Vulnerability Models

ECS 153 Spring Quarter 2021

Module 4

Vulnerability Classification

- Describe flaws from differing perspectives
  - Exploit-oriented
  - Hardware, software, interface-oriented
- Goals vary; common ones are:
  - Specify, design, implement computer system without vulnerabilities
  - Analyze computer system to detect vulnerabilities
  - Address any vulnerabilities introduced during system operation
  - Detect attempted exploitations of vulnerabilities

Example Flaws

- Use these to compare classification schemes
- First one: race condition (*xterm*)
- Second one: buffer overflow on stack leading to execution of injected code (*fingerd*)
- Both are very well known, and fixes available!
  - And should be installed everywhere …

Flaw #1: xterm

- *xterm* emulates terminal under X11 window system
  - Must run as *root* user on UNIX systems
    - No longer universally true; reason irrelevant here
- Log feature: user can log all input, output to file
  - User names file
  - If file does not exist, *xterm* creates it, makes owner the user
  - If file exists, *xterm* checks user can write to it, and if so opens file to append log to it

File Exists

- Check that user can write to file requires special system call
  - Because *root* can append to any file, check in *open* will always succeed

Check that user can write to file "/usr/tom/X"

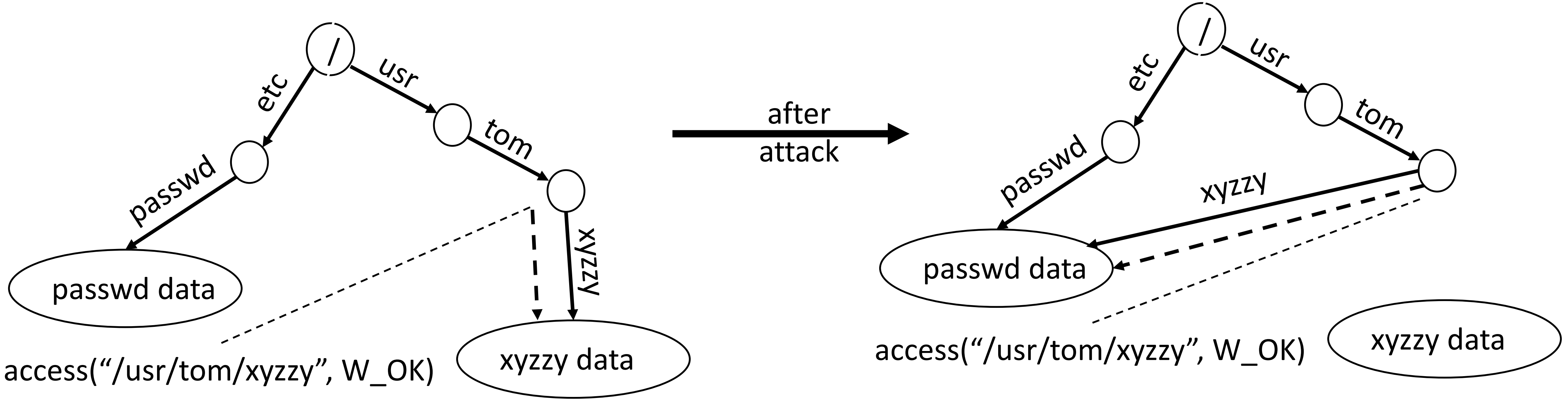
```
if (access("/usr/tom/X", W_OK) == 0){
```

Open "/usr/tom/X" to append log entries

```
 if ((fd = open("/usr/tom/X", O_WRONLY|O_APPEND))< 0){
         /* handle error: cannot open file */
 }
}
```

Problem

- Binding of file name “/usr/tom/X” to file object can change between first and second lines
  - left is at *access*; right is at *open*
  - Note file opened is *not* file checked

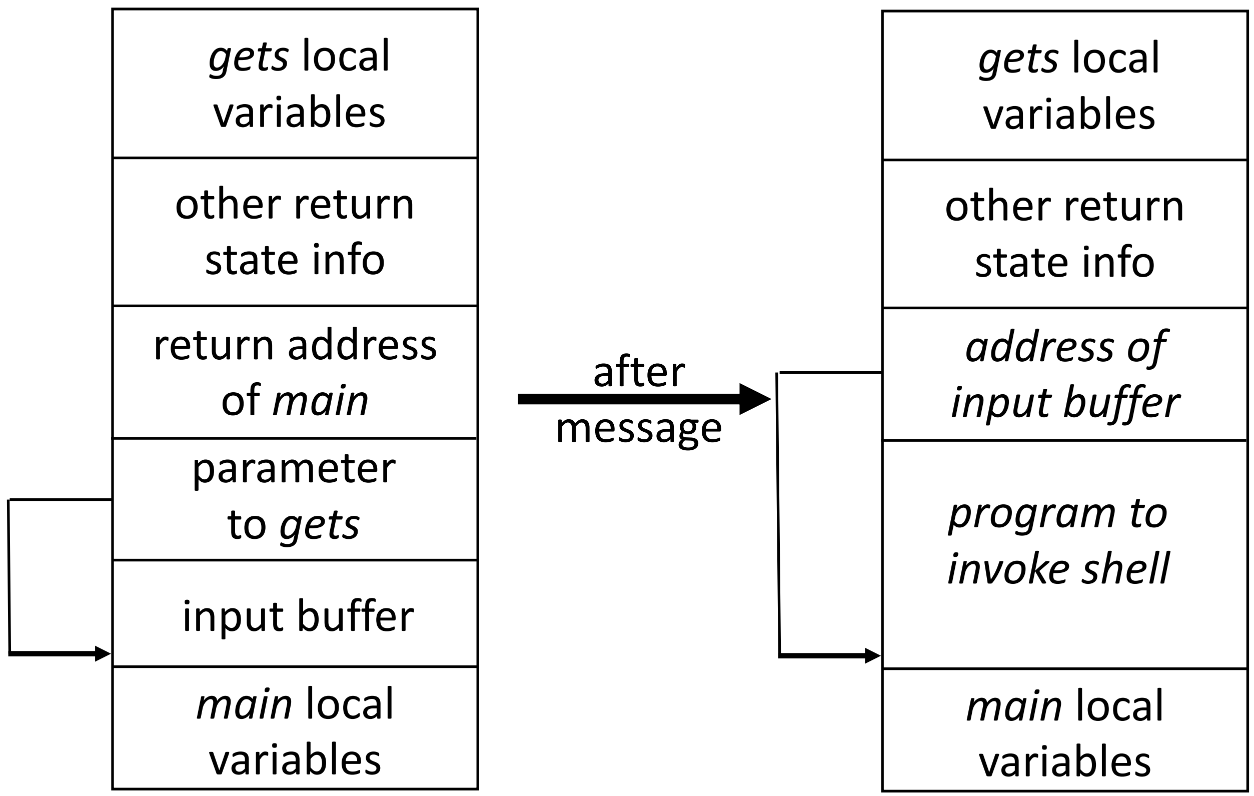


Flaw #2: *fingerd*

- Exploited by Internet Worm of 1988
  - Recurs in many places, even now
- *finger* client send request for information to server *fingerd* (*finger* daemon)
  - Request is name of at most 512 chars
  - What happens if you send more?

Buffer Overflow

- Extra chars overwrite rest of stack, as shown
- Can make those chars change return address to point to beginning of buffer
- If buffer contains small program to spawn shell, attacker gets shell on target system



Frameworks

- Goals dictate structure of classification scheme
  - Guide development of attack tool $\Rightarrow$ focus is on steps needed to exploit vulnerability
  - Aid software development process $\Rightarrow$ focus is on design and programming errors causing vulnerabilities
- Following schemes classify vulnerability as n-tuple, each element of n-tuple being classes into which vulnerability falls
  - Some have 1 axis; others have multiple axes

Research Into Secure Operating Systems (RISOS)

- Goal: aid computer, system managers in understanding security issues in OSes, and help determine how much effort required to enhance system security
- Attempted to develop methodologies and software for detecting some problems, and techniques for avoiding and ameliorating other problems
- Examined Multics, TENEX, TOPS-10, GECOS, OS/MVT, SDS-940, EXEC-8

Classification Scheme

- Incomplete parameter validation
- Inconsistent parameter validation
- Implicit sharing of privileged/confidential data
- Asynchronous validation/inadequate serialization
- Inadequate identification/authentication/authorization
- Violable prohibition/limit
- Exploitable logic error

Incomplete Parameter Validation

- Parameter not checked before use
- Example: emulating integer division in kernel (RISC chip involved)
  - Caller provided addresses for quotient, remainder
  - Quotient address checked to be sure it was in user's protection domain
  - Remainder address *not* checked
    - Set remainder address to address of process' level of privilege
    - Compute 25/5 and you have level 0 (kernel) privileges
- Check for type, format, range of values, access rights, presence (or absence)

Inconsistent Parameter Validation

- Each routine checks parameter is in proper format for that routine but the routines require different formats
- Example: each database record 1 line, colons separating fields
  - One program accepts colons, newlines as pat of data within fields
  - Another program reads them as field and record separators
  - This allows bogus records to be entered

Implicit Sharing of Privileged / Confidential Data

- OS does not isolate users, processes properly
- Example: file password protection
  - OS allows user to determine when paging occurs
  - Files protected by passwords
    - Passwords checked char by char; stops at first incorrect char
  - Position guess for password so page fault occurred between 1st, 2nd char
    - If no page fault, 1st char was wrong; if page fault, it was right
  - Continue until password discovered

Asynchronous Validation / Inadequate Serialization

- Time of check to time of use flaws, intermixing reads and writes to create inconsistencies
- Example: *xterm* flaw discussed earlier

Inadequate Identification / Authorization / Authentication

- Erroneously identifying user, assuming another's privilege, or tricking someone into executing program without authorization
- Example: OS on which access to file named "SYS$*DLOC$" meant process privileged
  - Check: can process access any file with qualifier name beginning with "SYS" and file name beginning with "DLO"?
  - If your process can access file "SYSA*DLOC$", which is ordinary file, your process is privileged

Violable Prohibition / Limit

- Boundary conditions not handled properly
- Example: OS kept in low memory, user process in high memory
  - Boundary was highest address of OS
  - All memory accesses checked against this
  - Memory accesses not checked beyond end of high memory
    - Such addresses reduced modulo memory size
  - So, process could access (memory size)+1, or word 1, which is part of OS …

Exploitable Logic Error

- Problems not falling into other classes
  - Incorrect error handling, unexpected side effects, incorrect resource allocation, etc.
- Example: unchecked return from monitor
  - Monitor adds 1 to address in user's PC, returns
    - Index bit (indicating indirection) is a bit in word
    - Attack: set address to be –1; adding 1 overflows, changes index bit, so return is to location stored in register 1
  - Arrange for this to point to bootstrap program stored in other registers
    - On return, program executes with system privileges

Legacy of RISOS

- First funded project examining vulnerabilities
- Valuable insight into nature of flaws
  - Security is a function of site requirements and threats
  - Small number of fundamental flaws recurring in many contexts
  - OS security not critical factor in design of OSes
- Spurred additional research efforts into detection, repair of vulnerabilities

Program Analysis (PA)

- Goal: develop techniques to find vulnerabilities
- Tried to break problem into smaller, more manageable pieces
- Developed general strategy, applied it to several OSes
  - Found previously unknown vulnerabilities

Classification Scheme

- Improper protection domain initialization and enforcement
  - Improper choice of initial protection domain
  - Improper isolation of implementation detail
  - Improper change
  - Improper naming
  - Improper deallocation or deletion
- Improper validation
- Improper synchronization
  - Improper indivisibility
  - Improper sequencing
- Improper choice of operand or operation

Improper Choice of Initial Protection Domain

- Initial incorrect assignment of privileges, security and integrity classes
- Example: on boot, protection mode of file containing identifiers of all users can be altered by any user
  - Under most policies, should not be allowed

Improper Isolation of Implementation Detail

- Mapping an abstraction into an implementation in such a way that the abstraction can be bypassed
- Example: virtual machines modulate length of time CPU is used by each to send bits to each other
- Example: Having raw disk accessible to system as ordinary file, enabling users to bypass file system abstraction and write directly to raw disk blocks

Improper Change

- Data is inconsistent over a period of time
- Example: *xterm* flaw
  - Meaning of "/usr/tom/X" changes between *access* and *open*
- Example: parameter is validated, then accessed; but parameter is changed between validation and access
  - Burroughs B6700 allowed allowed this

Improper Naming

- Multiple objects with same name
- Example: Trojan horse
    - *loadmodule* attack discussed earlier; “bin” could be a directory or a program
- Example: multiple hosts with same IP address
    - Messages may be erroneously routed

Improper Deallocation or Deletion

- Failing to clear memory or disk blocks (or other storage) after it is freed for use by others
- Example: program that contains passwords that a user typed dumps core
  - Passwords plainly visible in core dump

Improper Validation

- Inadequate checking of bounds, type, or other attributes or values
- Example: *fingerd*’s failure to check input length

Improper Indivisibility

- Interrupting operations that should be uninterruptable
  - Often: “interrupting atomic operations”
- Example: *mkdir* flaw (UNIX Version 7)
  - Created directories by executing privileged operation to create file node of type directory, then changed ownership to user
  - On loaded system, could change binding of name of directory to be that of password file after directory created but before change of ownership
  - Attacker can change administrator’s password

Improper Sequencing

- Required order of operations not enforced
- Example: one-time password scheme
  - System runs multiple copies of its server
  - Two users try to access same account
    - Server 1 reads password from file
    - Server 2 reads password from file
    - Both validate typed password, allow user to log in
    - Server 1 writes new password to file
    - Server 2 writes new password to file
  - Should have every read to file followed by a write, and vice versa; not two reads or two writes to file in a row

Improper Choice of Operand or Operation

- Calling inappropriate or erroneous instructions
- Example: cryptographic key generation software calling pseudorandom number generators that produce predictable sequences of numbers

Legacy

- First to explore automatic detection of security flaws in programs and systems
- Methods developed but not widely used
  - Parts of procedure could not be automated
  - Complexity
  - Procedures for obtaining system-independent patterns describing flaws not complete

NRL Taxonomy

- Goals:
  - Determine how flaws entered system
  - Determine when flaws entered system
  - Determine where flaws are manifested in system
- 3 different schemes used:
  - Genesis of flaws
  - Time of flaws
  - Location of flaws

Genesis of Flaws

- Intentional
  - Malicious
    - Trojan horse
      - Nonreplicating
      - Replicating
    - Trapdoor
    - Logic bomb
  - Nonmalicious
    - Covert channel
      - Storage channel
      - Timing channel
    - Other

- Inadvertent (unintentional) flaws classified using RISOS categories; not shown above
  - If most inadvertent, better design/coding reviews needed
  - If most intentional, need to hire more trustworthy developers and do more security-related testing

Time of Flaws

- Time of Introduction
  - Development
    - Requirements/specifications/design
    - Source code
    - Object code
  - Maintenance
  - Operation

- Development phase: all activities up to release of initial version of software
- Maintenance phase: all activities leading to changes in software performed under configuration control
- Operation phase: all activities involving patching and not under configuration control

Location of Flaw

- Location
  - Software
    - Operating system
      - System initialization
      - Memory management
      - Process management/scheduling
      - Device management
      - File management
      - Identification/authentication
      - Other/unknown
    - Application
    - Support
      - Privileged utilities
      - Unprivileged utilities
  - Hardware

- Focus effort on locations where most flaws occur, or where most serious flaws occur

Legacy

- Analyzed 50 flaws
- Concluded that, with a large enough sample size, an analyst could study relationships between pairs of classes
  - This would help developers focus on most likely places, times, and causes of flaws
- Focused on social processes as well as technical details
  - But much information required for classification not available for the 50 flaws

Aslam's Model

- Goal: treat vulnerabilities as faults and develop scheme based on fault trees
- Focuses specifically on UNIX flaws
- Classifications unique and unambiguous
  - Organized as a binary tree, with a question at each node. Answer determines branch you take
  - Leaf node gives you classification
- Suited for organizing flaws in a database

Top Level

- Coding faults: introduced during software development
    - Example: *fingerd*'s failure to check length of input string before storing it in buffer
- Emergent faults: result from incorrect initialization, use, or application
    - Example: allowing message transfer agent to forward mail to arbitrary file on system (it performs according to specification, but results create a vulnerability)

Coding Faults

- Synchronization errors: improper serialization of operations, timing window between two operations creates flaw
  - Example: *xterm* flaw
- Condition validation errors: bounds not checked, access rights ignored, input not validated, authentication and identification fails
  - Example: *fingerd* flaw

Emergent Faults

- Configuration errors: program installed incorrectly
  - Example: *tftp* daemon installed so it can access any file; then anyone can copy any file
- Environmental faults: faults introduced by environment
  - Example: on some UNIX systems, any shell with “-” as first char of name is interactive, so find a setuid shell script, create a link to name “-gotcha”, run it, and you has a privileged interactive shell

Legacy

- Tied security flaws to software faults
- Introduced a precise classification scheme
  - Each vulnerability belongs to exactly 1 class of security flaws
  - Decision procedure well-defined, unambiguous

Comparison and Analysis

- Point of view
  - If multiple processes involved in exploiting the flaw, how does that affect classification?
    - *xterm*, *fingerd* flaws depend on interaction of two processes (*xterm* and process to switch file objects; *fingerd* and its client)
- Levels of abstraction
  - How does flaw appear at different levels?
    - Levels are abstract, design, implementation, etc.

xterm and PA Classification

- Implementation level
  - *xterm*: improper change
  - attacker’s program: improper deallocation or deletion
  - operating system: improper indivisibility

xterm and PA Classification

- Consider higher level of abstraction, where directory is simply an object
  - create, delete files maps to writing; read file status, open file maps to reading
  - operating system: improper sequencing
    - During read, a write occurs, violating Bernstein conditions
- Consider even higher level of abstraction
  - attacker’s process: improper choice of initial protection domain
    - Should not be able to write to directory containing log file
    - Semantics of UNIX users require this at lower levels

xterm and RISOS Classification

- Implementation level
  - *xterm*: asynchronous validation/inadequate serialization
  - attacker’s process: exploitable logic error and violable prohibition/limit
  - operating system: inconsistent parameter validation

xterm and RISOS Classification

- Consider higher level of abstraction, where directory is simply an object (as before)
  - all: asynchronous validation/inadequate serialization
- Consider even higher level of abstraction
  - attacker’s process: inadequate identification/authentication/authorization
    - Directory with log file not protected adequately
    - Semantics of UNIX require this at lower levels

xterm and NRL Classification

- Time, location unambiguous
  - Time: during development
  - Location: Support:privileged utilities
- Genesis: ambiguous
  - If intentional:
    - Lowest level: inadvertent flaw of serialization/aliasing
  - If unintentional:
    - Lowest level: nonmalicious: other
  - At higher levels, parallels that of RISOS

xterm and Aslam’s Classification

- Implementation level
  - attacker’s process: object installed with incorrect permissions
    - attacker’s process can delete file
  - *xterm*: access rights validation error
    - *xterm* doesn’t properly validate file at time of access
  - operating system: improper or inadequate serialization error
    - deletion, creation should not have been interspersed with access, open
  - Note: in absence of explicit decision procedure, all could go into class race condition

The Point

- The schemes lead to ambiguity
  - Different researchers may classify the same vulnerability differently for the same classification scheme
- Not true for Aslam’s, but that misses connections between different classifications
  - *xterm* is race condition as well as others; Aslam does not show this

fingerd and PA Classification

- Implementation level
  - *fingerd*: improper validation
  - attacker’s process: improper choice of operand or operation
  - operating system: improper isolation of implementation detail

fingerd and PA Classification

- Consider higher level of abstraction, where storage space of return address is object
  - operating system: improper change
  - *fingerd*: improper validation
    - Because it doesn't validate the type of instructions to be executed, mistaking data for valid ones
- Consider even higher level of abstraction, where security-related value in memory is changing and data executed that should not be executable
  - operating system: improper choice of initial protection domain

fingerd and RISOS Classification

- Implementation level
  - *fingerd*: incomplete parameter validation
  - attacker’s process: violable prohibition/limit
  - operating system: inadequate identification/authentication/authorization

fingerd and RISOS Classification

- Consider higher level of abstraction, where storage space of return address is object
  - operating system: asynchronous validation/inadequate serialization
  - *fingerd*: inadequate identification/authentication/authorization
- Consider even higher level of abstraction, where security-related value in memory is changing and data executed that should not be executable
  - operating system: inadequate identification/authentication/authorization

fingerd and NRL Classification

- Time, location unambiguous
  - Time: during development
  - Location: support: privileged utilities
- Genesis: ambiguous
  - Known to be inadvertent flaw
  - Parallels that of RISOS

fingerd and Aslam Classification

- Implementation level
    - *fingerd*: boundary condition error
    - attacker’s process: boundary condition error
        - operating system: environmental fault
            - If decision procedure not present, could also have been access rights validation errors

Standards

- Descriptive databases used to identify vulnerabilities and weaknesses
- Examples:
  - Common Vulnerabilities and Exposures (CVE)
  - Common Weaknesses and Exposures (CWE)

CVE

- Goal: create a standard identification catalogue for vulnerabilities
  - So different vendors can identify vulnerabilities by one common identifier
  - Created at MITRE Corp.
- Governance
  - CVE Board provides input on nature of specific vulnerabilities, determines whether 2 reported vulnerabilities overlap, and provides general direction and very high-level management
  - Numbering Authorities assign CVE numbers within a distinct scope, such as for a particular vendor
- CVE Numbers: CVE-*year-number*
  - *Number* begins at 1 each year, and is at least 4 digits

Structure of Entry

Main fields:

- CVE-ID: *CVE identifier*
- Description: *what is the vulnerability*
- References: *vendor and CERT security advisories*
- Date Entry Created: *year month day as a string of 8 digits*

Example: Buffer Overflow in GNU C Library

CVE-ID: CVE-2016-3706

Description: Stack-based buffer overflow in the getaddrinfo function in sysdeps/posix/getaddrinfo.c in the GNU C Library (aka glibc or libc6) allows remote attackers to cause a denial of service (crash) via vectors involving hostent conversion. NOTE: this vulnerability exists because of an incomplete fix for CVE-2013-4458

References:

- CONFIRM:https://sourceware.org/bugzilla/show_bug.cgi?id=20010
- CONFIRM:https://sourceware.org/git/gitweb.cgi?p=glibc.git;h=4ab2ab03d4351914ee53248dc5aef4a8c88ff8b9
- CONFIRM:http://www-01.ibm.com/support/docview.wss?uid=swg21995039
- CONFIRM:https://source.android.com/security/bulletin/2017-12-01
- SUSE:openSUSE-SU-2016:1527
- URL:http://lists.opensuse.org/opensuse-updates/2016-06/msg00030.html
- SUSE:openSUSE-SU-2016:1779
- URL:http://lists.opensuse.org/opensuse-updates/2016-07/msg00039.html
- BID:88440
- URL:http://www.securityfocus.com/bid/88440
- BID:102073
- URL:http://www.securityfocus.com/bid/102073

Assigning CNA: N/A

Date Entry Created: 20160330

CVE Use

- CVE database begun in 1999
  - Contains some vulnerabilities from before 1999
- Currently over 82,000 entries
- Used by over 150 organizations
  - Security vendors such as Symantec, Trend Micro, Tripwire
  - Software and system vendors such as Apple, Juniper Networks, Red Hat, IBM
  - Other groups such as CERT/CC, U.S. NIST

CWE

- Database listing weaknesses underlying CVE vulnerabilities
  - Developed by CVE list developers, with help from NIST, vulnerabilities research community
- Organized as a list
  - Can also be viewed as a graph as some weaknesses are refinements of others
  - Not a tree as some nodes have multiple parents

Types of Entries

- *Category entry*: identifies set of entries with a characteristic of the current entry
- *Chain entry*: sequence of distinct weaknesses that can be linked together within software
  - One weakness can create necessary conditions to enable another weakness to be exploited
- *Compound element composite entry*: multiple weaknesses that must be present to enable an exploit
- *View entry*: view of the CWE database for particular weakness or set of weaknesses.
- *Weakness variant entry*: weakness described in terms of a particular technology or language
- *Weakness base entry*: more abstract description of weakness than a weakness variant entry, but in sufficient detail to lead to specific methods of detection and remediation
- *Weakness class*: describes weakness independently of any specific language or technology.

Examples

- CWE-631, Resource-Specific Weaknesses (a view entry)
  - Child: CWE-632, Weaknesses that Affect Files or Directories
  - Child: CWE-633, Weaknesses that Affect Memory
  - Child: CWE-634, Weaknesses that Affect System Processes
- CWE-680, Integer Overflow to Buffer Overflow (a chain entry)
  - Begins with integer overflow (CWE-190)
  - Leads to failure to restrict some operations to bounds of buffer (CWE-119)
- CWE-61, UNIX Symbolic Link (Symlink) Following (a composite entry)
  - Requires 5 weaknesses to be present before it can be exploited
  - CWE-362, CWE-340, CWE-216, CWE-386, CWE-732

Abstraction Level of Weaknesses

- Goal is to avoid problem of different classifications depending on the layer of abstraction
- Levels:
  - *Class*: weakness at an abstract level, independent of any programming language or environment
  - *Base*: weakness at an abstract level, with enough detail to enable development of methods of detection, prevention, remediation
  - *Variant*: weakness at a low level, usually tied to specific technology, system, programming language
- Useful demarcation of vulnerabilities related to design, implementation, or both

2020 CWE Top 25 Most Dangerous Software Weaknesses

- Developed by MITRE and SANS
- Based on published vulnerability data from the National Vulnerability Database (NVD)
- Uses data from 2018 and 2019
  - About 27,000 vulnerabilities associated with a weakness
- Scoring formula takes into account:
  - Number of vulnerabilities associated with a CWE
  - Severity of vulnerability based on CVSS
  - Combine these to get CWE level of danger

CWE Top 25 Weaknesses: 1–5

- Improper Neutralization of Input During Web Page Generation
  - CWE-79
  - Cross-site Scripting
- Out-of-bounds Write
  - CWE-787
- Improper Input Validation
  - CWE-20
- Out-of-bounds Read
  - CWE-125
- Improper Restriction of Operations within the Bounds of a Memory Buffer
  - CWE-119

CWE Top 25 Weaknesses: 6–10

- Improper Neutralization of Special Elements used in an SQL Command
  - CWE-89
  - SQL Injection
- Exposure of Sensitive Information to an Unauthorized Actor
  - CWE-200
- Use After Free
  - CWE-416
- Cross-Site Request Forgery (CSRF)
  - CWE-352
- Improper Neutralization of Special Elements used in an OS Command
  - CWE-78
  - OS Command Injection

CWE Top 25 Weaknesses: 11–15

- Integer Overflow or Wraparound
  - CWE-190
- Improper Limitation of a Pathname to a Restricted Directory
  - CWE-22
  - Path Traversal
- NULL Pointer Dereference
  - CWE-22
- Improper Authentication
  - CWE-287
- Unrestricted Upload of File with Dangerous Types
  - CWE-434

CWE Top 25 Weaknesses: 16–20

- Incorrect Permission Assignment for Critical Resource
  - CWE-732
- Improper Control of Generation of Code
  - CWE-94
  - Code Injection
- Insufficiently Protected Credentials
  - CWE-522
- Improper Restriction of XML External Entity Reference
  - CWE-611
- Use of Hard-coded Credentials
  - CWE-798

CWE Top 25 Weaknesses: 21–25

- Deserialization of Untrusted Data
  - CWE-502
- Improper Privilege Management
  - CWE-269
- Uncontrolled Resource Consumption
  - CWE-400
- Missing Authentication for Critical Function
  - CWE-306
- Missing Authorization
  - CWE-862

OWASP Top 10 Web Application Security Risks

- Injection
  - Includes SQL injection and command injection
- Broken authentication and session management
- Sensitive data exposure
- XML external entities
  - Older XML processors use these, and they can cause unauthorized disclosure, remote code execution, and other things
- Broken access control

OWASP Top 10 Web Application Security Risks

- Security misconfiguration
- Cross-site scripting
- Insecure deserialization
- Using components with known vulnerabilities
  - Aka the supply chain problem
- Insufficient logging and monitoring

Comparison of the Top 10/25 Lists

- Everything on the OWASP list is also on the CWE list
- Injection is very high on both lists
  - #6 and #10 on CWE list
  - #1 on OWASP list
- Their targets are different
  - CWE list covers vulnerabilities generally
  - OWASP list covers only web vulnerabilities

Summary

- Classification schemes requirements
  - Decision procedure for classifying vulnerability
  - Each vulnerability should have unique classification
- Above schemes do not meet these criteria
  - Inconsistent among different levels of abstraction
  - Point of view affects classification