Software Vulnerabilities and Exploits

Brad Karp
UCL Computer Science

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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

  Finding, exploiting, and exploiting a vulnerability

  Today: vulnerabilities in C programs that allow an attacker to execute his own arbitrary code within the vulnerable program

• 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
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 = 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 -= sizeof(locals); allocates local variables

Upon return from $f()$, deallocate stack frame:
- Set SP += sizeof(locals); deallocates local variables
- Set BP = saved frame pointer from stack; change to caller’s stack frame
- Set IP = 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");
    }
}
```

Increasing memory addresses

main()’s stack frame
void dorequest(int a, int b) {
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        dorequest(17, 38);
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    }
}
```
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;
}

int main(int argc, char **argv)
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    while (1) {
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}
```

Example: Stack Smashing

- **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");
  }

Diagram:
- **shell code**
- **local vars**
- **saved fp**
- **return addr**
- **args**
- **main()'s stack frame**
- **malicious input**
- **shell code**
- Increasing memory addresses

0x80707336
0x63441827
17
38

NOTE: The diagram illustrates the potential for stack smashing if malicious input is passed into the `dorequest` function.
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

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

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

int main(int argc, char **argv) {
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    }
}
```

Increasing memory addresses

- Shell code
- Local vars
- Saved fp
- Return addr
- Args
- Main()’s stack frame

Malicious input

Shell code

Example: Stack Smashing
Example: Stack Smashing

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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malicious input
void dorequest(int a, int b)
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    request... */
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int main(int argc, char **argv)
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Example: Stack Smashing

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int main(int argc, char **argv)
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    while (1) {
        dorequest(17, 38);
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}
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);
        printf (log, "completed\n");
    }
}
```
void dorequest(int a, int b) {
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  scanf("%s", request);
  /* process the request... */
  ...
  return;
}

int main(int argc, char **argv) {
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```

malicious input | NOP slide | shell code | local vars | saved fp | return addr | args | main()’s stack frame

Increasing memory addresses

0x80707336
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Example: Stack Smashing “2.0”

malicious input

NOP slide

Increasing memory addresses

local vars

shell code

0x80707336

saved fp

0x63441827

return addr

args

17

main()’s stack frame

38
Example: Stack Smashing “2.0”

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

```assembly
jmp 0x2a # 3 bytes
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W rites string address on stack!

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

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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 1\textsuperscript{st} 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", (int *) &i));
  printf("i = %d\n", i);
  ```

- Output:

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

Increasing memory addresses

- local vars
- saved fp
- return addr
- args
- caller’s stack frame
- fmt buffer

Increasing memory addresses
Abusing \%n to Overwrite Memory

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[suppose input = "%d%d%d\n"]
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char fmt[26];
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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

```c
char fmt[26];
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Increasing memory addresses

- local vars
- saved fp
- return addr
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- caller’s stack frame

fmt buffer
Abusing `%n` to Overwrite Memory (2)

- **Idea:**
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[input = "\xc0\xc8\xff\xbf%08x%08x%08x%08x%08x%n"]

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Increasing memory addresses

- local vars
- saved fp
- return addr
- args
- caller’s stack frame
- fmt buffer
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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

Still need to choose value we overwrite with…

Result: can overwrite chosen location with small integer

[Input = \xc0\xc8\xff\xbf\%08x\%08x\%n\%08x\%08x\%08x]
char fmt[26];
strncpy(fmt, input, 25);
printf(fmt, 1, 2, 3);
Controlling Value Written by %nn

• %nn 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 to 50 (0x32)
- %n writes number of output bytes to target address
- Result: least significant byte of 4-byte value at 0xbffffc8c0 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\textsuperscript{st} byte value to write]u%n
    %[2\textsuperscript{nd} byte value to write]u%n
    %[3\textsuperscript{rd} byte value to write]u%n
    %[4\textsuperscript{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: `wu-ftp < 2.6.0`:
  
  ```
  { 
    char buffer[512];
    snprintf (buffer, sizeof (buffer), user);
    buffer[sizeof (buffer) - 1] = '\0';
  }
  ```

• Ability to overwrite arbitrary memory makes format string vulnerabilities versatile:
  
  – Sure, can overwrite return address to return to shellcode, but 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