Last time

- Controls against security flaws in programs
- Various controls applicable to each of the stages in the software development lifecycle
- To get the best chance of controlling all of the flaws:
  - Standards describing the controls to be used
  - Processes implementing the standards
  - Audits ensuring adherence to the processes

Security controls—Documentation

- How can we control security vulnerabilities through the use of documentation?

- Write down the choices you made
  - And why you made them
- Just as importantly, write down things you tried that didn't work!
  - Let future developers learn from your mistakes
- Make checklists of things to be careful of
  - Especially subtle and non-obvious security-related interactions of different components

Security controls—Maintainance

- By the time the program is out in the field, one hopes that there are no more security flaws
  - But there probably are
- We've talked about ways to control flaws when modifying programs
  - Change management, code review, testing, documentation
- Is there something we can use to try to limit the number of flaws that make it out to the shipped product in the first place?

Standards, process, and audit

- Within an organization, have rules about how things are done at each stage of the software lifecycle
- These rules should incorporate the controls we've talked about earlier
- These are the organization's standards
- For example:
  - What design methodologies will you use?
  - What kind of implementation diversity?
  - Which change management system?
  - What kind of code review?
  - What kind of testing?

Standards, process, and audit

- Make formal processes specifying how each of these standards should be implemented
  - For example, if you want to do a guided code review, who explains the code to whom? In what kind of forum? How much detail?
- Have audits, where somebody (usually external to the organization) comes in and verifies that you're following your processes properly
- This doesn't guarantee flaw-free code, of course!

This time

- Protection in General-Purpose Operating Systems
  - History
  - Separation vs. Sharing
  - Segmentation and Paging
  - Access Control Matrix
  - Access Control Lists vs. Capabilities

Operating System

- 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

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 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

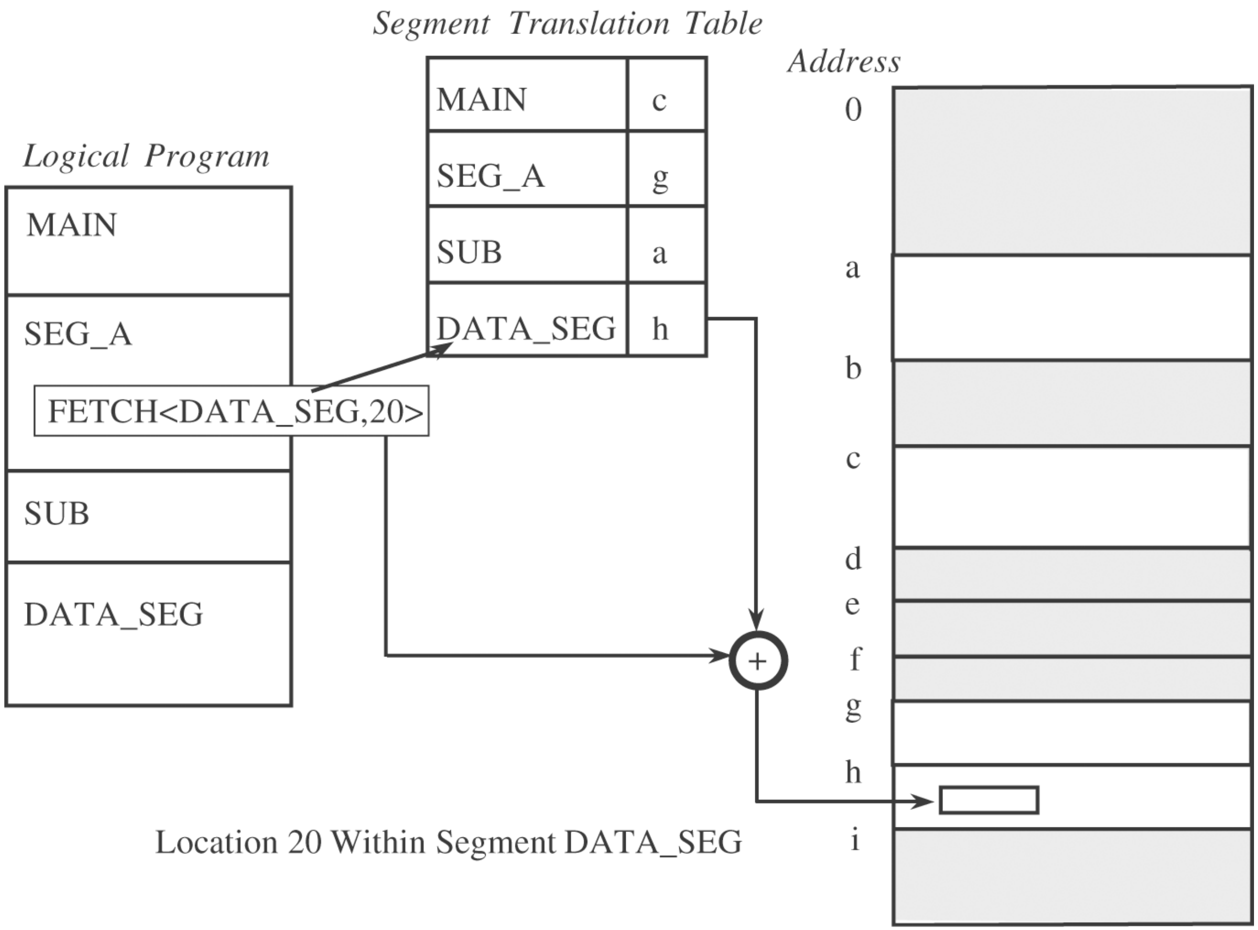
- Tagged architecture
  - Each memory word has one or more extra bits that identify access rights to word
  - Very flexible
  - Large overhead
  - Difficult to port OS from/to other hardware architectures
- Segmentation
- Paging

Segmentation

- Each program has multiple address spaces (segments)
- Could use 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
- OS can (transparently) relocate or resize segments and share them between processes
- Each segment has its own memory protection attributes

Segment Table



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), no out-of-bounds possible for offset
- OS keeps mapping from page # to its base physical address in Page Table
- Each page has its own memory protection attributes

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 provides both segmentation and paging
  - Linux uses a combination of segmentation and paging
    - Only simple form of segmentation to avoid portability issues
    - Segmentation cannot be turned off on x86
  - Same for Windows
- 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
  - Helps against some buffer overflows

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
    - Examples?
  - 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 hardly ever implemented as a matrix
  - Matrix would likely be sparse
  - Updates would likely be tedious
- 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
  - E.g., 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
  - E.g., Alice: {File 1:orw}, {File 2:rx}, {File 3:o}
- Unforgeability enforced by having OS store and maintain tokens or by cryptographic mechanisms
  - One such mechanism, digital signatures (see later), allows tokens to be handed out to processes/users. OS will detect tampering when process/user tries to get access with modified token.
- Owner of token might be allowed to transfer token to others
- Some research OSs (e.g., Hydra) have fine-grained support for tokens
  - Caller gives callee procedure only minimal set of tokens required
- 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
  - E.g., for efficiency reasons
- 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
- We cannot withdraw access from a user if user has already opened file

Recap

- Protection in General-Purpose Operating Systems
  - History
  - Separation vs. Sharing
  - Segmentation and Paging
  - Access Control Matrix
  - Access Control Lists vs. Capabilities

Next time

- Role-Based Access Control
- User Authentication
  - Authentication Factors
  - Passwords
  - Attacks on Passwords
  - Biometrics