CS 489 / 698: Software and Systems Security

Module 3: Operating System Security
access control and capabilities

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Outline

Why this topic?

Q: Recap: what does an operating system do?

A: Resource sharing — An operating system (OS) allows different "entities" to access different resources in a shared way.

- OS makes resources available to entities **if** required by them and **when** permitted by some policy (and availability).
  - What is a resource?
  - What is an entity?
  - How does an entity request for a resource?
  - How does a policy get specified?
  - How is the policy enforced?

All based on the requirement that:

- an entity can correctly identify itself **AND**,
- the OS can correctly authenticate the entity.

Goals of access control

In general, access control has three goals:

- Check on every access: else the operating system might fail to notice that access rights have been revoked
- Enforce least privilege: grant user/program access only to smallest number of objects required to perform a task
- Verify acceptable use: limit types of activity that can be performed on an object

Access control matrix

- Set of protected objects: O
  - E.g., files or hardware devices
- Set of subjects: S
  - E.g., users, processes acting on behalf of users
- Set of rights: R
  - E.g., read, write, execute, own
- Access control matrix consists of entries $a[s, o]$, where
  - $s \in S$
  - $o \in O$, and
  - $a[s, o] \subseteq R$

Example access control matrix

	File 1	**File 2**	**File 3**
Alice	orw	rx	o
Bob	r	orx	
Carol		rx	

Implementing access control matrix

In practice, access control matrix is rarely implemented as a matrix.

Q: Why?

A: Too fine-grained, hard to manage (e.g., adding a new subject or object requires the addition of an entire role or column respectively), too sparse $\implies$ waste of space.

Instead, an access control matrix is typically implemented as

- a set of access control lists
  - column-wise representation
- a set of privilege lists
  - row-wise representation
- a set of capabilities
  - cell-wise representation that encapsulates authentication as well
- or a combination

Outline

Access control lists (ACLs)

Each object has a list of subjects and their access rights

Example:

- File 1: {Alice:orw, Bob:r}
- File 2: {Alice:rx, Bob:orx, Carol:rx}
- File 3: {Alice:o}

Implementation on real-world operating systems:

- ACLs are implemented in Windows file system (NTFS), user entry can denote entire user group (e.g., "Students")
- Classic UNIX file system has a simpler model of ACLs.
  - Each file lists its owner, a group, and a third entry representing all other users.
  - For each class, there is a separate set of rights.
  - Groups are system-wide defined in `/etc/group`, use `chmod`/`chown`/`chgrp` for setting access rights to your files

Access control lists (ACLs)

Q: Which of the following can we do quickly for ACLs?

- Determine set of allowed users per object
- Determine set of objects that a user can access
- Revoke a user's access right to an object
- Revoke a user's access right to all objects
- Revoke all users' access rights to an object

A: Easy, Hard, Easy, Hard, Easy

Privilege lists

Each subject has a list of objects it can access with associated rights

Example:

- Alice: {File 1:orw, File 2:rx, File 3:o}
- Bob: {File 1:r, File 2:orx}
- Carol: {File 2:rx}

Implementation on real-world operating systems:

- Android / iOS permission framework
- POSIX capabilities (despite its name...)

Privilege lists

Q: Which of the following can we do quickly for privilege lists?

- Determine set of allowed users per object
- Determine set of objects that a user can access
- Revoke a user's access right to an object
- Revoke a user's access right to all objects
- Revoke all users' access rights to an object

A: Hard, Easy, Easy, Easy, Hard

Capabilities

A capability is an unforgeable token that gives its owner some access rights to an object.

Example:

- C1: {File 1:w}, C2: {File 2:r}, C3: {File 3: o}, C4: {File 2: x}
- Alice: {C1, C2, C3, C4}, Bob: {C2, C4}, Carol: {C4}

Some properties about capabilities-based system:

- Unforgeability enforced by either
  - a component running at a higher privilege level (e.g., kernel)
  - cryptographic mechanisms (e.g., digital signatures)
- Tokens might be transferable (or non-transferable)
- Tokens might be copyable (or non-copyable)
- Tokens serve both authentication and access control

Some research/experimental OSs (e.g., Fuchsia, seL4) have fine-grained support for tokens.

Capabilities

Q: Which of the following can we do quickly for capabilities?

- Determine set of allowed users per object
- Determine set of objects that a user can access
- Revoke a user's access right to an object
- Revoke a user's access right to all objects
- Revoke all users' access rights to an object

A: Hard, Easy, Easy, Easy, Easy

Outline

Why do we need security models?

Q: You have implemented the access control matrix (e.g., as ACLs, privilege lists, or capabilities), how can you be certain that the matrix is secure?

Security policies

- Many security policies have their roots in military scenarios
- Each object/subject has a sensitivity/clearance level
  - "Top Secret" $>_C$ "Secret" $>_C$ "Confidential" $>_C$ "Unclassified" where "$>_C$" means "more sensitive"
- Each object/subject might also be assigned to one or more compartments
  - E.g., "Soviet Union", "East Germany"
  - Need-to-know rule
- Subject s can access object o iff level(s) $\geq$ level(o) **AND** compartments(s) $\supseteq$ compartments(o)
  - s dominates o, short "$s \geq_{dom} o$"

Example

Q: Secret agent James Bond has clearance "Top Secret" and is assigned to compartment "East Germany".

Can he read a document with sensitivity level "Secret" and compartments "East Germany" and "Soviet Union"?

A: No

Lattices

Dominance relationship $\geq_{dom}$ defined in the security model is transitive and antisymmetric. It defines a partial order (neither $a \geq_{dom} b$ nor $b \geq_{dom} a$ might hold for two levels a and b).

This forms a lattice, i.e., for every a and b, there exists a

- unique lowest upper bound u for which $u \geq_{dom} a \wedge u \geq_{dom} b$
- unique greatest lower bound l for which $a \geq_{dom} l \wedge b \geq_{dom} l$

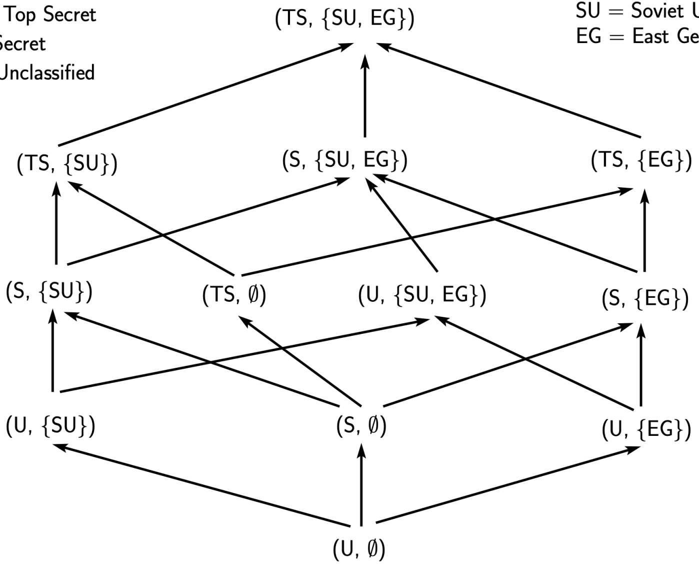
Transitively, there are also two elements U and L that dominates/is dominated by all levels:

- $U = (\text{“Top Secret”}, \{\text{“Soviet Union”}, \text{“East Germany”}\})$
- $L = (\text{“Unclassified”}, \emptyset)$

Example lattice

Sensitivity levels:
TS = Top Secret
S = Secret
U = Unclassified

Compartments:
SU = Soviet Union
EG = East Germany



The Bell-LaPadula model

Security goal: ensures that information does not flow to those not cleared for that level.

- The ss-property: s can read o iff $C(s) \geq_{dom} C(o)$
  - no read-up
- The $*$-property: s can write o iff $C(o) \geq_{dom} C(s)$
  - no write-down

Q: Why having the “no write-down” policy?

A: To prevent someone reading secret document and then summarizing it in an unclassified document

Q: How to transfer information from a high-sensitivity document to a lower-sensitivity document (i.e., declassification)?

A: via trusted subjects

Biba integrity model

Security goal: ensures that information cannot be modified by those not cleared for that level.

- Dual of Bell-La Padula model
- Subjects and objects are ordered by an integrity classification scheme, $I(s)$ and $I(o)$
- Should subject s have access to object o?

- The ss-property: s can read o only iff $I(o) \geq_{dom} I(s)$
  - Unreliable information cannot "contaminate" subject
  - no read-down
- The $*$-property: s can modify o only iff $I(s) \geq_{dom} I(o)$
  - Unreliable subject cannot modify data with high integrity information
  - no write-up

Low Watermark Property

- Biba's access rules are very restrictive, a subject cannot ever read lower integrity object
- Can use dynamic integrity levels instead
  - Subject Low Watermark Property:
    If subject s reads object o, then $I(s) = glb(I(s), I(o))$, where $glb()$ = greatest lower bound
  - Object Low Watermark Property:
    If subject s modifies object o, then $I(o) = glb(I(s), I(o))$
- Integrity of subject/object can only go down, information flows down

Review of Bell-La Padula & Biba

- Very simple, which makes it possible to even prove correctness properties about them
  - E.g., can prove that if a system starts in a secure state, the system will remain in a secure state
- Probably too simple for great practical benefit
  - Need declassification
  - Need both confidentiality and integrity, not just one
  - What about object creation?
- Information leaks might still be possible through covert channels in an implementation of the model

Chinese Wall security policy

Security goal: dealing with conflicts of interests — Once you've decided for a side of the wall, there is no easy way to get to the other side.

Once you have been able to access information about a particular kind of company, you will no longer be able to access information about other companies of the same kind.

- Useful for consulting, legal, or accounting firms
- Need history of accessed objects
- Access rights change over time

- ss-property: Subject s can access object o iff each object previously accessed by s either belongs to the same company as o or belongs to a different kind of company than o does
- *-property: For a write access to o by s, we also need to ensure that all objects readable by s either belong to the same company as o or have been sanitized

Example

- Fast Food Companies = {McDonalds, Wendy's}
- Book Stores = {Chapters, Amazon}
- Alice has accessed information about McDonalds
- Bob has accessed information about Wendy's

- ss-property prevents Alice from accessing information about Wendy's, but not about Chapters or Amazon
  - Similar for Bob
- Suppose Alice could write information about McDonalds to Chapters and Bob could read this information from Chapters
  - Indirect information flow violates Chinese Wall Policy
  - *-property forbids this kind of write

Outline

What is seL4?

Overview: seL4 is an open source, high-assurance, high-performance operating system microkernel.

- Available on GitHub under GPLv2 license
- Contains a comprehensive set of mathematical proofs for correctness and security
- Arguably the fastest microkernel in the world
- Aims to be a piece of software that runs at the heart of any system and controls all accesses to resources

Monolithic kernel vs microkernel

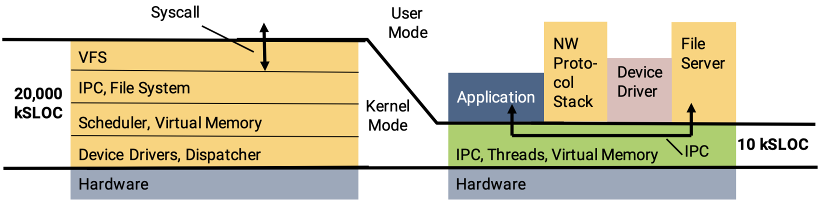
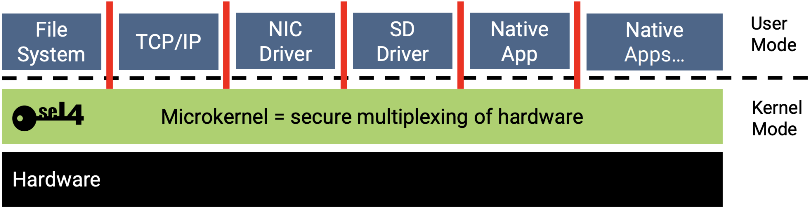


Figure illustrating the difference between

- monolithic kernel (e.g., the Linux kernel) on the left and
- microkernel (e.g., seL4) (on the right)

Adapted from seL4 Whitepaper.

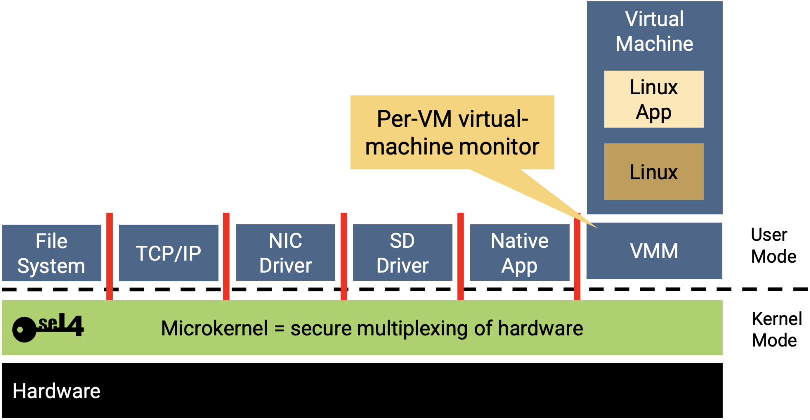
Microkernel



All operating-system services are user-level processes:

- file systems
- device drivers
- network stack
- power management
- . . .

Microkernel as hypervisor



Adapted from seL4 Overview Slides on seL4 Summit 2022

seL4 capability system

General principle: anything goes through seL4 needs a capability!

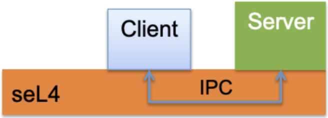
A capability is an object reference that conveys specific rights to a particular object

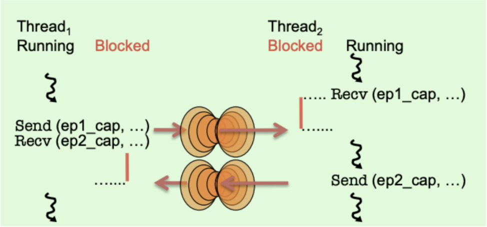
- Capability = Access Token: prima-facie evidence of privilege
- Access rights include read, write, send, reply, execute, ...
- Kernel object is one of ten object types

Any system call is invoking a capability: `r = cap.method(args);`

seL4 protected procedure calls (IPC)

Protected procedure call (IPC for historical reasons) is a fundamental operation in seL4.





Q: How would a normal open syscall be like in seL4?

A: `Call(ext4fs_endpoint_cap, OPEN_FILE, <extra-args>)`

- Mint `reply_cap`
- `Send(ext4fs_endpoint_cap, reply_cap, ...)`
- `Recv(reply_cap, ...)`

seL4 kernel objects

- **Endpoints** are used to perform protected function calls
- **Reply Objects** represent a return path from a protected procedure call
- **Address Spaces** provide the sandboxes around components (thin wrappers abstracting hardware page tables)
- **Cnodes** store capabilities representing a component's access rights
- **Thread Control Blocks** represent threads of execution
- **Scheduling Contexts** represent the right to access a certain fraction of execution time on a core
- **Notifications** are synchronisation objects (similar to semaphores)
- **Frames** represent physical memory that can be mapped into address spaces
- **Interrupt Objects** provide access to interrupt handling
- **Untypeds** unused (free) physical memory that can be converted ("retyped") into any of the other types.

$\langle$ **End** $\rangle$