• Buffer overflow vulnerabilities account for a large number of program exploits

• What else can go wrong?
  – inadequate input handling
    • input size
    • input interpretation
    • input syntax
  – inadequate environment handling
    • environment variables
    • race conditions
Input Validation

● A program can receive input in many different ways
  – user input, database, network data, configuration files

● A program often expects the data to be of a particular length, have a particular format, etc.

● An attacker might have control over the input and feed any data of her choosing

● Attacker’s goal might be to
  – crash programs
  – execute arbitrary code
  – obtain sensitive information
• We need to place **adequate checks on the input data**
  
  – **input size**
    * insufficient memory allocation leads to overflow vulnerabilities
    * various types of overflow exist: stack, heap, global data buffer overflows
  
  – **input interpretation**
    * often data comes in a specific format and must be checked for compliance
    * e.g., protocol headers, character encodings, URLs, etc.
    * failure to verify input format can lead to different types of injection vulnerabilities
**Input Validation**

- **Injection attack** refers to ability of input data to influence program flow
  - command injection
    - the input is used to execute additional commands using privileges of the process
    - example: checking printer queue
      ```c
      void main(int argc, char *argv[])
      {
        char buf[1024];
        sprintf(buf, "lpq %s", argv[1]);
        system("buf");
      }
      ```
    - what if `argv[1]` is "p1; ls /" or "p1& echo ‘root:abcdef012345’| cat - > /etc/passwd"?
      - arbitrary commands can be executed
Injection Attacks

- Injection attack (cont.)
  - SQL injection
    - user-supplied input is used to construct SQL request
    - injection attack convinces the application to run SQL code that was not intended
    - example 1: web application allows to query a table
      ```sql
      SELECT office, building, phone
      FROM employees
      WHERE name = '$name';
      ```
    - now assume that the supplied input is not simply Bob
      ```sql
      SELECT office, building, phone
      FROM employees
      WHERE name = 'Bob'; DROP TABLE employees; --';
      ```
• **SQL injection** (cont.)
  
  – example 2: web authentication mechanism that emails forgotten passwords

  • the SQL query can look like

    ```sql
    SELECT somefields
    FROM table
    WHERE field = '$email';
    ```

  • by manipulating the query, information about the field names, table name, and stored information can be guessed

  • e.g., the query below will give an different error if the guessed field email does not exist

    ```sql
    SELECT somefields
    FROM table
    WHERE field = 'x' AND email IS NULL;--';
    ```
Injection Attacks

- **SQL injection** (cont.)
  - example 2 (cont.)
    - after guessing field names, other information can be guessed
      
      ```
      SELECT email, passwd, name
      FROM members
      WHERE email = 'x' OR name LIKE '%Bob%';
      
      SELECT email, passwd, name
      FROM members
      WHERE email = 'bob@example.com' AND passwd='hello1';
      
      • furthermore, we can alter the table
      
      SELECT email, passwd, name
      FROM members
      WHERE email='x';
      INSERT INTO members (email', 'passwd', 'name',) VALUES ('user@buffalo.edu', 'pwd', 'Jen Smith');--';
      ```
Injection Attacks

- Injection attacks
  - code injection
    - various forms of attacks exist that permit execution of attacker’s code
    - example: PHP remote code injection using include file
      - PHP script can contain lines of the form
        ```php
        include $path . 'functions.php';
        require($color . '.php');
        ```
      - in addition to pointing to local code, any remote code can be executed as well
      - e.g., the request can be of the form
Injection Attacks

- Injection attacks
  - format string problem
    - was discovered in 2000 and affects any function that uses a format string
    - vulnerable print functions: printf, fprintf, sprintf, vprintf, ...
    - vulnerable logging functions: syslog, err, warn
    - e.g., consider the following function
      ```c
      void main(int argc, char *argv[]) {
        fprintf(stdout, argv[1]);
      }
      ```
    - what happens if the first argument is “%s%s%s%s”? will crash or print memory contents
Injection Attacks

- Format string problem
  - correct usage of such functions should be
    ```c
    void main(int argc, char *argv[]) {
        fprintf(stdout, "%s", argv[1]);
    }
    ```
  - full exploit uses print operator `\%n`
    - `\%n` writes the number of characters printed so far to the memory pointed by its argument
    - e.g., `printf("%s\%n", argv[1], &x)` will store number 15 in `x` if the string `argv[1]` is 15 characters long
    - the parameter value of the stack is interpreted as a pointer to integer value and the location to which it points is overwritten
Injection Attacks

- **Format string problem**
  - what remains is to figure out how to get the address attacker’d like in the appropriate position in the stack
  - besides C/C++, all other languages that use format strings are vulnerable
  - examples of past exploits
    - wu-ftp 2.* – remote root
    - Linux rpc.statd – remote root
    - IRIX telnetd – remote root
    - BSD chpass – local root

- Many other types of input interpretation vulnerabilities exist
• Syntax validation
  – since input data cannot be controlled, we need to verify that the data syntax is as expected
    • e.g., ASCII characters, email format, integer, etc.
  – it is safest to specify what is allowed rather than what is not allowed
    • if blocking potentially dangerous input is used, some (possibly not known yet) vulnerabilities can be missed
  – a difficulty arises when multiple encodings can be used
    • e.g., program disallows ‘/’ as dangerous
    • attacker replaces ‘/’ with Unicode representation %C0%af
    • in such case, first normalize the input using a single minimal representation and then check for acceptability
Input Validation

- Failure to validate input syntax properly lead to a number of exploits
  - Nimda worm attacked MS IIS using command
    \[ \text{http://victim.com/scripts/../winnt/system32/cmd.exe?\langle\text{some command}\rangle} \]
    - here \(\langle\text{some command}\rangle\) is passed to cmd.exe
  - scripts directory of IIS has execute permissions
  - input checking would prevent the above string, but Unicode characters helped
    \[ \text{http://victim.com/scripts/..%c0%af..%c0%afwinnt/system32/cmd.exe?\langle\text{some command}\rangle} \]
    - IIS first checked input and then expanded Unicode
• Another concern is the size of integer values
  
  – integer values of inadequate length might result in integer overflow vulnerability

• char buf[1024];
  void vulnerable() {
    int len = read_int_from_network();
    char *p = get_len_bytes();
    if (len > sizeof(buf)) {
        error("length too large");
        return;
    }
    memcpy(buf, p, len);
  }

what is wrong with the code?
Let’s look at the code more closely

- **memcpy prototype is**
  
  ```c
  void memcpy(void *dest, const void *src, size_t n);
  ```

- **definition of size_t:**
  ```c
  typedef unsigned int size_t;
  ```

- we are using signed `len` in place of an unsigned integer

- do you see the problem now?

Attacker can provide a negative value for `len`

- if won’t notice anything wrong

- `memcpy()` is executed with negative third argument

- third argument is implicitly cast to `unsigned int` and becomes a very large positive integer
Integer Overflow

• Now `memcpy` copies huge amount of memory into `buf` causing a buffer overrun
  – this casting bug is hard to spot

• C compiler doesn’t warn about type mismatch between signed int and unsigned int
  – it silently inserts an implicit cast

• Another similar example
  ```c
  const long MAX_LEN = 20000;
  short len = strlen(input);
  if (len < MAX_LEN)
    copy_len_bytes;
  ```
  – how long does input need to be to bypass the check?
• One more example:

```c
size_t len = read_int_from_network();
char *buf = malloc(len+5);
read(fd, buf, len);
```

• What’s wrong with this code?
  – no buffer overrun problems (5 spare bytes)
  – no sign problems (all integers are unsigned)

• But `len+5` can overflow if `len` is too large
  – if `len = 0xFFFFFFFF`, then `len+5 = 4`
  – allocate a 4-byte buffer, then read a lot more bytes into it
  – classic buffer overflow!
Integer Overflow

- Truncation and integer casting are direct causes of integer overflow
  - you have to know programming language’s semantics very well to avoid all pitfalls

- Where would integer overflow matter?
  - allocating space using calculations
  - calculating indices into arrays
  - checking whether an overflow could occur

- What type of casting can occur in C?
  - signed int to unsigned int; signed int to long signed or unsigned int
  - unsigned int to signed; unsigned int to long signed or unsigned
  - donwcasting
More on casting in C

- for binary operators +, −, *, /, %, &, |, ^
  - if at least one operand is unsigned long, both are cast to unsigned long
  - otherwise, if both operands are 32 bits (int) or less, they are both upcast to int (and the result is int)

- for unary operators
  - ~ changes type, i.e., ~((unsigned short)0) is int
  - ++ and − − don’t change type
Interaction with the Environment

- Program input is not the only place over which attacker has control
  - the program interacts with other system components
  - e.g., environment variables, operating system, libraries, other programs, devices, etc.

- Environment variables
  - they are character strings which are passed to a process from its parent and can be used during execution
  - they can also be changed to any value
  - environment variables are used in a wide variety of OSs
  - some well-known environment variables
    - PATH, LD_LIBRARY_PATH, IFS
Interaction with the Environment

- Example attack using environment variables
  - assume that some setuid program loads dynamic libraries at runtime
  - the system searches environment variable LD_LIBRARY_PATH for appropriate libraries
  - attacker can set LD_LIBRARY_PATH to reference its copy of the library, which will get executed with privileges of the setuid program
  - what can be done?
    - modern operating systems now don’t use this environment variable when euid (egid) differs from ruid (resp. rgid)
    - alternatively, use statically linked executables at the cost of memory efficiency
• Now suppose a setuid program executes `system(ls)`
  
  – attacker can set PATH to be . and place a program called `ls` in this directory
  
  – attacker can now execute arbitrary code as the setuid program
  
  – what can be done?
    
    • modern systems block this environment variable when the program is running as root
    
    • reset PATH within the program to be of a standard form such as `/bin:/usr/bin`
    
    • don’t add . into the PATH variable
      
      – if it must be added, it belongs at the end
• Unfortunately, resetting the PATH variable is not enough
  – the IFS variable also require attention
  – example 1: using system() call
    • say, attacker adds “s” to the IFS variable
    • `system(ls)` becomes `system(l)`, place program `l` in the appropriate directory
  – example 2: executing a shell script
    • PATH variable is reset inside the script using commands
      `PATH="/bin:/sbin:/usr/bin"; export PATH`
    • adding “=” to IFS will cause the first command to be interpreted as a command to execute with arguments

• Writing secure privileged shell scripts is very difficult, avoid using them
Interaction with the Environment

- Another type of attacks deals with access to shared resources by several processes
  - interaction with other resources that programs use such as temporary files
  - such race conditions lead to many subtle bugs that are difficult to find and fix
  - example: Ghostscript temporary files
    - Ghostscript creates many temporary files
    - the file names are often generated by `maketemp()`
      
```c
name = maketemp("/tmp/gs_XXXXXXXX");
fopen(name, "w");
```

Interaction with the Environment

• Race conditions (cont.)
  – the problem with Ghostscript’s implementation is that file names are predictable, derived from process ID
  – attack
    • create symbolic link /tmp/gs_123456 -> /etc/passwd at the right time
    • this causes Ghostscript to rewrite /etc/passwd
    • similar problems exist with enscript and other programs that use temporary files
  – to address the problem, use atomic \( \text{mkstemp}() \) which creates and opens a file atomically
Conclusions

- There is a very large number of potential vulnerabilities
  - they range in sophistication, goal, and mechanisms
  - overflows, injections, etc.
- Many vulnerabilities can be addressed through careful input checking and validation
- Some other vulnerabilities are difficult to address without operating system support
- Producing safe code is non-trivial
  - how do we do that?