Module 3: Operating System Security
access control and capabilities

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Outline

1. Introduction to access control
2. Implementing the access control matrix
3. Models for security policies
4. Case study: seL4 microkernel
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

<table>
<thead>
<tr>
<th></th>
<th>File 1</th>
<th>File 2</th>
<th>File 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alice</td>
<td>orw</td>
<td>rx</td>
<td>o</td>
</tr>
<tr>
<td>Bob</td>
<td>r</td>
<td>orx</td>
<td></td>
</tr>
<tr>
<td>Carol</td>
<td></td>
<td>rx</td>
<td></td>
</tr>
</tbody>
</table>
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 ⇒ 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
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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:
- 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.
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
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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:
- 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 \[ \text{level}(s) \geq \text{level}(o) \text{ AND } \text{compartments}(s) \supseteq \text{compartments}(o) \]
  - _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 \( u \geq_{dom} a \land u \geq_{dom} b \)
- unique greatest lower bound \( l \) for which \( a \geq_{dom} l \land b \geq_{dom} l \)

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

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

Microkernel = secure multiplexing of hardware

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: \( r = \text{cap}\text{.method(args)}; \)
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.
〈 End 〉