Secure Architecture Principles

- Isolation and Least Privilege
- Access Control Concepts
- Operating Systems
- Browser Isolation and Least Privilege

Acknowledgments: Lecture slides are from the Computer Security course taught by Dan Boneh and John Mitchell at Stanford University. When slides are obtained from other sources, a reference will be noted on the bottom of that slide. A full list of references is provided on the last slide.
Secure Architecture Principles

Isolation and Least Privilege
Principles of Secure Design

• Compartamentalization
  – Isolation
  – Principle of least privilege

• Defense in depth
  – Use more than one security mechanism
  – Secure the weakest link
  – Fail securely

• Keep it simple
Principle of Least Privilege

• What’s a privilege?
  – Ability to access or modify a resource
• Assume compartmentalization and isolation
  – Separate the system into isolated compartments
  – Limit interaction between compartments
• Principle of Least Privilege
  – A system module should only have the minimal privileges needed for its intended purposes
Principle of Least Privilege

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Monolithic design

System

Network
User input
File system

Network
User device
File system
Monolithic design

Network
User input
File system

System

Network
User device
File system
Monolithic design

- Network
- User input
- File system

Network
User device
File system
Component design

- Network
- User input
- File system
- Network
- User device
- File system
Component design

Network → User input → File system → Network

User device

File system
Component design

Network → Component design → Network
User input → Component design → User device
File system → Component design → File system
Principle of Least Privilege

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Example: Mail Agent

- **Requirements**
  - Receive and send email over external network
  - Place incoming email into local user inbox files
- **Sendmail**
  - Traditional Unix
  - Monolithic design
  - Historical source of many vulnerabilities
- **Qmail**
  - Compartamentalized design
OS Basics (before examples)

- Isolation between processes
  - Each process has a UID
    - Two processes with same UID have same permissions
      - A process may access files, network sockets, ...
        - Permission granted according to UID
  - Relation to previous terminology
    - Compartment defined by UID
    - Privileges defined by actions allowed on system resources
Qmail design

• Isolation based on OS isolation
  – Separate modules run as separate “users”
  – Each user only has access to specific resources

• Least privilege
  – Minimal privileges for each UID
  – Only one “setuid” program
    • setuid allows a program to run as different users
  – Only one “root” program
    • root program has all privileges
Structure of qmail

- qmail-smtpd
- qmail-local
- qmail-remote
- qmail-lspawn
- qmail-rspawn
- qmail-send
- qmail-queue
- qmail-inject

Incoming external mail

Incoming internal mail
Isolation by Unix UIDs

qmailq – user who is allowed to read/write mail queue
Structure of qmail

- **qmail-smtpd**
  - Reads incoming mail directories
  - Splits message into header, body
  - Signals qmail-send

- **qmail-queue**

- **qmail-send**

- **qmail-rspawn**

- **qmail-remote**

- **qmail-lspawn**

- **qmail-local**

- **qmail-inject**
Structure of qmail

- **qmail-smtpd**
- **qmail-local**
- **qmail-remote**
- **qmail-lspawn**
- **qmail-rspawn**
- **qmail-send**
- **qmail-queue**
- **qmail-inject**

**qmail-send signals**
- qmail-lspawn if local
- qmail-remote if remote
Structure of qmail

- qmail-smtpd
- qmail-queue
- qmail-send
- qmail-inject

qmail-lspawn
- Spawns qmail-local
- qmail-local runs with ID of user receiving local mail
Structure of qmail

- qmail-smtpd
- qmail-queue
- qmail-send
- qmail-lspawn
- qmail-local
  - Delivers local mail
Structure of qmail

- qmail-smtpd
- qmail-queue
- qmail-send
- qmail-rspawn
- qmail-remote
- qmail-inject

qmail-remote
- Delivers message to remote MTA
Isolation by Unix UIDs

qmailq – user who is allowed to read/write mail queue

setuid user who is allowed to read/write mail queue

qmail-d

qmail-smtpd

qmail-local

qmail-remote

qmail-send

qmail-inject

qmail-queue

qmail-send

qmail-lspawn

qmail-rspawn

qmail-send

qmail-local

root

setuid user

John Mitchell
Android process isolation

• Android application sandbox
  – Isolation: Each application runs with its own UID in own VM
    • Provides memory protection
    • Communication limited to using Unix domain sockets
    • Zygote (spawn another process) run as root
  – Interaction: reference monitor checks permissions on inter-component communication
  – Least Privilege: Applications announces permission
    • User grants access at install time
Discussion?

- Principle of Least Privilege
- Qmail example
- Android app sandbox example
Secure Architecture Principles

Access Control Concepts
Access control

- Assumptions
  - System knows who the user is
    - Authentication via name and password, other credential
  - Access requests pass through gatekeeper (reference monitor)
    - System must not allow monitor to be bypassed
# Access control matrix

![Access control matrix diagram]

The table represents an access control matrix for subjects (users) and objects (files). Each cell indicates the access permissions for a user on an object. For example:

- **User 1** has read access to File 1, write access to File 2, and read access to File n.
- **User 2** has write access to all files.
- **User 3** has read access to both File 2 and File 3.
- **User m** has read access to File 1, write access to File 2, read access to File 3, write access to File n, and read access to File n.

The matrix is organized with subjects listed in the left column and objects listed at the top. Access permissions are indicated in the cells.
Implementation concepts

- Access control list (ACL)
  - Store column of matrix with the resource
- Capability
  - User holds a “ticket” for each resource
  - Two variations
    - store row of matrix with user, under OS control
    - unforgeable ticket in user space

| User   | File 1 | File 2 | ...
|--------|--------|--------|--------
| User 1 | read   | write  | -      |
| User 2 | write  | write  | -      |
| User 3 | -      | -      | read   |
| ...    |        |        |        |
| User m | Read   | write  | write  |

Access control lists are widely used, often with groups
Some aspects of capability concept are used in many systems
ACL vs Capabilities

• Access control list
  – Associate list with each object
  – Check user/group against list
  – Relies on authentication: need to know user

• Capabilities
  – Capability is unforgeable ticket
    • Random bit sequence, or managed by OS
    • Can be passed from one process to another
  – Reference monitor checks ticket
    • Does not need to know identify of user/process
ACL vs Capabilities

- User U
  - Process P
    - User U
      - Process Q
        - User U
          - Process R
    - Capability c,d,e
      - Process P
        - Capability c,e
          - Process Q
        - Capability c
          - Process R
    - Capability c,e
      - Process R
ACL vs Capabilities

• Delegation
  – Cap: Process can pass capability at run time
  – ACL: Try to get owner to add permission to list?
    • More common: let other process act under current user

• Revocation
  – ACL: Remove user or group from list
  – Cap: Try to get capability back from process?
    • Possible in some systems if appropriate bookkeeping
      – OS knows which data is capability
      – If capability is used for multiple resources, have to revoke all or none ...
    • Indirection: capability points to pointer to resource
      – If C → P → R, then revoke capability C by setting P=0
Roles (aka Groups)

- Role = set of users
  - Administrator, PowerUser, User, Guest
  - Assign permissions to roles; each user gets permission

- Role hierarchy
  - Partial order of roles
  - Each role gets permissions of roles below
  - List only new permissions given to each role
Role-Based Access Control

Advantage: users change more frequently than roles
Access control summary

• Access control involves reference monitor
  – Check permissions: 〈user info, action〉→ yes/no
  – Important: no way around this check
• Access control matrix
  – Access control lists vs capabilities
  – Advantages and disadvantages of each
• Role-based access control
  – Use group as “user info”; use group hierarchies
Discussion?

• Access control matrix
  – Access control list (ACL)
  – Capabilities
• Role-based access control
Secure Architecture Principles
Operating Systems
Unix access control

- Process has user id
  - Inherit from creating process
  - Process can change id
    - Restricted set of options
    - Special “root” id
      - All access allowed
- File has access control list (ACL)
  - Grants permission to user ids
  - Owner, group, other

<table>
<thead>
<tr>
<th>User</th>
<th>File 1</th>
<th>File 2</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>User 1</td>
<td>read</td>
<td>write</td>
<td>-</td>
</tr>
<tr>
<td>User 2</td>
<td>write</td>
<td>write</td>
<td>-</td>
</tr>
<tr>
<td>User 3</td>
<td>-</td>
<td>-</td>
<td>read</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>User m</td>
<td>Read</td>
<td>write</td>
<td>write</td>
</tr>
</tbody>
</table>
Unix file access control list

• Each file has owner and group
• Permissions set by owner
  – Read, write, execute
  – Owner, group, other
  – Represented by vector of four octal values
• Only owner, root can change permissions
  – This privilege cannot be delegated or shared
• Setid bits - Discuss in a few slides
Process effective user id (EUID)

• Each process has three IDs (+ more under Linux)
  – Real user ID (RUID)
    • same as the user ID of parent (unless changed)
    • used to determine which user started the process
  – Effective user ID (EUID)
    • from set user ID bit on the file being executed, or sys call
    • determines the permissions for process
      – file access and port binding
  – Saved user ID (SUID)
    • So previous EUID can be restored

• Real group ID, effective group ID, used similarly
Process Operations and IDs

• Root
  – ID=0 for superuser root; can access any file

• Fork and Exec
  – Inherit three IDs, except exec of file with setuid bit

• Setuid system call
  – seteuid(newid) can set EUID to
    • Real ID or saved ID, regardless of current EUID
    • Any ID, if EUID=0

• Details are actually more complicated
  – Several different calls: setuid, seteuid, setreuid
Setid bits on executable Unix file

• Three setid bits
  – Setuid - set EUID of process to ID of file owner
  – Setgid - set EGID of process to GID of file
  – Sticky
    • Off: if user has write permission on directory, can rename or remove files, even if not owner
    • On: only file owner, directory owner, and root can rename or remove file in the directory
Example

```
...;
...;
exec( );
```

```
RUID 25
...;
...;
```

```
EUID 18
Owner 18
-rw-r--r--
file
```

```
RUID 25
EUID 25
Owner 25
-rw-r--r--
file
```

```
RUID 25
EUID 25
Owner 18
...;
...;
i=getruid();
setuid(i);
...;
...;
```

```
RUID 25
EUID 18
Owner 18
```

```
RUID 25
EUID 25
Owner 25
```

```
RUID 25
EUID 25
```

```
```

```
```

```
```
Unix summary

• Good things
  – Some protection from most users
  – Flexible enough to make things possible

• Main limitation
  – Too tempting to use root privileges
  – No way to assume some root privileges without all root privileges
Weakness in isolation, privileges

• Network-facing Daemons
  – Root processes with network ports open to all remote parties, e.g., sshd, ftpd, sendmail, ...

• Rootkits
  – System extension via dynamically loaded kernel modules

• Environment Variables
  – System variables such as LIBPATH that are shared state across applications. An attacker can change LIBPATH to load an attacker-provided file as a dynamic library
Weakness in isolation, privileges

• Shared Resources
  – Since any process can create files in /tmp directory, an untrusted process may create files that are used by arbitrary system processes

• Time-of-Check-to-Time-of-Use (TOCTTOU)
  – Typically, a root process uses system call to determine if initiating user has permission to a particular file, e.g. /tmp/X.
  – After access is authorized and before the file open, user may change the file /tmp/X to a symbolic link to a target file /etc/shadow.
Access control in Windows

• Some basic functionality similar to Unix
  – Specify access for groups and users
    • Read, modify, change owner, delete
• Some additional concepts
  – Tokens
  – Security attributes
• Generally
  – More flexible than Unix
    • Can define new permissions
    • Can transfer some but not all privileges (cf. capabilities)
Process has set of tokens

• Security context
  – Privileges, accounts, and groups associated with the process or thread
  – Presented as set of tokens

• Impersonation token
  – Used temporarily to adopt a different security context, usually of another user
Object has security descriptor

- Specifies who can perform what actions on the object
  - Header (revision number, control flags, ...)
  - SID of the object's owner
  - SID of the primary group of the object
  - Two attached optional lists:
    - Discretionary Access Control List (DACL) - users, groups, ...
    - System Access Control List (SACL) - system logs, ..
Example access request

Access token

User: Mark
Group1: Administrators
Group2: Writers

Security descriptor

Revision Number
Control flags
Owner SID
Group SID
DACL Pointer
SACL Pointer

Deny
Writers
Read, Write

Priority:
Explicit Deny
Explicit Allow
Inherited Deny
Inherited Allow

Access request: write
Action: denied

• User Mark requests write permission
• Descriptor denies permission to group
• Reference Monitor denies request
(DACL for access, SACL for audit and logging)
Impersonation Tokens  (compare to setuid)

- Process adopts security attributes of another
  - Client passes impersonation token to server
- Client specifies impersonation level of server
  - Anonymous
    - Token has no information about the client
  - Identification
    - Obtain the SIDs of client and client's privileges, but server cannot impersonate the client
  - Impersonation
    - Impersonate the client on the local system
  - Delegation
    - Lets server impersonate client on local, remote systems
Weakness in isolation, privileges

• Similar problems to Unix
  – E.g., Rootkits leveraging dynamically loaded kernel modules

• Windows Registry
  – Global hierarchical database to store data for all programs
  – Registry entry can be associated with a security context that limits access; common to be able to write sensitive entry

• Enabled By Default
  – Historically, many Windows deployments also came with full permissions and functionality enabled
Secure Architecture Principles

Browser Isolation and Least Privilege
Web browser: an analogy

Operating system

- Subject: Processes
  - Has User ID (UID, SID)
  - Discretionary access control

- Objects
  - File
  - Network
  - ...

- Vulnerabilities
  - Untrusted programs
  - Buffer overflow
  - ...

Web browser

- Subject: web content (JavaScript)
  - Has “Origin”
  - Mandatory access control

- Objects
  - Document object model
  - Frames
  - Cookies / localStorage

- Vulnerabilities
  - Cross-site scripting
  - Implementation bugs
  - ...

The web browser enforces its own internal policy. If the browser implementation is corrupted, this mechanism becomes unreliable.
Components of security policy

• Frame-Frame relationships
  – canScript(A,B)
    • Can Frame A execute a script that manipulates arbitrary/nontrivial DOM elements of Frame B?
  – canNavigate(A,B)
    • Can Frame A change the origin of content for Frame B?

• Frame-principal relationships
  – readCookie(A,S), writeCookie(A,S)
    • Can Frame A read/write cookies from site S?
Chromium Security Architecture

- Browser ("kernel")
  - Full privileges (file system, networking)
- Rendering engine
  - Up to 20 processes
  - Sandboxed
Chromium

Communicating sandboxed components

See: http://dev.chromium.org/developers/design-documents/sandbox/
Design Decisions

• Compatibility
  – Sites rely on the existing browser security policy
  – Browser is only as useful as the sites it can render
  – Rules out more “clean slate” approaches

• Black Box
  – Only renderer may parse HTML, JavaScript, etc.
  – Kernel enforces coarse-grained security policy
  – Renderer to enforces finer-grained policy decisions

• Minimize User Decisions
### Task Allocation

<table>
<thead>
<tr>
<th>Rendering Engine</th>
<th>Browser Kernel</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTML parsing</td>
<td>Cookie database</td>
</tr>
<tr>
<td>CSS parsing</td>
<td>History database</td>
</tr>
<tr>
<td>Image decoding</td>
<td>Password database</td>
</tr>
<tr>
<td>JavaScript interpreter</td>
<td>Window management</td>
</tr>
<tr>
<td>Regular expressions</td>
<td>Location bar</td>
</tr>
<tr>
<td>Layout</td>
<td>Safe Browsing blacklist</td>
</tr>
<tr>
<td>Document Object Model</td>
<td>Network stack</td>
</tr>
<tr>
<td>Rendering</td>
<td>SSL/TLS</td>
</tr>
<tr>
<td>SVG</td>
<td>Disk cache</td>
</tr>
<tr>
<td>XML parsing</td>
<td>Download manager</td>
</tr>
<tr>
<td>XSLT</td>
<td>Clipboard</td>
</tr>
<tr>
<td></td>
<td>Both</td>
</tr>
<tr>
<td>URL parsing</td>
<td></td>
</tr>
<tr>
<td>Unicode parsing</td>
<td></td>
</tr>
</tbody>
</table>
Summary

• Security principles
  – Isolation
  – Principle of Least Privilege
  – Qmail example
• Access Control Concepts
  – Matrix, ACL, Capabilities
• OS Mechanisms
  – Unix: UID, ACL, Setuid
  – Windows: SID, Tokens, Security Descriptor, Impersonation
• Browser security architecture
  – Isolation and least privilege example