual Machine (PVM)
  - 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 pretend to access the system hardware**
  - Just function calls to access system functions

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 computers
    - Manipulate memory mappings
    - Set system timers
    - Access devices
  - Migrate an entire OS & its applications from one computer 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

The 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

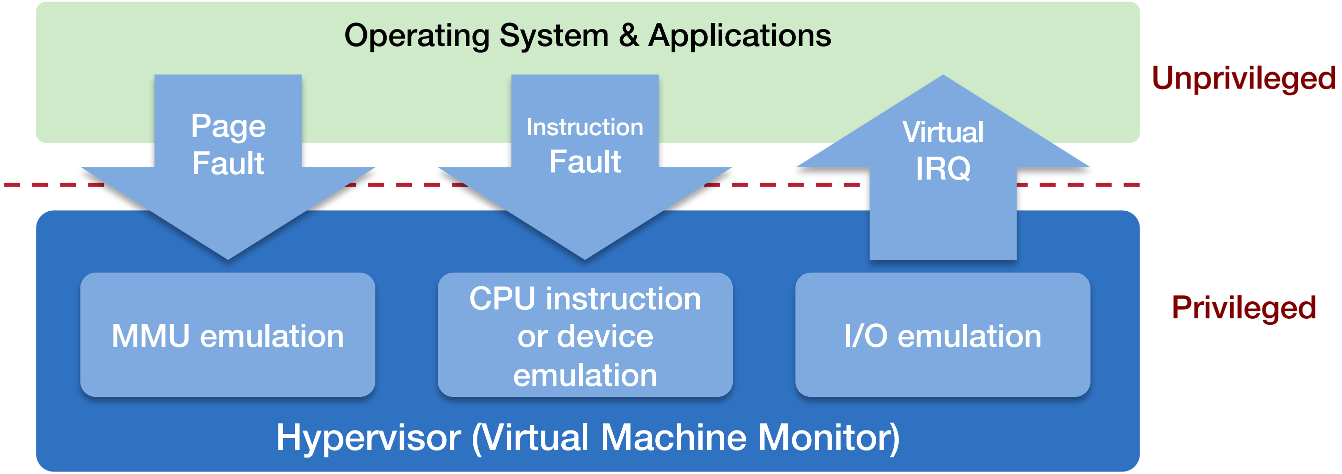
An OS is just a bunch of code!

- **Privileged vs. unprivileged instructions**
  - If regular applications execute privileged instructions, they trap
  - Operating systems are allowed to execute privileged instructions
- **With machine virtualization**
  - We deprivilege the operating system
  - The VMM runs at a higher privilege level than the OS
- **The VMM catches the trap**
  - If it turns out that the attempt to execute the privileged instruction occurred in the kernel code, the hypervisor (VMM) emulates the instruction
  - Trap & Emulate

Hypervisor

Application or Guest OS runs until:

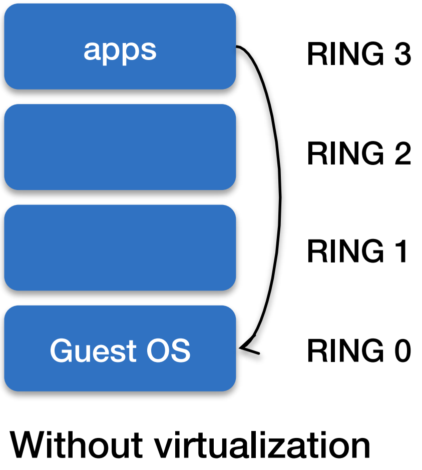
- Privileged instruction traps
- System interrupts
- Exceptions (page faults)
- Explicit call: `VMCALL` (Intel) or `VMMCALL` (AMD)

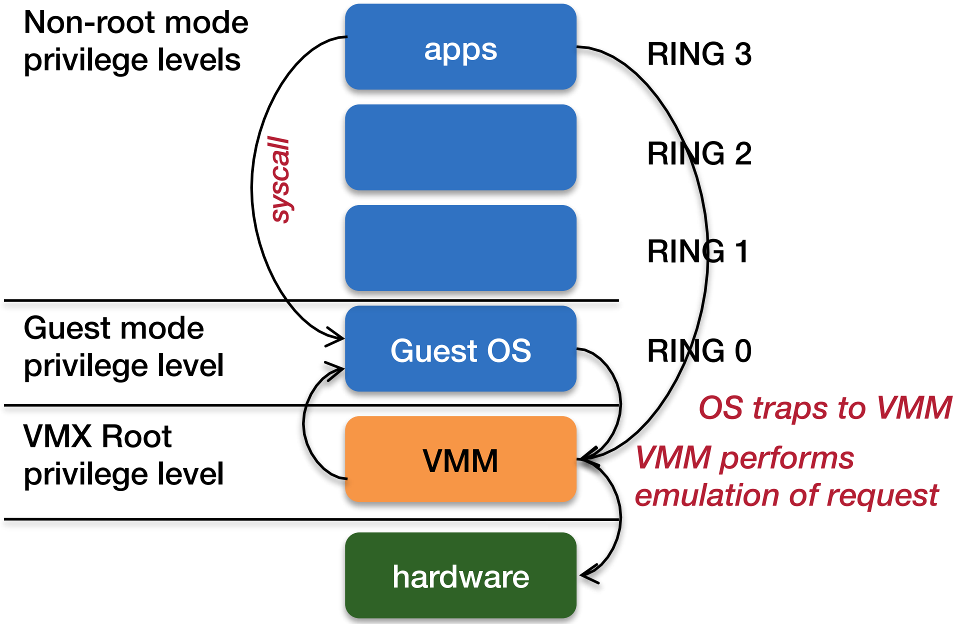


Hardware support for virtualization

Root mode (Intel example)

– Layer of execution more privileged than the kernel





Architectural Support

- **Intel Virtual Technology, AMD-V**
- **ARM Virtualization Extensions**
  - New mode (HYP) and new privilege level (non-secure privilege level 2)

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 (usually in BIOS)
  - Configure what controls VM exits
  - Processor state: saved & restored in guest & host areas
- **VM Entry: go from hypervisor to VM**
  - Load state from the guest OS area
- **VM Exit**
  - VM-exit: like a trap – information contains the cause of the exit
  - Processor state saved in guest area
  - Processor state loaded from host area

Two Approaches to Running VMs

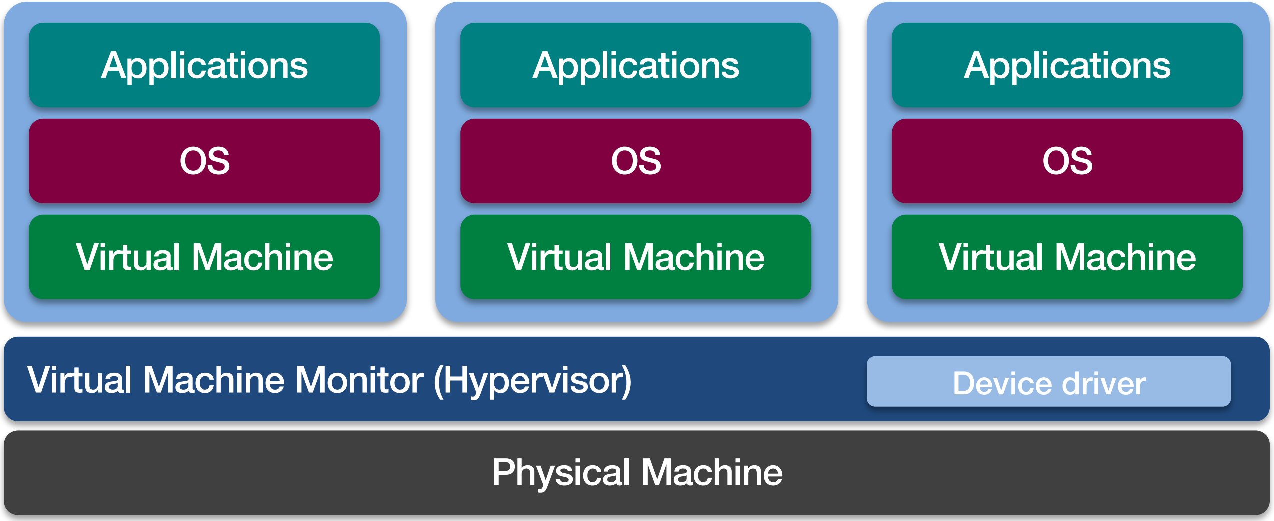
1. **Native VM (hypervisor model)**
2. **Hosted VM**

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

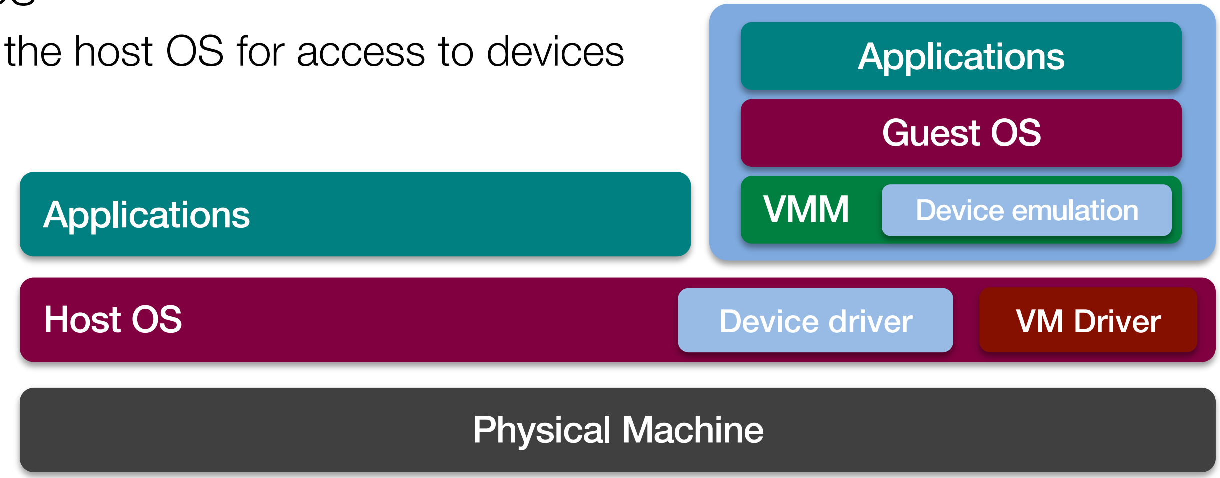


Hosted Virtual Machine

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

Example: VMware Workstation



Security Benefits of Using Virtual Machines

Virtual machines isolate multiple operating systems

- **Attacks & malware can target the guest OS & apps**
- **Malware cannot escape from the infected guest OS**
  - If a guest OS is compromised or fails
    - the host and other OSes are unaffected
    - The ability of other OSes to access resources is unaffected
    - The performance of other OSes is unaffected
  - Cannot infect the host OS
  - Cannot infect the VMM
  - Cannot infect other VMs on the same computer

Security Benefits of Using Virtual Machines

- **Recovery from snapshots**
  - Easy to revert to a previous version of the system
- **Easy to replicate virtual machines**
  - Treat the system as a virtual "appliance"
  - If it gets infected with malware, just start another appliance
- **Operate as a test environment**
  - Great for testing suspicious software
  - See what files have been modified
  - Compare before/after states
  - Restore to pre-installed state

Risks

- **Same as with introducing other new computers**
  - Poorly configured access policies
  - Untrusted or unpatched software
  - "Default" system installations (e.g., full Linux distributions)
- **An attacker may enable virtualization**
  … and install a new virtual machine in a computing environment
  - It acts like a real computer
  - Private file system
  - Undetected by other VMs
  - Admins might not notice one more system on the network

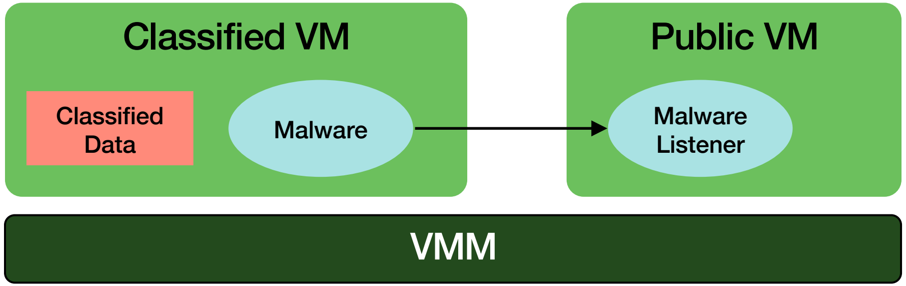
Risks: Covert Channels

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

Containment via Sandboxing: Restricting what applications can do

Running untrusted applications

- **Jail / container / VM solutions**
  - Great for running services
- **Not really useful for applications**
  - These need to be launched by users & interact with their environment

The sandbox

sand•box, ˈsan(d)-ˌbäks, *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

Containers are a form of sandboxing… but we want to focus on giving users the ability to run apps & restrict what those apps can do

Application sandboxing

via system call hooking & user-level validation

System Call Interposition

System calls interface with system 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

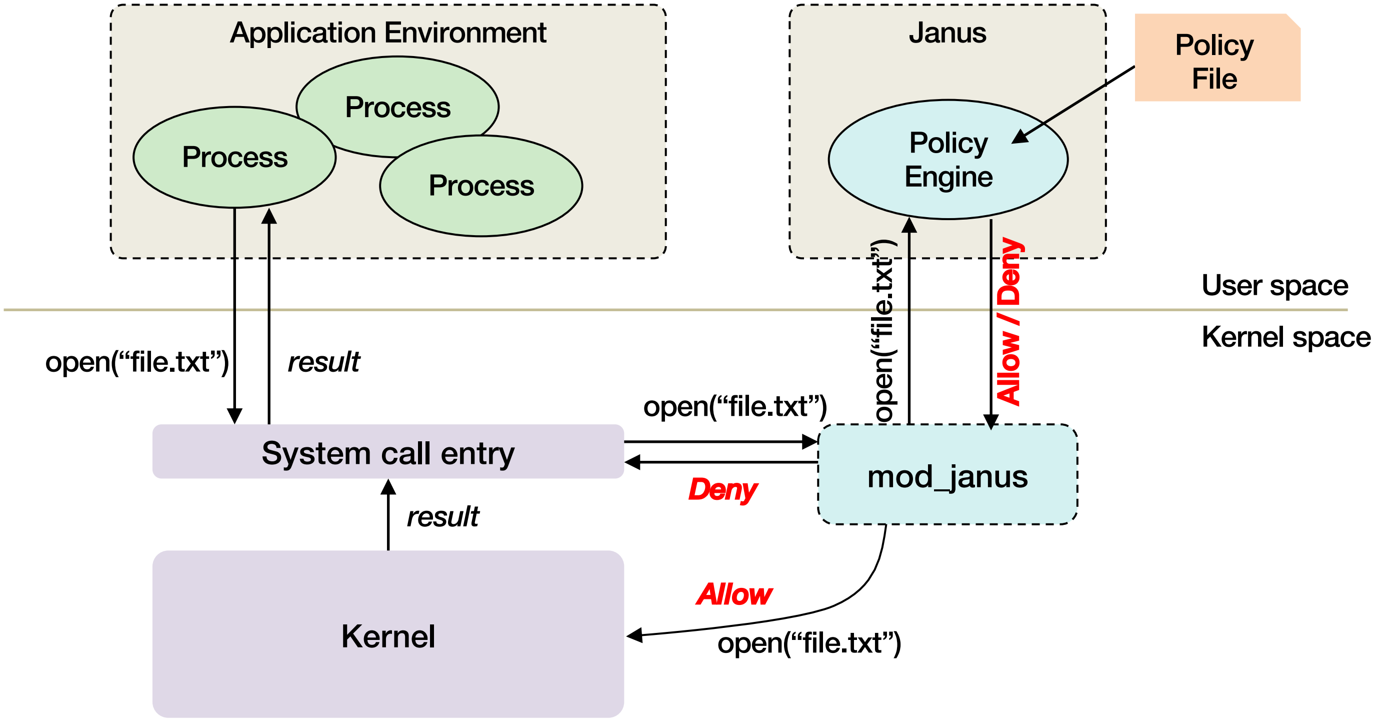
- **Sandboxing via system call interposition**
  - Intercept, inspect, and approve an app's system calls

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

Example: Janus

App sandboxing tool implemented as a loadable kernel module



Implementation Challenge

Janus must 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**

Application sandboxing

via integrated OS support

Linux seccomp-BPF

seccomp-BPF = SECure COMPuting with Berkeley Packet Filters

- **Linux capabilities**
  - Dealt with granting elevated privileges to processes
  - No ability to restrict access to regular files
- **Linux namespaces**
  - Limit access to mount points, processes
- ***chroot* – no ability to be selective about files**

seccomp-BPF allows the user to attach a system call filter to a process and its descendants

- Enumerate allowable system calls and their parameters (but not pointer values)

- **Used extensively in Android and Firefox**

Linux seccomp-BPF

- **Uses the Berkeley Packet Filter (BPF) interpreter**
  - seccomp sends "packets" that represent system calls to BPF
- **BPF allows us to define rules to inspect each request and take an action**
  - *Kill the task*
  - *Disallow & send SIGSYS*
  - *Return an error*
  - *Allow*
- **Turned on via the `prctl()` system call – *process control***

Seccomp is not a complete sandbox but is a tool for building sandboxes

- Needs to work with other components: Namespaces, capabilities, control groups
- Potential for comprehension problems – BPF is a very low level interface

Linux AppArmor (Application Armor)

Linux Security Module for Mandatory Access Control via path-based policies

- **Goal:**
  - Confine programs by defining files & capabilities they can access, regardless of user
- **Human-readable policy profiles define**
  - File read/write/execute access by name
  - Network usage
  - Use of POSIX *capabilities*
  - Execution of other programs
  - Access to specific kernel interfaces (like ptrace, /proc)

AppArmor operates at the LSM hook framework in the kernel, checking operations at strategic points in the kernel – not at the system call entry point

seccomp vs. AppArmor

Docker & other containers use AppArmor to restrict file access

- **Seccomp:** filters system calls
  - Allow system calls to be filtered
  - Specify which system calls are allowed & place restrictions on their parameters
  - Reduces attack surface of the kernel
- **AppArmor:** controls access to objects
  - Installed as a Linux Security Module
  - Allows user to blacklist & whitelist a program's access to objects (files, networks)
- **Capabilities:** grants specific privileged access
  - Allows granting only select elevated privileges to applications

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

Browser-based application sandboxing

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**

Challenge:

How do you keep plugins from doing bad things?

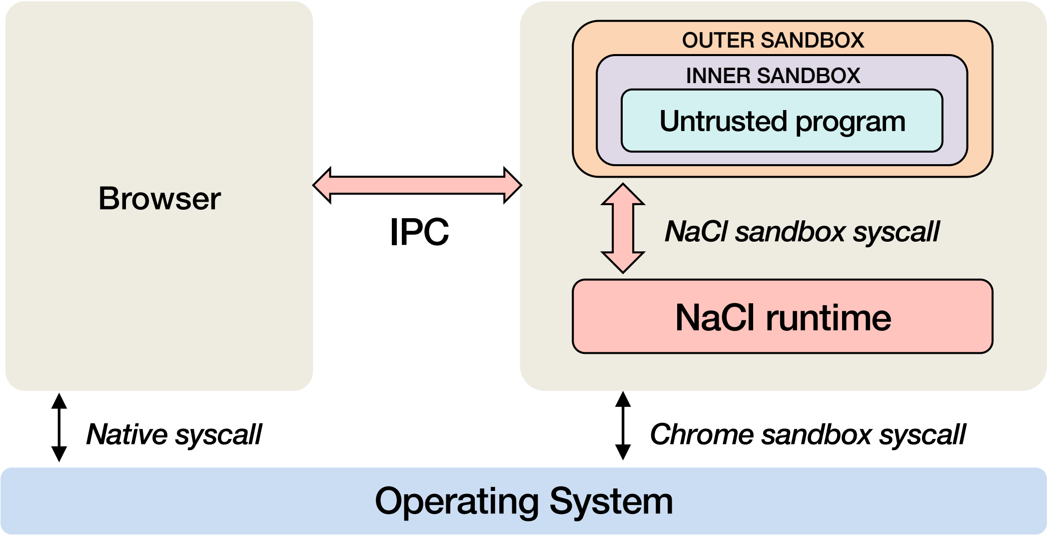
Chromium Native Client (NaCl)

- **Browser plug-in 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**
  - Trusted code does not run in a sandbox
  - Untrusted code has to run in a sandbox
- **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
    - Support for ARM 32-bit, x86-32, x86-64, MIPS32
    - Pepper Plugin API (PPAPI): portability for 2D/3D graphics & audio
  - 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
  - Uses static analysis to detect security defects in code; disallow self-modifying code



Portability

- **Portable Native Client (PNaCl)**
  - Architecture independent
  - Developers compile code once to run on any website & architecture
  - Compiled to a *portable executable* (**pexe**) file
  - Chrome translates pexe into native code prior to exectution

Java sandbox

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**
  - We can hope they have all been found & fixed
- **In general, Java is pretty secure**
  - Array bounds checking, memory management
  - Security manager with access controls
  - But use of native methods allows you to bypass security checks

Solving the problem

- **Access controls don't stop the problem**
- **Privilege escalation limiting mechanisms work better**
  - Containment mechanisms (like containers) work well for servers - but not for end-user software
- **Running software in a sandbox is great**
  - Mobile phones rely on this – often too restrictive for computers
  - You must trust that users won't be convinced to grant the wrong access rights
- **Attacks that exploit human behavior are hard to prevent**
  - We're dealing with human nature
  - We're used to accepting a pop-up message and entering a password
  - Better detection in browsers & mail clients helps … but risks junking legitimate content
- **Simple software – without automatically-run macros is also good**
  - A simple text editor vs. MS-Word … but isn't acceptable to a lot of users

It's still a big problem

The End