CS 458 / 658
Computer Security and Privacy

Module 3
Operating System Security

Winter 2011

Operating systems

- An operating system allows different users to access different resources in a shared way
- The operating system needs to control this sharing and provide an interface to allow this access
- Identification and authentication are required for this access control
- We will start with memory protection techniques and then look at access control in more general terms

Module outline

1. Protection in general-purpose operating systems
2. User authentication
3. Security policies and models
4. Trusted operating system design

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2. User authentication
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History

- Operating systems evolved as a way to allow multiple users use the same hardware
  - Sequentially (based on executives)
  - Interleaving (based on monitors)
- OS makes resources available to users if required by them and permitted by some policy
- OS also protects users from each other
  - Attacks, mistakes, resource overconsumption
- Even for a single-user OS, protecting a user from him/herself is a good thing
  - Mistakes, malware

Protected objects

- CPU
- Memory
- I/O devices (disks, printers, keyboards,...)
- Programs
- Data
- Networks

Separation

- Keep one user's objects separate from other users
- Physical separation
  - Use different physical resources for different users
  - Easy to implement, but expensive and inefficient
- Temporal separation
  - Execute different users' programs at different times
- Logical separation
  - User is given the impression that no other users exist
  - As done by an operating system
- Cryptographic separation
  - Encrypt data and make it unintelligible to outsiders
  - Complex

Sharing

- Sometimes, users do want to share resources
  - Library routines (e.g., libc)
  - Files or database records
- OS should allow flexible sharing, not "all or nothing"
  - Which files or records? Which part of a file/record?
  - Which other users?
  - Can other users share objects further?
  - What uses are permitted?
    - Read but not write, view but not print (Feasibility?)
    - Aggregate information only
  - For how long?

Memory and address protection

- Prevent program from corrupting other programs or data, operating system and maybe itself
- Often, the OS can exploit hardware support for this protection, so it's cheap
  - See CS 350 memory management slides
- Memory protection is part of translation from virtual to physical addresses
  - Memory management unit (MMU) generates exception if something is wrong with virtual address or associated request
  - OS maintains mapping tables used by MMU and deals with raised exceptions

Protection techniques

- Fence register
  - Exception if memory access below address in fence register
  - Protects operating system from user programs
  - Single-user OS only
- Base/bounds register pair
  - Exception if memory access below/above address in base/bounds register
  - Different values for each user program
  - Maintained by operating system during context switch
  - Limited flexibility

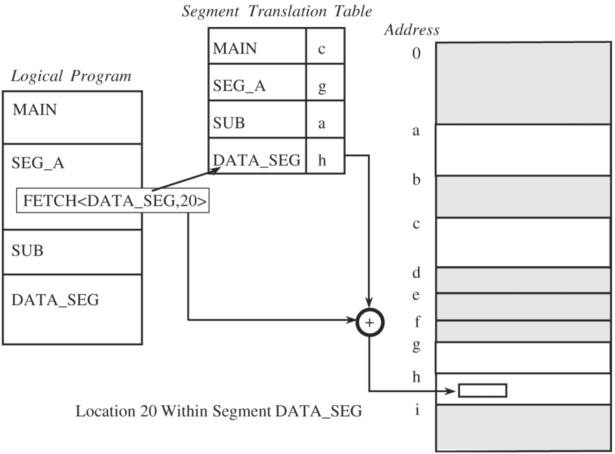
Protection techniques

- Tagged architecture
  - Each memory word has one or more extra bits that identify access rights to word
  - Very flexible
  - Large overhead
  - Difficult to port OS from/to other hardware architectures
- Segmentation
- Paging

Segmentation

- Each program has multiple address spaces (segments)
- Different segments for code, data, and stack
  - Or maybe even more fine-grained, e.g., different segments for data with different access restrictions
- Virtual addresses consist of two parts:
  - <segment name, offset within segment>
- OS keeps mapping from segment name to its base physical address in Segment Table
  - A segment table for each process
- OS can (transparently) relocate or resize segments and share them between processes
- Segment table also keeps protection attributes

Segment table



(Protection attributes are missing)

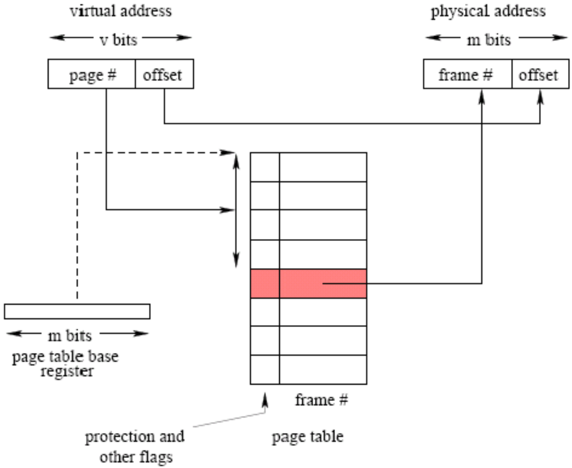
Review of segmentation

- Advantages:
  - Each address reference is checked for protection by hardware
  - Many different classes of data items can be assigned different levels of protection
  - Users can share access to a segment, with potentially different access rights
  - Users cannot access an unpermitted segment
- Disadvantages:
  - External fragmentation
  - Dynamic length of segments requires costly out-of-bounds check for generated physical addresses
  - Segment names are difficult to implement efficiently

Paging

- Program (i.e., virtual address space) is divided into equal-sized chunks (pages)
- Physical memory is divided into equal-sized chunks (frames)
- Frame size equals page size
- Virtual addresses consist of two parts:
  - <page #, offset within page>
  - # bits for offset = $\log_2$(page size)
- OS keeps mapping from page # to its base physical address in Page Table
- Page table also keeps memory protection attributes

Paging



Source: CS 350 slides

Review of paging

- Advantages:
  - Each address reference is checked for protection by hardware
  - Users can share access to a page, with potentially different access rights
  - Users cannot access an unpermitted page
- Disadvantages:
  - Internal fragmentation
  - Assigning different levels of protection to different classes of data items not feasible

x86 architecture

- x86 architecture has both segmentation and paging
  - Linux and Windows use both
    - Only simple form of segmentation, helps portability
    - Segmentation cannot be turned off on x86
- Memory protection bits indicate no access, read/write access or read-only access
- Recent x86 processors also include NX (No eXecute) bit, forbidding execution of instructions stored in page
  - Enabled in Windows XP SP 2 and some Linux distros
  - E.g., make stack/heap non-executable
    - Does this avoid all buffer overflow attacks?

Access control

- Memory is only one of many objects for which OS has to run access control

- In general, access control has three goals:
  - Check every access: Else OS might fail to notice that access has been revoked
  - Enforce least privilege: Grant program access only to smallest number of objects required to perform a task
    - Access to additional objects might be harmless under normal circumstances, but disastrous in special cases
  - Verify acceptable use: Limit types of activity that can be performed on an object
    - E.g., for integrity reasons (ADTs)

Access control matrix

- Set of protected objects: O
  - E.g., files or database records
- Set of subjects: S
  - E.g., humans, processes acting on behalf of humans or group of humans/processes
- 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

- Access control matrix is rarely implemented as a matrix
  - Why?
- Instead, an access control matrix is typically implemented as
  - a set of access control lists
    - column-wise representation
  - a set of capabilities
    - row-wise representation
  - or a combination

Access control lists (ACLs)

- Each object has a list of subjects and their access rights
  - File 1: Alice:orw, Bob:r, File 2: Alice:rx, Bob:orx, Carol:rx
  - ACLs are implemented in Windows file system (NTFS), user entry can denote entire user group (e.g., "Students")
  - Classic UNIX file system has simple 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

- 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 or all objects

Capabilities

- A capability is an unforgeable token that gives its owner some access rights to an object
  - Alice: File 1:orw, File 2:rx, File 3:o
- Unforgeability enforced by having OS store and maintain tokens or by cryptographic mechanisms
  - E.g., digital signatures (see later) allow tokens to be handed out to processes/users. OS will detect tampering when process/user tries to get access with modified token.
- Tokens might be transferrable
- Some research OSs (e.g., Hydra) have fine-grained support for tokens
  - Caller gives callee procedure only minimal set of tokens
- Answer questions from previous slide for capabilities

Combined usage of ACLs and cap.

- In some scenarios, it makes sense to use both ACLs and capabilities
  - Why?
- In a UNIX file system, each file has an ACL, which is consulted when executing an open() call
- If approved, caller is given a capability listing type of access allowed in ACL (read or write)
  - Capability is stored in memory space of OS
- Upon read()/write() call, OS looks at capability to determine whether type of access is allowed
- Problem with this approach?

Role-based access control (RBAC)

- In a company, objects that a user can access often do not depend on the identity of the user, but on the user's job function (role) within the company
  - Salesperson can access customers' credit card numbers, marketing person only customer names
- In RBAC, administrator assigns users to roles and grants access rights to roles
  - Sounds similar to groups, but groups are less flexible
- When a user takes over new role, need to update only her role assignment, not all her access rights
- Available in many commercial databases

RBAC extensions

- RBAC also supports more complex access control scenarios
- Hierarchical roles
  - "A manager is also an employee"
  - Reduces number of role/access rights assignments
- Users can have multiple roles and assume/give up roles as required by their current task
  - "Alice is a manager for project A and a tester for project B"
  - User's current session contains currently initiated role
- Separation of Duty
  - "A payment order needs to be signed by both a manager and an accounting person, where the two cannot be the same person"

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User authentication

- Computer systems often have to identify and authenticate users before authorizing them
- Identification: Who are you?
- Authentication: Prove it!
- Identification and authentication is easy among people that know each other
  - For your friends, you do it based on their face or voice
- More difficult for computers to authenticate people sitting in front of them
- Even more difficult for computers to authenticate people accessing them remotely

Authentication factors

- ThreeFour classes of authentication factors
- Something the user knows
  - Password, PIN, answer to "secret question"
- Something the user has
  - ATM card, badge, browser cookie, physical key, uniform
- Something the user is
  - Biometrics (fingerprint, voice pattern, face,...)
  - Have been used by humans forever, but only recently by computers
- Something about the user's context
  - Location, time

Combination of auth. factors

- Different classes of authentication factors can be combined for more solid authentication
  - Two- or multi-factor authentication
- Using multiple factors from the same class might not provide better authentication
- "Something you have" can become "something you know"
  - Token can be easily duplicated, e.g., magnetic strip on ATM card
  - Token ("fob") displays number that changes over time and that needs to be entered for authentication
    - Malware can intercept number, see optional reading

Passwords

- Probably oldest authentication mechanism used in computer systems
- User enters user ID and password, maybe multiple attempts in case of error
- Usability problems
    - Forgotten passwords might not be recoverable (though this has been changing recently, see later)
    - Entering passwords is inconvenient
    - If password is disclosed to unauthorized individual, the individual can immediately access protected resource
        - Unless we use multi-factor authentication
    - If password is shared among many people, password updates become difficult

Password guessing attacks

- Brute-force: Try all possible passwords using exhaustive search
- Can test 350,000 Microsoft Word passwords per second on a 3-GHz Pentium 4
- For passwords of length 8 consisting only of letters, there are about $2 \cdot 10^{11}$ possibilities
- Takes 600,000 seconds or 166 hours to test them
  - Expected wait till success is 83 hours
- Easy to buy more hardware if payoff is worth it
  - Parallelizing search and running it on Graphics Processing Unit can achieve a speedup of 25
- Can make attack harder by including digits and special characters in password
- However,. . .

Password guessing attacks

- …exhaustive search assumes that people choose passwords randomly, which is often not the case
- Attacker can do much better by exploiting this
- For example, Password Recovery Toolkit (PRTK) assumes that a password consists of a root and a pre- or postfix appendage
  - "password1", "abc123", "123abc"
- Root is taken from dictionaries (names, English words, …)
- Appendage is two-digit combination, date, single symbol, …
- PRTK could have cracked 55% of 34,000 leaked MySpace passwords in 8 hours
  - Even though passwords turned out to better than passwords from previous studies

Password guessing attacks

- So should we just give up on passwords?
- Attack requires that attacker has encrypted password file or encrypted document
  - Offline attack
- Instead, attacker might want to guess your banking password by trying to log in to your bank's website
  - Online attack
- Online guessing attacks are detectable
  - Bank shuts down online access to your bank account after n failed login attempts (typically $n \leq 5$)
  - But! How can an attacker circumvent this lockout?

Choosing good passwords

- Use letters, numbers and special characters
- Choose long passwords
  - At least eight characters
- Avoid guessable roots
- If supported, use pass phrase
  - Mix upper and lower case, introduce misspellings and special characters
  - Avoid common phrases (e.g., advertisement slogans)

Password hygiene

- Writing down passwords is more secure than storing many passwords on a networked computer or re-using same password across multiple sites
  - Unreasonable to expect users to remember long passwords, especially when changed often
  - Requires physical security for password sheet, don't use sticky notes
- Change passwords regularly
  - Especially if shorter than eight characters
  - Should users be forced to change their password?
  - Leads to password cycling and similar
    - "myFavoritePwd" -> "dummy" -> "myFavoritePwd"
    - goodPwd."1" -> goodPwd."2" -> goodPwd."3"

Password hygiene

- Don't reveal passwords to others
    - In email or over phone
        - If your bank really wants your password over the phone, switch banks
    - Studies have shown that people disclose passwords for a cup of coffee, chocolate, or nothing at all
        - Caveat of these studies?
- Don't enter password that gives access to sensitive information on a public computer (e.g., Internet café)
    - Don't do online banking on them
    - While traveling, forward your email to a free Webmail provider and use throwaway (maybe weak) password

Attacks on password files

- Website/computer needs to store information about a password in order to validate entered password

- Storing passwords in plaintext is dangerous, even when file is read protected from regular users
  - Password file might end up on backup tapes
  - Intruder into OS might get access to password file
  - System administrator has access to file and might use passwords to impersonate users at other sites
    - Many people re-use passwords across multiple sites

Defending against attacks

- Store only a digital fingerprint of the password (using a cryptographic hash, see later) in the password file
- When logging in, system computes fingerprint of entered password and compares it with user's stored fingerprint
- Still allows guessing attacks when password file leaks

Defending against attacks

- UNIX makes guessing attacks harder by including user-specific salt in the password fingerprint
  - Salt is initially derived from time of day and process ID of /bin/passwd
  - Salt is then stored in the password file in plaintext
- Two users who happen to have the same password will likely have different fingerprints
- Makes guessing attacks harder, can't just build a single table of fingerprints and passwords and use it for any password file

Defending against attacks

- Store an encrypted version of the password in the password file
- Need to keep encryption key away from attacker
- As opposed to fingerprints, this approach allows system to (easily) re-compute password if necessary
    - E.g., have system email password to predefined email address when user forgets password
    - Has become the norm for many websites
    - In fact, some people use this reminder mechanism whenever they want to log in to a website

Interception attacks

- Attacker intercepts password while it is in transmission from client to server
- One-time passwords make intercepted password useless for later logins
  - Fobs (see earlier)
  - Challenge-response protocols

Challenge-response protocols

- Server sends a random challenge to a client
- Client uses challenge and password to compute a one-time password
- Client sends one-time password to server
- Server checks whether client's response is valid
- Given intercepted challenge and response, attacker might be able to brute-force password

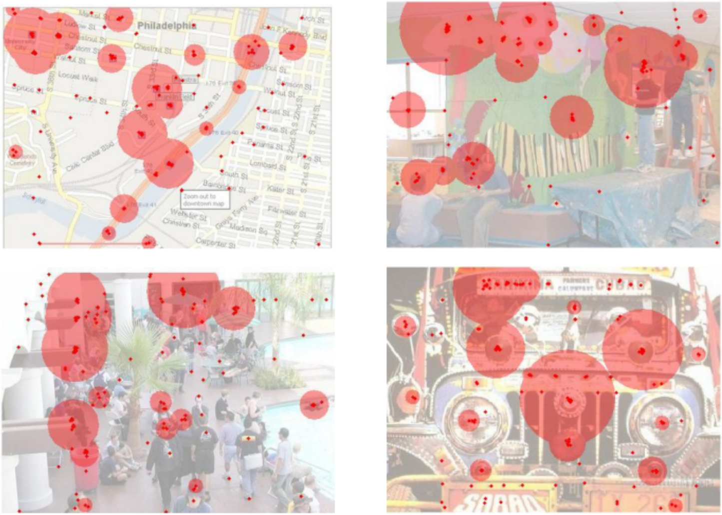
Interception attacks

- There are cryptographic protocols (e.g., SRP) that make intercepted information useless to an attacker
- On the web, passwords are transmitted mostly in plain
  - Sometimes, digital fingerprint of them
  - Encryption (TLS, see later) protects against interception attacks on the network
- Alternative solutions are difficult to deploy
  - Patent issues, changes to HTTP protocol, hardware
- And don't help against interception on the client side
  - Malware

Graphical passwords

- Graphical passwords are an alternative to text-based passwords
- Multiple techniques, e.g.,
    - User chooses a picture; to log in, user has to re-identify this picture in a set of pictures
    - User chooses set of places in a picture; to log in, user has to click on each place
- Issues similar to text-based passwords arise
    - E.g., choice of places is not necessarily random
- Shoulder surfing becomes a problem
- Ongoing research

Graphical passwords



http://www.usenix.org/events/sec07/tech/thorpe.html

Server authentication

- With the help of a password, system authenticates user (client)
- But user should also authenticate system (server) else password might end up with attacker!
- Classic attack:
  - Program displays fake login screen
  - When user "logs in", programs prints error message, sends captured user ID/password to attacker, and ends current session (which results in real login screen)
  - That's why Windows trains you to press <CTRL-ALT-DELETE> for login, key combination cannot be overridden by attacker
- Today's attack:
  - Phishing

Biometrics

- Biometrics have been hailed as a way to get rid of the problems with password and token-based authentication
- Unfortunately, they have their own problems
- Idea: Authenticate user based on physical characteristics
  - Fingerprints, iris scan, voice, handwriting, typing pattern,...
- If observed trait is sufficiently close to previously stored trait, accept user
  - Observed fingerprint will never be completely identical to a previously stored fingerprint of the same user

Local vs. remote authentication

- Biometrics work well for local authentication, but are less suited for remote authentication or for identification
- In local authentication, a guard can ensure that:
  - I put my own finger on a fingerprint scanner, not one made out of gelatin
    - MythBusters demonstrated how easy it is to fool a fingerprint scanner
  - I stand in front of a camera and don't just hold up a picture of somebody else
- In remote authentication, this is much more difficult

Authentication vs. identification

- Authentication: Does a captured trait correspond to a particular stored trait?
- Identification: Does a captured trait correspond to any of the stored traits?
  - Identification is an (expensive) search problem, which is made worse by the fact that in biometrics, matches are based on closeness, not on equality (as for passwords)
- False positives can make biometrics-based identification useless
  - False positive: Alice is accepted as Bob
  - False negative: Alice is incorrectly rejected as Alice

Biometrics-based identification

- Example (from Bruce Schneier's "Beyond Fear"):
  - Face-recognition software with (unrealistic) accuracy of 99.9% is used in a football stadium to detect terrorists
    - 1-in-1,000 chance that a terrorist is not detected
    - 1-in-1,000 chance that innocent person is flagged as terrorist
  - If one in 10 million stadium attendees is a known terrorist, there will be 10,000 false alarms for every real terrorist
  - Remember "The Boy Who Cried Wolf"?
- After pilot study, German FBI recently concluded that this kind of surveillance is useless
  - Average detection accuracy was 30%

Other problems with biometrics

- Privacy
  - Why should my employer (or a website) have information about my fingerprints, iris,..?
    - Aside: Why should a website know my date of birth, my mother's maiden name,... for "secret questions"?
  - What if this information leaks? Getting a new password is easy, but much more difficult for biometrics
- Accuracy: False negatives are annoying
  - What if there is no other way to authenticate?
  - What if I grow a beard, hurt my finger,...?
- Secrecy: Some of your biometrics are not particularly secret
  - Face, fingerprints,...

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Trusted operating systems

- Trusting an entity means that if this entity misbehaves, the security of the system fails
- We trust an OS if we have confidence that it provides security services, i.e.,
  - Memory and file protection
  - Access control and user authentication
- Typically a trusted operating system builds on four factors:
  - Policy: A set of rules outlining what is secured and why
  - Model: A model that implements the policy and that can be used for reasoning about the policy
  - Design: A specification of how the OS implements the model
  - Trust: Assurance that the OS is implemented according to design

Trusted software

- Software that has been rigorously developed and analyzed, giving us reason to trust that the code does what it is expected to do and nothing more
- Functional correctness
  - Software works correctly
- Enforcement of integrity
  - Wrong inputs don't impact correctness of data
- Limited privilege
  - Access rights are minimized and not passed to others
- Appropriate confidence level
  - Software has been rated as required by environment
- Trust can change over time, e.g., based on experience

Security policies

- Many OS security policies have their roots in military security policies
  - That's where lots of research funding came from
- Each object/subject has a sensitivity/clearance level
  - "Top Secret" > "Secret" > "Confidential" > "Unclassified"

    where ">" 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 $\geq$ o"

Example

- 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”?
- Which documents can he read?

Commercial security policies

- Rooted in military security policies
- Different classification levels for information
  - E.g., external vs. internal
- Different departments/projects can call for need-to-know restrictions
- Assignment of people to clearance levels typically not as formally defined as in military
  - Maybe on a temporary/ad hoc basis

Other security policies

- So far we've looked only at confidentiality policies
- Integrity of information can be as or even more important than its confidentiality
  - E.g., Clark-Wilson Security Policy
  - Based on well-formed transactions that transition system from a consistent state to another one
  - Also supports Separation of Duty (see RBAC slides)
- Another issue is dealing with conflicts of interests
  - Chinese Wall Security Policy
  - Once you've decided for a side of the wall, there is no easy way to get to the other side

Chinese Wall security policy

- 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
- 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

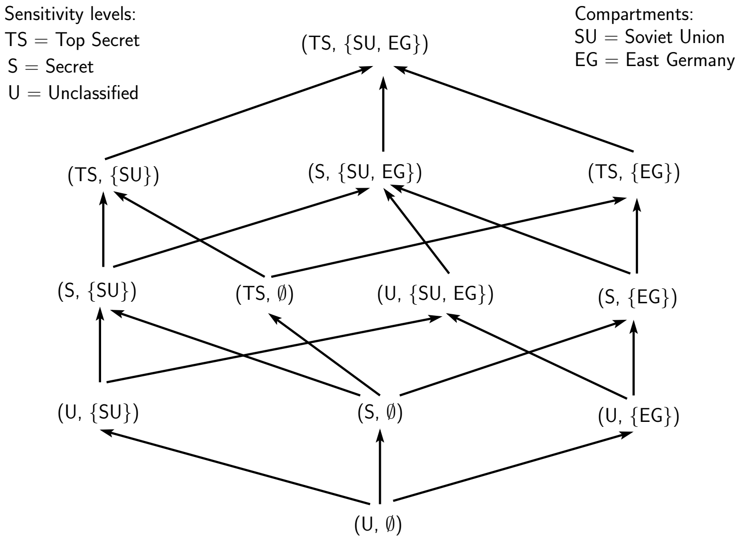
Security models

- Many security models have been defined and interesting properties about them have been proved
- Unfortunately, for many models, their relevance to practically used security policies is not clear
- We'll focus on two prominent models
  - Bell-La Padula Confidentiality Model
  - Biba Integrity Model
  - See text for others
- Targeted at Multilevel Security (MLS) policies, where subjects/objects have clearance/classification levels

Lattices

- Dominance relationship $\geq$ defined in military security model is transitive and antisymmetric
- Therefore, it defines a partial order (neither a $\geq$ b nor b $\geq$ a might hold for two levels a and b)
- In a lattice, for every a and b, there is a unique lowest upper bound u for which u $\geq$ a and u $\geq$ b and a unique greatest lower bound l for which a $\geq$ l and b $\geq$ l
- There are also two elements U and L that dominate/are dominated by all levels
  - U = ("Top Secret", {"Soviet Union", "East Germany"})
    L = ("Unclassified", $\emptyset$)

Example lattice



Bell-La Padula confidentiality model

- Regulates information flow in MLS policies, e.g., lattice-based ones
- Users should get information only according to their clearance
- Should subject s with clearance C(s) have access to object o with classification C(o)?
- Underlying principle: Information can only flow up
- ss-property ("no read up"): s should have read access to o only if $C(s) \geq C(o)$
- *-property ("no write down"): s should have write access to o only if $C(o) \geq C(s)$

Example

- No read up is straightforward
- No write down avoids the following leak:
  - James Bond reads secret document and summarizes it in a confidential document
  - Miss Moneypenny with clearance “confidential” now gets access to secret information
- In practice, subjects are programs (acting on behalf of users)
  - Else James Bond couldn’t even talk to Miss Moneypenny
  - If program accesses secret information, OS ensures that it can’t write to confidential file later
  - Even if program does not leak information
  - Might need explicit declassification operation for usability purposes

Biba integrity model

- Prevent inappropriate modification of data
- 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?
- Write access: s can modify o only if $I(s) \geq I(o)$
  - Unreliable person cannot modify file containing high integrity information
- Read access: s can read o only if $I(o) \geq I(s)$
  - Unreliable information cannot "contaminate" subject

Low Watermark Property

- Biba's access rules are very restrictive, a subject cannot ever view 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 prove 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

Information flow control

- An information flow policy describes authorized paths along which information can flow
- For example, Bell-La Padula describes a lattice-based information flow policy
- In compiler-based information flow control, a compiler checks whether the information flow in a program could violate an information flow policy
- How does information flow from a variable x to a variable y?
- Explicit flow: E.g., `y:= x;` or `y:= x / z;`
- Implicit flow: `If x = 1 then y := 0; else y := 1`

Information flow control (cont.)

- See text for other sample statements
- Input parameters of a program have a (lattice-based) security classification associated with them
- Compiler then goes through the program and updates the security classification of each variable depending on the individual statements that update the variable (using dynamic BLP/Biba)
- Ultimately, a security classification for each variable that is output by the program is computed
- User (more likely, another program) is allowed to see this output only if allowed by the user's (program's) security classification

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Trusted system design elements

- Design must address which objects are accessed how and which subjects have access to what
  - As defined in security policy and model
- Security must be part of design early on
  - Hard to retrofit security, see Windows 95/98
- Eight design principles for security
- Least privilege
  - Operate using fewest privileges possible
- Economy of mechanism
  - Protection mechanism should be simple and straightforward
- Open design
  - Avoid security by obscurity
  - Secret keys or passwords, but not secret algorithms

Security design principles (cont.)

- Complete mediation
  - Every access attempt must be checked
- Permission based / Fail-safe defaults
  - Default should be denial of access
- Separation of privileges
  - Two or more conditions must be met to get access
- Least common mechanism
  - Every shared mechanism could potentially be used as a covert channel
- Ease of use
  - If protection mechanism is difficult to use, nobody will use it or it will be used in the wrong way

Security features of trusted OS

- Identification and authentication
  - See earlier
- Access control
- Object reuse protection
- Complete mediation
- Trusted path
- Accountability and audit
- Intrusion detection

Access control

- Mandatory access control (MAC)
  - Central authority establishes who can access what
  - Good for military environments
  - For implementing Chinese Wall, Bell-La Padula, Biba
- Discretionary access control (DAC)
  - Owners of an object have (some) control over who can access it
  - You can grant others access to your home directory
  - In UNIX, Windows,...
- RBAC is neither MAC nor DAC
- Possible to use combination of these mechanisms

Object reuse protection

- Alice allocates memory from OS and stores her password in this memory
- After using password, she returns memory to OS
  - By calling free() or simply by exiting procedure if memory is allocated on stack
- Later, Bob happens to be allocated the same piece of memory and he finds Alice's password in it
- OS should erase returned memory before handing it out to other users
- Defensive programming: Erase sensitive data yourself before returning it to OS
  - How can compiler interfere with your good intentions?
- Similar problem exists for files, registers and storage media

Hidden data

- Hidden data is related to object reuse protection
- You think that you deleted some data, but it is still hidden somewhere
  - Deleting a file will not physically erase file on disk
  - Deleting an email in GMail will not remove email from Google's backups
  - Deleting text in MS Word might not remove text from document
  - Putting a black box over text in a PDF leaves text in PDF
  - Shadow Copy feature of Windows Vista keeps file snapshots to enable restores

Complete mediation / trusted path

- Complete mediation
  - All accesses must be checked
  - Preventing access to OS memory is of little use if it is possible to access the swap space on disk
- Trusted path
  - Give assurance to user that her keystrokes and mouse clicks are sent to legitimate receiver application
  - Remember the fake login screen?
  - Turns out to be quite difficult for existing desktop environments, both Linux and Windows
    - Don't run sudo if you have an untrusted application running on your desktop

Accountability and audit

- Keep an audit log of all security-related events
- Provides accountability if something goes bad
  - Who deleted the sensitive records in the database?
  - How did the intruder get into the system?
- An audit log does not give accountability if attacker can modify the log
- At what granularity should events be logged?
  - For fine-grained logs, we might run into space/efficiency problems or finding actual attack can be difficult
  - For coarse-grained logs, we might miss attack entirely or don't have enough details about it

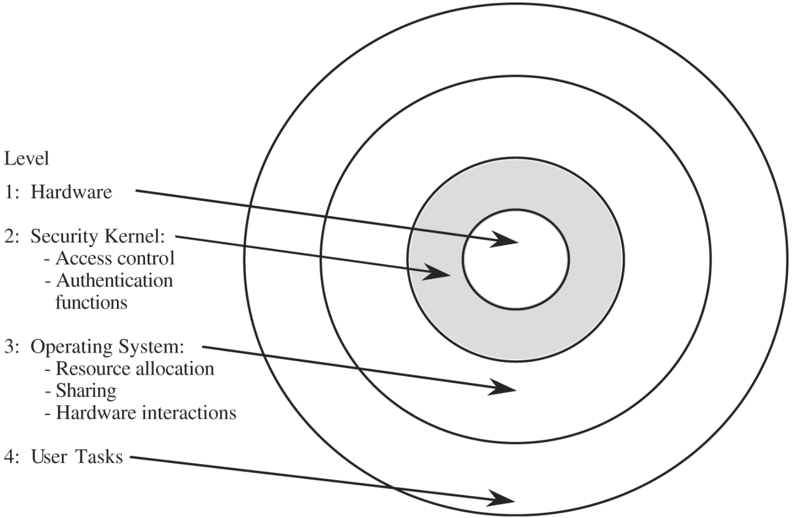
Intrusion detection

- There shouldn't be any intrusions in a trusted OS
- However, writing bug-free software is hard, people make configuration errors,...
- Audit logs might give us some information about an intrusion
- Ideally, OS detects an intrusion as it occurs
- Typically, by correlating actual behaviour with normal behaviour
- Alarm if behaviour looks abnormal
- See later in Network Security module

Trusted computing base (TCB)

- Part of a trusted OS that is necessary to enforce OS security policy
  - Changing non-TCB part of OS won't affect OS security, changing its TCB-part will
  - TCB better be complete and correct
- TCB can be implemented either in different parts of the OS or in a separate security kernel
- Separate security kernel makes it easier to validate and maintain security functionality
- Security kernel runs below the OS kernel, which makes it more difficult for an attacker to subvert it

Security kernel



Rings

- Some processors support this kind of layering based on “rings”
- If processor is operating in ring n, code can access only memory and instructions in rings $\geq$ n
- Accesses to rings $<$ n trigger interrupt/exception and inner ring will grant or deny access
- x86 architecture supports four rings, but Linux and Windows use only two of them
    - user and supervisor mode
    - i.e., don’t have security kernel
- Some research OSs (Multics, SCOMP) use more

Reference monitor

- Crucial part of the TCB
- Collection of access controls for devices, files, memory, IPC,. . . ,
- Not necessarily a single piece of code
- Must be tamperproof, unbypassable and analyzable
- Interacts with other security mechanism, e.g., user authentication

Virtualization

- Virtualization is a way to provide logical separation (isolation)
- Different degrees of virtualization
- Virtual memory
  - Page mapping gives each process the impression of having a separate memory space
- Virtual machines
  - Also virtualize I/O devices, files, printers,...
  - Currently very popular (VMware, Xen, Parallels,...)
  - If Web browser runs in a virtual machine, browser-based attacks are limited to the virtual environment
  - On the other hand, a rootkit could make your OS run in a virtual environment and be very difficult to detect ("Blue Pill")

Least privilege in popular OSs

- Pretty poor
- Windows pre-NT: any user process can do anything
- Windows pre-Vista: fine-grained access control. However, in practice, many users just ran as administrators, which can do anything
  - Some applications even required it
- Windows Vista
  - Easier for users to temporarily acquire additional access rights ("User Account Control")
  - Integrity levels, e.g., Internet Explorer is running at lowest integrity level, which prevents it from writing up and overwriting all a user's files

Least privilege in popular OSs (cont.)

- Traditional UNIX: a root process has access to anything, a user process has full access to user's data
- SELinux and AppArmor provide Mandatory Access Control (MAC) for Linux, which allows the implementation of least privilege
  - No more root user
  - Support both confidentiality and integrity
  - Difficult to set up
- Other, less invasive approaches for UNIX
  - Chroot, compartmentalization, SUID (see next slides)
- What about the iPhone?

Chroot

- Sandbox/jail a command by changing its root directory
  - `chroot /new/root command`
- Command cannot access files outside of its jail
- Some commands/programs are difficult to run in a jail
- But there are ways to break out of the jail

Compartmentalization

- Split application into parts and apply least privilege to each part
- OpenSSH splits SSH daemon into a privileged monitor and an unprivileged, jailed child
  - Confusingly, this option is called UsePrivilegeSeparation. But this is different from Separation of Privileges (see earlier)
- Child receives (maybe malicious) network data from a client and might get corrupted
- Child needs to contact monitor to get access to protected information (e.g., password file)
  - Small, well-defined interface
  - Makes it much more difficult to also corrupt monitor
- Monitor shuts down child if behaviour is suspicious

setuid/suid bit

- In addition to bits denoting read, write and execute access rights, UNIX ACLs also contain an suid bit
- If suid bit is set for an executable, the executable will execute under the identity of its owner, not under the identity of the caller
  - /usr/bin/passwd belongs to root and has suid bit set
  - If a user calls /usr/bin/passwd, the program will assume the root identity and can thus update the password file
- Make sure to avoid "confused deputy" attack
  - Eve executes /usr/bin/passwd and manages to convince the program that it is Alice who is executing the program. Eve can thus change Alice's password

Assurance

- How can we convince others to trust our OS?
- Testing
  - Can demonstrate existence of problems, but not their absence
  - Might be infeasible to test all possible inputs
  - Penetration testing: Ask outside experts to break into your OS
- Formal verification
  - Use mathematical logic to prove correctness of OS
  - Has made lots of progress recently
  - Unfortunately, OSs are probably growing faster in size than research advances

Assurance (cont.)

- Validation
    - Traditional software engineering methods
    - Requirements checking, design and code reviews, system testing

Evaluation

- Have trusted entity evaluate OS and certify that OS satisfies some criteria
- Two well-known sets of criteria are the "Orange Book" of the U.S. Department of Defense and the Common Criteria
- Orange Book lists several ratings, ranging from "D" (failed evaluation, no security) to "A1" (requires formal model of protection system and proof of its correctness, formal analysis of covert channels)
  - See text for others
  - Windows NT has C2 rating, but only when it is not networked and with default security settings changed
  - Most UNIXes are roughly C1

Common criteria

- Replace Orange Book, more international effort
- Have Protection Profiles, which list security threats and objectives
- Products are rated against these profiles
- Ratings range from EAL 1 (worst) to EAL 7 (best)
- Windows XP has been rated EAL 4+ for the Controlled Access Protection Profile (CAPP), which is derived from Orange Book's C2
  - Interestingly, the continuous release of security patches for Windows XP does not affect its rating

Recap

- Protection in general-purpose operating systems
- User authentication
- Security policies and models
- Trusted operating system design