View access control as a matrix

Objects

Subjects

	File 1	File 2	File 3	…	File n
User 1	read	write	-	-	read
User 2	write	write	write	-	-
User 3	-	-	-	read	read
…					
User m	read	write	read	write	read

- **Subjects (processes/users) access objects (e.g., files)**
- **Each cell of matrix has allowed permissions**

Two ways to slice the matrix

- **Along columns:**
  - Kernel stores list of who can access object along with object
  - Most systems you've used probably do this
  - Examples: Unix file permissions, Access Control Lists (ACLs)
- **Along rows:**
  - Capability systems do this
  - More on these later…

Outline

1. Unix protection
2. Unix security holes
3. Capability-based protection
4. Microarchitectural attacks

Example: Unix protection

- **Each process has a User ID & one or more group IDs**
- **System stores with each file:**
  - User who owns the file and group file is in
  - Permissions for user, any one in file group, and other
- **Shown by output of `ls -l` command:**

```
  user group other owner group
- rw-  rw-   r--   dm   cs140   ...   index.html
```

  - Each group of three letters specifies a subset of `read`, `write`, and `execute` permissions
  - User permissions apply to processes with same user ID
  - Else, group permissions apply to processes in same group
  - Else, other permissions apply

Unix continued

- **Directories have permission bits, too**
  - Need write permission on a directory to create or delete a file
  - Execute permission means ability to use pathnames in the directory, separate from read permission which allows listing
- **Special user `root` (UID 0) has all privileges**
  - E.g., Read/write any file, change owners of files
  - Required for administration (backup, creating new users, etc.)
- **Example:**
  - `drwxr-xr-x 56 root wheel 4096 Apr 4 10:08 /etc`
  - Directory writable only by root, readable by everyone
  - Means non-root users cannot directly delete files in `/etc`

Non-file permissions in Unix

- **Many devices show up in file system**
  - E.g., `/dev/tty1` permissions just like for files
- **Other access controls not represented in file system**
- **E.g., must usually be root to do the following:**
  - Bind any TCP or UDP port number less than 1024
  - Change the current process's user or group ID
  - Mount or unmount most file systems
  - Create device nodes (such as `/dev/tty1`) in the file system
  - Change the owner of a file
  - Set the time-of-day clock; halt or reboot machine

Example: Login runs as root

- **Unix users typically stored in files in `/etc`**
  - Files `passwd`, `group`, and often `shadow` or `master.passwd`
- **For each user, files contain:**
  - Textual username (e.g., "`dm`", or "`root`")
  - Numeric user ID, and group ID(s)
  - One-way hash of user's password: $\{\text{salt}, H(\text{salt}, \text{passwd})\}$
  - Other information, such as user's full name, login shell, etc.
- **`/usr/bin/login` runs as root**
  - Reads username & password from terminal
  - Looks up username in `/etc/passwd`, etc.
  - Computes H(salt, typed password) & checks that it matches
  - If matches, sets group ID & user ID corresponding to username
  - Execute user's shell with `execve` system call

Setuid

- **Some legitimate actions require more privs than UID**
  - E.g., how should users change their passwords?
  - Stored in root-owned `/etc/passwd` & `/etc/shadow` files
- **Solution: Setuid/setgid programs**
  - Run with privileges of file's owner or group
  - Each process has *real* and *effective* UID/GID
  - *real* is user who launched setuid program
  - *effective* is owner/group of file, used in access checks
  - Actual rules and interfaces somewhat complicated [Chen]
- **Shown as "s" in file listings**
  - `-rws--x--x 1 root root 52528 Oct 29 08:54 /bin/passwd`
  - Obviously need to own file to set the setuid bit
  - Need to own file and be in group to set setgid bit

Setuid (continued)

- **Examples**
  - `passwd` – changes user's password
  - `su` – acquire new user ID (given correct password)
  - `sudo` – run one command as root
  - `ping` (historically) – uses raw IP sockets to send/receive ICMP
- **Have to be very careful when writing setuid code**
  - Attackers can run setuid programs any time (no need to wait for root to run a vulnerable job)
  - Attacker controls many aspects of program's environment
- **Example attacks when running a setuid program**
  - Change PATH or IFS if setuid prog calls system(3)
  - Set maximum file size to zero (if app rebuilds DB)
  - Close fd 2 before running program—may accidentally send error message into protected file

Linux capabilities

- **Ping needs raw network access, not ability to delete all files**
- **Linux subdivides root's privileges into** $\sim$ 40 **capabilities, e.g.:**
  - `cap_net_admin` – configure network interfaces (IP address, etc.)
  - `cap_net_raw` – use raw sockets (bypassing UDP/TCP)
  - `cap_sys_boot` – reboot; `cap_sys_time` – adjust system clock
- **Usually root gets all, but behavior can be modified by "securebits" (see prctl(2))**
- **Capabilities *don't* survive *execve* unless bits are set in *both* thread & inode (exception: ambient capabilities)**
- **"*Effective*" bit in inode acts like setuid for capability**

```
$ ls -al /usr/bin/ping
-rwxr-xr-x 1 root root 61168 Nov 15 23:57 /usr/bin/ping
$ getcap /usr/bin/ping
/usr/bin/ping = cap_net_raw+ep
```

- **See also: getcap(8), setcap(8), capsh(1)**

Other permissions

- **When can process *A* send a signal to process *B* with *kill*?**
  - Allow if sender and receiver have same effective UID
  - But need ability to kill processes you launch even if suid
  - So allow if real UIDs match, as well
  - Can also send SIGCONT w/o UID match if in same session
- **Debugger system call *ptrace***
  - Lets one process modify another's memory
  - Setuid gives a program more privilege than invoking user
  - So don't let a process ptrace a more privileged process
  - E.g., Require sender to match real & effective UID of target
  - Also disable/ignore setuid if ptraced target calls *exec*
  - Exception: root can *ptrace* anyone

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A security hole

- Even without root or setuid, attackers can trick root owned processes into doing things…
- Example: Want to clear unused files in `/tmp`
- Every night, automatically run this command as root:

```
find /tmp -atime +3 -exec rm -f -- {} \;
```

- find identifies files not accessed in 3 days
  - executes `rm`, replacing `{}` with file name
- `rm -f --` *path* deletes file *path*
  - Note "--" prevents *path* from being parsed as option
- What's wrong here?

An attack

find/rm	Attacker
	mkdir ("/tmp/badetc") creat ("/tmp/badetc/passwd")
readdir ("/tmp") → "badetc" lstat ("/tmp/badetc") → DIRECTORY readdir ("/tmp/badetc") → "passwd"	
unlink ("/tmp/badetc/passwd")	

An attack

find/rm	Attacker
	mkdir ("/tmp/badetc") creat ("/tmp/badetc/passwd")
readdir ("/tmp") → "badetc" lstat ("/tmp/badetc") → DIRECTORY readdir ("/tmp/badetc") → "passwd"	
	rename ("/tmp/badetc" → "/tmp/x") symlink ("/etc", "/tmp/badetc")
unlink ("/tmp/badetc/passwd")	

- Time-of-check-to-time-of-use [TOCTTOU] bug
  - find checks that `/tmp/badetc` is not symlink
  - But meaning of file name changes before it is used

xterm command

- Provides a terminal window in X-windows
- Used to run with setuid root privileges
  - Requires kernel pseudo-terminal (pty) device
  - Required root privs to change ownership of pty to user
  - Also writes protected utmp/wtmp files to record users
- Had feature to log terminal session to file

```
fd = open (logfile, O_CREAT|O_WRONLY|O_TRUNC, 0666);
/* ... */
```

- What's wrong here?

xterm command

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```
if (access (logfile, W_OK) < 0)
  return ERROR;

fd = open (logfile, O_CREAT|O_WRONLY|O_TRUNC, 0666);
/* ... */
```

- `xterm` is root, but shouldn't log to file user can't write
- `access` call avoids dangerous security hole
  - Does permission check with *real*, not *effective* UID

xterm command

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- `xterm` is root, but shouldn't log to file user can't write
- `access` call avoids dangerous security hole
  - Does permission check with *real*, not *effective* UID

  - **Wrong: Another TOCTTOU bug**

An attack

xterm	Attacker
	creat ("/tmp/log")
access ("/tmp/log") → OK	
	unlink ("/tmp/log") symlink ("/tmp/log" → "/etc/passwd")
open ("/tmp/log")	

- **Attacker changes `/tmp/log` between check and use**
  - xterm unwittingly overwrites `/etc/passwd`
  - Another TOCTTOU bug
- **OpenBSD man page: "CAVEATS: access() is a potential security hole and should never be used."**

Preventing TOCCTOU

- **Use new APIs that are relative to an opened directory fd**
  - openat, renameat, unlinkat, symlinkat, faccessat
  - fchown, fchownat, fchmod, fchmodat, fstat, fstatat
  - `O_NOFOLLOW` flag to open avoids symbolic links in last component
  - But can still have TOCTTOU problems with hardlinks
- **Lock resources, though most systems only lock files (and locks are typically advisory)**
- **Wrap groups of operations in OS transactions**
  - Microsoft supports for transactions on Windows Vista and newer CreateTransaction, CommitTransaction, RollbackTransaction
  - A few research projects for POSIX [Valor] [TxOS]

SSH configuration files

- **SSH 1.2.12 client ran as root for several reasons:**
  - Needed to bind TCP port under 1024 (privileged operation)
  - Needed to read client private key (for host authentication)
- **Also needed to read & write files owned by user**
  - Read configuration file `~/.ssh/config`
  - Record server keys in `~/.ssh/known_hosts`
- **Software structured to avoid TOCTTOU bugs:**
  - First bind socket & read root-owned secret key file
  - Second drop *all* privileges—set real, & effective UIDs to user
  - Only then access user files
  - Idea: avoid using any user-controlled arguments/files until you have no more privileges than the user
  - What might still have gone wrong?

Trick question: ptrace bug

- **Actually do have more privileges than user!**
  - Bound privileged port and read host private key
- **Dropping privs allows user to "debug" SSH**
  - Depends on OS, but at the time several had *ptrace* implementations that made SSH vulnerable
- **Once in debugger**
  - Could use privileged port to connect anywhere
  - Could read secret host key from memory
  - Could overwrite local user name to get privs of other user
- **The fix: restructure into 3 processes!**
  - Perhaps overkill, but really wanted to avoid problems
- **Today some linux distros restrict ptrace with Yama**

A Linux security hole

- **Some programs acquire then release privileges**
  - E.g., `su user` is setuid root, becomes `user` if password correct
- **Consider the following:**
  - A and B unprivileged processes owned by attacker
  - A ptraces B (works even with Yama, as B could be child of A)
  - A executes "`su user`" to its own identity
  - With effective UID (EUID) 0, `su` asks for password & waits
  - While A's EUID is 0, B execs `su root`
    (B's exec honors setuid—not disabled—since A's EUID is 0)
  - A types password, gets shell, and is attached to `su root`
  - Can manipulate `su root`'s memory to get root shell

Editorial

- **Previous examples show two limitations of Unix**
- **Many OS security policies *subjective* not *objective***
  - When can you signal/debug process? Re-bind network port?
  - Rules for non-file operations somewhat incoherent
  - Even some file rules weird (creating hard links to files)
- **Correct code is much harder to write than incorrect**
  - Delete file without traversing symbolic link
  - Read SSH configuration file (requires 3 processes??)
  - Write mailbox owned by user in dir owned by root/mail
- **Don't just blame the application writers**
  - Must also blame the interfaces they program to

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Another security problem [Hardy]

- **Setting: A multi-user time sharing system**
  - This time it's not Unix
- **Wanted Fortran compiler to keep statistics**
  - Modified compiler `/sysx/fort` to record stats in `/sysx/stat`
  - Gave compiler "home files license"—allows writing to anything in `/sysx` (kind of like Unix setuid)
- **What's wrong here?**

A confused deputy

- **Attacker could overwrite any files in `/sysx`**
  - System billing records kept in `/sysx/bill` got wiped
  - Probably command like `fort -o /sysx/bill file.f`
- **Is this a bug in the compiler `fort`?**
  - Original implementors did not anticipate extra rights
  - Can't blame them for unchecked output file
- **Compiler is a "confused deputy"**
  - Inherits privileges from invoking user (e.g., read `file.f`)
  - Also inherits privileges from home files license
  - Which master is it serving on any given system call?
  - OS doesn't know if it just sees `open ("/sysx/bill", ...)`

Recall access control matrix

Objects

Subjects

	File 1	File 2	File 3	...	File n
User 1	read	write	-	-	read
User 2	write	write	write	-	-
User 3	-	-	-	read	read
...					
User m	read	write	read	write	read

Capabilities

- **Slicing matrix along rows yields capabilities**
  - E.g., For each process, store a list of objects it can access
  - Process explicitly invokes particular capabilities
- **Can help avoid confused deputy problem**
  - E.g., Must give compiler an argument that both specifies the output file and conveys the capability to write the file (think about passing a file descriptor, not a file name)
  - So compiler uses no *ambient authority* to write file
- **Three general approaches to capabilities:**
  - Hardware enforced (Tagged architectures like M-machine)
  - Kernel-enforced (Hydra, KeyKOS)
  - Self-authenticating capabilities (like Amoeba)
- **Good history in [Levy]**

Hydra [Wulf]

- **Machine & programing environment built at CMU in '70s**
- **OS enforced object modularity with capabilities**
  - Could only call object methods with a capability
- **Augmentation let methods manipulate objects**
  - A method executes with the capability list of the object, not the caller
- **Template methods take capabilities from caller**
  - So method can access objects specified by caller

KeyKOS [Bomberger]

- **Capability system developed in the early 1980s**
  - Inspired many later systems: EROS, Coyotos
- **Goal: Extreme security, reliability, and availability**
- **Structured as a "nanokernel"**
  - Kernel proper only 20,000 likes of C, 100KB footprint
  - Avoids many problems with traditional kernels
  - Traditional OS interfaces implemented outside the kernel (including binary compatibility with existing OSes)
- **Basic idea: No privileges other than capabilities**
  - Means kernel provides purely *objective* security mechanism
  - As objective as pointers to objects in OO languages
  - In fact, partition system into many processes akin to objects

Unique features of KeyKOS

- **Single-level store**
  - Everything is persistent: memory, processes, ...
  - System periodically checkpoints its entire state
  - After power outage, everything comes back up as it was (may just lose the last few characters you typed)
- **"Stateless" kernel design only caches information**
  - All kernel state reconstructible from persistent data
- **Simplifies kernel and makes it more robust**
  - Kernel never runs out of space in memory allocation
  - No message queues, etc. in kernel
  - Run out of memory? Just checkpoint system

KeyKOS capabilities

- **Refered to as "keys" for short**
- **Types of keys:**
  - *devices* – Low-level hardware access
  - *pages* – Persistent page of memory (can be mapped)
  - *nodes* – Container for 16 capabilities
  - *segments* – Pages & segments glued together with nodes
  - *meters* – right to consume CPU time
  - *domains* – a thread context
- **Anyone possessing a key can grant it to others**
  - But creating a key is a privileged operation
  - E.g., requires "prime meter" to divide it into submeters

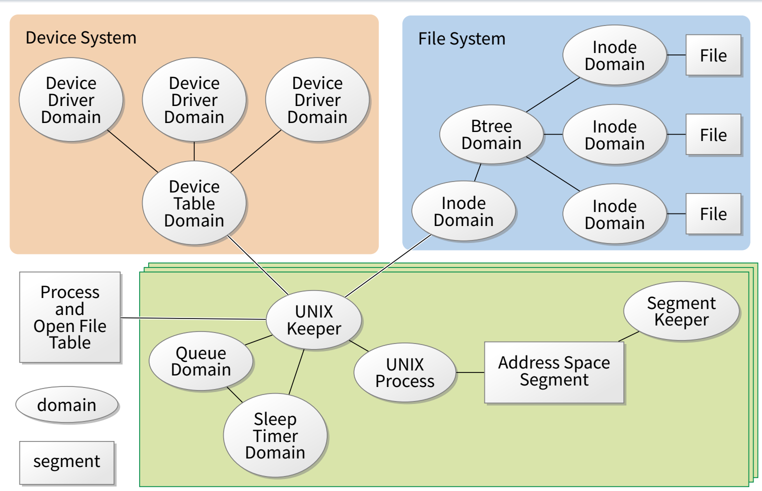
Capability details

- **Each domain has a number of key "slots":**
  - 16 general-purpose key slots
  - *address slot* – contains segment with process VM
  - *meter slot* – contains key for CPU time
  - *keeper slot* – contains key for exceptions
- **Segments also have an associated keeper**
  - Process that gets invoked on invalid reference
- **Meter keeper (allows creative scheduling policies)**
- **Calls generate return key for calling domain**
  - (Not required—other forms of message don't do this)

KeyNIX: UNIX on KeyKOS

- **"One kernel per process" architecture**
  - Hard to crash kernel
  - Even harder to crash system
- **A process's kernel is its keeper**
  - Unmodified Unix binary makes Unix syscall
  - Invalid KeyKOS syscall, transfers control to Unix keeper
- **Of course, kernels need to share state**
  - Use shared segment for process and file tables

KeyNIX overview



Keynix I/O

- **Every file is a different process**
  - Elegant, and fault isolated
  - Small files can live in a node, not a segment
  - Makes the `namei()` function very expensive
- **Pipes require queues**
  - This turned out to be complicated and inefficient
  - Interaction with signals complicated
- **Other OS features perform very well, though**
  - E.g., fork is six times faster than Mach 2.5

Self-authenticating capabilities

- **Every access must be accompanied by a capability**
  - For each object, OS stores random *check* value
  - Capability is: {Object, Rights, MAC(*check*, Rights)}
    (MAC = cryptographic *Message Authentication Code*)
- **OS gives processes capabilities**
  - Process creating resource gets full access rights
  - Can ask OS to generate capability with restricted rights
- **Makes sharing very easy in distributed systems**
- **To revoke rights, must change *check* value**
  - Need some way for everyone else to reacquire capabilities
- **Hard to control propagation**

Amoeba

- **A distributed OS, based on capabilities of form:**
  - server port, object ID, rights, check
- **Any server can listen on any machine**
  - Server port is hash of secret
  - Kernel won't let you listen if you don't know secret
- **Many types of object have capabilities**
  - Files, directories, processes, devices, servers (E.g., X windows)
- **Separate file and directory servers**
  - Can implement your own file server, or store other object types in directories, which is cool
- **Check is like a secret password for the object**
  - Server records check value for capabilities with all rights
  - Restricted capability's check is hash of old check, rights

Limitations of capabilities

- **IPC performance a losing battle with CPU makers**
  - CPUs optimized for "common" code, not context switches
  - Capability systems usually involve many IPCs
- **Capability model never fully took off as kernel API**
  - Requires changes throughout application software
  - Call capabilities "file descriptors" or "Java pointers" and people will use them
  - But discipline of pure capability system challenging so far
  - People sometimes quip that capabilities are an OS concept of the future and always will be
- **But real systems do use capabilities**
  - Firefox security based on language-level object capabilities
  - FreeBSD now ships with Capsicum, making capabilities available

Capsicum [Watson]

- **Capability API in FreeBSD 9**
- `cap_enter` **enters a process into capability mode**
- **APIs can be used to restrict file descriptor permissions**
- **Limit read, write, ioctls, etc.**
- **Used by various base system binaries**
- **Supported by a growing number of applications**
- **Patches exist to use Capsicum for Chrome's sandboxing**

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Cache timing attacks

```
char *buf;

int
victim (int secret_byte)
{
    return buf[secret_byte*64];
}
```

- **Accessing memory based on secret data can leak the data**
- **Approach 1: Flush/Evict + Reload**
  - Share `buf` with victim process (shared lib or deduplication)
  - Flush `buf` from cache (`clflush` instruction, or overflow capacity)
  - After `victim` time reads of `buf`, fast line tells you `secret_byte`
- **Approach 2: Prime + Probe**
  - No shared memory, but attacker primes cache with its own buffer
  - Victim's `buf` access evicts one of attacker's cache lines
  - Slow cache line (+ cache mapping) reveals secret data

Speculative execution key to performance

```
unsigned char *array1, *array2;
int array1_size, array2_size;

void
lookup (int input)
{
  if (input < array1_size)
    return array2[array1[input] * 4096]
}
```

- **CPU predicts branches to mask memory latency**
  - E.g., predict `input < array_size` even if `array1_size` not cached
  - Wait to get `array1_size` from memory before retiring instructions
  - *Squash* incorrectly predicted instructions by reverting registers
  - But can't revert cache state, only registers
- **Example: intel Haswell**
  - Spectutatively executes up to 192 micro-ops
  - Indexes branch target buffer by bottom 31 bits of branch address

Spectre attack [Kocher]

```
unsigned char *array1, *array2;
int array1_size, array2_size;

void
victim (int input)
{
  if (input < array1_size)
    return array2[array1[input] * 4096]
}
```

- **Say attacker supplies `input`, wants to read `array1[input]`**
  - `input` can exceed bounds, reference any byte in address space
- **Ensure `array1` cached, but `array1_size` and `array2` uncached**
- **Flush+reload attack on `array2` now reveals `array1[input]`**
  - CPU will likely predict branch taken (don't usually overflow)
  - Speculatively load from `array2` before seeing `array1_size`
  - Reloaded cache line reveals `array1[input]`

Many more variants of Spectre

- **Attack on JavaScript JIT**
  - Malicious JavaScript reads secrets outside of JavaScript sandbox
- **eBPF compiles packet filters in kernel (e.g., for tcpdump)**
  - Can generate code to reveal arbitrary kernel memory
- **Can even use victim code that's not supposed to be executed**
  - Mistrain branch predictor on indirect branch
  - Speculatively execute arbitrary "spectre gadget" in victim process
  - Same cache impact even if gadget execution entirely squashed
  - Has been used to leak host memory from inside virtual machine
- **Use other speculation channels**
  - E.g., CPU predicts that previous store does not conflict with a load

Mitigation

- **Replace array bounds checks with index masking (used by Chrome)**
  - `return array2[array1[input&0xffff] * 4096]`
  - Limits distance of bounds violation
- **Place JavaScript sandbox in separate address space**
- **XOR pointers with type-dependent poison values (in JITs)**
- **Make CPUs a bit better about leaking state through side channels**
- **Insert "gratuitous" memory barriers to prevent speculation on sensitive data**
- **Unfortunately general solution still an open problem**