Operating Systems Security

CS 1660: Introduction to Computer Systems Security

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Source: XKCD
Many layers of abstraction:

- **Kernel**: core of the OS, controls hardware, resource access
  - Various subsystems (memory management, networking, storage, ...)
- **Execution modes**:
  - **user mode**: access to resources mediated by the kernel
  - **kernel mode**: full and direct access to resources
Processes

The kernel manages applications as processes (or threads)

Every process has:

• Process ID (PID)
• Virtual memory
• Effective user
Processes

The kernel manages applications as processes (or threads)
Every process has:
• Process ID (PID)
• Virtual memory
• Effective user

Kernel provides
• Separate address space from other process
• Time/resource sharing
• Access control
Processes
<table>
<thead>
<tr>
<th>Process Name</th>
<th>Mem...</th>
<th>Threads</th>
<th>Ports</th>
<th>PID</th>
<th>User</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firefox</td>
<td>10.09 GB</td>
<td>162</td>
<td>1,387</td>
<td>3561</td>
<td>deemer</td>
</tr>
<tr>
<td>Virtual Machine Service</td>
<td>7.92 GB</td>
<td>24</td>
<td>83</td>
<td>35580</td>
<td>deemer</td>
</tr>
<tr>
<td>FirefoxCP Isolated Web Content</td>
<td>5.19 GB</td>
<td>39</td>
<td>158</td>
<td>3569</td>
<td>deemer</td>
</tr>
<tr>
<td>Docker</td>
<td>4.10 GB</td>
<td>42</td>
<td>333</td>
<td>32597</td>
<td>deemer</td>
</tr>
<tr>
<td>Microsoft PowerPoint</td>
<td>3.59 GB</td>
<td>42</td>
<td>13,784</td>
<td>3516</td>
<td>deemer</td>
</tr>
<tr>
<td>FirefoxCP Isolated Web Content</td>
<td>1.91 GB</td>
<td>33</td>
<td>140</td>
<td>3568</td>
<td>deemer</td>
</tr>
<tr>
<td>FirefoxCP Isolated Web Content</td>
<td>1.30 GB</td>
<td>32</td>
<td>136</td>
<td>3567</td>
<td>deemer</td>
</tr>
<tr>
<td>FirefoxCP Isolated Web Content</td>
<td>1.30 GB</td>
<td>33</td>
<td>139</td>
<td>3566</td>
<td>deemer</td>
</tr>
<tr>
<td>FirefoxCP Isolated Web Content</td>
<td>830.4 MB</td>
<td>29</td>
<td>114</td>
<td>6432</td>
<td>deemer</td>
</tr>
<tr>
<td>Preview</td>
<td>773.0 MB</td>
<td>6</td>
<td>1,713</td>
<td>11577</td>
<td>deemer</td>
</tr>
<tr>
<td>FirefoxCP Isolated Web Content</td>
<td>659.7 MB</td>
<td>29</td>
<td>115</td>
<td>66660</td>
<td>deemer</td>
</tr>
<tr>
<td>Open and Save Panel Service (Preview)</td>
<td>526.2 MB</td>
<td>4</td>
<td>2,596</td>
<td>11578</td>
<td>deemer</td>
</tr>
<tr>
<td>Terminal</td>
<td>519.3 MB</td>
<td>7</td>
<td>459</td>
<td>3476</td>
<td>deemer</td>
</tr>
<tr>
<td>Finder</td>
<td>457.7 MB</td>
<td>8</td>
<td>1,456</td>
<td>3292</td>
<td>deemer</td>
</tr>
<tr>
<td>Discord Helper (Renderer)</td>
<td>420.0 MB</td>
<td>40</td>
<td>805</td>
<td>11208</td>
<td>deemer</td>
</tr>
<tr>
<td>Docker Desktop</td>
<td>414.3 MB</td>
<td>29</td>
<td>7,939</td>
<td>32617</td>
<td>deemer</td>
</tr>
<tr>
<td>FirefoxCP Isolated Web Content</td>
<td>407.9 MB</td>
<td>29</td>
<td>113</td>
<td>63607</td>
<td>deemer</td>
</tr>
<tr>
<td>FirefoxCP Isolated Web Content</td>
<td>405.5 MB</td>
<td>32</td>
<td>137</td>
<td>3576</td>
<td>deemer</td>
</tr>
</tbody>
</table>

**MEMORY PRESSURE**

- Physical Memory: 32.00 GB
- Memory Used: 28.48 GB
- Cached Files: 3.46 GB
- Swap Used: 8.80 GB
- App Memory: 9.95 GB
- Wired Memory: 3.00 GB
- Compressed: 14.92 GB
View Processes in Linux

• **ps**: displays snapshot of running processes
  – `ps -ef`: show all processes
  – `ps -u <username>`: show processes for a user

• **top, htop**: fancier list of processes
  – `top -u <username>`: filter by username

• **kill <pid>**: terminates a process
Process Management

• Each process has a context, which includes the user, parent process, and address space

• Kernel enforces policies to decide which resources each processes can use
System calls (syscalls)

- Primary way processes interact with kernel
- OS provides a “library” of syscalls for nearly all OS functions
  - Files: read, write, open, close, chmod, ...
  - Process management: fork, clone, kill, ...
  - Networking: socket, bind, connect

On syscall, process “yields” to kernel, executes in privileged kernel mode
System services (daemons)

• Background process that performs common tasks
• Started at boot time
• Could run with higher permissions than users

Typical services:
– Remote SSH connections
– Web servers
– Logging
AAA: Authentication, Authorization, Accounting

Authorization: how to specify access rights to resources
• To authorize => to define access policy
Users

• Each process is associated with a user
• Specific users can have more privileges than regular users
  – Install or remove programs
  – Change rights of other users
  – Modify the configuration of the system
• Unix: root is a “super-user” with no restrictions
Users

- Each process is associated with a user
- Specific users can have more privileges than regular users

- **Unix:** *root* is a “super-user” with no restrictions
How to we manage users?
Discretionary Access Control (DAC)

• Users can protect what they own
  – The owner may grant access to others
  – The owner may define the type of access (read/write/execute) given to others

• DAC is the standard model used in operating systems

• Mandatory Access Control (MAC)
  – Multiple levels of security for users and documents (i.e. confidential, restricted, secret, top secret)
  – A user can create documents with just his level of security
General Principles

- Files and folders are managed by the operating system
- Applications, including shells, access files through an API
- Access control entry (ACE)
  - Allow/deny a certain type of access to a file/folder by user/group
- Access control list (ACL)
  - Collection of ACEs for a file/folder
- A file handle provides an opaque identifier for a file/folder
- File operations
  - Open file: returns file handle
  - Read/write/execute file
  - Close file: invalidates file handle
- Hierarchical file organization
  - Tree (Windows)
  - DAG (Linux)
Access Control Entries and Lists

• An **Access Control List (ACL)** for a resource (e.g., a file or folder) is a sorted list of zero or more **Access Control Entries (ACEs)**.

• An ACE refers specifies that a certain set of accesses (e.g., read, execute and write) to the resources is allowed or denied for a user or group.

• Examples of ACEs for folder “Bob’s CS166 Grades”
  – Bob; Read; Allow
  – TAs; Read; Allow
  – TWD; Read, Write; Allow
  – Bob; Write; Deny
  – TAs; Write; Allow
Closed vs. Open Policy

Closed policy
– Also called “default secure”
- Give Tom read access to “foo”
- Give Bob r/w access to “bar”
- Tom: I would like to read “foo”
  – Access allowed
- Tom: I would like to read “bar”
  – Access denied

Open Policy
- Deny Tom read access to “foo”
- Deny Bob r/w access to “bar”
- Tom: I would like to read “foo”
  – Access denied
- Tom: I would like to read “bar”
  – Access allowed
Clicker Question (1)

An ACL with no entries on a file?

A. Access Allowed to all with Open Policy
   Access Allowed to all with Closed Policy

B. Access Denied to all with Open Policy
   Access Allowed to all with Closed Policy

C. Access Allowed to all with Open Policy
   Access Denied to all with Closed Policy

D. Access Denied to all Open Policy
   Access Denied to all Closed Policy

E. It is not possible to realize
Clicker Question (1) - Answer

An ACL with no entries on a file?

A. Access Allowed to all with Open Policy
   Access Allowed to all with Closed Policy

B. Access Denied to all with Open Policy
   Access Allowed to all with Closed Policy

C. Access Allowed to all with Open Policy
   Access Denied to all with Closed Policy

D. Access Denied to all Open Policy
   Access Denied to all Closed Policy

E. It is not possible to realize
Closed Policy with Negative Authorizations and Deny Priority

• Give Tom r/w access to “bar”
• Deny Tom write access to “bar”
• Tom: I would like to read “bar”
  – Access allowed
• Tom: I would like to write “bar”
  – Access denied
• Policy is used by Windows to manage access control to the file system
Role-Based Access Control

• Within an organization **roles** are created for various job functions

• The permissions to perform certain operations are assigned to specific roles

• Users are assigned particular role, with which they acquire the computer authorizations

• Users are not assigned permissions directly, but only acquire them through their role
Access Control: File System
Linux vs. Windows

• Linux
  – Allow-only ACEs
  – Access to file depends on ACL of file and of all its ancestor folders
  – Start at root of file system
  – Traverse path of folders
  – Each folder must have execute (cd) permission
  – Different paths to same file not equivalent
  – File’s ACL must allow requested access

• Windows
  – Allow and deny ACEs
  – By default, deny ACEs precede allow ones
  – Access to file depends only on file’s ACL
  – ACLs of ancestors ignored when access is requested
  – Permissions set on a folder usually propagated to descendants (inheritance)
  – System keeps track of inherited ACE’s
Linux File Access Control

• File Access Control for:
  – Files
  – Directories
  – Therefore...
    • \dev\ : devices
    • \mnt\ : mounted file systems
    • What else? Sockets, pipes, symbolic links...
Unix Permissions

• Standard for all UNIXes
• Every file is owned by a user and has an associated group
• Permissions often displayed in compact 10-character notation
• To see permissions, use `ls -l`

```
jk@sphere:~/test$ ls -l
total 0
-rw-r----- 1 jk ugrad 0 2005-10-13 07:18 file1
-rwxrwxrwx 1 jk ugrad 0 2005-10-13 07:18 file2
```
Unix File Types and Basic Permissions

- d (directory)
  - r (read)
  - w (write)
  - x (execute)
- r (read)
- w (write)
- x (execute)
- r (read)
- w (write)
- x (execute)
- r (read)
- w (write)
- x (execute)

file type

user

- r (read)
- w (write)
- x (execute)

group

- r (read)
- w (write)
- x (execute)

other

- r (read)
- w (write)
- x (execute)
## Permissions Examples (Regular Files)

<table>
<thead>
<tr>
<th>Permissions</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-rw-r--r--</code></td>
<td>read/write for owner, read-only for everyone else</td>
</tr>
<tr>
<td><code>-rw-r-----</code></td>
<td>read/write for owner, read-only for group, forbidden to others</td>
</tr>
<tr>
<td><code>-rwx------</code></td>
<td>read/write/execute for owner, forbidden to everyone else</td>
</tr>
<tr>
<td><code>-r--r--r--</code></td>
<td>read-only to everyone, including owner</td>
</tr>
<tr>
<td><code>-rwxrwxrwx</code></td>
<td>read/write/execute to everyone</td>
</tr>
</tbody>
</table>
Permissions for Directories

- Permissions bits interpreted differently for directories
- **Read** bit allows listing names of files in directory, but not their properties like size and permissions
- **Write** bit allows creating and deleting files within the directory
- **Execute** bit allows entering the directory and getting properties of files in the directory
- Lines for directories in `ls -l` output begin with `d`, as below:

```
jk@sphere:~/test$ ls -l
Total 4
drwxr-xr-x 2 jk ugrad 4096 2005-10-13 07:37 dir1
-rw-r--r-- 1 jk ugrad 0 2005-10-13 07:18 file1
```
## Permissions Examples (Directories)

<table>
<thead>
<tr>
<th>Permissions</th>
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</tr>
</thead>
<tbody>
<tr>
<td>drwxr-xr-x</td>
<td>all can enter and list the directory, only owner can add/delete files</td>
</tr>
<tr>
<td>drwxrwx---</td>
<td>full access to owner and group, forbidden to others</td>
</tr>
<tr>
<td>drwx--x---</td>
<td>full access to owner, group can access known filenames in directory, forbidden to others</td>
</tr>
<tr>
<td>-rwxrwxrwx</td>
<td>full access to everyone</td>
</tr>
</tbody>
</table>
## Octal Notation Examples

<table>
<thead>
<tr>
<th>Octal</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>644 or 0644</td>
<td>read/write for owner, read-only for everyone else</td>
</tr>
<tr>
<td>775 or 0775</td>
<td>read/write/execute for owner and group, read/execute for others</td>
</tr>
<tr>
<td>640 or 0640</td>
<td>read/write for owner, read-only for group, forbidden to others</td>
</tr>
<tr>
<td>2775</td>
<td>same as 775, plus setgid (useful for directories)</td>
</tr>
<tr>
<td>777 or 0777</td>
<td>read/write/execute to everyone (<em>dangerous!</em>))</td>
</tr>
<tr>
<td>1777</td>
<td>same as 777, plus sticky bit</td>
</tr>
</tbody>
</table>
Becoming Root

- **su**
  - Changes home directory, PATH, and shell to that of root, but doesn’t touch most of environment and doesn’t run login scripts

- **sudo <command>**
  - Run just one command as root

- **su [-] <user>**
  - Become another non-root user
  - Root does not require to enter password
### Examples of Changing Permissions

<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>chown -R root dir1</code></td>
<td>Changes ownership of <code>dir1</code> and everything within it to <code>root</code></td>
</tr>
<tr>
<td><code>chmod g+w,o-rwx file1 file2</code></td>
<td>Adds group write permission to <code>file1</code> and <code>file2</code>, denying all access to others</td>
</tr>
<tr>
<td><code>chmod -R g=rwX dir1</code></td>
<td>Adds group read/write permission to <code>dir1</code> and everything within it, and group execute permission on files or directories where someone has execute permission</td>
</tr>
<tr>
<td><code>chgrp testgrp file1</code></td>
<td>Sets <code>file1</code>’s group to <code>testgrp</code>, if the user is a member of that group</td>
</tr>
<tr>
<td><code>chmod u+s file1</code></td>
<td>Sets the setuid bit on <code>file1</code>. (Doesn’t change execute bit.)</td>
</tr>
</tbody>
</table>
The /tmp Directory

• In Unix systems, directory /tmp is
  – Readable by any user
  – Writable by any user
  – Usually wiped on reboot

• Convenience
  – Place for temporary files used by applications
  – Files in /tmp are not subject to the user’s space quota

• What could go wrong?
  – Sharing of resources may lead to vulnerabilities
Special Permission Bits

- Three other permission bits exist
  - Set-user-ID (“suid” or “setuid”) bit
  - Set-group-ID (“sgid” or “setgid”) bit
  - Sticky bit
Set-user-ID

• Set-user-ID ("suid" or "setuid") bit
  – On executable files, causes the program to run as file owner regardless of who runs it
  – Ignored for everything else
  – In 10-character display, replaces the 4th character (x or -) with s (or S if not also executable)
    -rwsr-xr-x: setuid, executable by all
    -rwxr-xr-x: executable by all, but not setuid
    -rwSr--r--: setuid, but not executable - not useful
Setuid Programs

• Unix processes have two user IDs:
  – real user ID: user launching the process
  – effective user ID: user whose privileges are granted to the process

• An executable file can have the set-user-ID property (setuid) enabled

• If a user A executes setuid file owned by B, then the effective user ID of the process is B and not A
Setuid Programs

• System call `setuid(uid)` allows a process to change its effective user ID to `uid`
• Some programs that access system resources are owned by root and have the setuid bit set (setuid programs)
  — e.g., passwd and su
• Writing secure setuid programs is tricky because vulnerabilities may be exploited by malicious user actions
Set-group-ID

- **Set-group-ID (“sgid” or “setgid”) bit**
  - On executable files, causes the program to run with the file’s group, regardless of whether the user who runs it is in that group
  - On directories, causes files created within the directory to have the same group as the directory, useful for directories shared by multiple users with different default groups
  - Ignored for everything else
  - In 10-character display, replaces 7th character (x or -) with s (or S if not also executable)
    - `-rwxr-sr-x`: setgid file, executable by all
    - `drwxrwsr-x`: setgid directory; files within will have group of directory
    - `-rw-r-Sr--`: setgid file, but not executable - not useful
Sticky Bit

- On directories, prevents users from deleting or renaming files they do not own
- Ignored for everything else
- In 10-character display, replaces 10\textsuperscript{th} character (x or -) with t (or T if not also executable)

\texttt{drwrxrwxrwt}: sticky bit set, full access for everyone
\texttt{drwxrwx--T}: sticky bit set, full access by user/group
\texttt{drwxr--r-T}: sticky, full owner access, others can read (useless)
Symbolic Link

- In Unix, a symbolic link (aka symlink) is a file that points to (stores the path of) another file.
- A process accessing a symbolic link is transparently redirected to accessing the destination of the symbolic link.
- Symbolic links can be chained, but not to form a cycle.

```
ln -s really_long_directory/even_longer_file_name myfile
```
Octal Notation

• Standard syntax is nice for simple cases, but bad for complex changes
  – Alternative is octal notation, i.e., three or four digits from 0 to 7
• Digits from left (most significant) to right (least significant):
  \[ \text{[special bits][user bits][group bits][other bits]} \]
• Special bit digit =
  \((4 \text{ if setuid}) + (2 \text{ if setgid}) + (1 \text{ if sticky})\)
• All other digits =
  \((4 \text{ if readable}) + (2 \text{ if writable}) + (1 \text{ if executable})\)
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<td>1777</td>
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Root

- “root” account is a super-user account, like Administrator on Windows
- Multiple roots possible
- File permissions do not restrict root
- This is *dangerous*, but necessary, and OK with good practices
Becoming Root

• **su**
  – Changes home directory, PATH, and shell to that of root, but doesn’t touch most of environment and doesn’t run login scripts

• **sudo <command>**
  – Run just one command as root

• **su [-] <user>**
  – Become another non-root user
  – Root does not require to enter password
Changing Permissions

• Permissions are changed with `chmod` or through a GUI like Konqueror.

• Only the file owner or root can change permissions.

• If a user owns a file, the user can use `chgrp` to set its group to any group of which the user is a member.

• Root can change file ownership with `chown` (and can optionally change group in the same command).

• `chown`, `chmod`, and `chgrp` can take the `-R` option to recur through subdirectories.
Example of Changing Permissions

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<td>Adds group write permission to file1 and file2, denying all access to others</td>
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<tr>
<td><code>chmod -R g=rwX dir1</code></td>
<td>Adds group read/write permission to dir1 and everything within it, and group execute permission on files or directories where someone has execute permission</td>
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<tr>
<td><code>chgrp testgrp file1</code></td>
<td>Sets file1’s group to testgrp, if the user is a member of that group</td>
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<tr>
<td><code>chmod u+s file1</code></td>
<td>Sets the setuid bit on file1. (Doesn’t change execute bit.)</td>
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Limitations of Unix Permissions

- Unix permissions are not perfect
  - Groups are restrictive
  - Limitations on file creation
- Linux optionally uses POSIX ACLs
  - Builds on top of traditional Unix permissions
  - Several users and groups can be named in ACLs, each with different permissions
  - Allows for finer-grained access control
- Each ACL is of the form `type:[name]:rwx`
  - Setuid, setgid, and sticky bits are outside the ACL system
Gone for Ten Seconds

• You leave your desk for 10 seconds without locking your machine
• The attacker sits at your desk and types:
  % cp /bin/sh /tmp
  % chmod 4777 /tmp/sh
• The first command makes a copy of shell sh
• The second command makes sh a setuid program

What happens next?
• The attacker can run the copy of the shell with your privileges
• For example:
  – Can read your files
  – Can change your files
Gone for Ten Seconds: Demo

bob@handin-ca166-as138:~$ whoami
bob
bob@handin-ca166-as138:~$ cd /bin
bob@handin-ca166-as138:/bin$ cp sh /tmp
bob@handin-ca166-as138:/bin$ cd /tmp
bob@handin-ca166-as138:/tmp$ chmod 4777 sh
bob@handin-ca166-as138:/tmp$ exit
exit
alice@handin-ca166-as138:~$
Historical setuid Unix Vulnerabilities: lpr

• Command lpr
  – running as root setuid
  – copied file to print, or symbolic link to it, to spool file named with 3-digit job number (e.g., print954.spool) in /tmp
  – Did not check if file already existed
  – Random sequence was predictable and repeated after 1,000 times

• How can we exploit this?

• Attack
  – A dangerous combination: setuid, /tmp, symlinks, ...
  – Create new password file newpasswd
  – Print a very large file
  – lpr –s /etc/passwd
  – Print a small file 999 times
  – lpr newpasswd
  – The password file is overwritten with newpasswd
Beyond Setuid and Files

• Writing setuid programs is tricky
  – Easy to inadvertently create security vulnerabilities
  – Unix variants have subtle different behaviors in setuid-related calls

• Access control to files is tricky
  – A user file can be accessed by any user process
  – Shared folders and predictable file names create security vulnerabilities

• Consider alternatives
  – Manage system resources via services
  – Use databases instead of files and shared folders
  – Use RPCs (including database queries) to request access to system resources
What We Have Learned

• What is an operating system
• Processes, users, services
• Access control models (DAC and RBAC)
• Setuid programs
• Dangers of symlinks, setuid, and shared directories
  – A demo if you are “Gone for Ten Seconds”