Format String Vulnerability

```
printf ( user_input );
```

The above statement is quite common in C programs. In the lecture, we will find out what can go wrong if the program is running with privileges (e.g. `Set-UID` program).

1 Format String

- What is a format string?

```
printf ("The magic number is: %d\n", 1911);
```

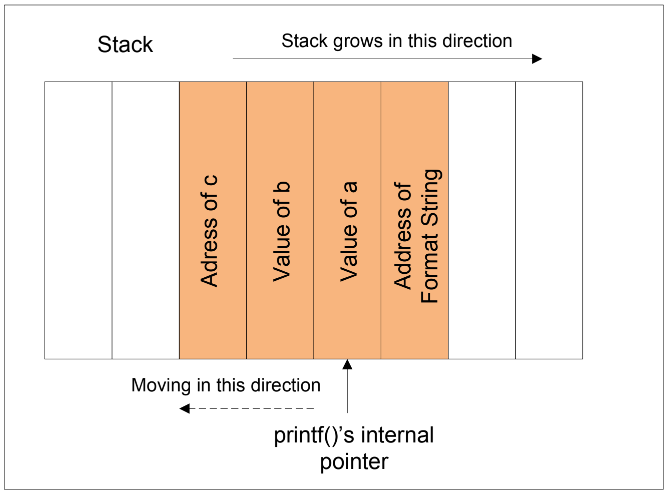
The text to be printed is "The magic number is:", followed by a format parameter '%d', which is replaced with the parameter (1911) in the output. Therefore the output looks like: The magic number is: 1911. In addition to %d, there are several other format parameters, each having different meaning. The following table summarizes these format parameters:

Parameter	Meaning	Passed as
%d	decimal (int)	value
%u	unsigned decimal (unsigned int)	value
%x	hexadecimal (unsigned int)	value
%s	string ((const) (unsigned) char *)	reference
%n	number of bytes written so far, (* int)	reference

- The stack and its role at format strings

The behavior of the format function is controlled by the format string. The function retrieves the parameters requested by the format string from the stack.

```
printf ("a has value %d, b has value %d, c is at address: %08x\n",
                          a, b, &c);
```



- What if there is a miss-match between the format string and the actual arguments?

```
printf ("a has value %d, b has value %d, c is at address: %08x\n",
                         a, b);
```

  - In the above example, the format string asks for 3 arguments, but the program actually provides only two (i.e. a and b).
  - Can this program pass the compiler?
    - The function `printf()` is defined as function with variable length of arguments. Therefore, by looking at the number of arguments, everything looks fine.
    - To find the miss-match, compilers needs to understand how `printf()` works and what the meaning of the format string is. However, compilers usually do not do this kind of analysis.
    - Sometimes, the format string is not a constant string, it is generated during the execution of the program. Therefore, there is no way for the compiler to find the miss-match in this case.
  - Can `printf()` detect the miss-match?
    - The function `printf()` fetches the arguments from the stack. If the format string needs 3 arguments, it will fetch 3 data items from the stack. Unless the stack is marked with a boundary, `printf()` does not know that it runs out of the arguments that are provided to it.
    - Since there is no such a marking. `printf()` will continue fetching data from the stack. In a miss-match case, it will fetch some data that do not belong to this function call.
  - What trouble can be caused by `printf()` when it starts to fetch data that is meant for it?

2 Attacks on Format String Vulnerability

- Crashing the program

```
printf ("%s%s%s%s%s%s%s%s%s%s%s%s");
```

  - For each `%s`, `printf()` will fetch a number from the stack, treat this number as an address, and print out the memory contents pointed by this address as a string, until a NULL character (i.e., number 0, not character 0) is encountered.
  - Since the number fetched by `printf()` might not be an address, the memory pointed by this number might not exist (i.e. no physical memory has been assigned to such an address), and the program will crash.
  - It is also possible that the number happens to be a good address, but the address space is protected (e.g. it is reserved for kernel memory). In this case, the program will also crash.

- Viewing the stack

```
printf ("%08x %08x %08x %08x %08x\n");
```

  - This instructs the printf-function to retrieve five parameters from the stack and display them as 8-digit padded hexadecimal numbers. So a possible output may look like:

```
40012980 080628c4 bffff7a4 00000005 08059c04
```

- Viewing memory at any location
  - We have to supply an address of the memory. However, we cannot change the code; we can only supply the format string.
  - If we use `printf(%s)` without specifying a memory address, the target address will be obtained from the stack anyway by the `printf()` function. The function maintains an initial stack pointer, so it knows the location of the parameters in the stack.
  - Observation: the format string is usually located on the stack. If we can encode the target address in the format string, the target address will be in the stack. In the following example, the format string is stored in a buffer, which is located on the stack.

```
int main(int argc, char *argv[])
{
  char user_input[100];
  ... ... /* other variable definitions and statements */

  scanf("%s", user_input); /* getting a string from user */
  printf(user_input); /* Vulnerable place */

  return 0;
}
```

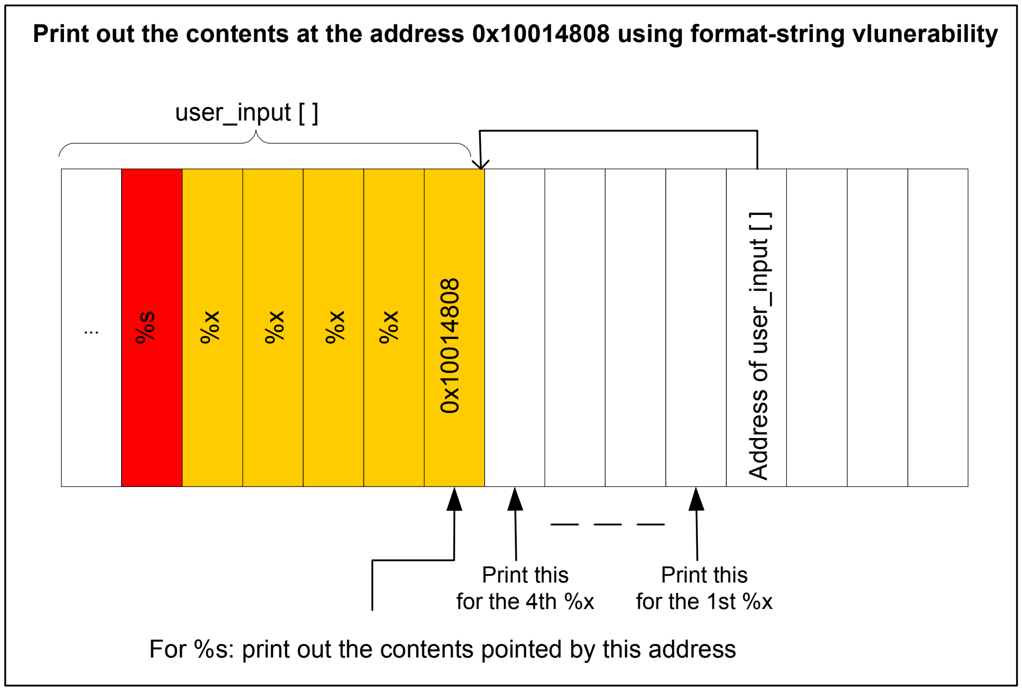
  - If we can force the printf to obtain the address from the format string (also on the stack), we can control the address.

```
printf ("\x10\x01\x48\x08  %x %x %x %x %s");
```

  - `\x10\x01\x48\x08` are the four bytes of the target address. In C language, `\x10` in a string tells the compiler to put a hexadecimal value `0x10` in the current position. The value will take up just one byte. Without using `\x`, if we directly put `"10"` in a string, the ASCII values of the characters `'1'` and `'0'` will be stored. Their ASCII values are 49 and 48, respectively.

- `%x` causes the stack pointer to move towards the format string.
- Here is how the attack works if `user_input[]` contains the following format string:

  `"\x10\x01\x48\x08  %x %x %x %x %s".`


Print out the contents at the address 0x10014808 using format-string vlunerability
user_input [ ]
...
%s
%x
%x
%x
%x
0x10014808
Address of user_input [ ]
Print this for the 4th %x
Print this for the 1st %x
For %s: print out the contents pointed by this address

- Basically, we use four `%x` to move the `printf()`'s pointer towards the address that we stored in the format string. Once we reach the destination, we will give `%s` to `print()`, causing it to print out the contents in the memory address `0x10014808`. The function `printf()` will treat the contents as a string, and print out the string until reaching the end of the string (i.e. 0).
- The stack space between `user_input[]` and the address passed to the `printf()` function is not for `printf()`. However, because of the format-string vulnerability in the program, `printf()` considers them as the arguments to match with the `%x` in the format string.
- The key challenge in this attack is to figure out the distance between the `user_input[]` and the address passed to the `printf()` function. This distance decides how many `%x` you need to insert into the format string, before giving `%s`.

• Writing an integer to nearly any location in the process memory

- `%n`: The number of characters written so far is stored into the integer indicated by the corresponding argument.

```
    int i;
    printf ("12345%n", &i);
```

- It causes `printf()` to write 5 into variable i.
- Using the same approach as that for viewing memory at any location, we can cause `printf()` to write an integer into any location. Just replace the `%s` in the above example with `%n`, and the contents at the address `0x10014808` will be overwritten.

- Using this attack, attackers can do the following:
  - Overwrite important program flags that control access privileges
  - Overwrite return addresses on the stack, function pointers, etc.
- However, the value written is determined by the number of characters printed before the `%n` is reached. Is it really possible to write arbitrary integer values?
  - Use dummy output characters. To write a value of 1000, a simple padding of 1000 dummy characters would do.
  - To avoid long format strings, we can use a width specification of the format indicators.

- Countermeasures.
  - Address randomization: just like the countermeasures used to protect against buffer-overflow attacks, address randomization makes it difficult for the attackers to find out what address they want to read/write.