CSE551: Advanced Computer Security

7. Assembly (x86) & Control Flow Hijack

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The slide is based on Prof. Sang Kil Cha's lecture slide

HW1

- Write a critique for the two papers:
  - Using Frankencerts for Automated Adversarial Testing of Certificate Validation in SSL/TLS Implementations, ***IEEE S&P 2014***
  - Beauty and the Burst: Remote Identification of Encrypted Video Streams, ***USENIX Security 2017***

Introduction to Software Security

Secure Software?

Can we say a program is secure if it considers the CIA properties?

Where there is engineering, there is a ***security problem***

Why?

Humans always make ***mistakes***

Software Security is About Software Bugs

- Find software bugs
- Exploit software bugs
- Patch software bugs

Software Bug

- Software bug is an *error/fault/mistake* in the code that produces **an unexpected result**

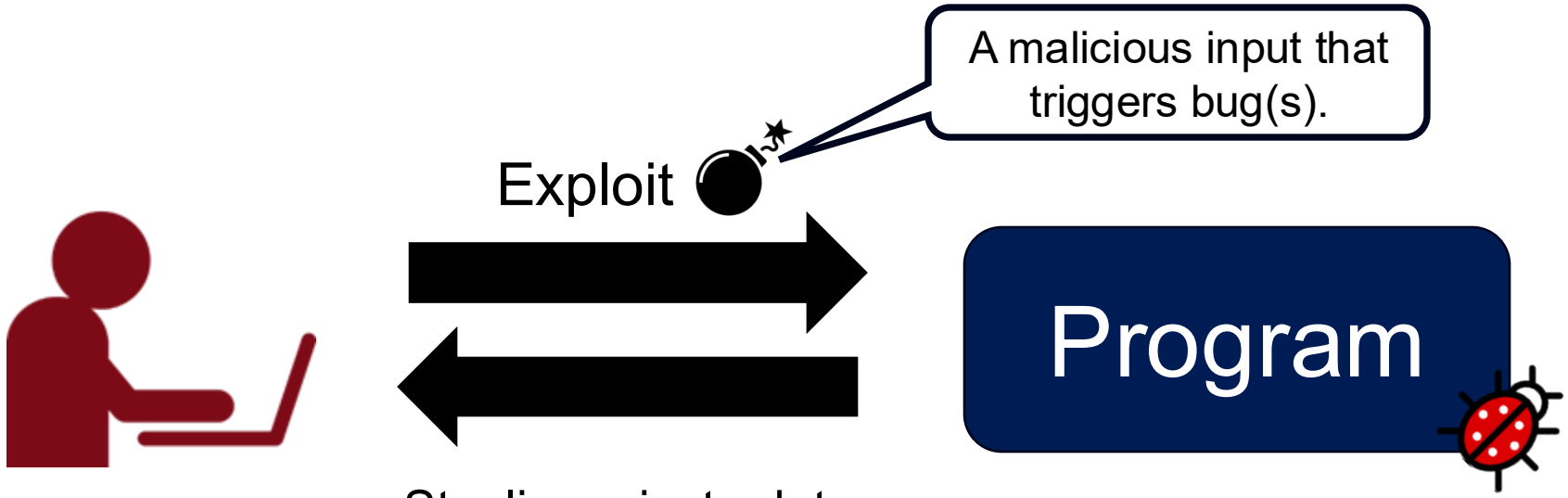
Thinking like an adversary is important for security

Software Bugs is the Key

- ***Root cause*** of many security problems including malware, hacking incidents, phishing, privacy leakage, etc.

Not Every Bug is Security Critical

- Bug is an error in program that makes it malfunction
  - Ex) Compute wrong outputs for corner case inputs
- Vulnerability is a bug that causes security issues



- Stealing private data
- Executing arbitrary commands
- ...

Example #1

- Consider the python code below for *bank application*
  - Takes in the amount of money you want to transfer
  - Your balance and the recipient's balance will be updated

```
my_balance = 1000
def send(recipient):
    print("How much do you want to send?")
    val = read_int()
    if (val <= my_balance):
        my_balance = my_balance – val
        ... # Increase the balance of recipient
```

Input : **100** → my_balance: **1000 → 900**

What can go wrong with this code?

Example #2

- Next, consider the following C code
  - Reads in a string input and prints it back

```
int main(void) {
    char buf[32];
    printf("Input your name: ");
    scanf("%s", buf);
    printf("Your name: %s\n", buf);
    return 0;
}
```

Input : “**Seongil**” → Printed output: **"Your name: Seongil"**

What can go wrong with this code?

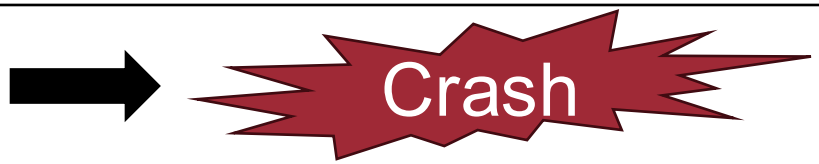
Example #2

- Next, consider the following C code
  - Reads in a string input and prints it back

```
int main(void) {
    char buf[32];
    printf("Input your name: ");
    scanf("%s", buf);
    printf("Your name: %s\n", buf);
    return 0;
}
```

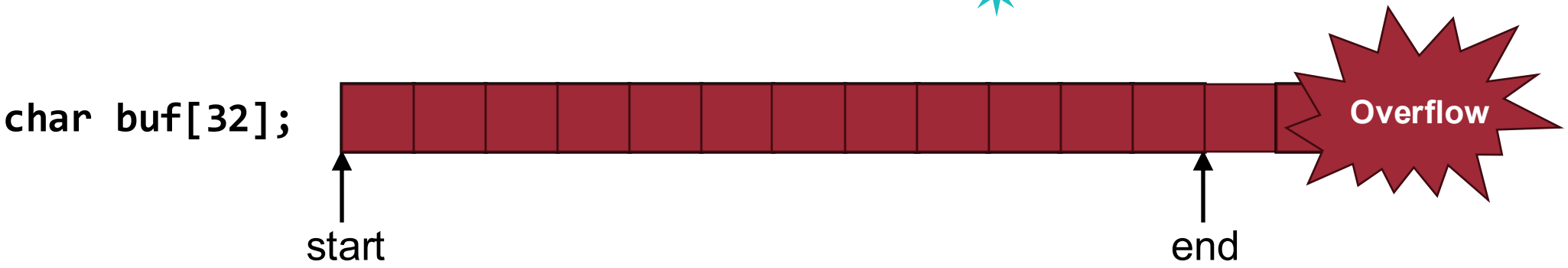
Input : "**AAAA…A**"

(long string)



This is infamous *buffer overflow* vulnerability

Buffer Overflow & Memory Corruption



- C has no automatic check on array index and boundary
  - Allows writing past the end of an array
  - This is call buffer overflow, or BOF in short
  - Such write will corrupt other variables and data in the memory

Q. How can a hacker do bad things (e.g., code execution, privilege escalation) with this?

To answer this, we must learn assembly

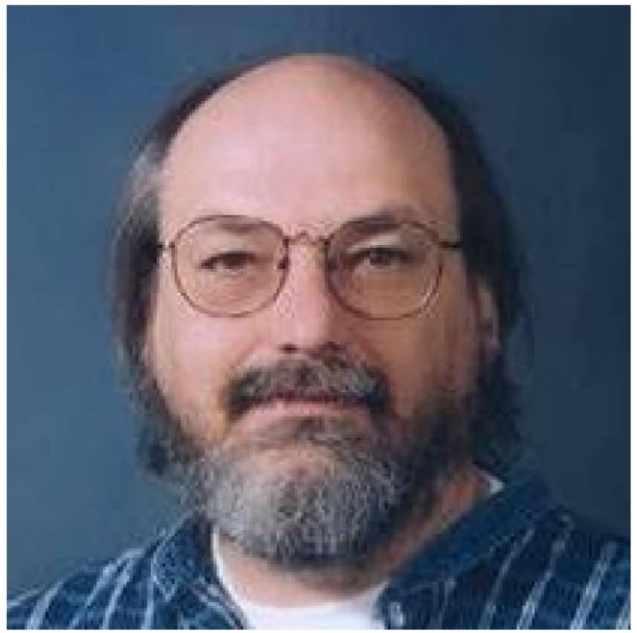
Our Goal in Software Security

- Find out whether a program is secure or not

- To do so, we need to see how the ***binary code*** (= executable code) executes on a machine!

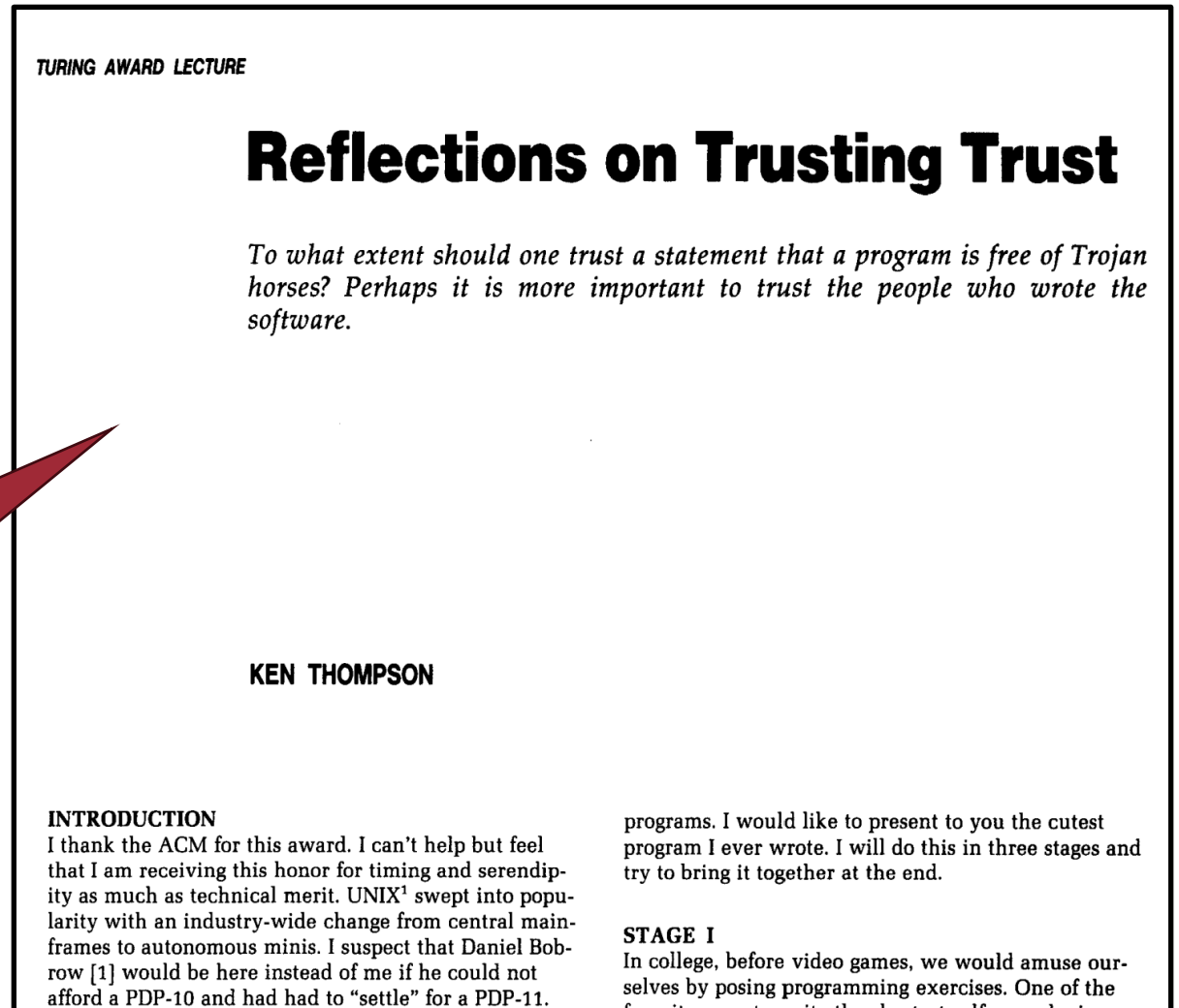
So, Why Binary Code?

- Reflections on Trusting Trust, *CACM 1984*



Cannot trust a program without looking at its binary code

https://www.computer.org/profiles/kenneth-thompson/



TURING AWARD LECTURE

Reflections on Trusting Trust

To what extent should one trust a statement that a program is free of Trojan horses? Perhaps it is more important to trust the people who wrote the software.

KEN THOMPSON

INTRODUCTION

I thank the ACM for this award. I can't help but feel that I am receiving this honor for timing and serendipity as much as technical merit. UNIX[1] swept into popularity with an industry-wide change from central mainframes to autonomous minis. I suspect that Daniel Bobrow [1] would be here instead of me if he could not afford a PDP-10 and had had to "settle" for a PDP-11.

programs. I would like to present to you the cutest program I ever wrote. I will do this in three stages and try to bring it together at the end.

STAGE I

In college, before video games, we would amuse ourselves by posing programming exercises. One of the

Assembly

Compilation

- Converting a high-level language into a machine language that the computer can understand

```
int test (int a){
    return 32;
}
```

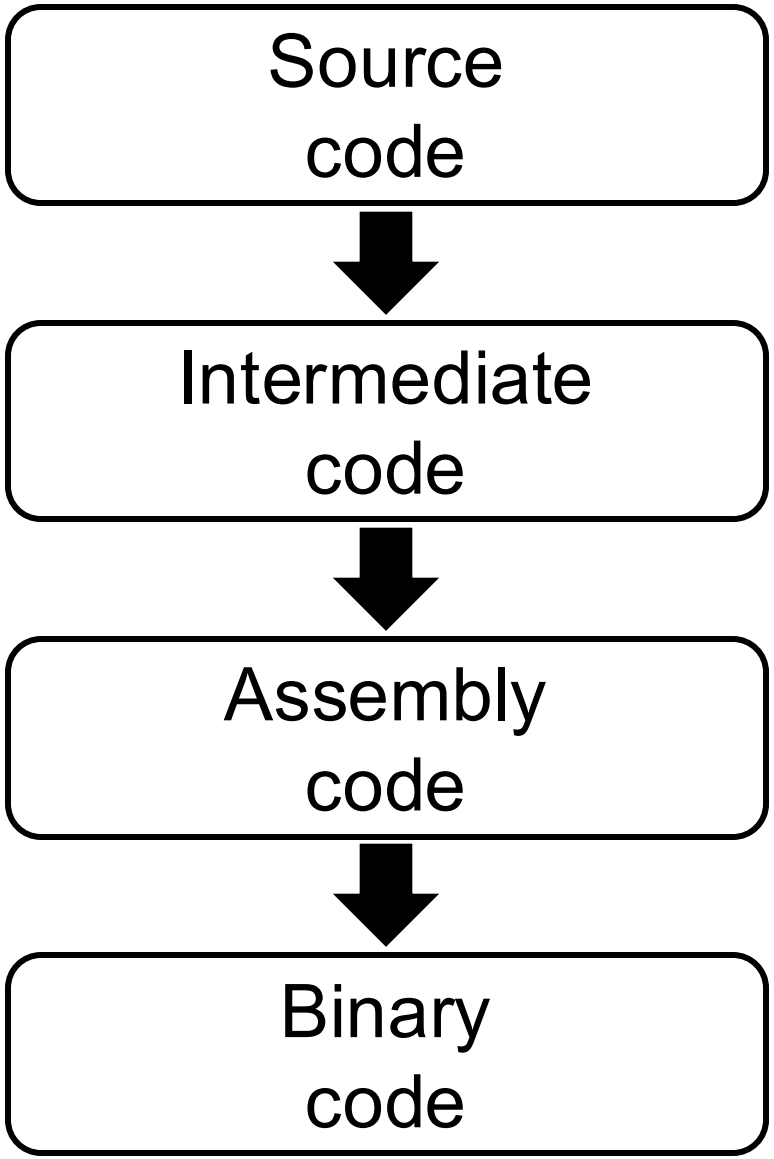
High-level language

Compile

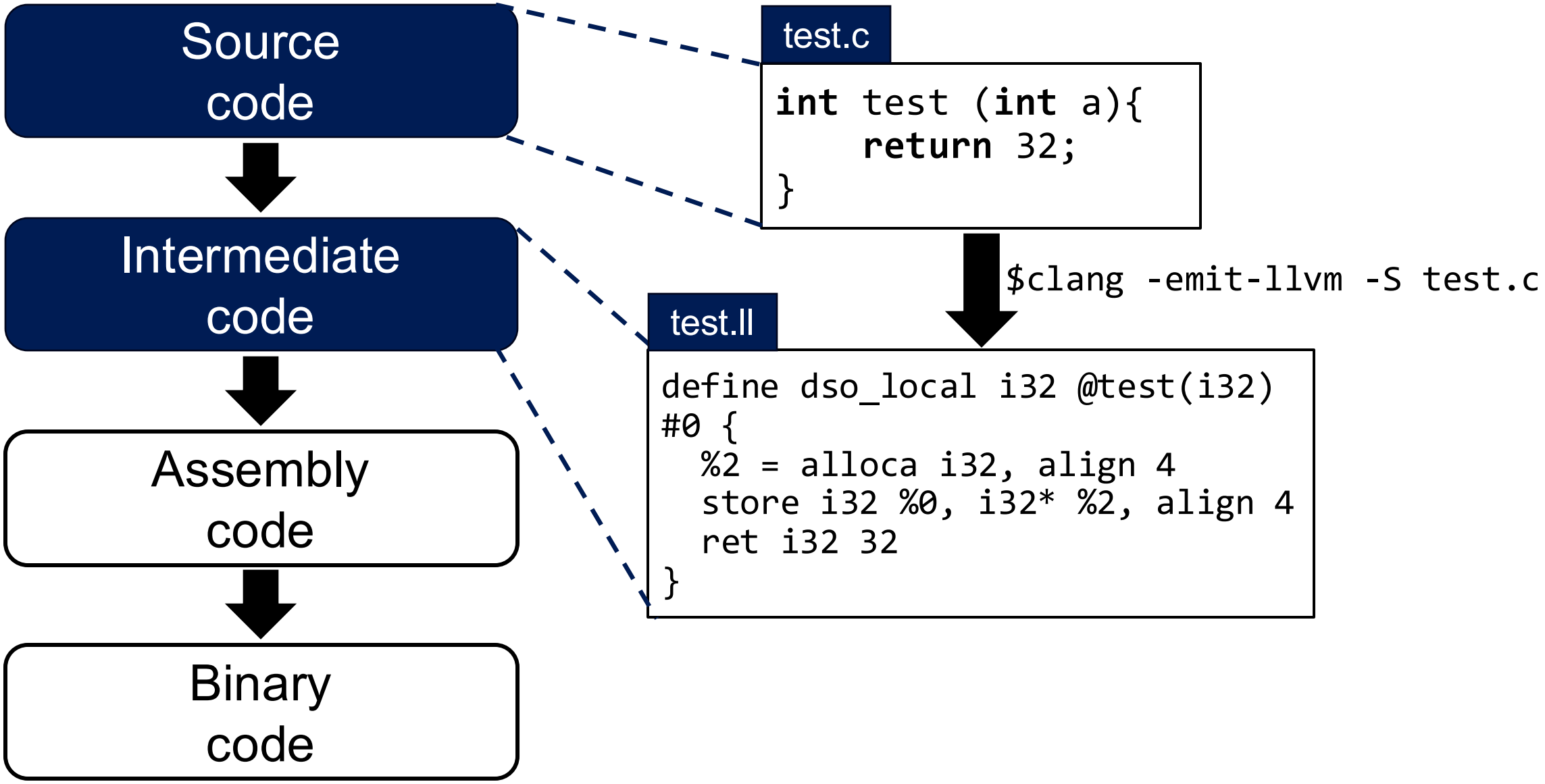
```
01000101010100100101
01001000100000101010
11100011010101010100
10101000010101010010
11100101010010111010
```

Machine language

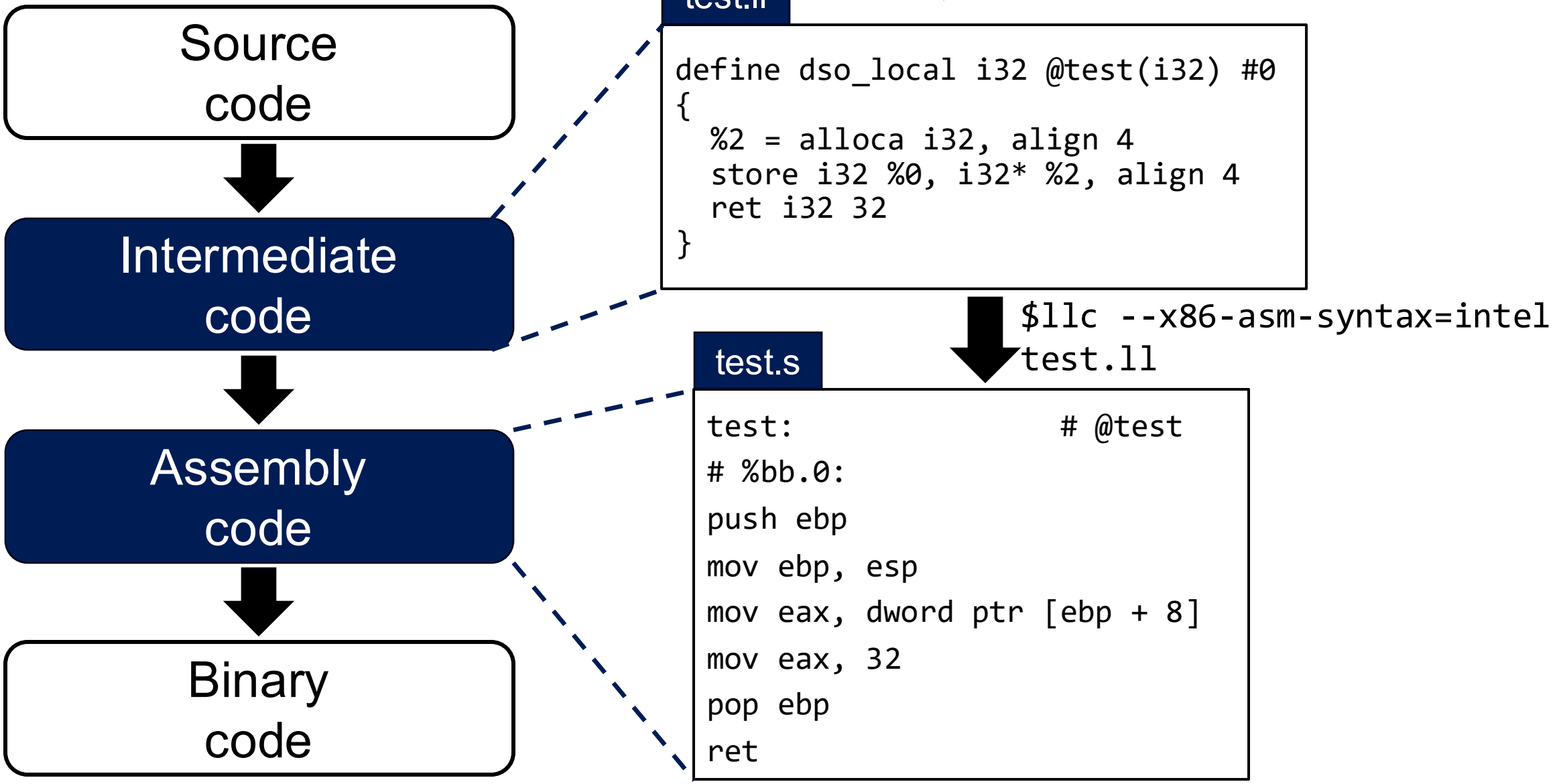
Compilation Process



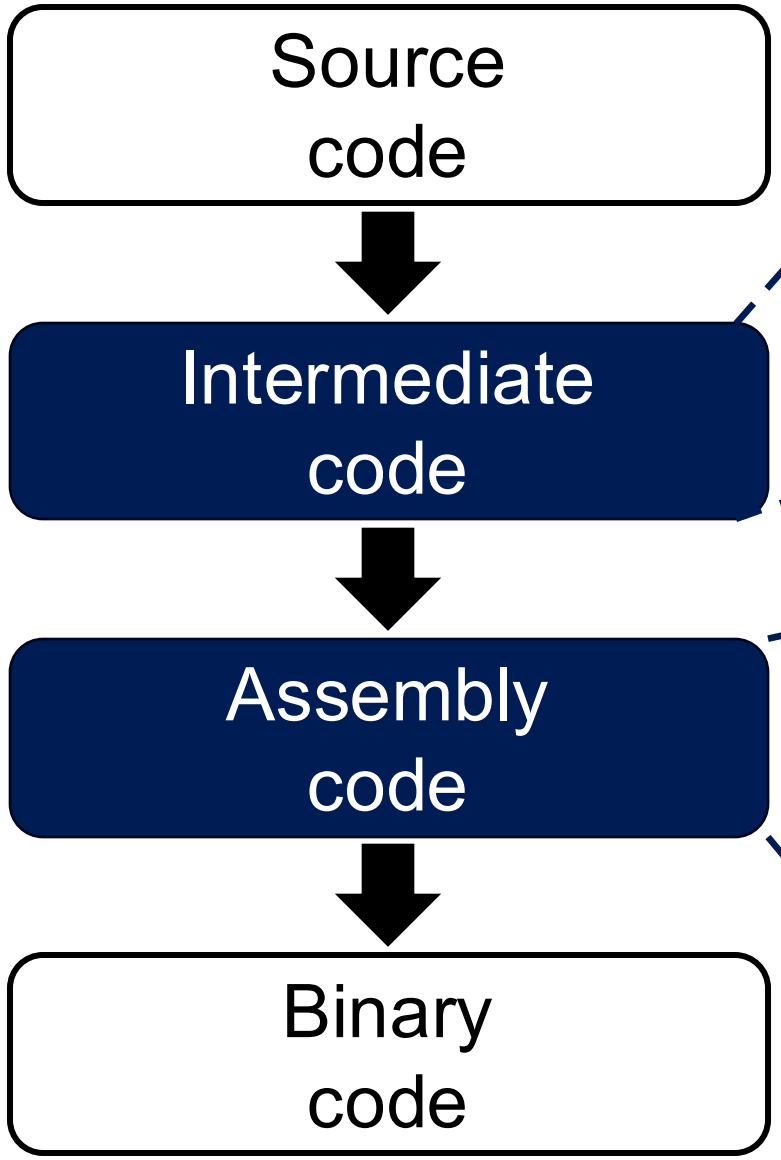
Compilation Process



Compilation Process



Compilation Process



test.ll

```
define dso_local i32 @test(i32) #0
{
  %2 = alloca i32, align 4
  store i32 %0, i32* %2, align 4
  ret i32 32
}
```

Intel syntax

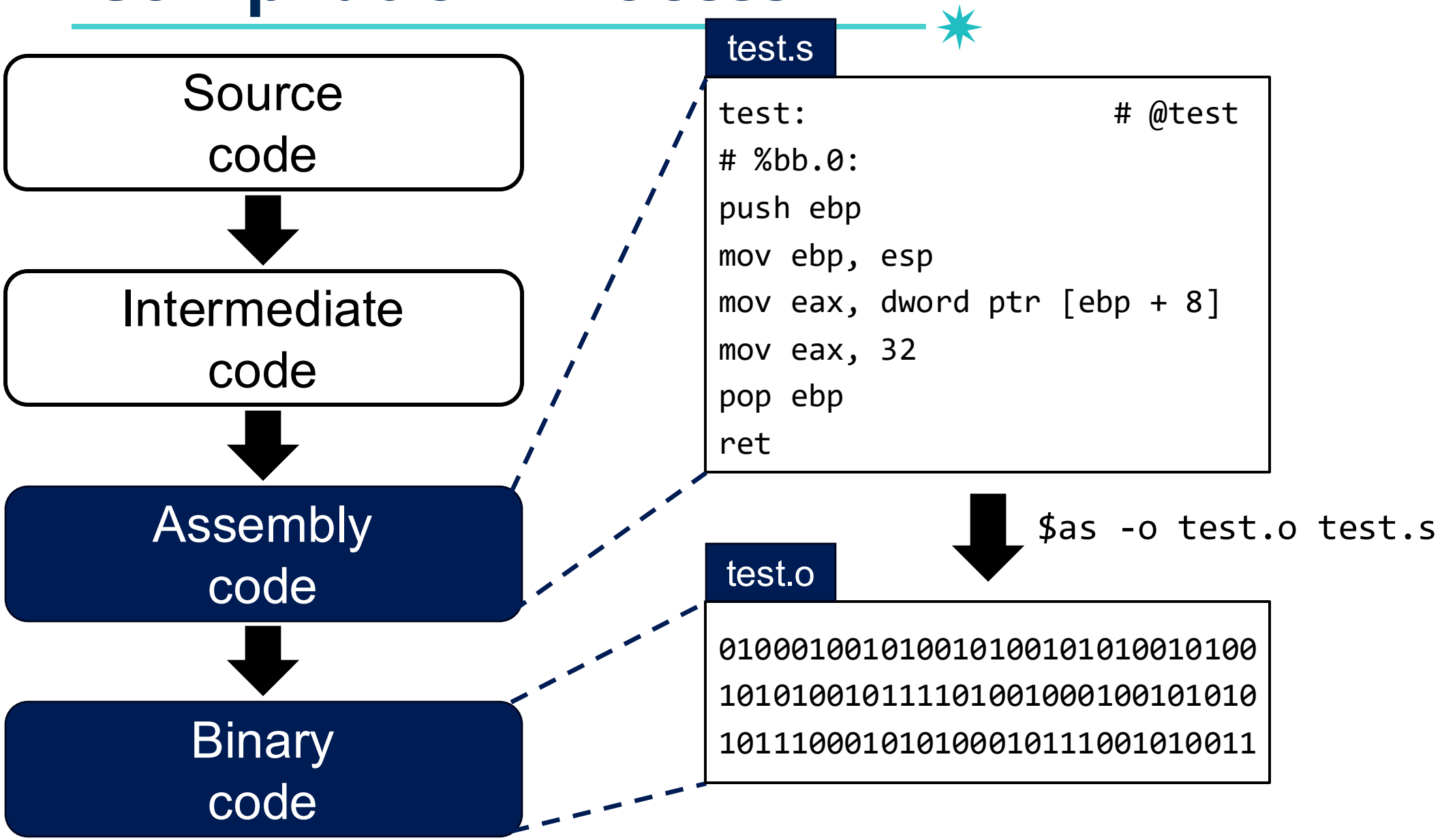
$llc --x86-asm-syntax=intel test.ll

test.s

```
test:                                   # @test
# %bb.0:
push ebp
mov ebp, esp
mov eax, dword ptr [ebp + 8]
mov eax, 32
pop ebp
ret
```

The last human-readable format

Compilation Process



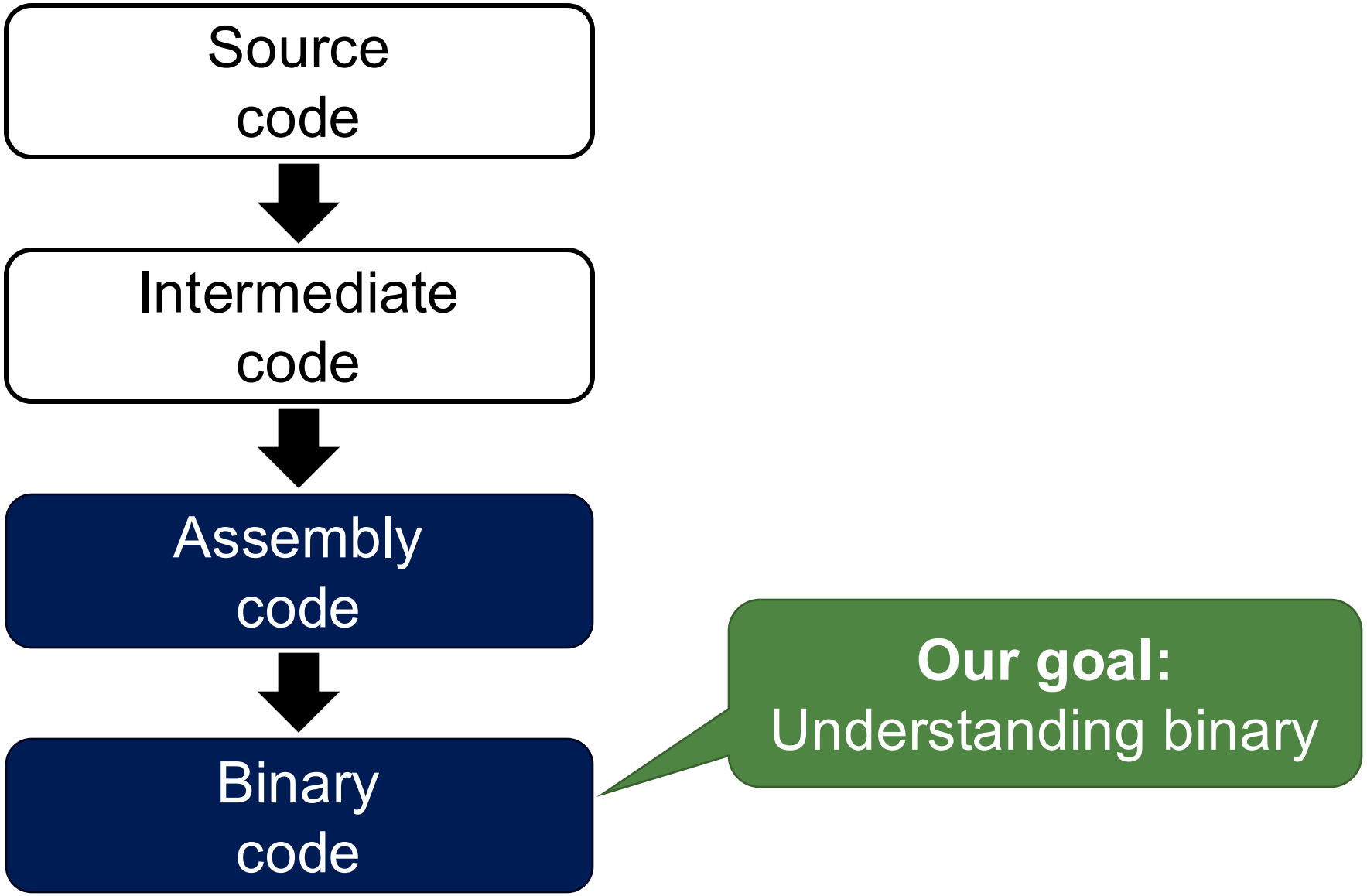
GNU AS (Assembler)


```
$as -o test.o test.s
$ls test.o
```

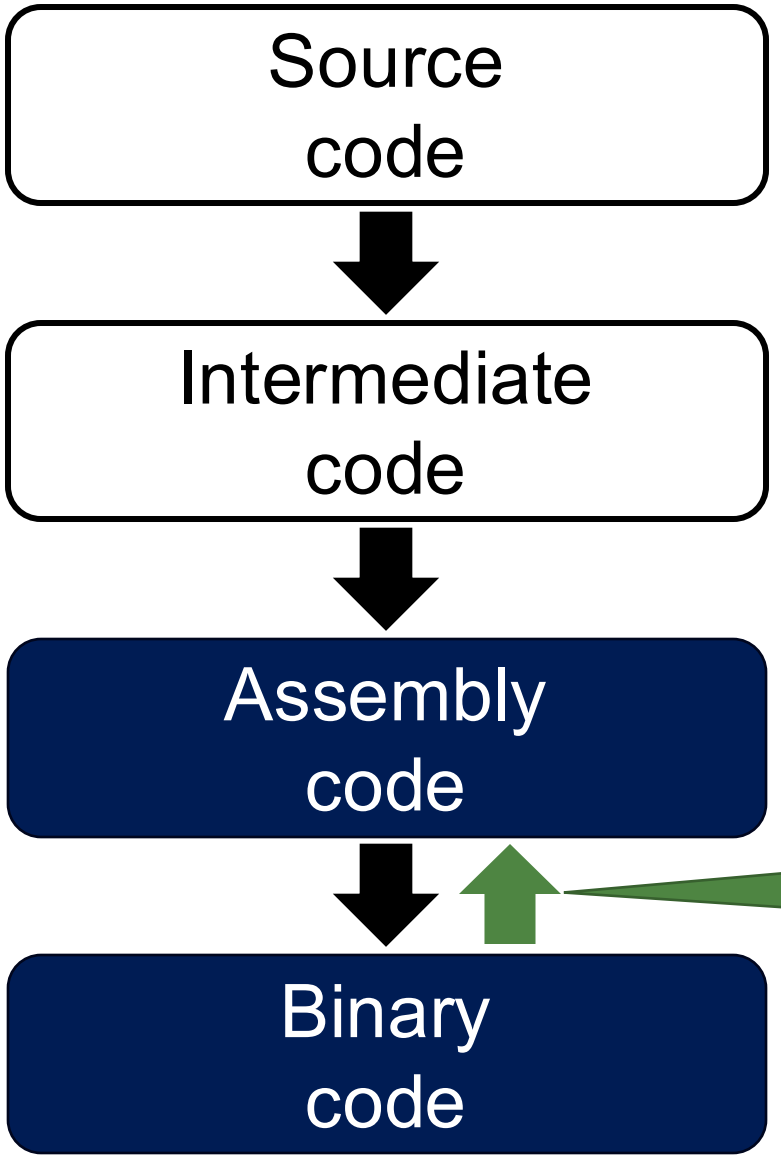
```
.intel_syntax noprefix

mov eax, ebx
…
```

Compilation Process



Disassembling Binary Code



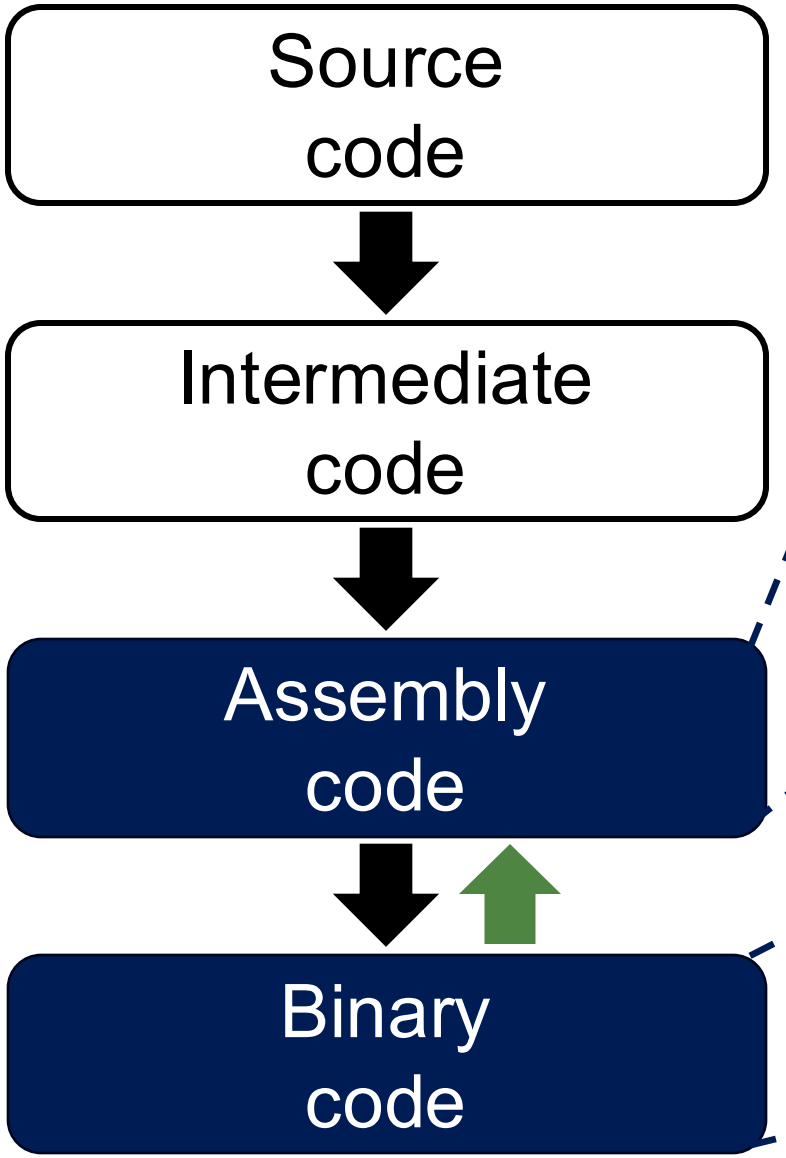
Disassembly!

Disassembler:
- Objdump
- IDA
- B2R2
- …

GNU `objdump`

- One of the GNU Binutils
- Perform disassembly on the file

GNU objdump



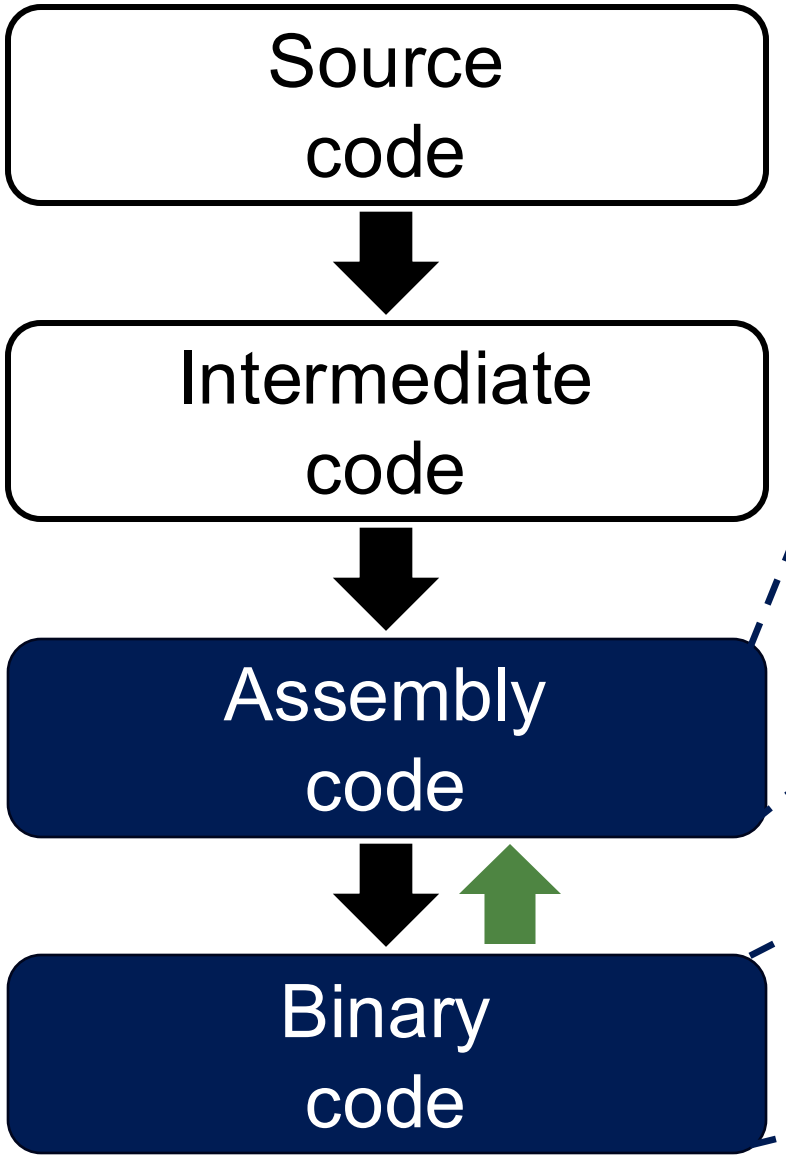

```
00000000 <test>:
 0: 55                    push ebp
 1: 89 e5                 mov  ebp,esp
 3: 8b 45 08              mov  eax,DWORD PTR [ebp+0x8]
 6: b8 20 00 00 00        mov  eax,0x20
 b: 5d                    pop  ebp
 c: c3                    ret
```

```
$ objdump -M intel -d test.o
```

test.o

```
01000100101001010010101001010010
10101001011110100100010010101010
10111000101010001011001010011
```

GNU objdump



Address

Binary code

Disassembled assembly code

```
00000000 <test>:
 0:  55                    push ebp
 1:  89 e5                 mov  ebp,esp
 3:  8b 45 08              mov  eax,DWORD PTR [ebp+0x8]
 6:  b8 20 00 00 00        mov  eax,0x20
 b:  5d                    pop  ebp
 c:  c3                    ret
```

```
$ objdump -M intel -d test.o
```

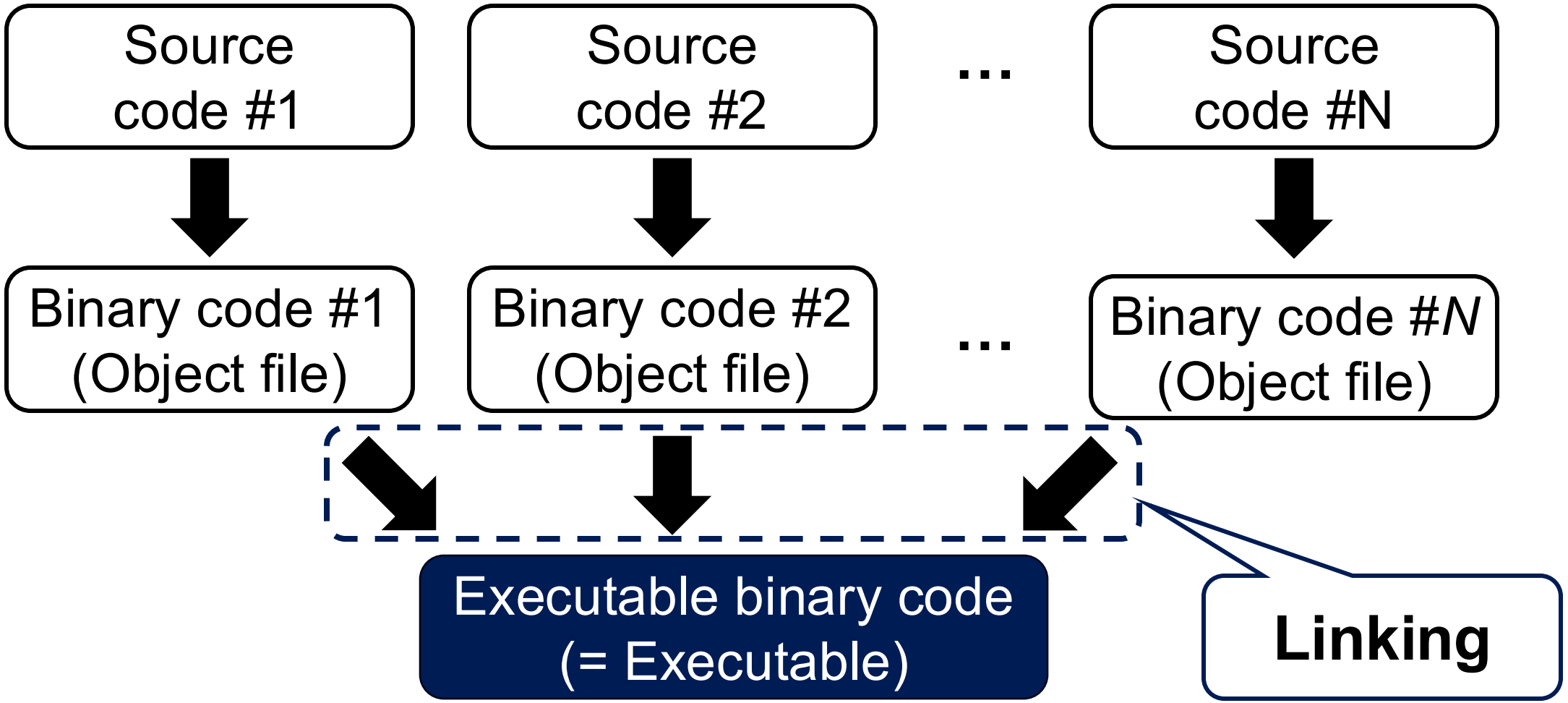
test.o

```
01000100101001010010101001010010
10101001011110100100010010101010
10111000101010001011001010011
```

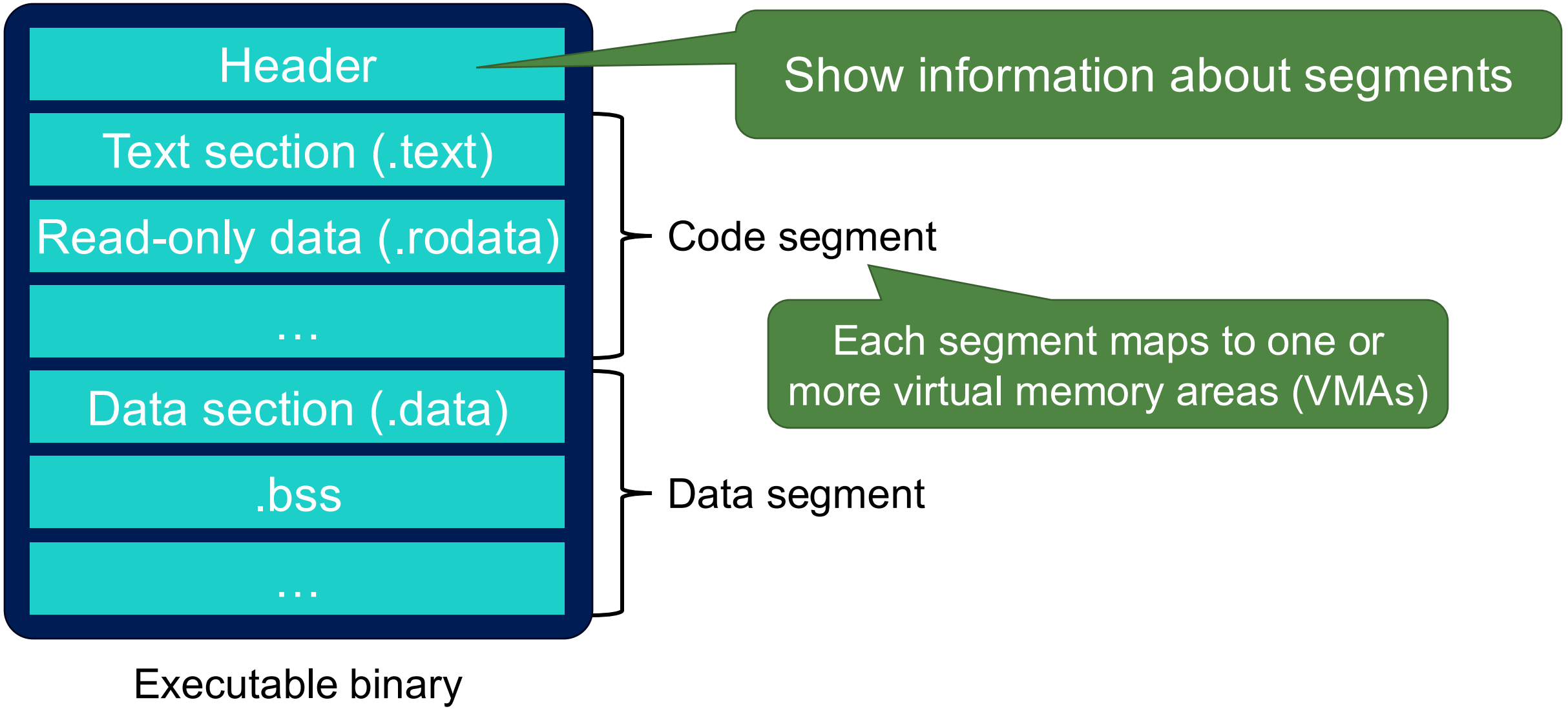
Disassembly is Difficult!

- The very first step of binary analysis, but it is extremely challenging because of
  - Indirect branches
    - `jmp eax`
    - `call eax`
  - Mixture of code and data

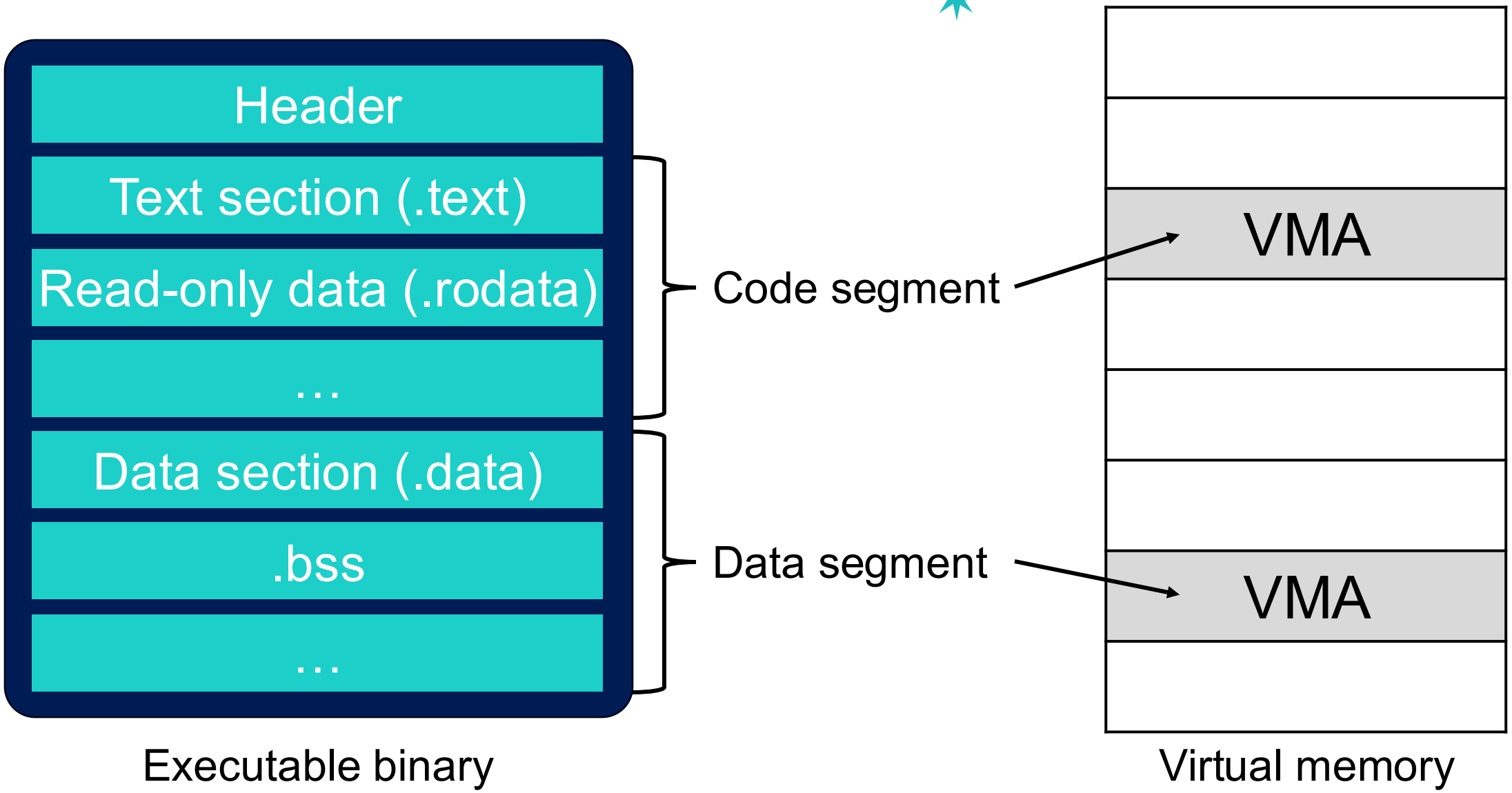
Linking


Source code #1
Source code #2
...
Source code #N
Binary code #1 (Object file)
Binary code #2 (Object file)
...
Binary code #N (Object file)
Executable binary code (= Executable)
Linking

Executable Binary (=Executable, Binary)



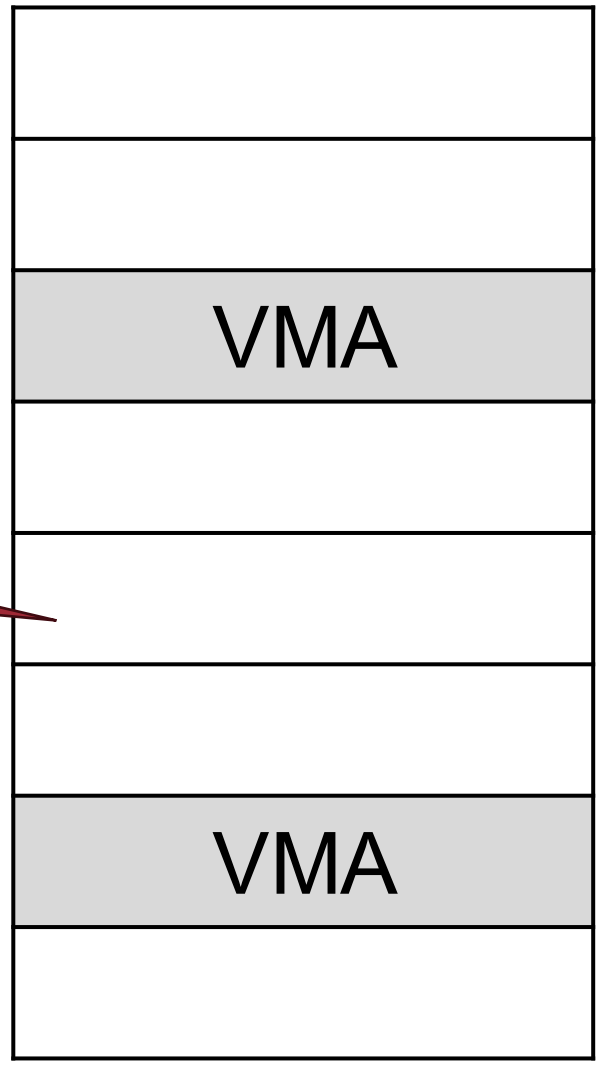
Executable Binary (=Executable, Binary)



Segmentation Fault

- a.k.a., SegFault or Access violation

Happens when we reference an unmapped memory address



x86 (IA-32) Architecture

x86 Instruction Set Architecture

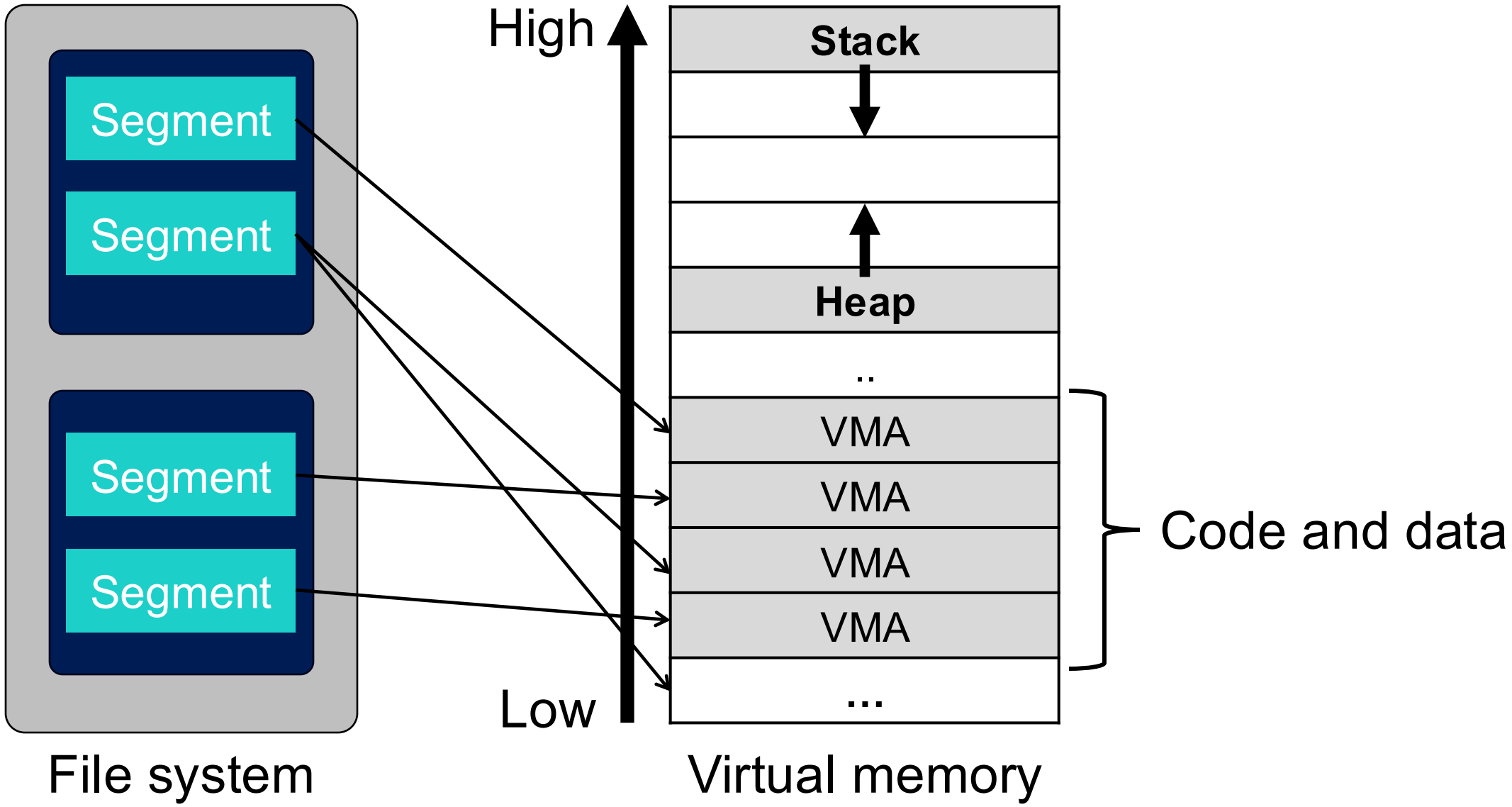
- Developed by Intel in 1985
- CISC (Complex Instruction Set Computer) architecture
- **32-bit** address space
- One of the most common architecture

History of x86 ISA

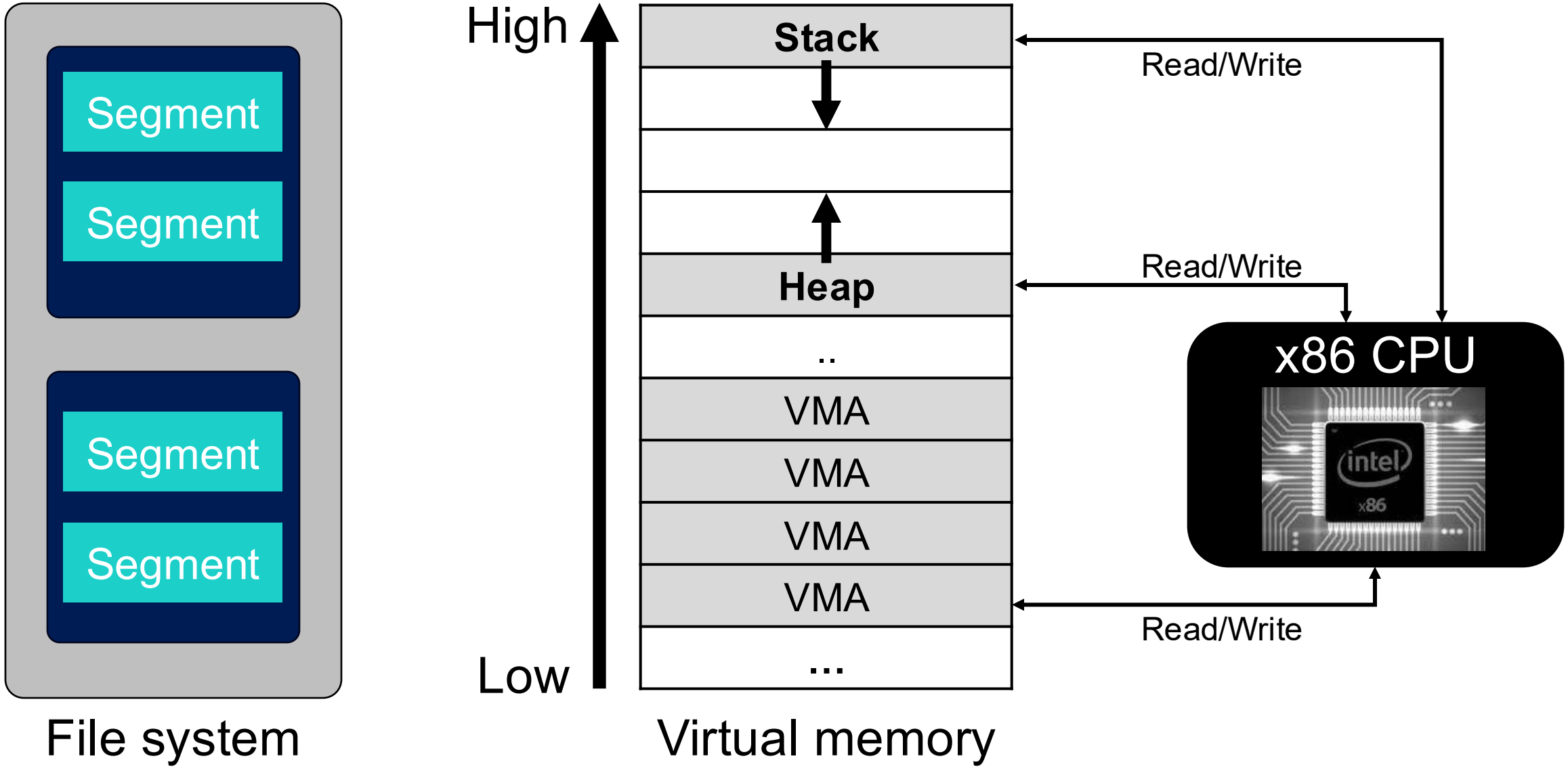
- (**8086**) 16-bit address space (in 1978)
- (**x86 or IA-32**) 32-bit address space (in 1985)
- (**x86-64 or x64 or AMD64**) 64-bit address space (in 2003)

This course will focus on x86 (IA-32) architecture

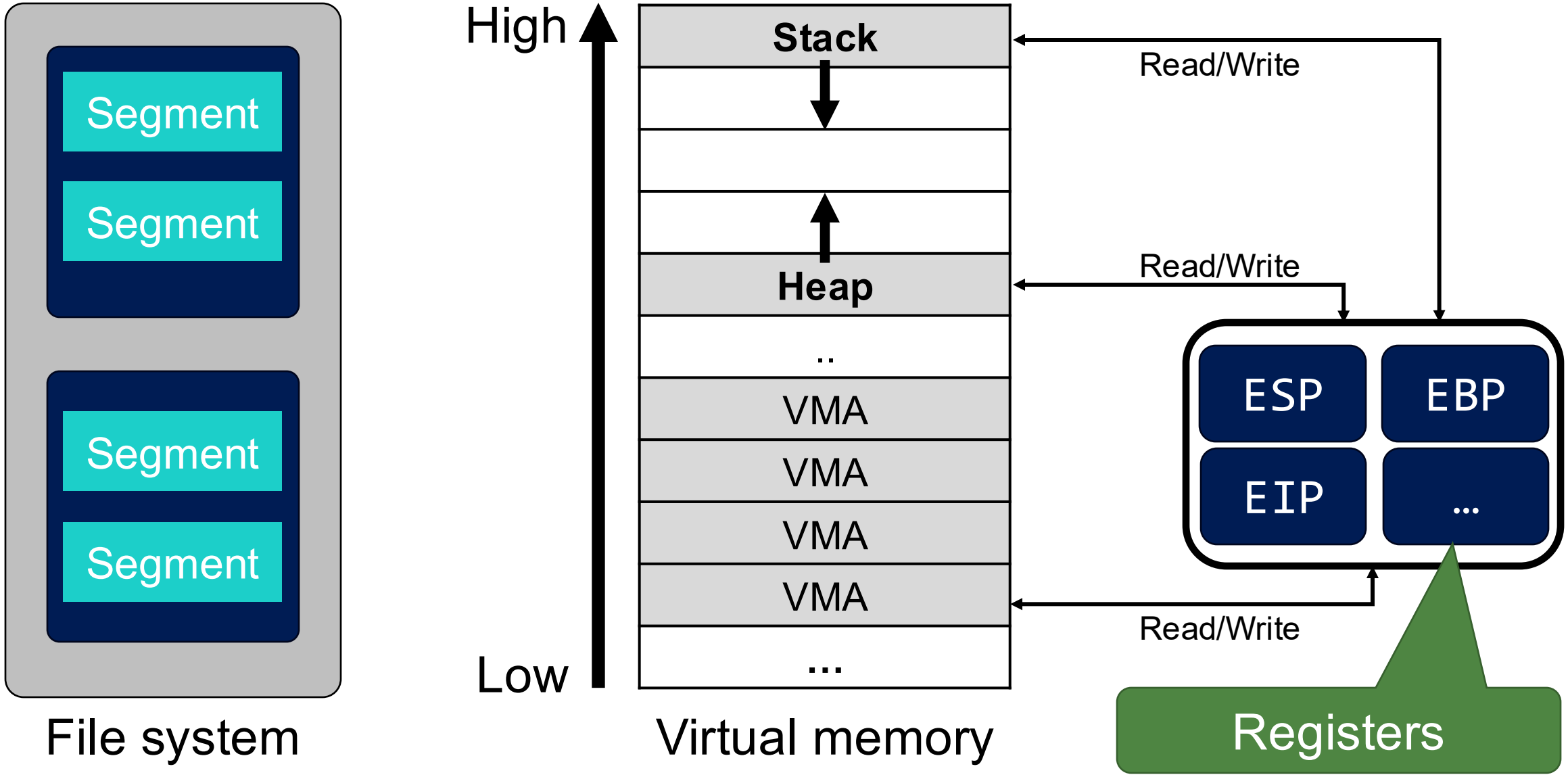
Memory Layout and CPU Registers



Memory Layout and CPU Registers



Memory Layout and CPU Registers



Registers in x86

- Program counter (instruction pointer)
  - **`EIP:`** points to the instruction to execute
- Stack pointers
  - **`ESP:`** points to the top of the stack
  - **`EBP:`** points to the base of the current stack frame
- Status register (FLAGS register)
  - **`EFLAGS:`** contains the current condition flags
- Other general purpose registers
  - **`EAX`**, **`EBX`**, **`ECX`**, **`EDX`**, **`ESI`**, **`EDI`**

All of them have a size of a ***double word*** (=32 bit)

Size of Registers

- x86 registers are 32-bit
- A word is the natural unit of data used by a processor
  - Typically, a word size is 32 bits on a 32-bit machine

- However, Intel defines a word is 16 bits on x86 (32-bit machine)

History of Intel/AMD Processors

- 1978: 8086
- 1982: 80286

16-bit processor,
Registers (`SP, BP, IP, ...`)

- 1985: 80386
- 1989: 80486
- ...

32-bit processor,
Registers (ESP, EBP, EIP, ...)

- 2003: Opteron
- 2005: Prescott
- 2006: Core 2
- 2008: Core i7
- …

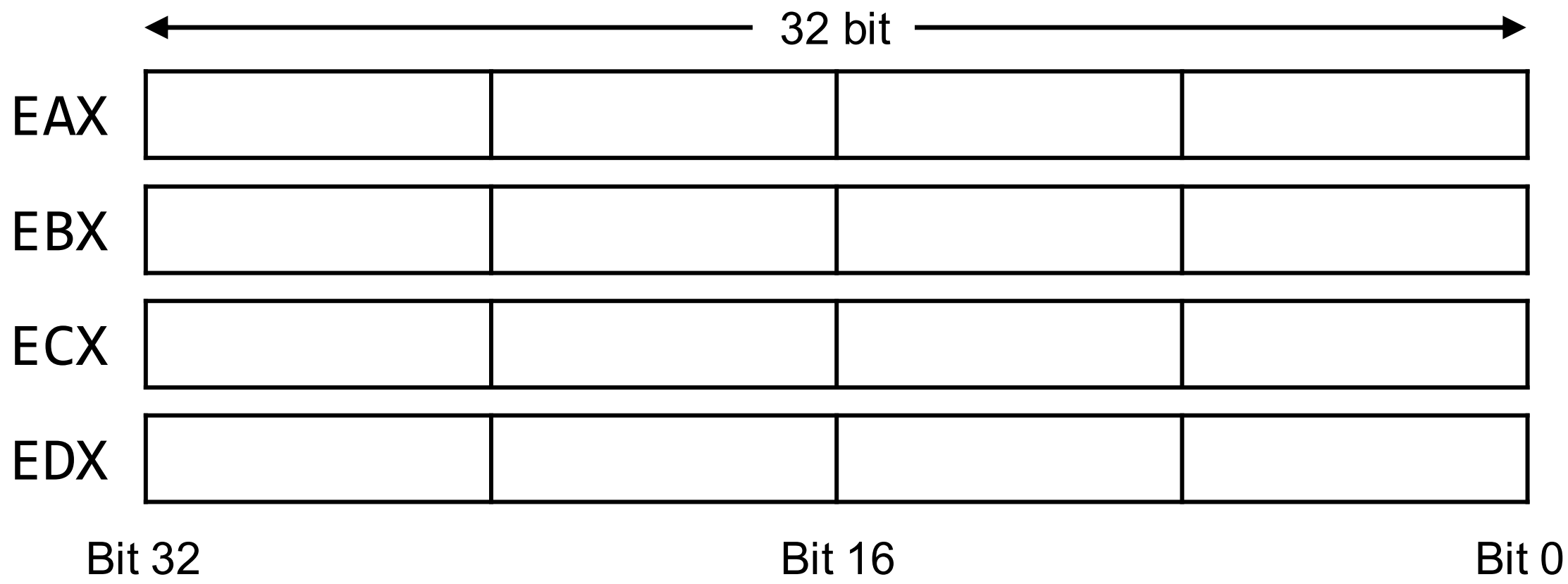
64-bit processor,
Registers (RSP, RBP, RIP, ...)

x86 Convention

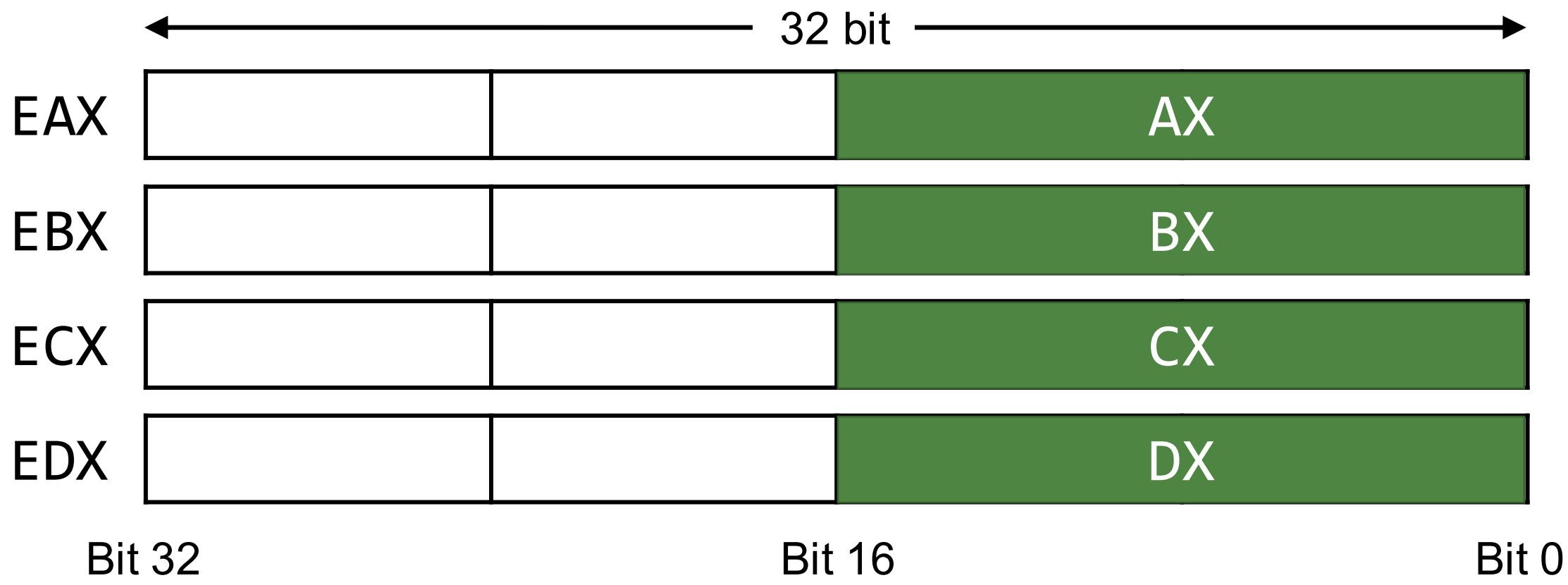
- Word = 16 bits
- Double Word (DWORD) = 32 bits

- Linear address space = 0 ~ 2^{32} bits

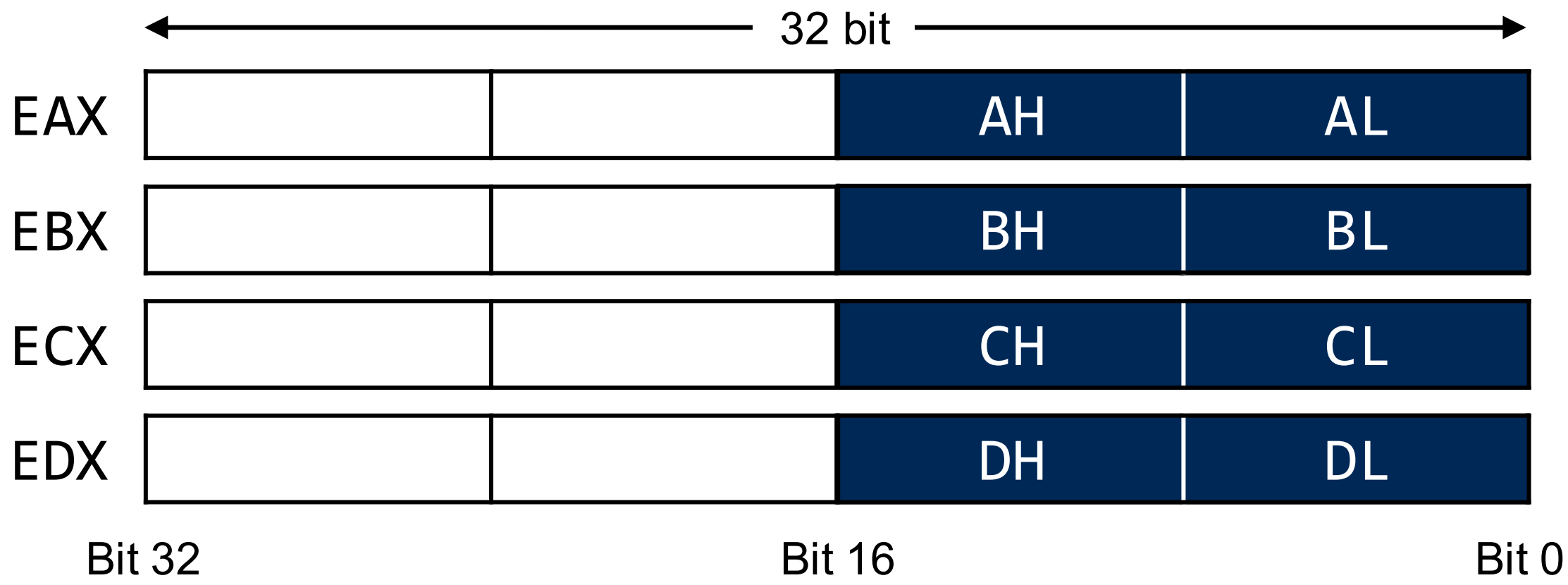
x86 Register Access



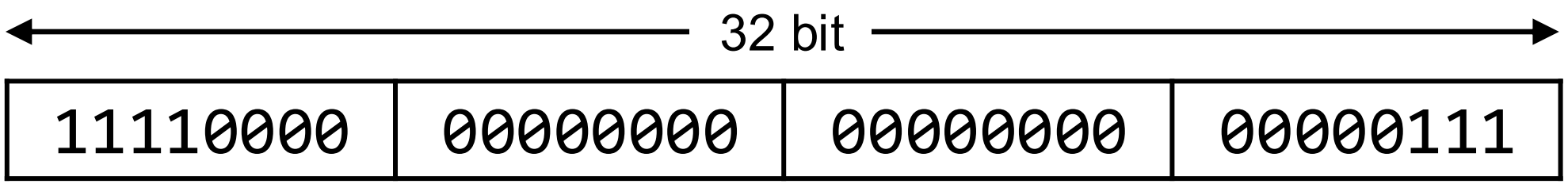
x86 Register Access



x86 Register Access



x86 Register Access




```
AX 00000000  00000111
AH 00000000
AL           00000111
```

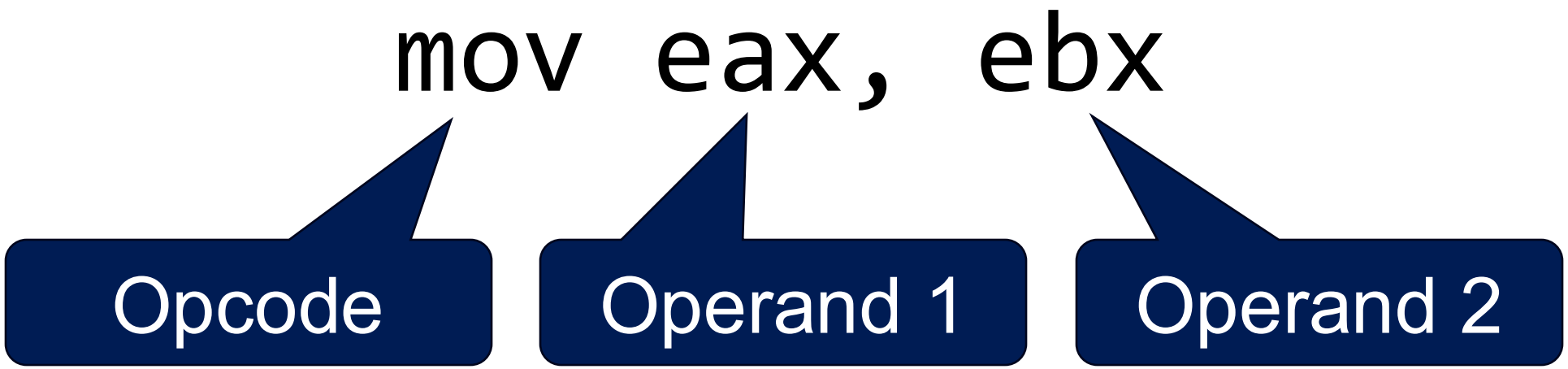
x86 Memory Access = Byte Addressing

x86 Assembly Basics

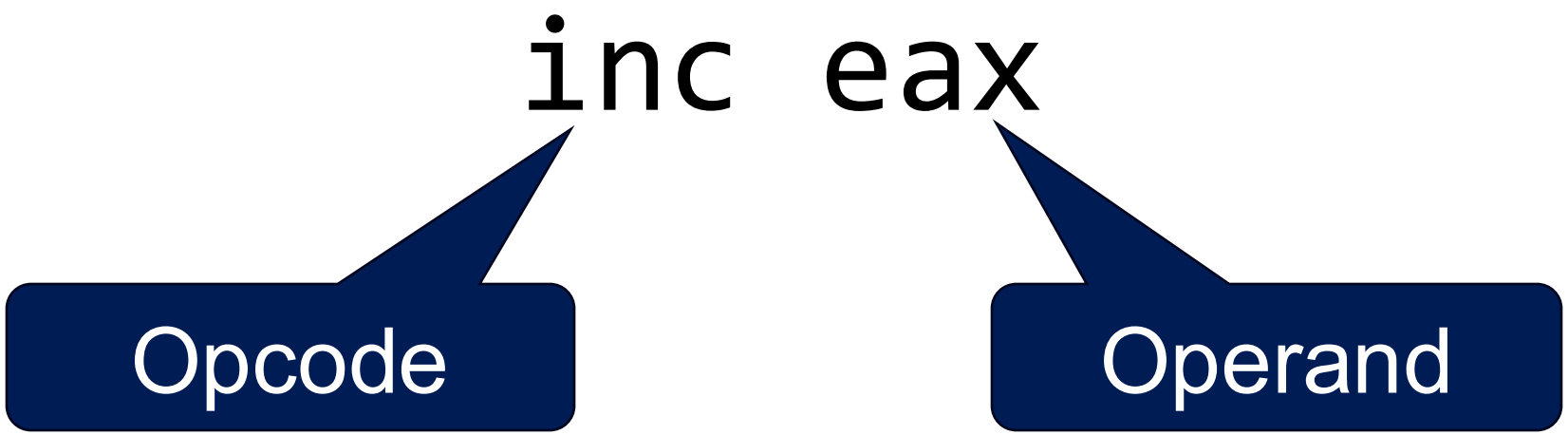
Basic Formats

- Three formats of Instructions
  - 2 operands
  - 1 operands
  - 0 operands

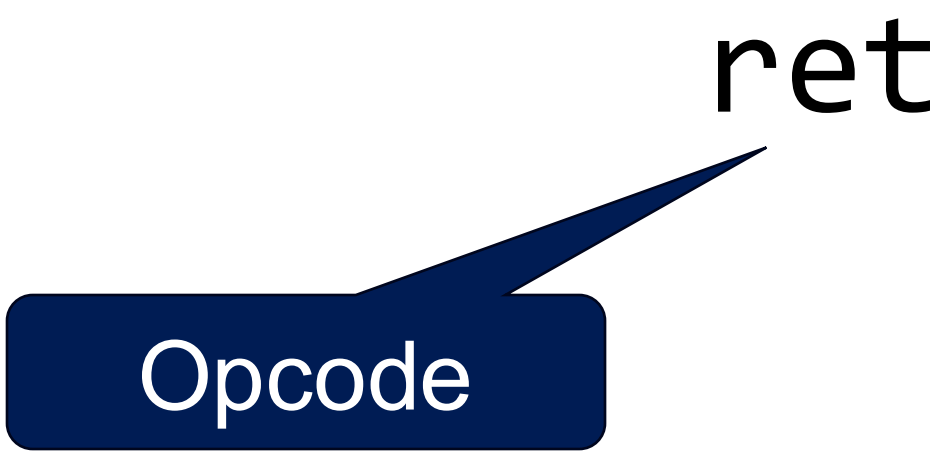
Basic Format #1: Instructions with 2 Operands



Basic Format #2: Instructions with 1 Operand



Basic Format #3: Instructions with 0 Operand



Intel vs AT&T Format

- There are two ways to represent x86 assembly code

AT&T

```
mov %eax, %ebx
```

Intel

```
mov ebx, eax
```

We will use the Intel syntax

Opcode Decides Semantics


```
mov eax, ebx
```

```
eax ← ebx
```

```
sub esp, 0x8
```

```
esp ← esp – 0x8
```

```
inc eax
```

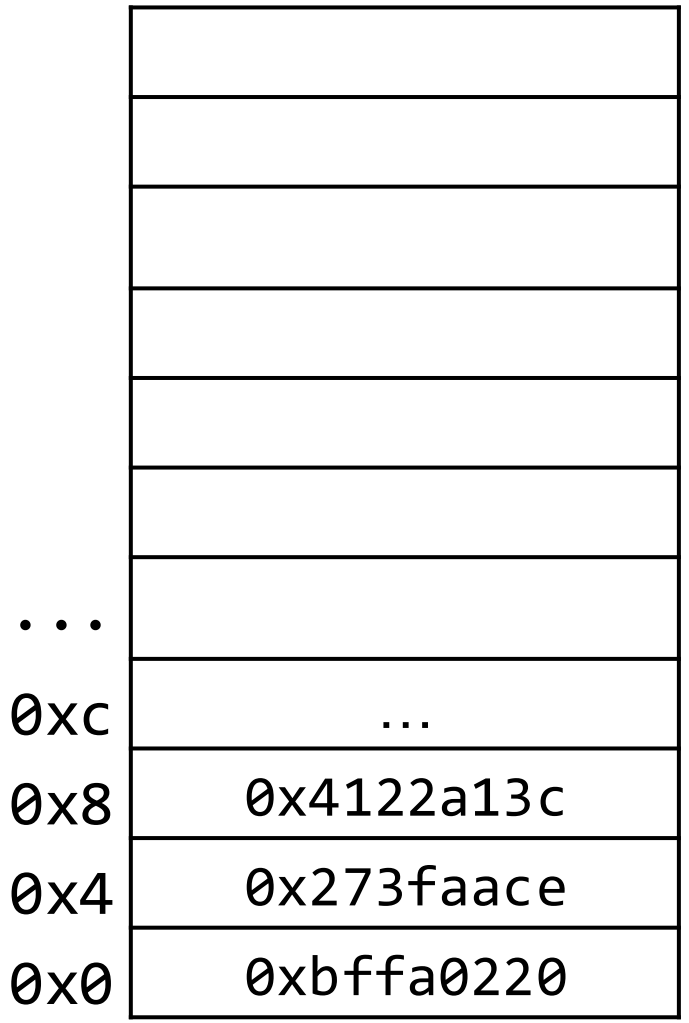
```
eax ← eax + 1
```

Operand Types

Memory pointed by ebx

```
mov eax, [ebx]
```

Register



Registers

eax

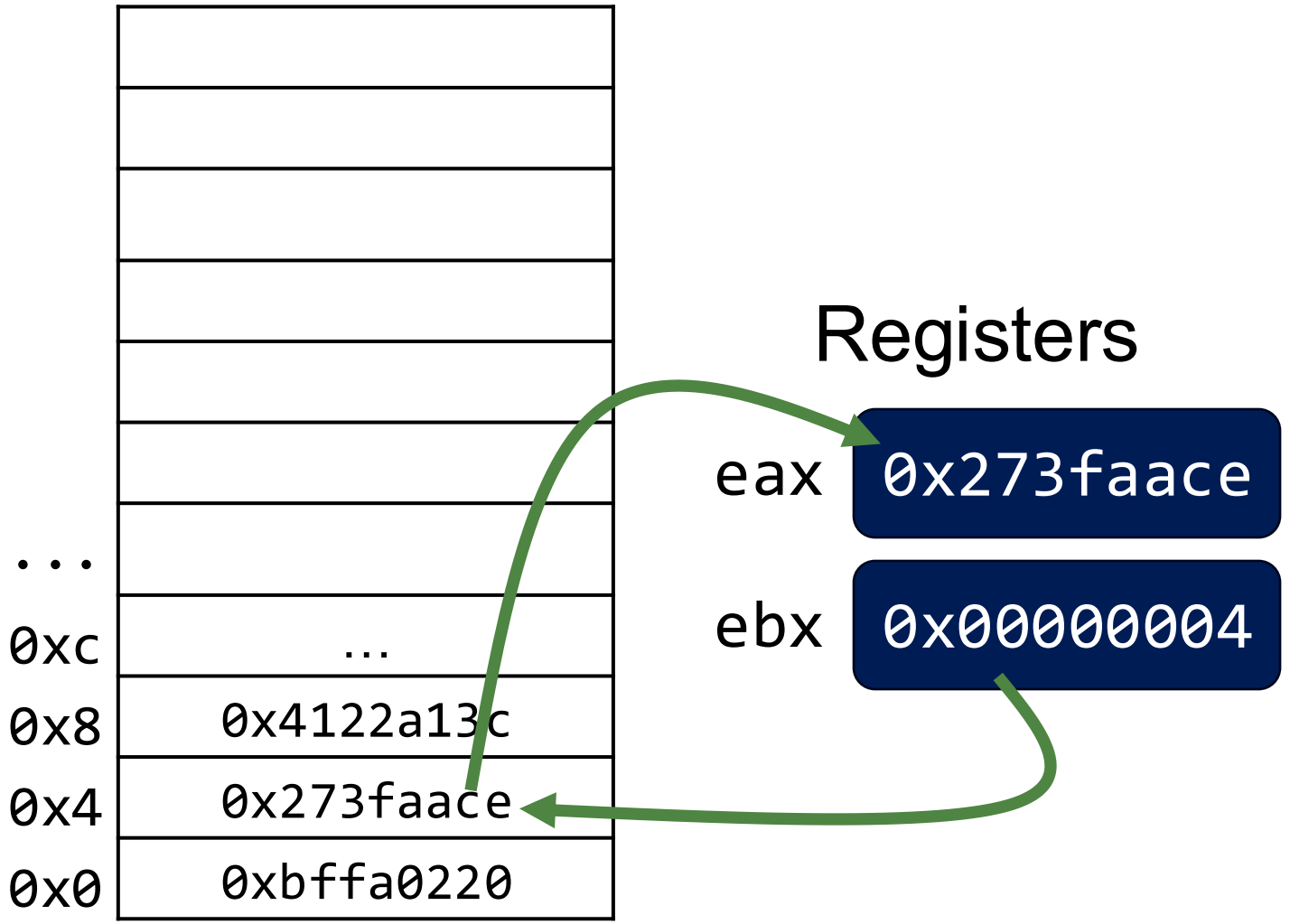
ebx 0x00000004

Operand Types

Memory pointed by ebx

```
mov eax, [ebx]
```

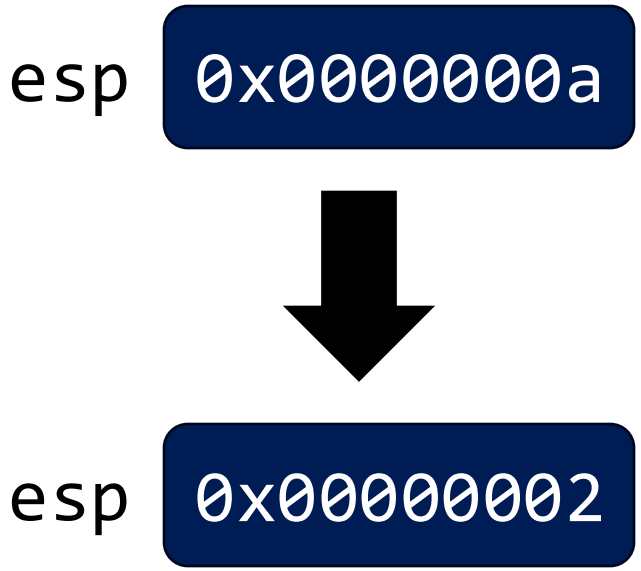
Register



Operand Types


```
sub esp, 0x8
```

Constant integer



Operand Types


```
mov cl, BYTE ptr [eax]
```

Pointer Directive


```
mov [esi], al    ; ok
mov [esi], 1     ; error
```

Error: ambiguous operand size for 'mov'

Because it could be any of the followings

- `mov BYTE PTR [esi], 1`
- `mov WORD PTR [esi], 1`
- `mov DWORD PTR [esi], 1`
- `mov QWORD PTR [esi], 1`

Therefore, we need pointer directive ☺

Moving Data Around (mov)

- `mov eax, ebx`
- `mov al, bl`

} Register to Register

- `mov [eax], ebx`

} Register to Memory

- `mov eax, [ebx]`
- `mov eax, [ebx + edx * 4]`
- `mov al, BYTE PTR [esi]`

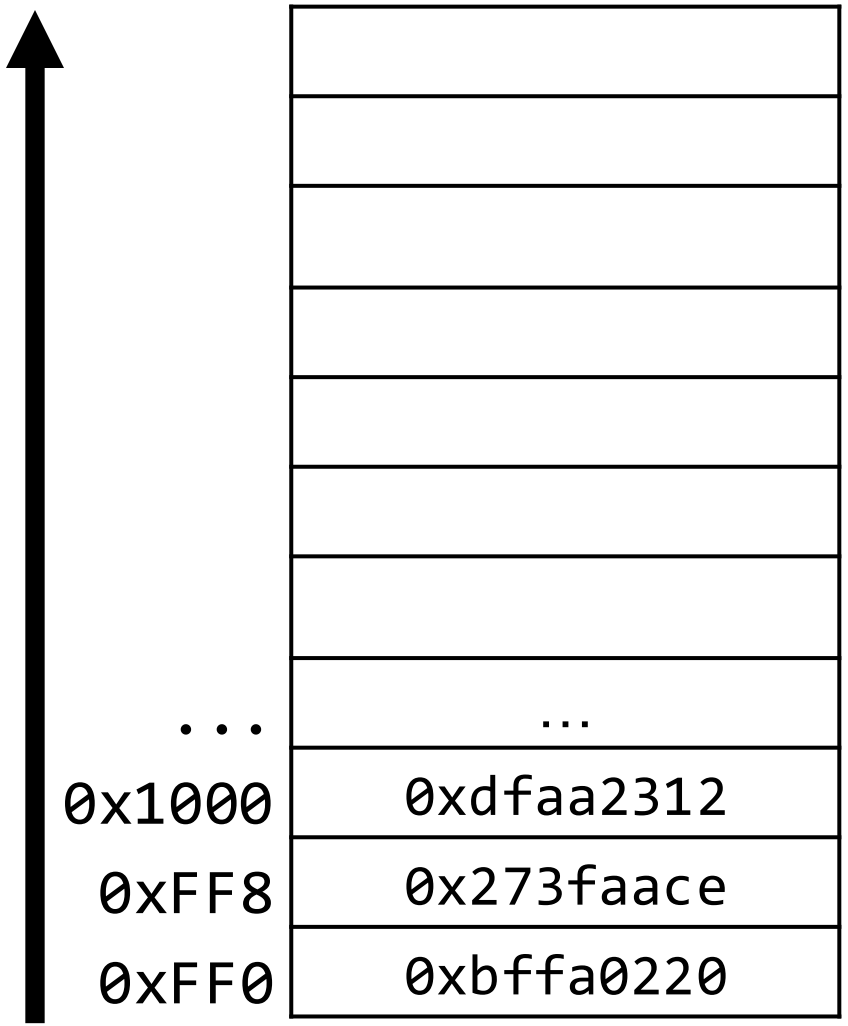
} Memory to Register

- `mov eax, 42`
- `mov BYTE PTR [eax], 42`

} Constant to Memory/Register

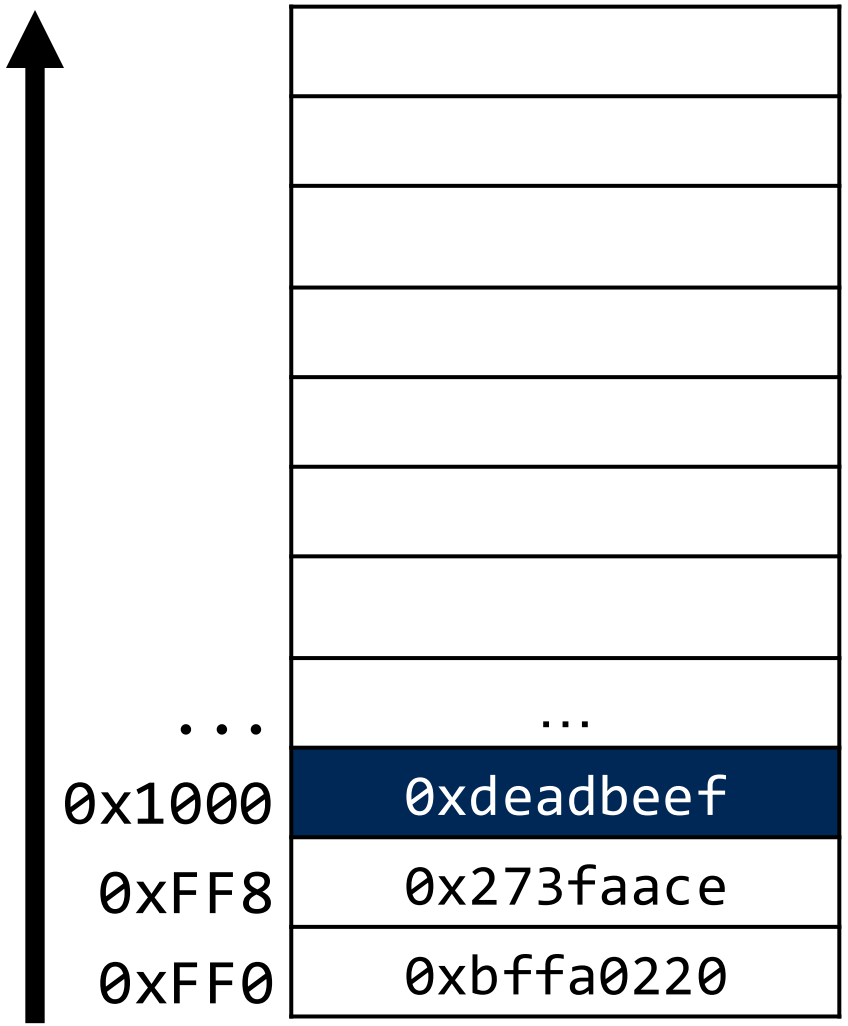
Example: Storing a DWORD in Memory


```
mov [eax], 0xdeadbeef     ; eax = 0x1000
```



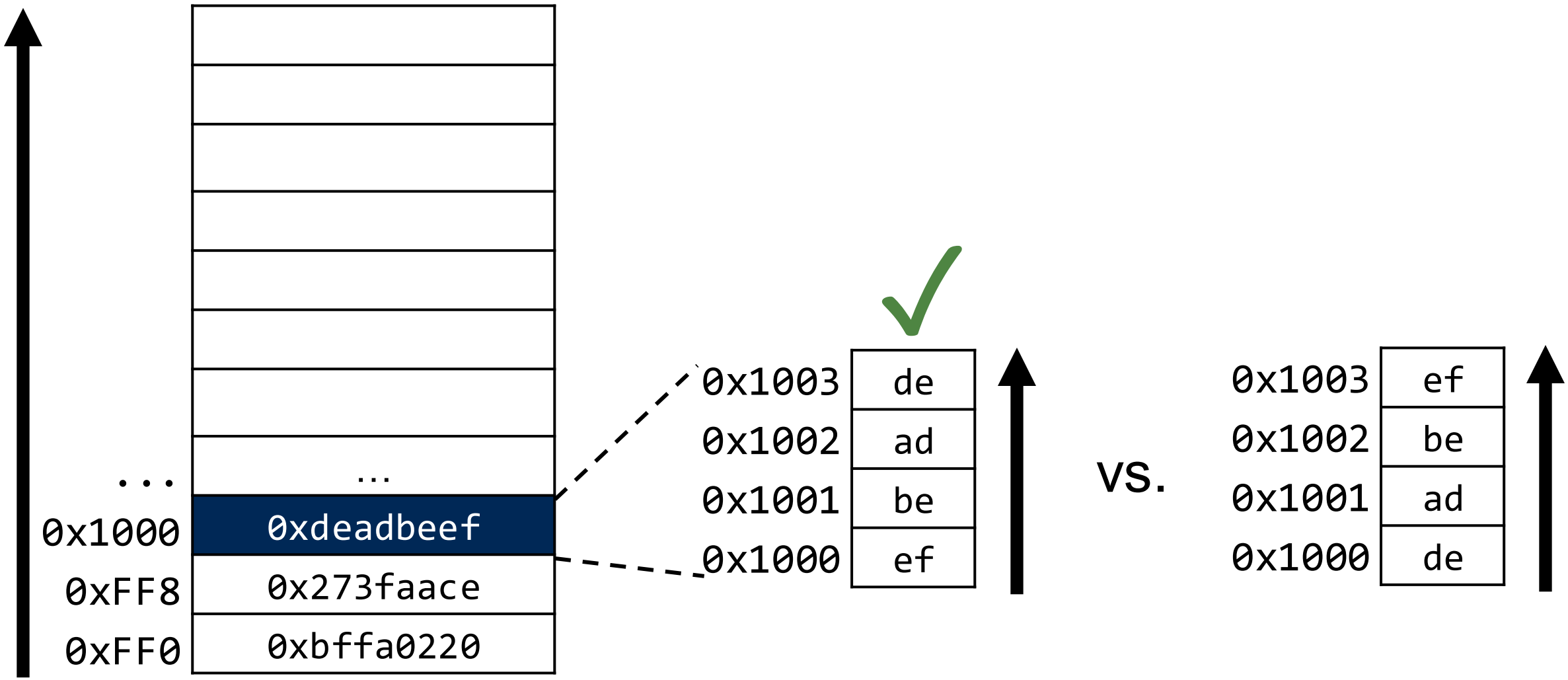
Example: Storing a DWORD in Memory


```
mov [eax], 0xdeadbeef     ; eax = 0x1000
```



Example: Storing a DWORD in Memory

```
mov [eax], 0xdeadbeef    ; eax = 0x1000
```



Endianness

- The order in which a sequence of bytes are stored in memory

- Big Endian = The MSB goes to the lowest address
- Little Endian = The LSB goes to the lowest address

x86 uses Little Endian

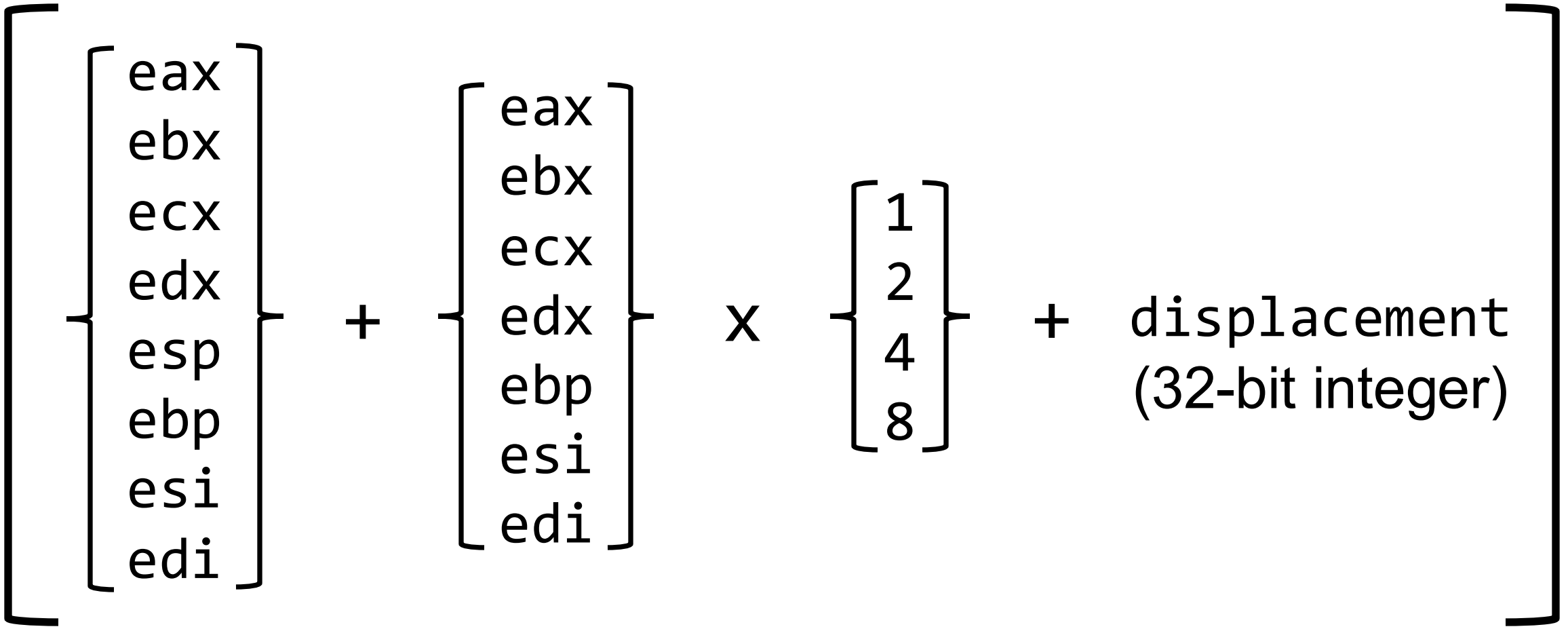
Addressing Modes

Specify how a memory operand is interpreted to derive an effective address

- **register**
  - ✓`mov eax, [eax]`
- **register + register**
  - ✓`mov eax, [eax + ebx]`
- **displacement**
  - ✓`mov eax, [0x1000]`
- **register + register × scale + displacement**
  - ✓`mov eax, [eax + ebx * 4 + 0x1000]`

Addressing Modes

Specify how a memory operand is interpreted to derive an effective address



Loading Address (lea)


```
lea eax, [ebx]
lea eax, [ebp-0x8]
```

Memory address to Register

What is the Difference?

```
mov eax, [ebp + 0x10]
```

vs.

```
lea eax, [ebp + 0x10]
```

```
eax ← *(ebp + 0x10)
```

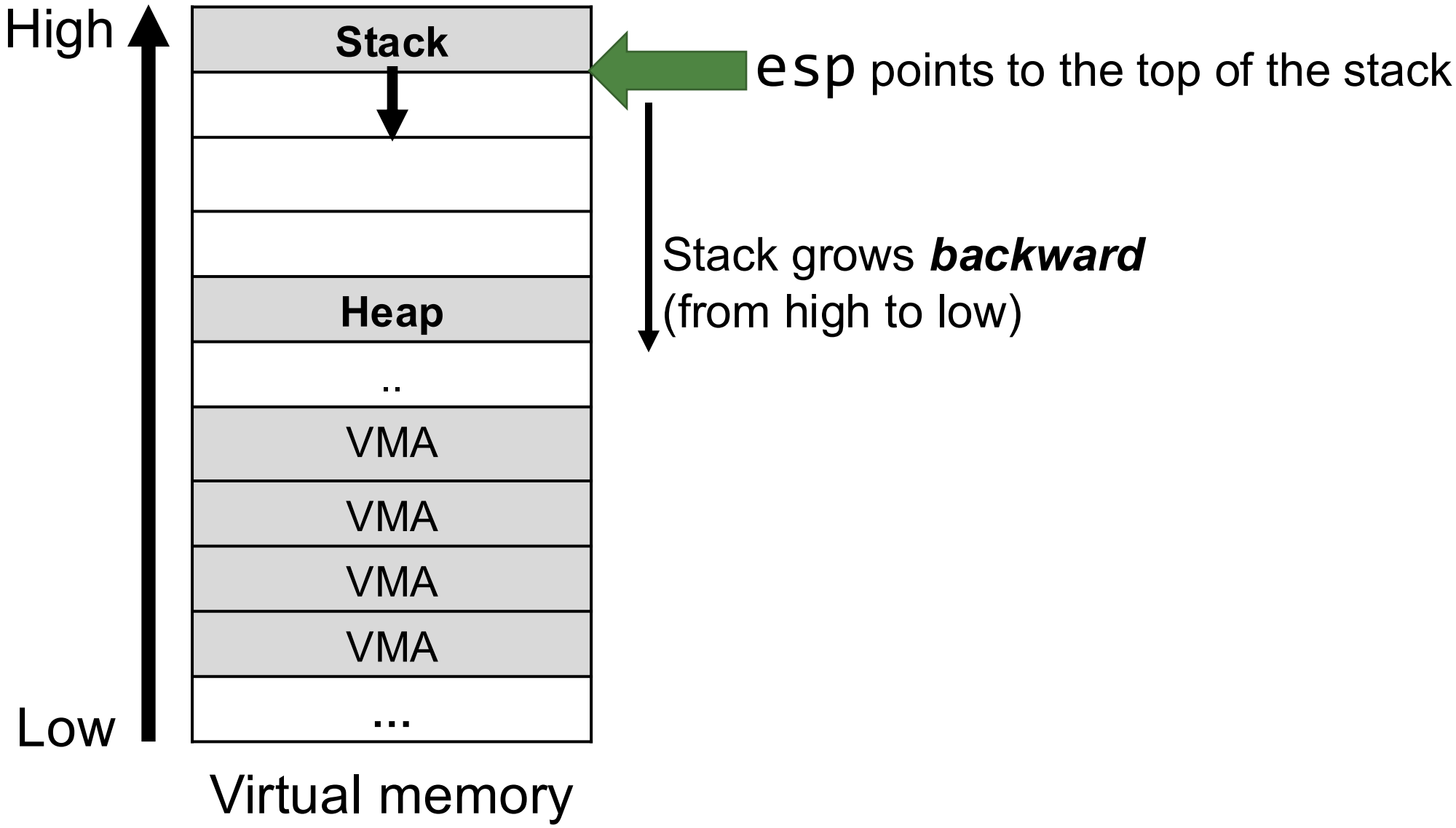
vs.

```
eax ← (ebp + 0x10)
```

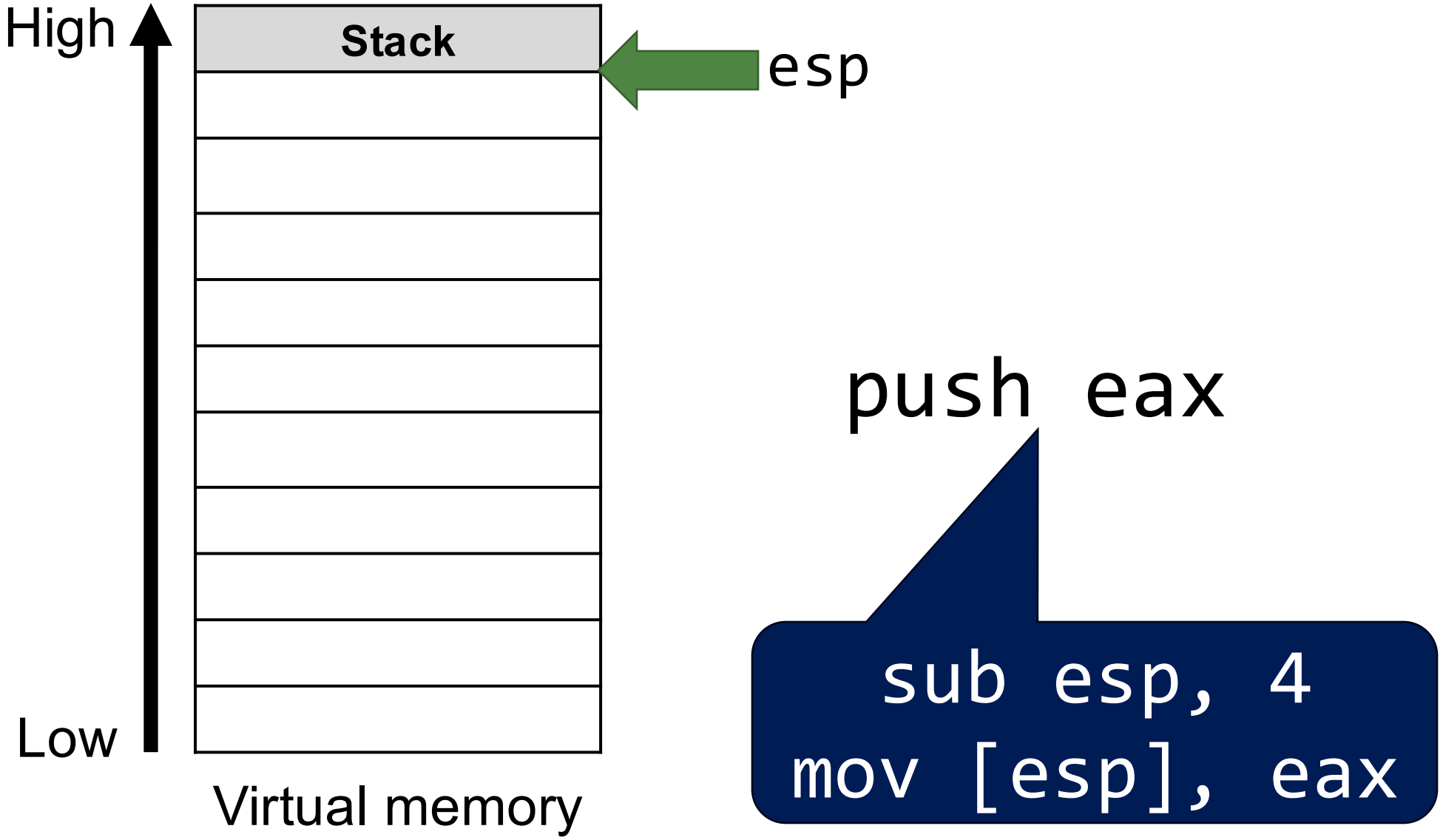
Stack Memory

- Stack stores data in a LIFO (Last-In-First-Out) fashion. When a function is invoked, a new ***stack frame*** is allocated at the top of the stack memory

Stack Operations



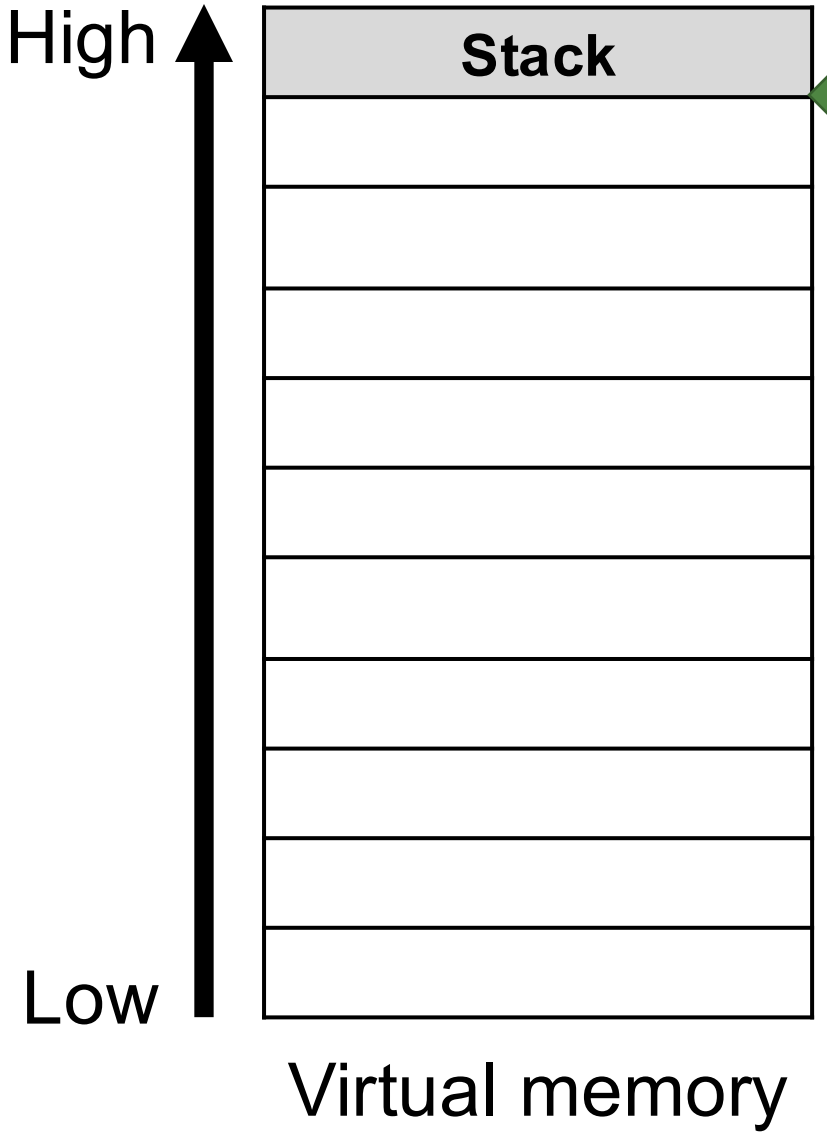
Stack Operations – Push and Pop




```
push eax
```

```
sub esp, 4
mov [esp], eax
```

Stack Operations – Push and Pop



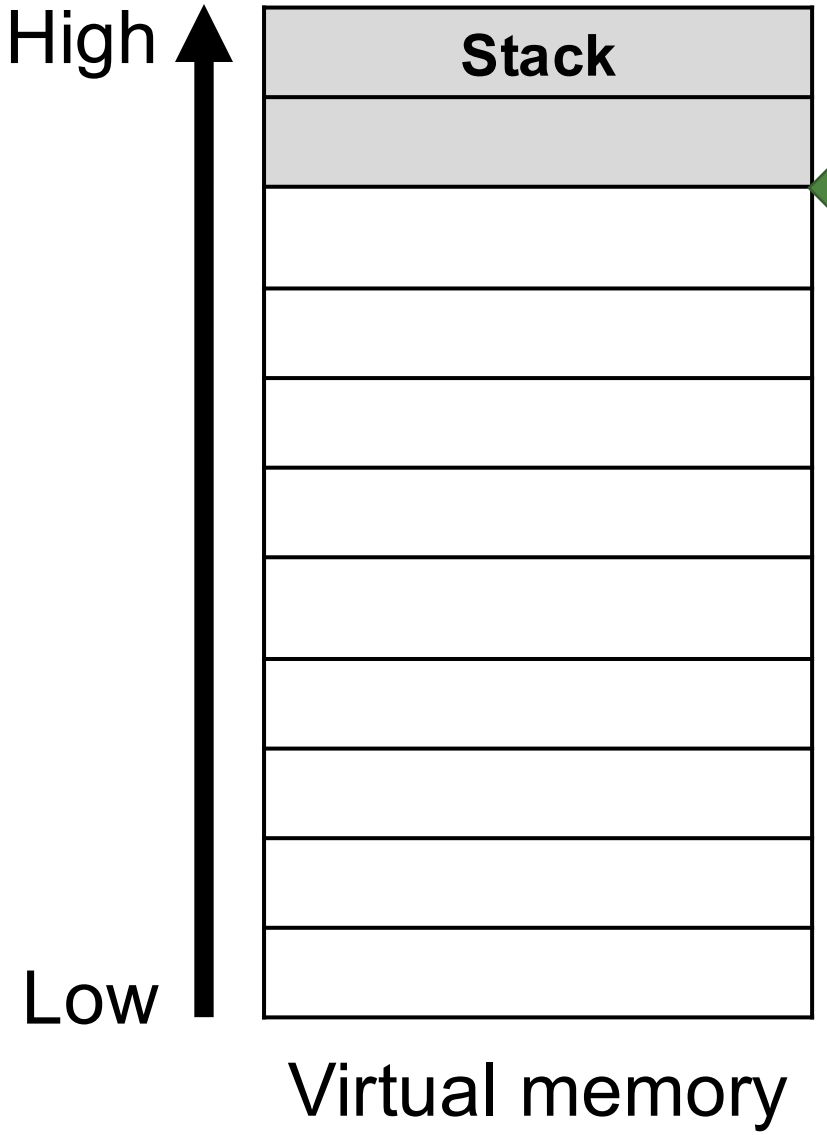
push eax

```
sub esp, 4
mov [esp], eax
```

Registers

eax 0x00000009

Stack Operations – Push and Pop



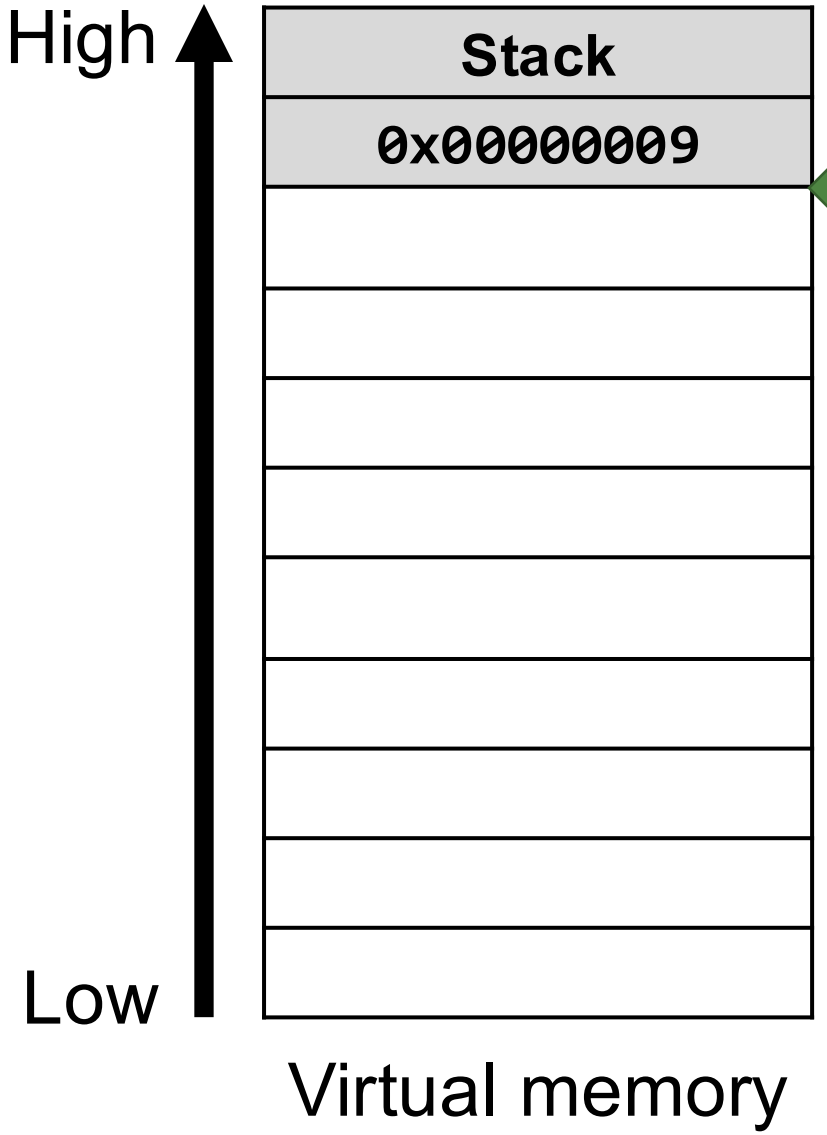
push eax

```
sub esp, 4
mov [esp], eax
```

Registers

eax 0x00000009

Stack Operations – Push and Pop



push eax

Registers

eax 0x00000009

```
sub esp, 4
mov [esp], eax
```

Stack Operations (push)

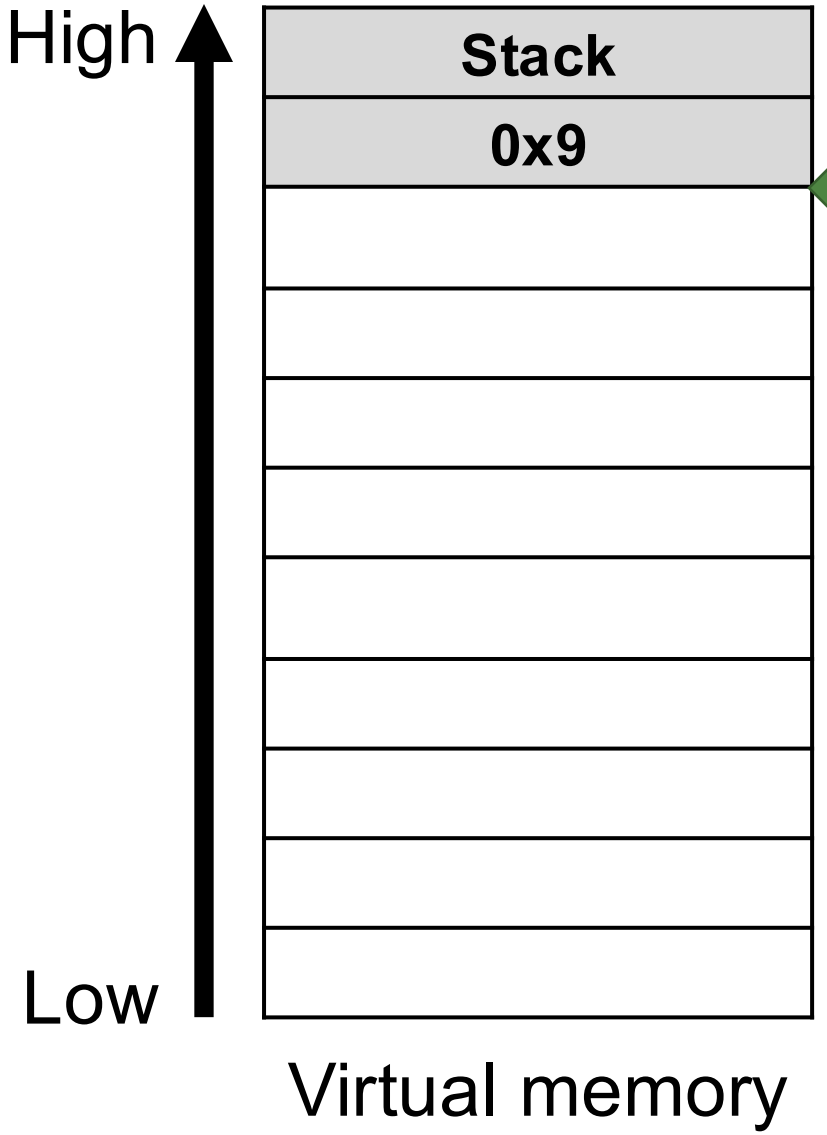
`push eax`	Push register on the stack
`push 0x42`	Push constant on the stack
`push [eax]`	Push a value at the memory address on the stack

```
push x
```

=

```
sub esp, 4
mov [esp], x
```

Stack Operations – Push and Pop



pop ecx

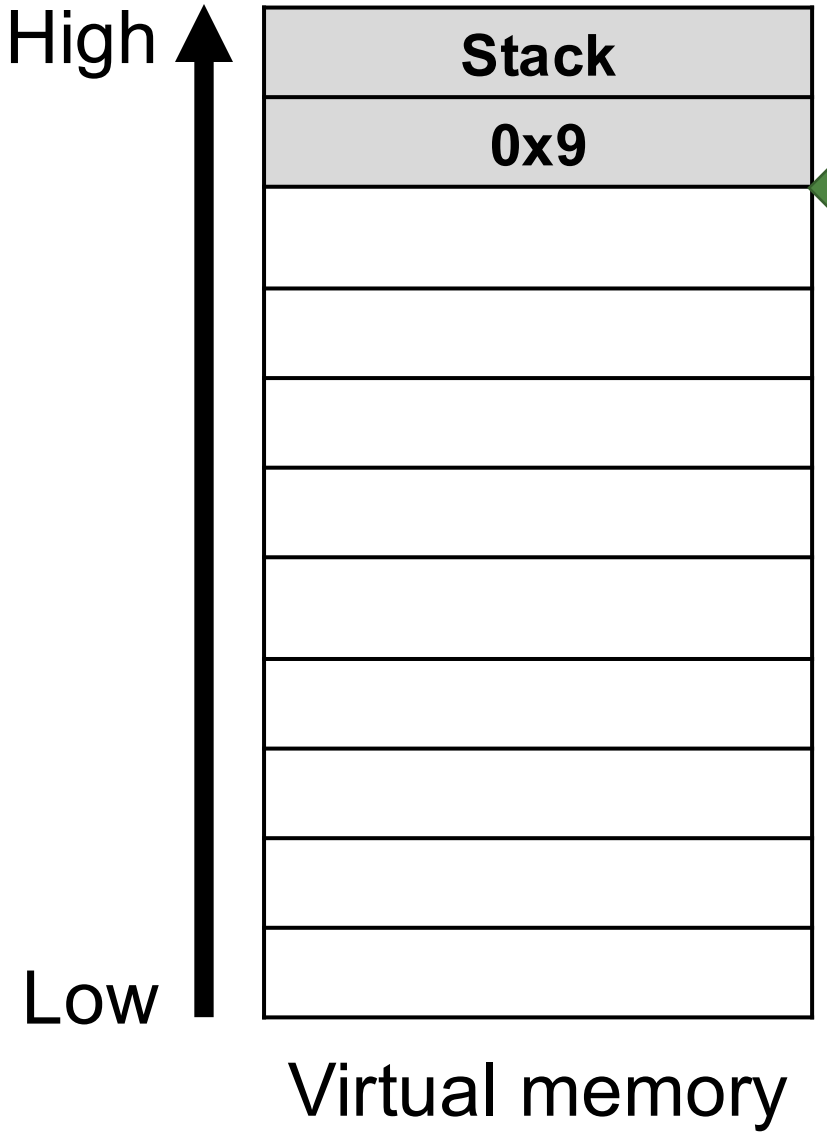
```
mov ecx, [esp]
add esp, 4
```

Registers

ecx 0x13ef0ca1

(before)

Stack Operations – Push and Pop



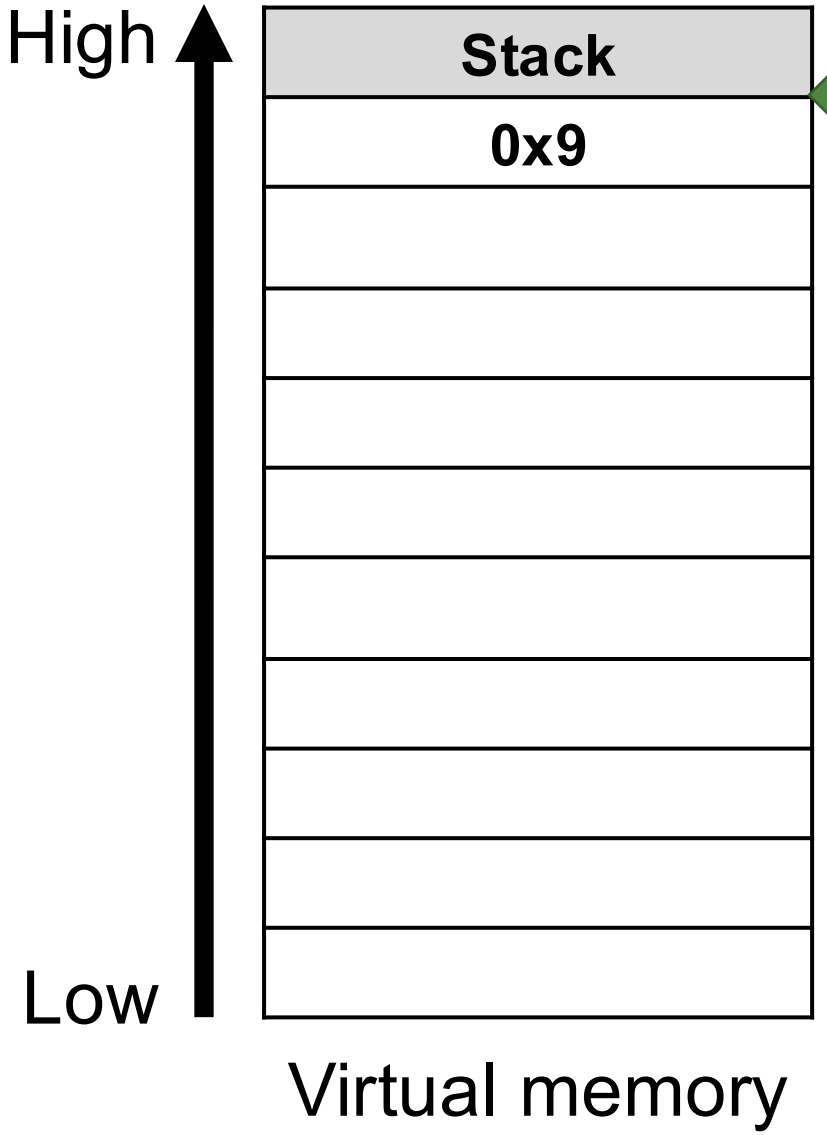
pop ecx

```
mov ecx, [esp]
add esp, 4
```

Registers

ecx 0x00000009 (after)

Stack Operations – Push and Pop



pop ecx

```
mov ecx, [esp]
add esp, 4
```

Registers

ecx 0x00000009

(after)

Stack Operations (pop)

`pop eax`	Pop the top element of the stack into register
`pop [eax]`	Pop the top element of the stack into the memory address

```
pop x
```

=

```
mov x, [esp]
add esp, 4
```

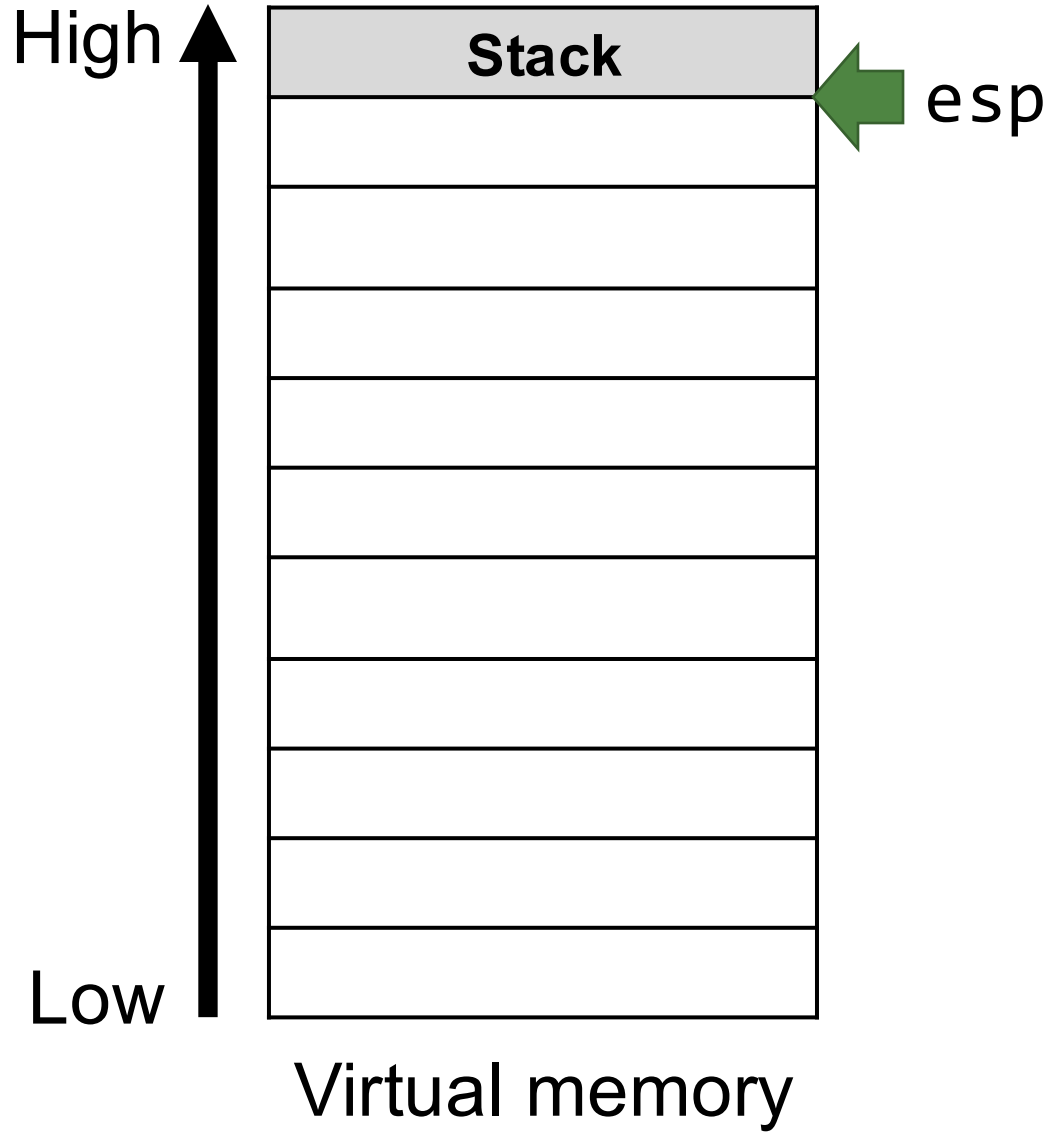
Stack Operations (leave)


```
leave 〓 mov esp, ebp
        pop ebp
```

Function Call (call)

```
    …
    call foo
nextret:
    nop
    nop
    …
foo:
    nop
    nop
```

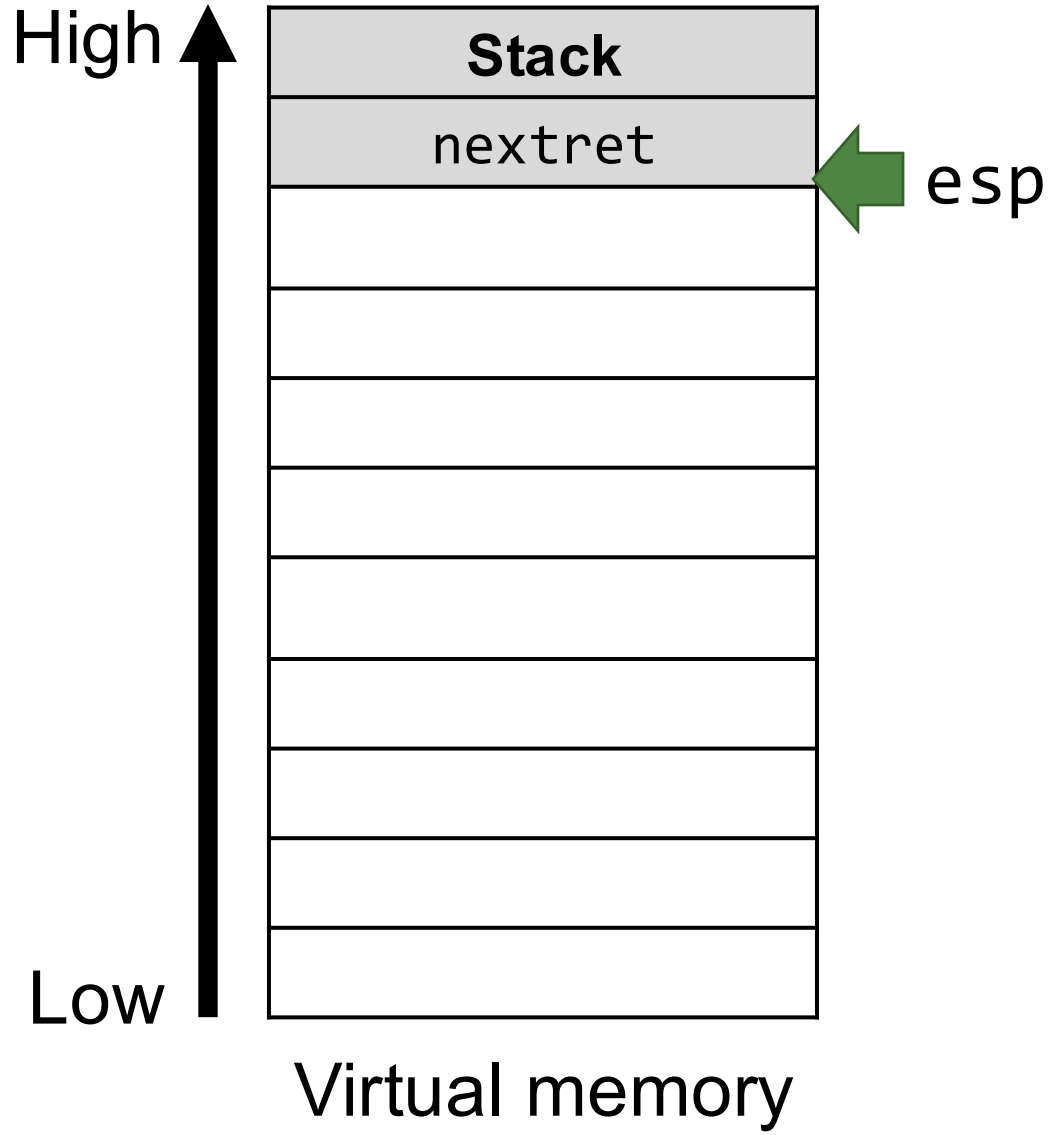
```
push nextret
jmp foo
```



Function Call (call)

```
    …
    call foo
nextret:
    nop
    nop
    …
foo:
    nop
    nop
```

```
push nextret
jmp foo
```

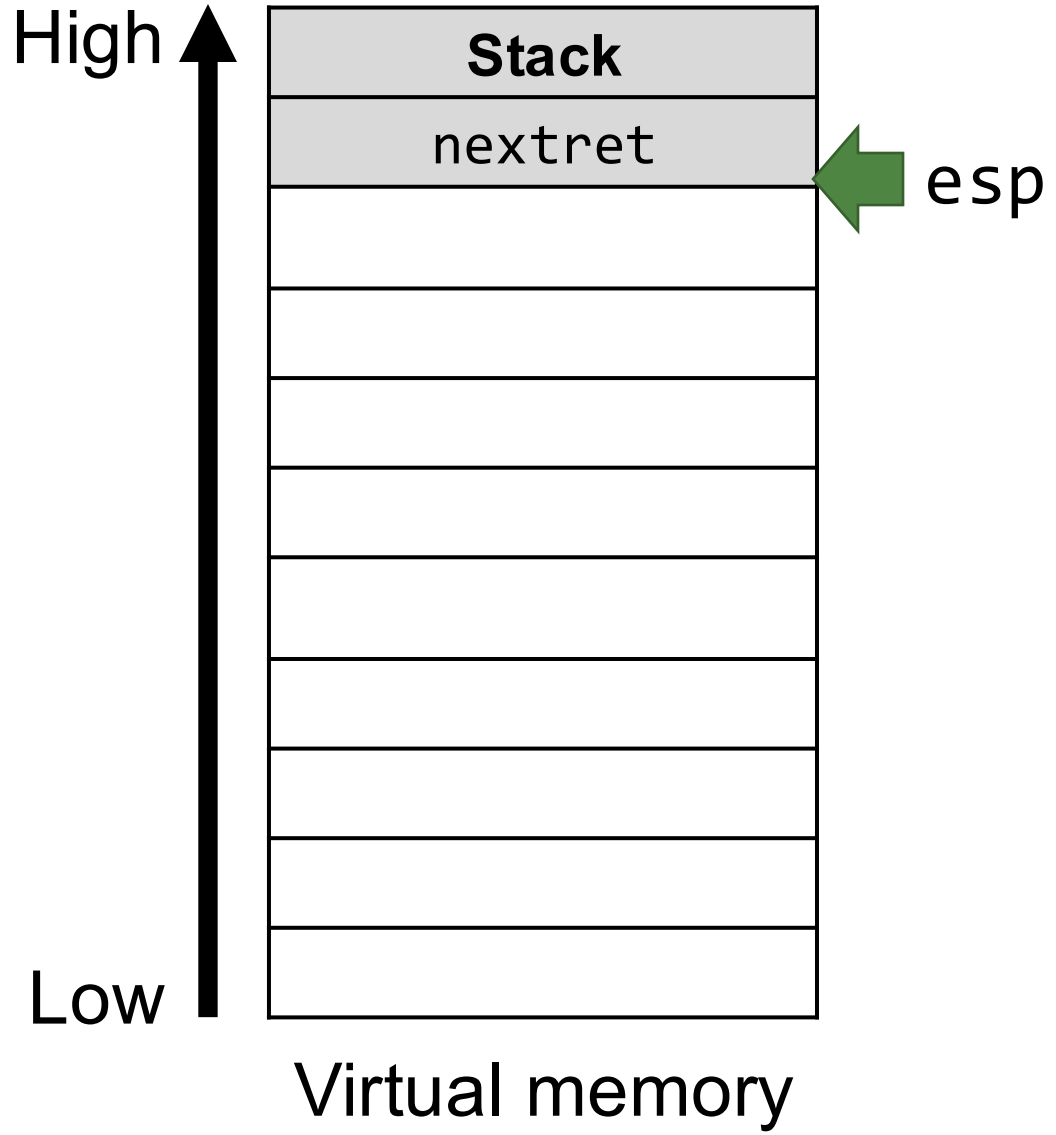


Function Call (call)

```
    …
    call foo
nextret:
    nop
    nop
    …
foo:
    nop
    nop
```

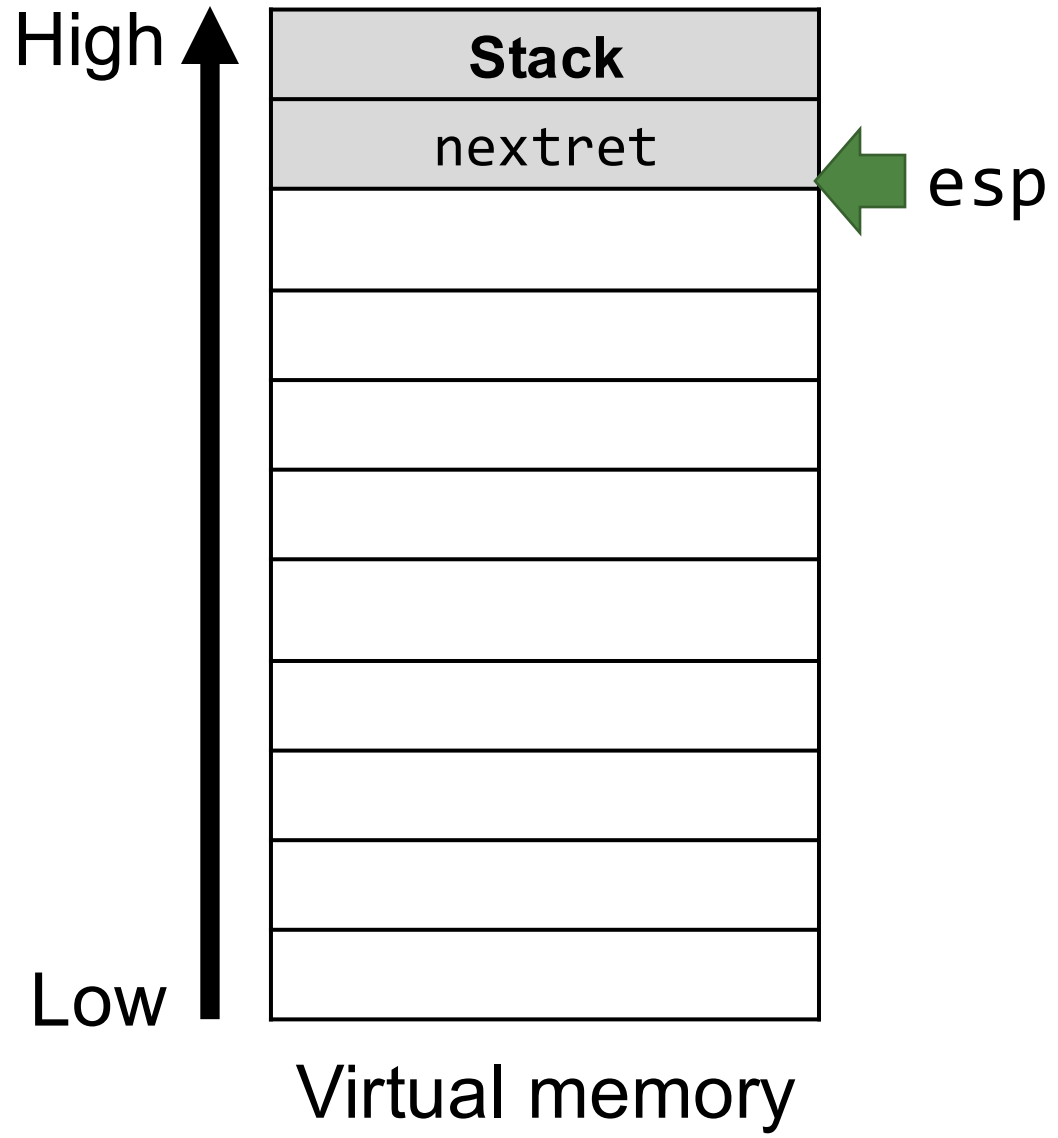
```
push nextret
jmp foo
```

Control flow



Function Return (ret)

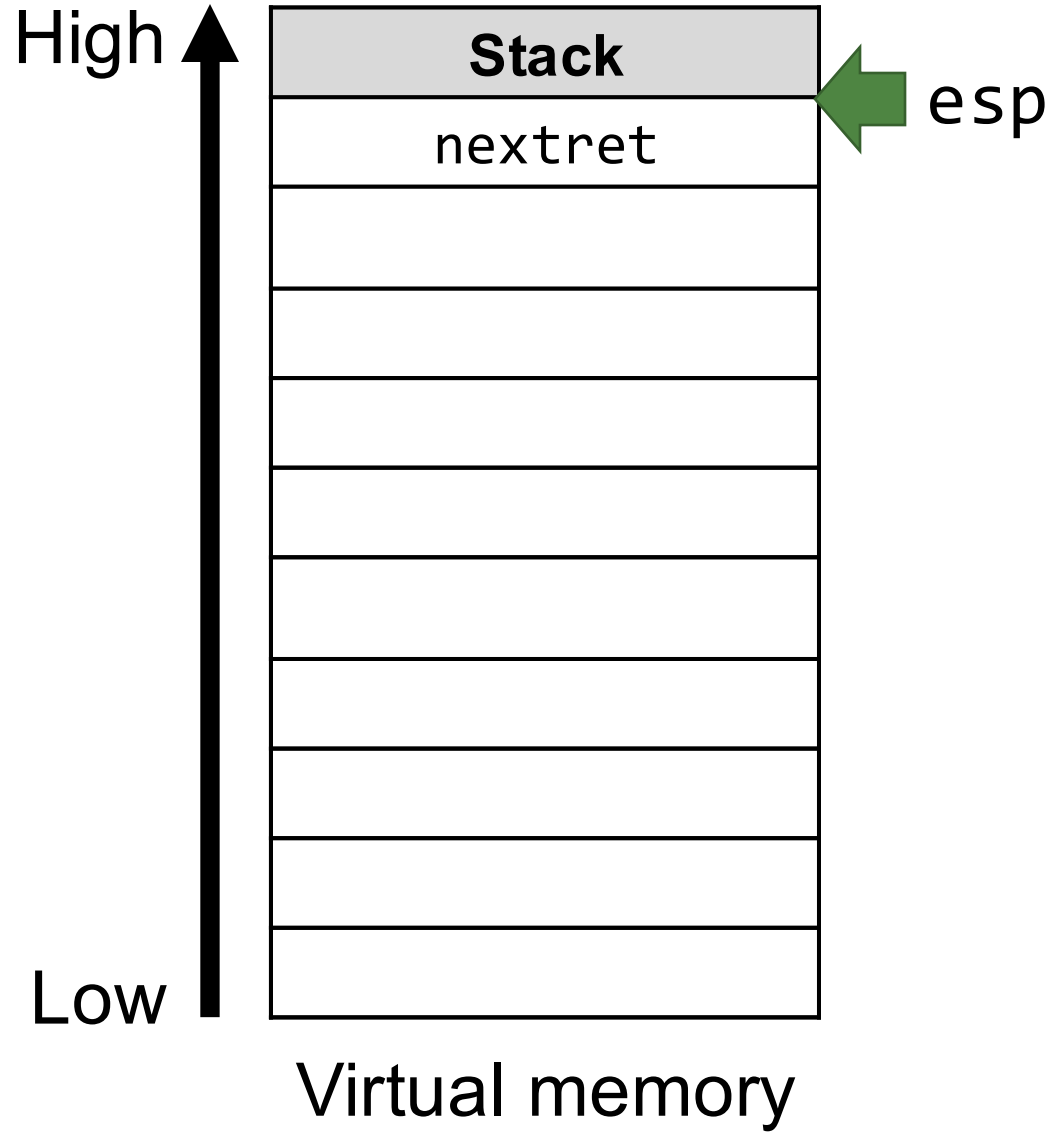
```
ret = pop eip
```



Function Return (ret)

`ret` = `pop eip`

`eip` `nextret`



Arithmetic and Logical Operations

- `add eax, [ebx]`
- `sub esp, 0x40`
- `inc ecx`
- `dec edx`
- `and [eax + ecx], ebx`
- `xor edx, ebx`
- `shl eax, 1`
- `...`

Control Flows


```
if ( x ) {
   /* A */
}
else {
   /* B */
}
```

```
while (x) {
}
```

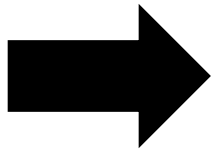
```
for (i = 0; i < n ; i++) {
}
```

How to represent in assembly?

Control Flows in Assembly (1)

- There are only “if” and “goto” (no “else”)

```
if ( x ) {
  /* A */
}
else {
  /* B */
}
```



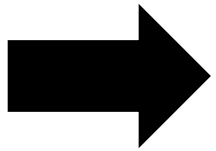
How assembly looks like…

```
   if (!x) goto F;
   /* A */
   goto DONE;
F:
   /* B */
DONE:
```

Control Flows in Assembly (2)

- There are only “if” and “goto” (no “else”)

```
while (x) {
    /* body */
}
```



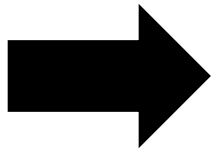
How assembly looks like…

```
WHILE:
    if (!x) goto DONE;
    /* body */
    goto WHILE;
DONE:
```

Control Flows in Assembly (3)

- There are only “if” and “goto” (no “else”)

```
for (i = 0; i < n ; i++) {
  /* body */
}
```

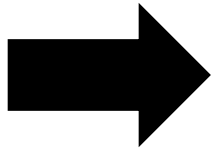


How assembly looks like…

```
    i = 0;
LOOP:
    if (i >= n) goto DONE;
    /* body */
    i++;
    goto LOOP;
DONE:
```

Control Flows in Assembly (Example)


```
if (!x) goto F;
```



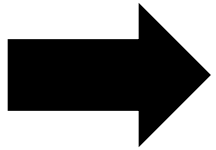
```
cmp x, 0
je F
```

Test if x is zero

If x=zero then goto F

Control Flows in Assembly (Example)

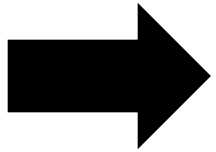

```
if (!x) goto F;
```



```
cmp x, 0
je F
```

Test if `i >= n`

```
if (i >= n) goto F;
```



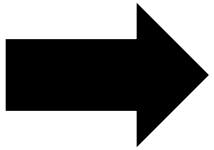
```
cmp i, n
jge F
```

If `i >= n` then goto F

Control Flows in Assembly (Example)

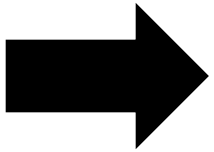
Where do we store the result of comparison (cmp)?

```
if (!x) goto F;
```



```
cmp x, 0
je F
```

```
if (i >= n) goto F;
```

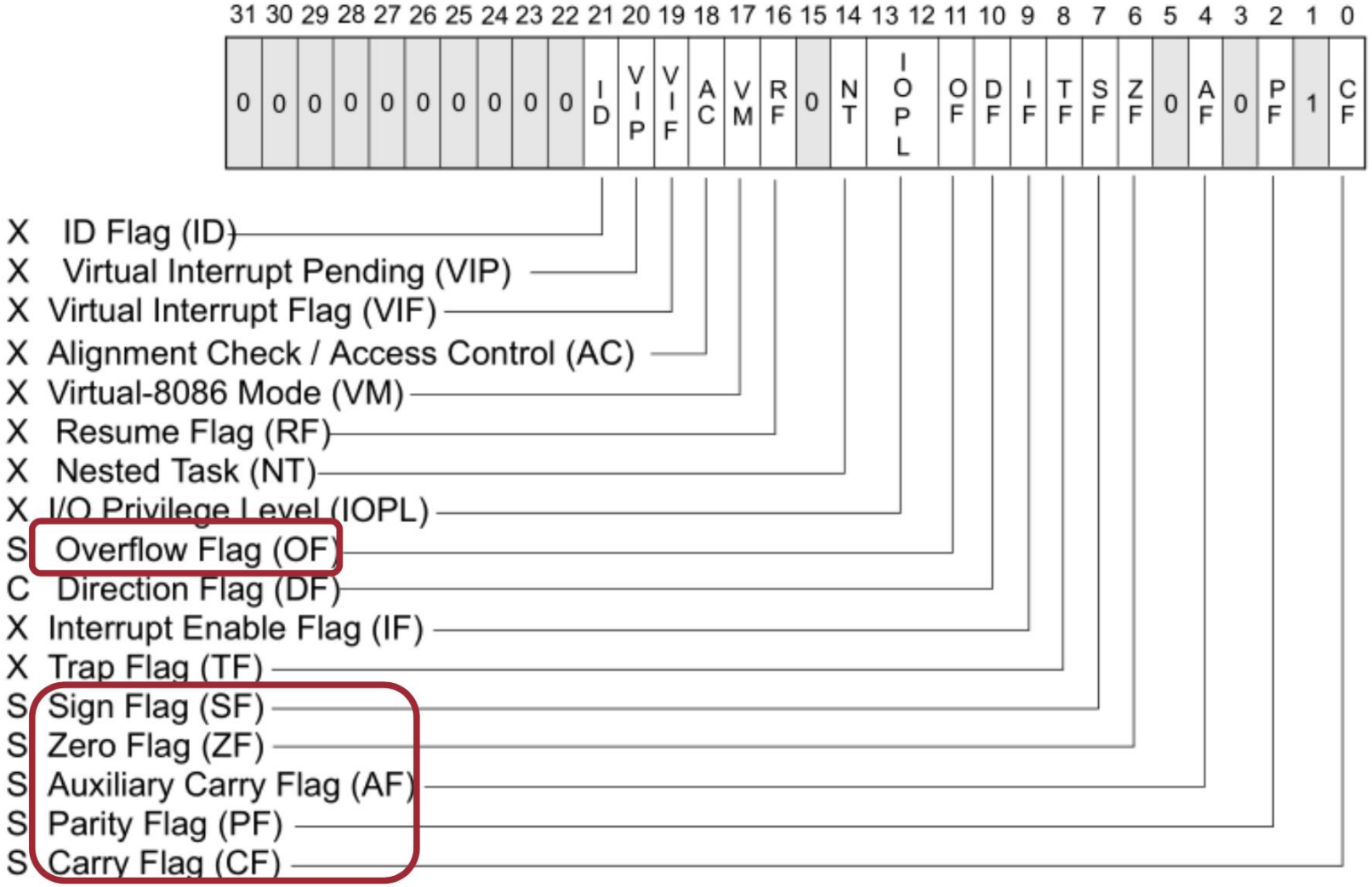


```
cmp i, n
jge F
```

EFLAGS: Storing the Processor State

- EFLAGS is a status register used in x86, which is essentially a collection of status flag bits

- There are approximately 20 different flag bits used in x86, but we are mainly interested in 6 condition flags:
  - OF: Overflow flag
  - SF: Sign flag
  - ZF: Zero flag
  - AF: Auxiliary carry flag
  - PF: Parity flag
  - CF: Carry flag


31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
0 0 0 0 0 0 0 0 0 0 0 ID VIP VIF AC VM RF 0 NT IOPL OF DF IF TF SF ZF 0 AF 0 PF 1 CF
X ID Flag (ID)
X Virtual Interrupt Pending (VIP)
X Virtual Interrupt Flag (VIF)
X Alignment Check / Access Control (AC)
X Virtual-8086 Mode (VM)
X Resume Flag (RF)
X Nested Task (NT)
X I/O Privilege Level (IOPL)
S Overflow Flag (OF)
C Direction Flag (DF)
X Interrupt Enable Flag (IF)
X Trap Flag (TF)
S Sign Flag (SF)
S Zero Flag (ZF)
S Auxiliary Carry Flag (AF)
S Parity Flag (PF)
S Carry Flag (CF)
S Indicates a Status Flag
C Indicates a Control Flag
X Indicates a System Flag
Reserved bit positions. DO NOT USE.
Always set to values previously read.

Branch Instructions

Assume that a comparison instruction (`cmp`) precedes the branch instruction

Branch Instruction	Condition	Description
`ja`	`CF = 0 and ZF = 0`	Jump if above
`jb`	`CF = 1`	Jump if below
`je`	`ZF = 1`	Jump if equal
`jl`	`SF ≠ F`	Jump if less
`jle`	`ZF = 1 or SF ≠ F`	Jump if less or equal
`jna`	`CF = 1 or ZF = 1`	Jump if not above
`jnb`	`CF = 0`	Jump if not below
`jz`	`ZF = 1`	Jump if zero
… (many more)		

Summary So Far

- We learned how to move around data
  - `mov, lea, push, pop, etc.`
- We learned how to perform arithmetic and logical operations
  - `add, sub, and, or, etc.`
- We also learned how to control program flows
  - `cmp, jmp, ja, jz, etc.`

Already Turing Complete!

x86 Execution Model

Recap: Stack Frame

- When a function is invoked, a new ***stack frame*** is allocated at the top of the stack memory

- Also, called as procedure frame or activation record

Our Example


```
int purple(int a1, int a2) {
    return 2 + a1 - a2;
}

int blue(int a1) {
    return 1 + purple(a1, b);
}

int red(int a1) {
    return blue(a1 - 42);
}
```

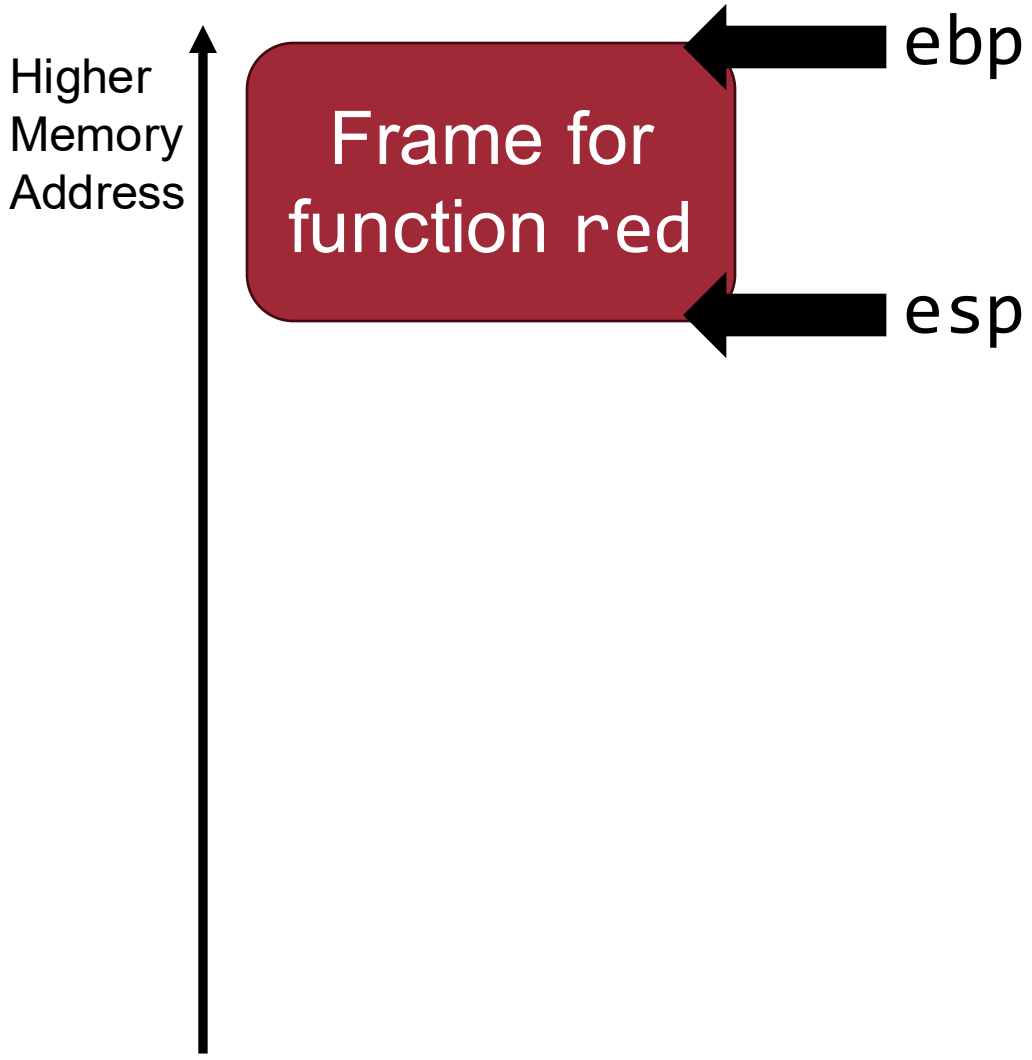
Our Example – Stack

```
int purple(int a1, int a2) {
    return 2 + a1 - a2;
}

int blue(int a1) {
    return 1 + purple(a1, b);
}

int red(int a1) {
    return blue(a1 - 42);
}
```

Start



Recap: Registers in x86

- Program counter (instruction pointer)
  - **`EIP`**: points to the instruction to execute
- Stack pointers
  - **`ESP`**: points to the top of the stack
  - **`EBP`**: points to the base of the current stack frame
- Status register (FLAGS register)
  - **`EFLAGS`**: contains the current condition flags
- Other general purpose registers
  - **`EAX`**, **`EBX`**, **`ECX`**, **`EDX`**, **`ESI`**, **`EDI`**

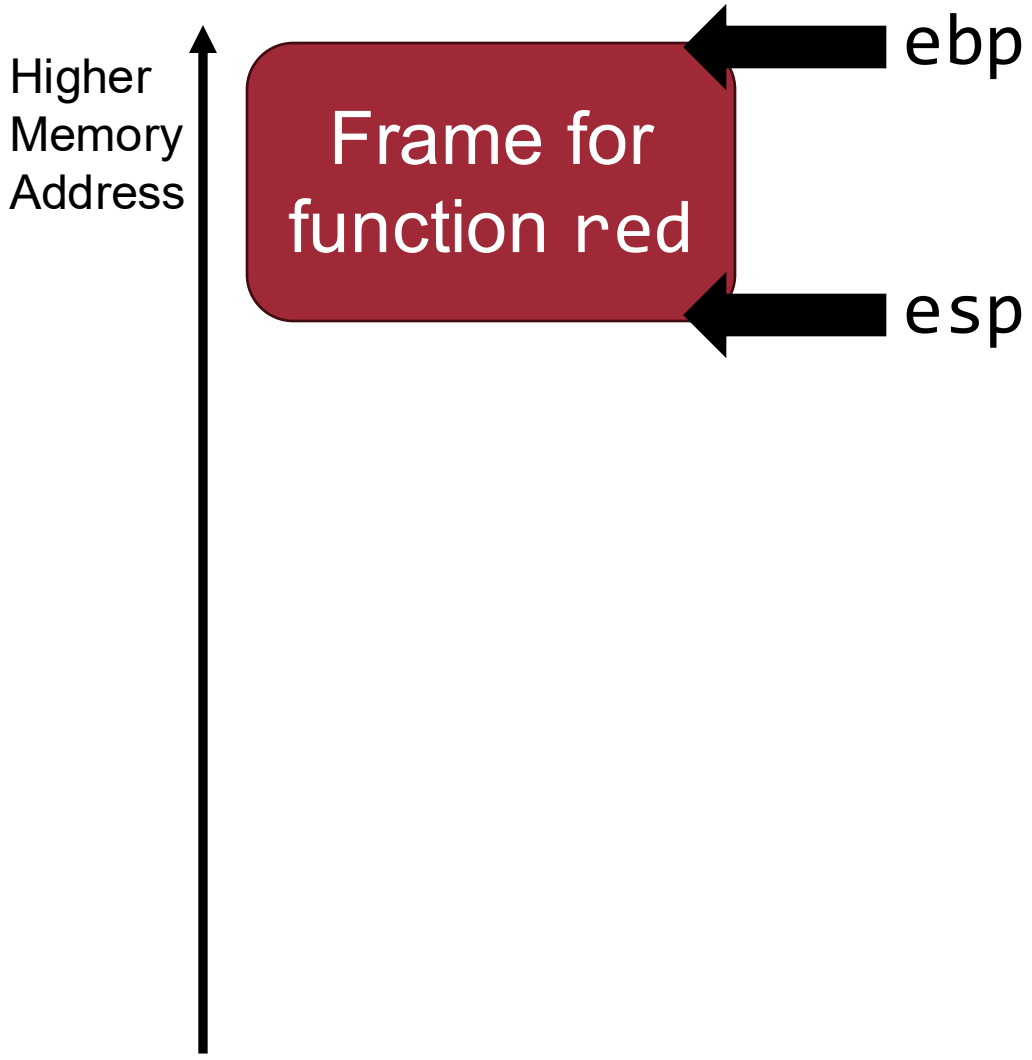
Our Example – Stack


```
int purple(int a1, int a2) {
    return 2 + a1 - a2;
}

int blue(int a1) {
    return 1 + purple(a1, b);
}

int red(int a1) {
    return blue(a1 - 42);
}
```

Start



Our Example – Stack


```
int purple(int a1, int a2) {
    return 2 + a1 - a2;
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}

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    return blue(a1 - 42);
}
```

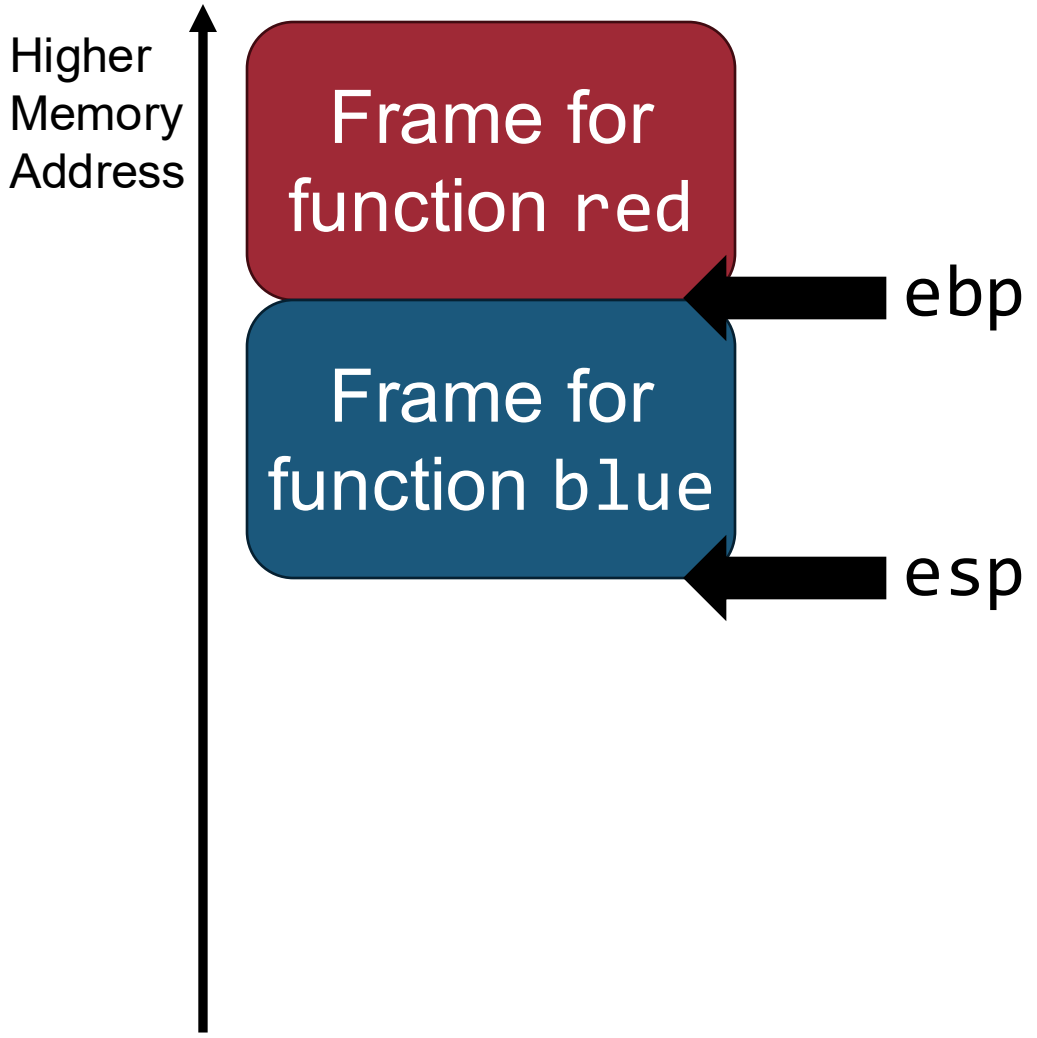

Our Example – Stack

```
int purple(int a1, int a2) {
    return 2 + a1 - a2;
}

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    return blue(a1 - 42);
}
```
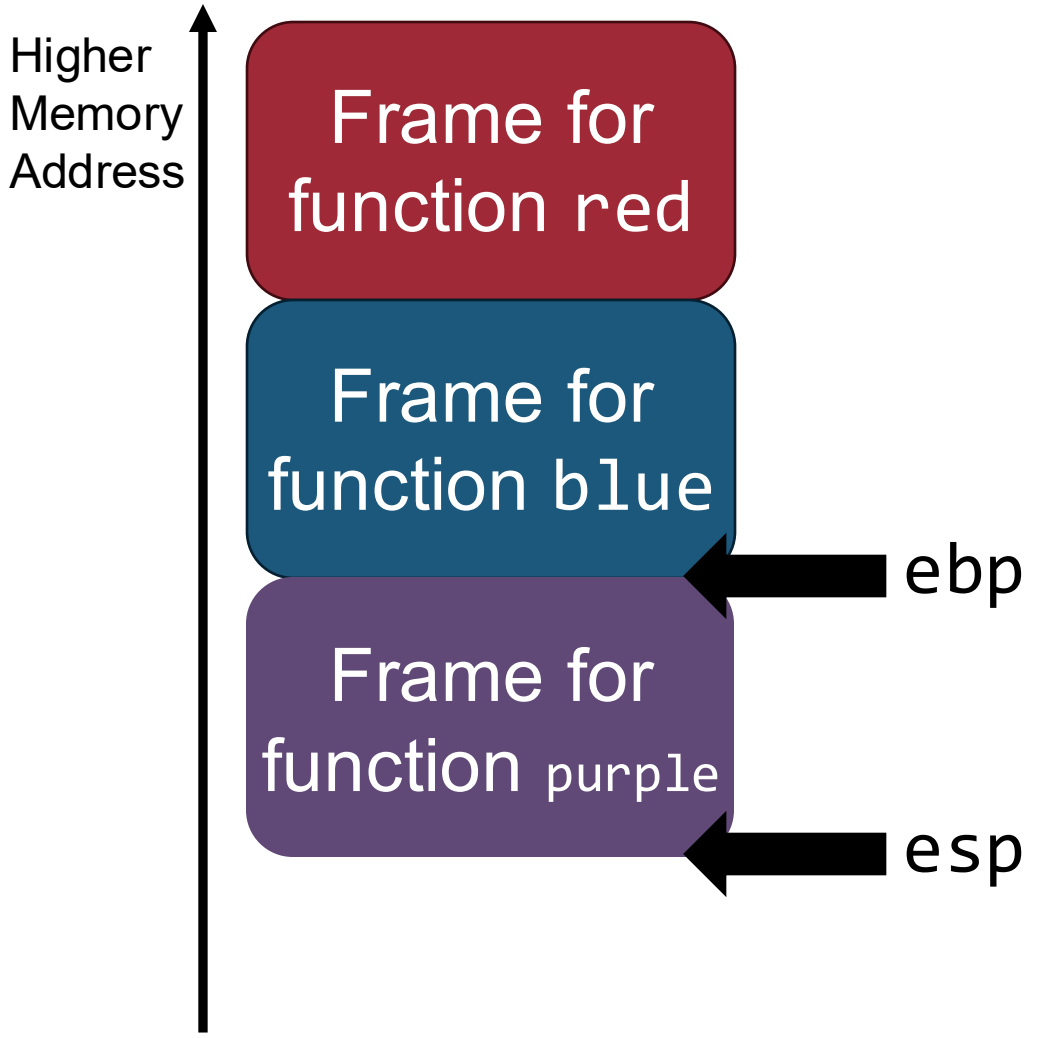
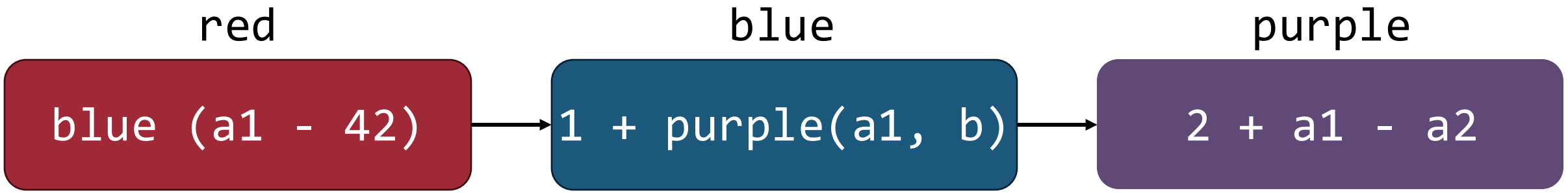



Questions



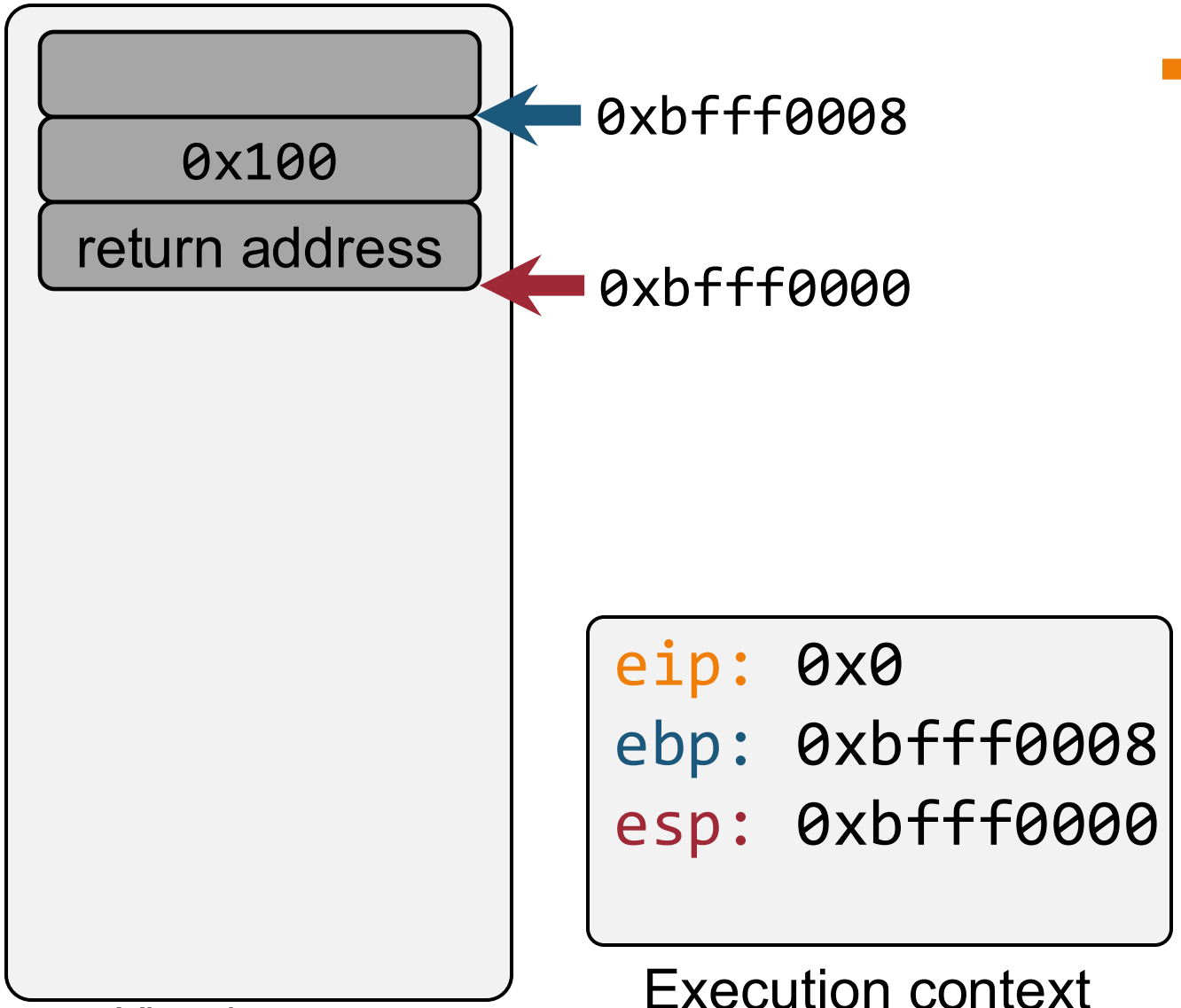
- How do we pass function parameters?
- When a function returns, how do we restore the register values of the caller
- Where do we store local variables?

We can easily get the answer by compiling the example program and disassembling the resulting binary

Disassembled Code (x86)


```
<red>:
   0:   push   ebp
   1:   mov    ebp,esp
   3:   sub    esp,0x28
   6:   mov    DWORD PTR [ebp-0xc],0x0
   d:   mov    eax,DWORD PTR [ebp+0x8]
  10:   sub    eax,0x2a
  13:   mov    DWORD PTR [esp],eax
  16:   call   Blue
  1b:   mov    edx,DWORD PTR [ebp-0xc]
  1e:   add    eax,edx
  20:   leave
  21:   ret

<blue>:
  22:   push   ebp
  23:   mov    ebp,esp
  25:   sub    esp,0x28
  28:   mov    DWORD PTR [ebp-0xc],0x1
  2f:   mov    eax, DWORD PTR [ebp-0xc]
  32:   mov    DWORD PTR [esp+0x4], eax
  36:   mov    eax, DWORD PTR [ebp+0x8]
  39:   mov    DWORD PTR [esp], eax
  3c:   call   purple
  41:   mov    edx, DWORD PTR [ebp-0xc]
  44:   add    eax, edx
  46:   leave
  47:   ret

<purple>:
  48:   push   ebp
  49:   mov    ebp,esp
  4b:   sub    esp,0x10
  4e:   mov    DWORD PTR [ebp -0x4],0x2
  55:   mov    eax,DWORD PTR [ebp+0x8]
  58:   mov    eax,DWORD PTR [ebp-0x4]
  5b:   add    eax,edx
  5d:   sub    eax,DWORD PTR [ebp+0xc]
  60:   leave
  61:   ret
```

Execution Example




```
eip: 0x0
ebp: 0xbfff0008
esp: 0xbfff0000
```

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example

Points to instruction to be executed

```
eip:  0x1
ebp:  0xbfff0008
esp:  0xbfff0000
```

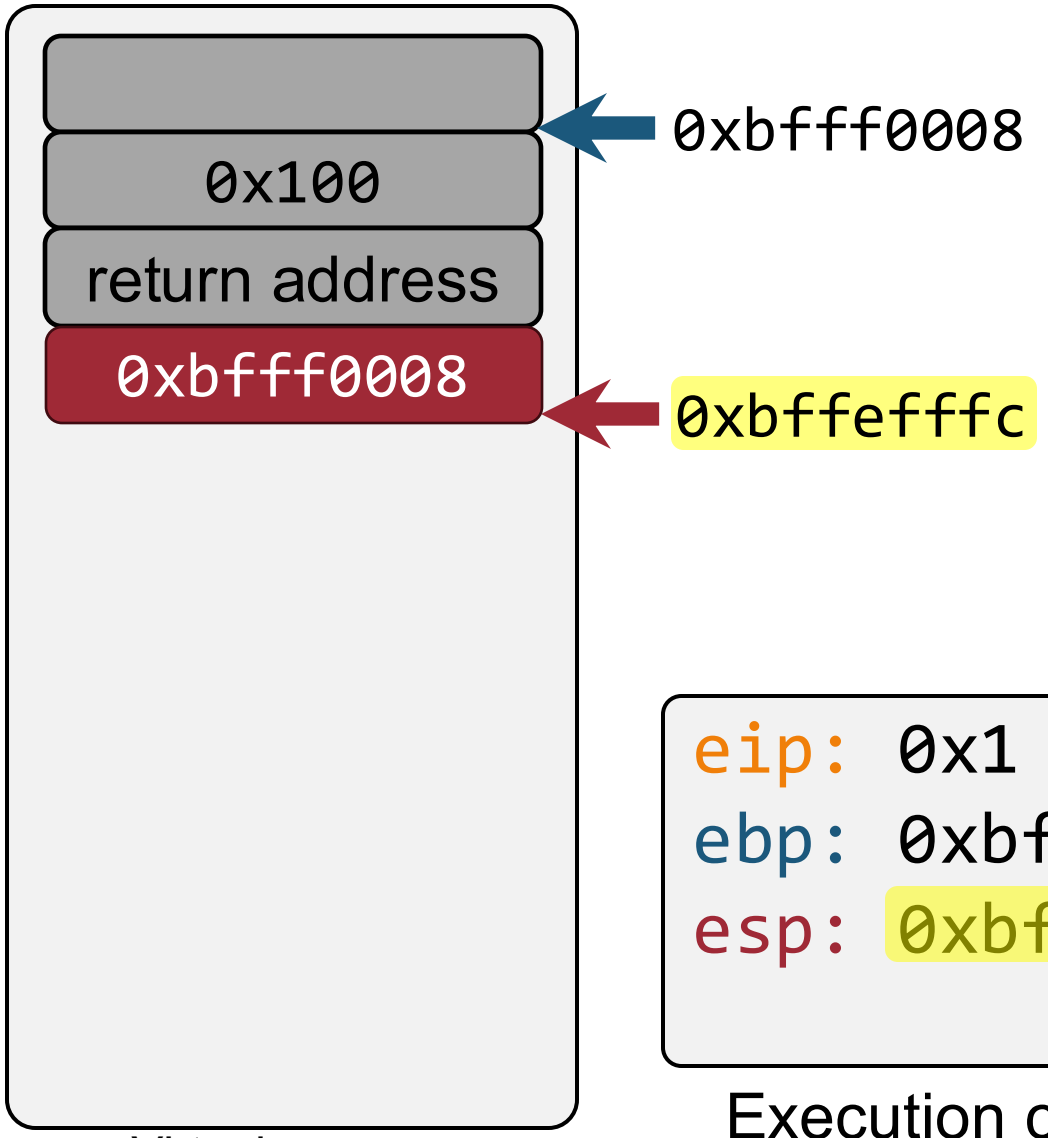
Execution context

Currently executed instruction

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example

Save the base address of the previous function's stack frame



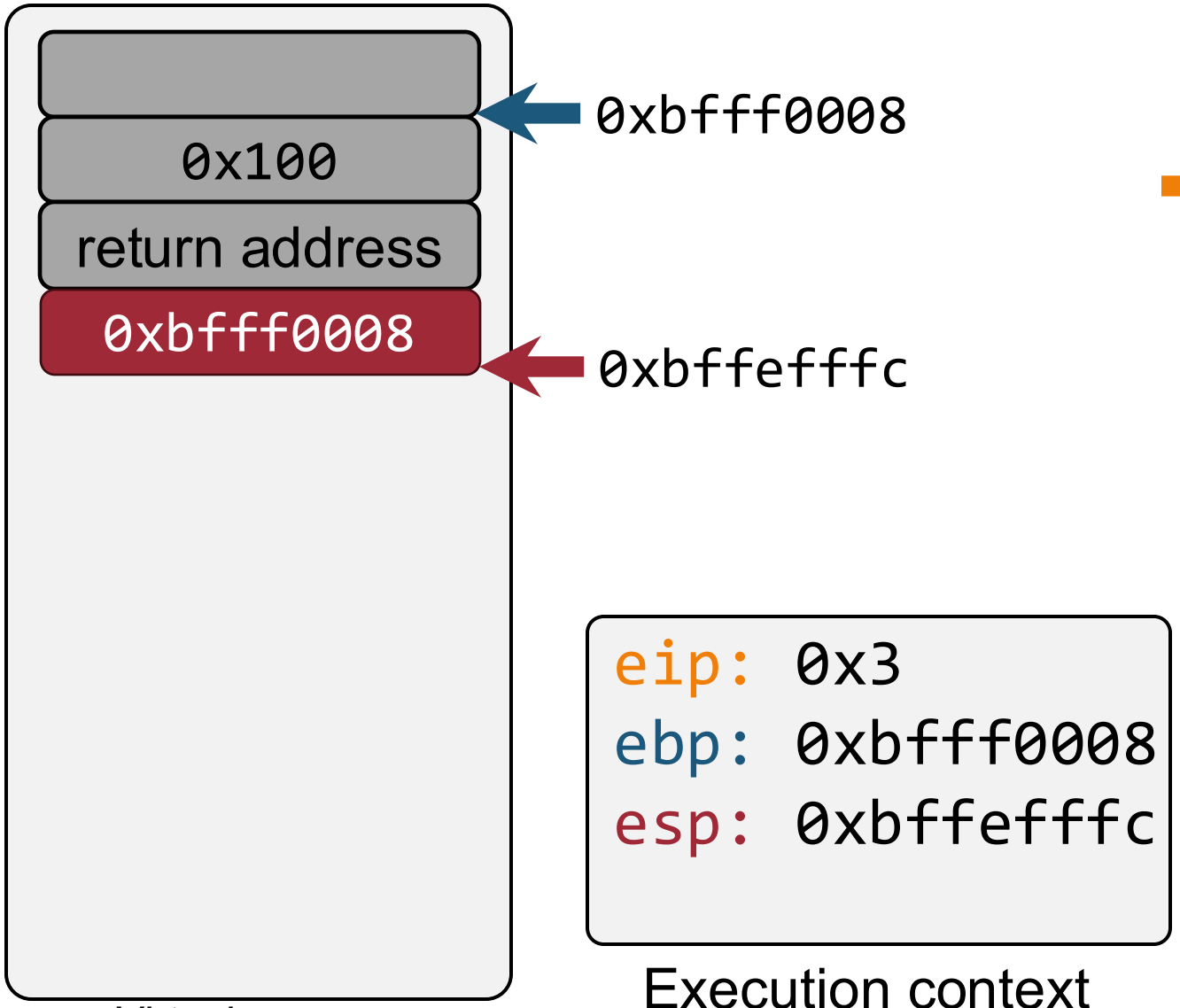
Virtual memory

```
eip: 0x1
ebp: 0xbfff0008
esp: 0xbffefffc
```

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example




```
eip: 0x3
ebp: 0xbfff0008
esp: 0xbffefffc
```

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example

Now, ebp points to the base of the current stack frame

Virtual memory

0xbfff0008

0xbffefffc

```
eip: 0x3
ebp: 0xbffefffc
esp: 0xbffefffc
```

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

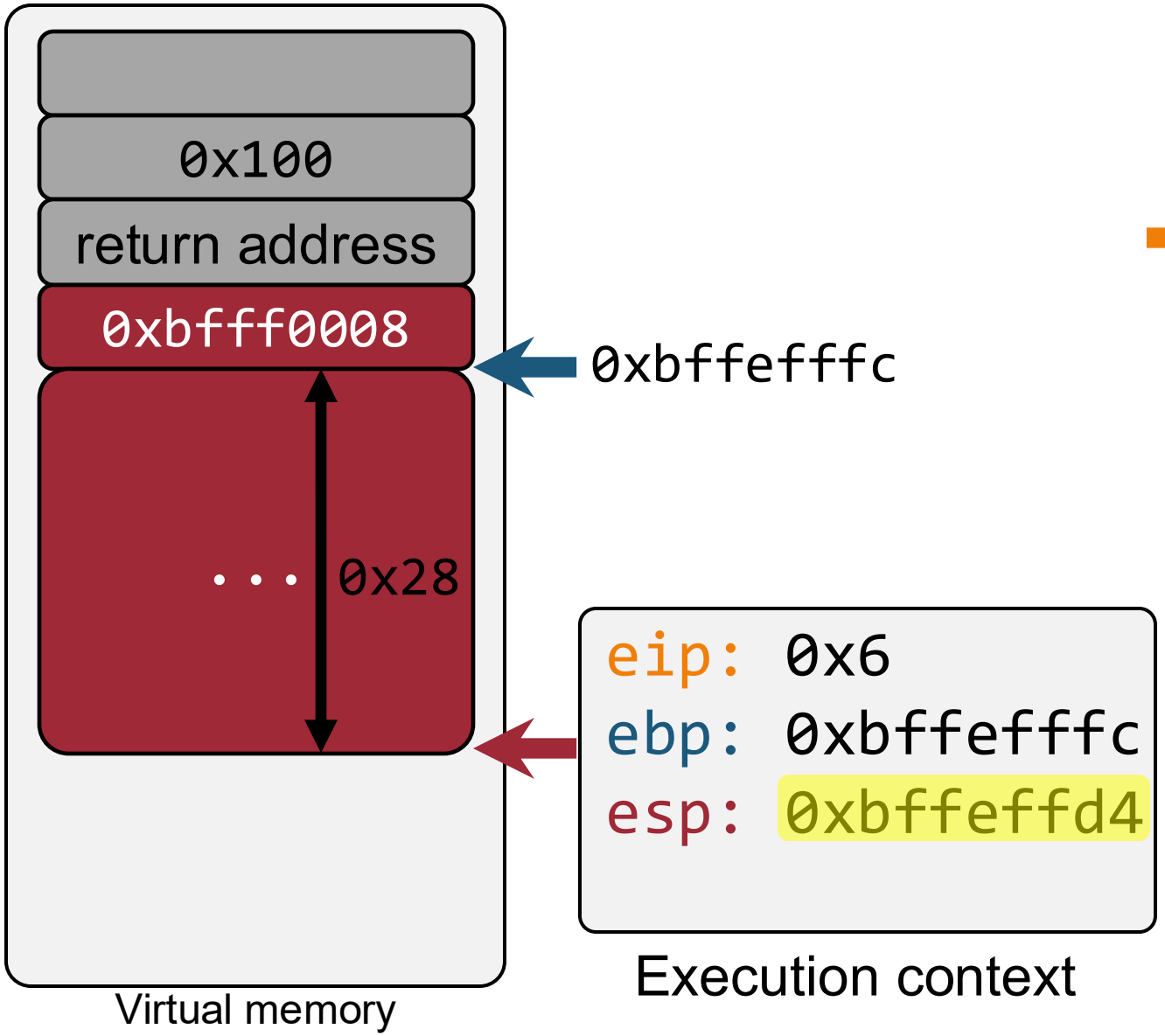
Execution Example


```
eip: 0x6
ebp: 0xbffefffc
esp: 0xbffefffc
```

Execution context

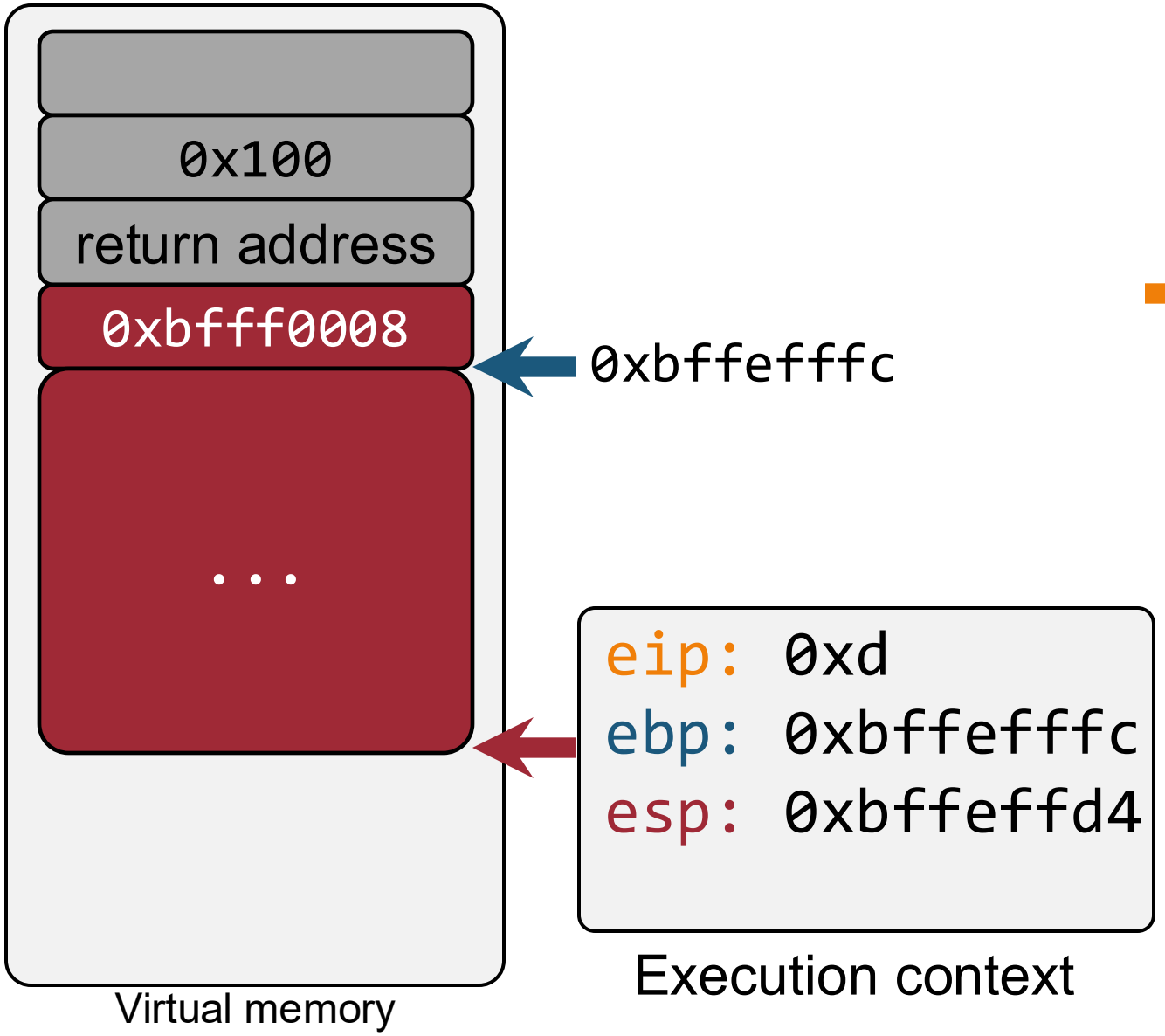
```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example



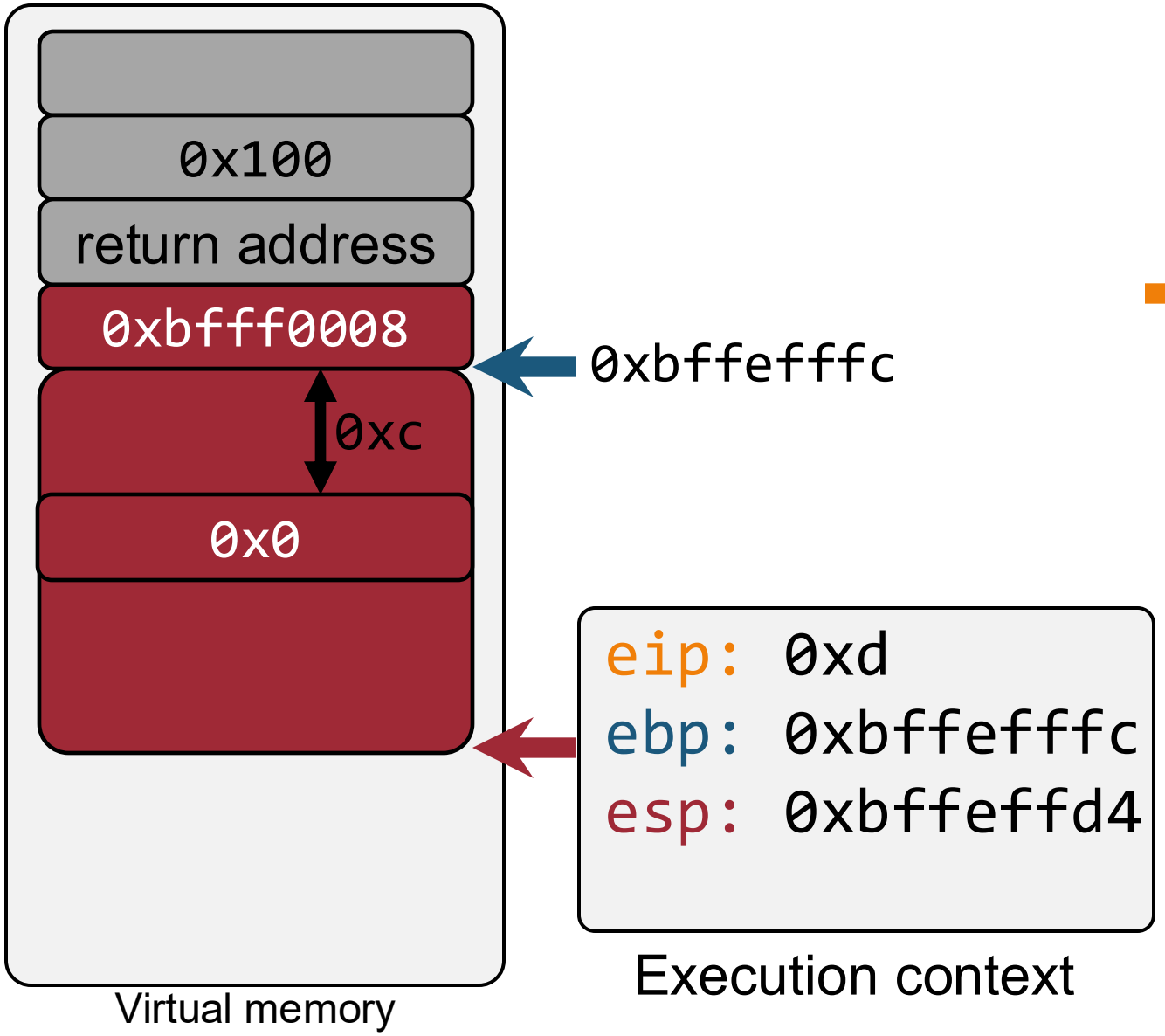

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example



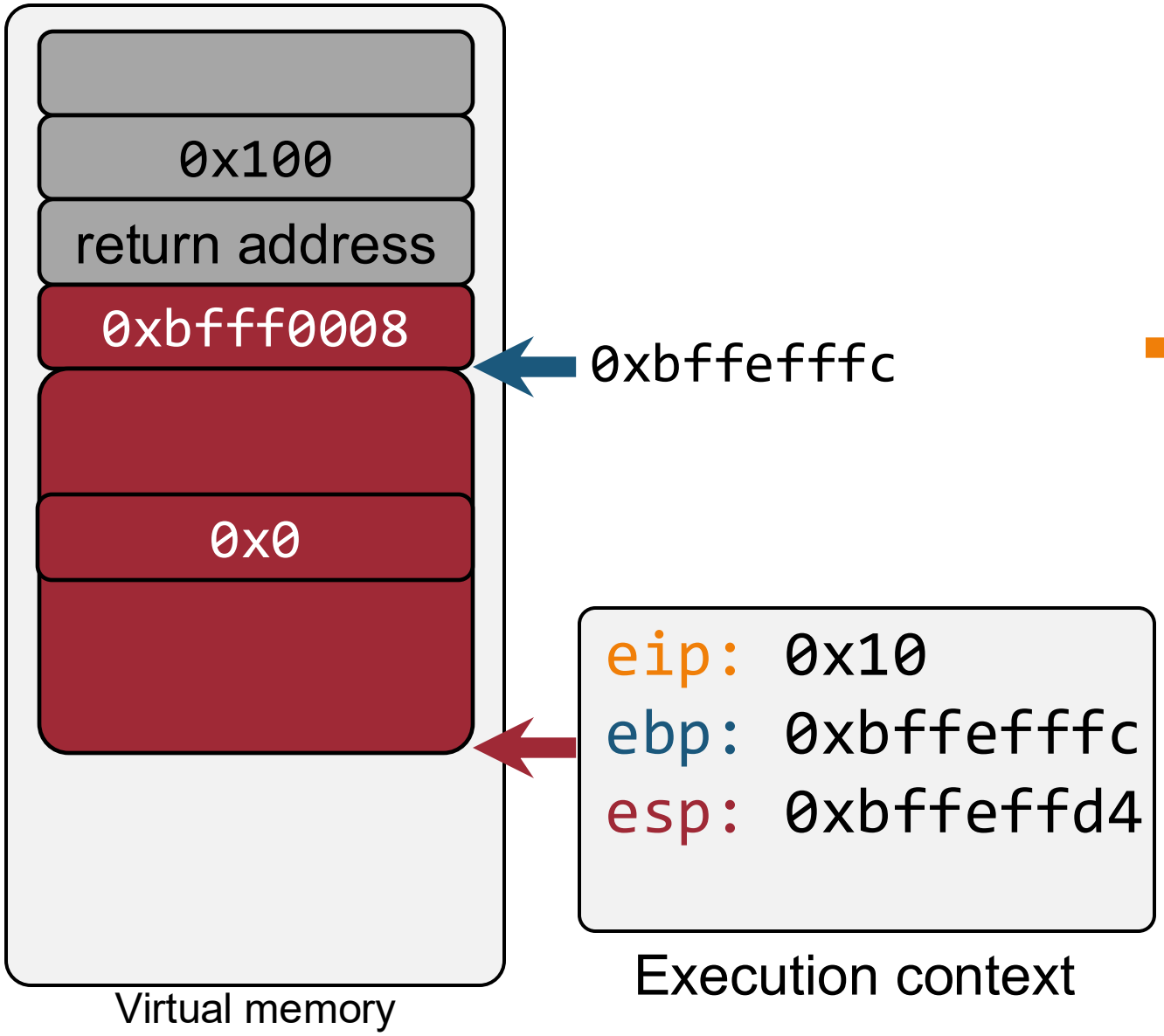

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example



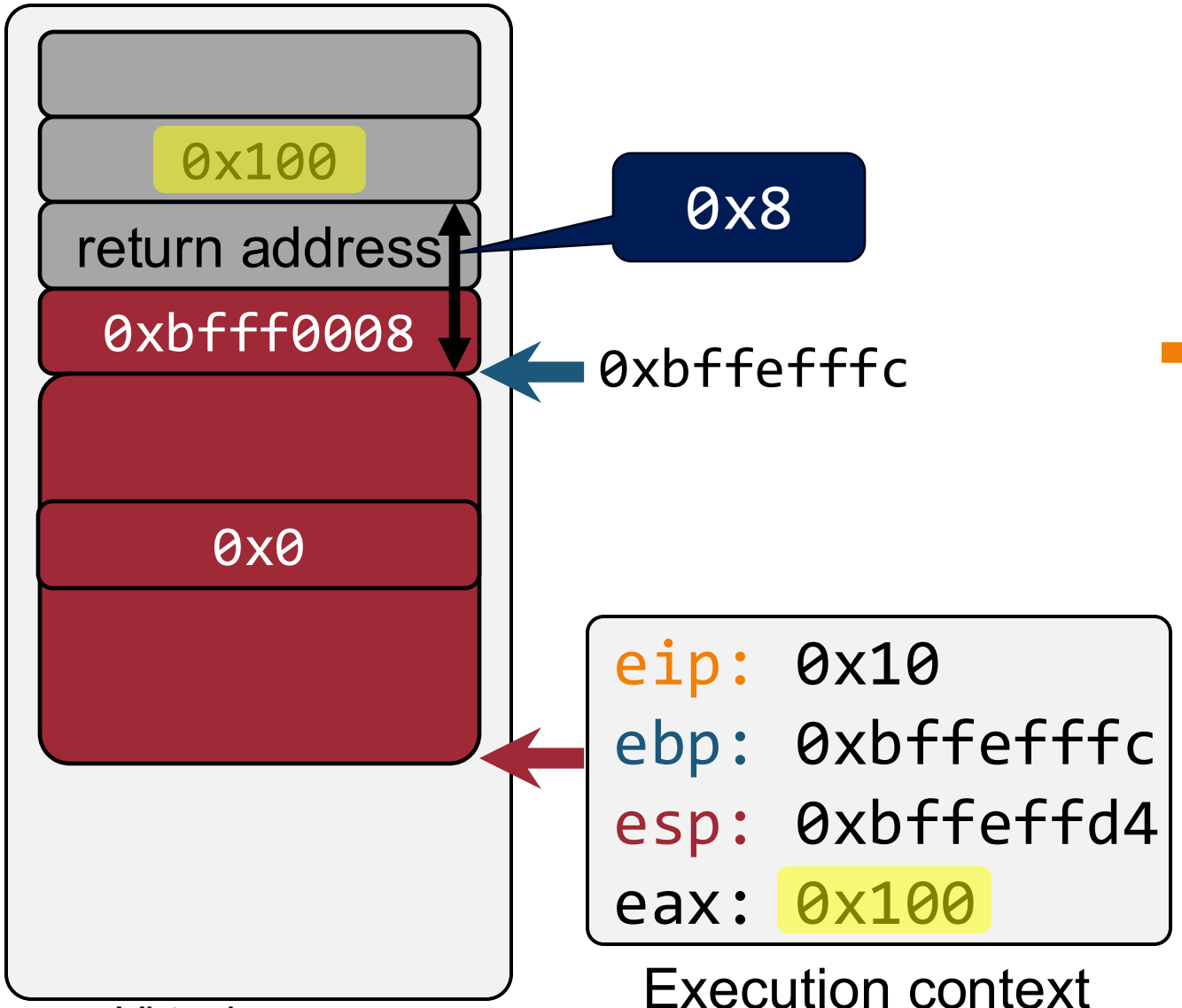

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example



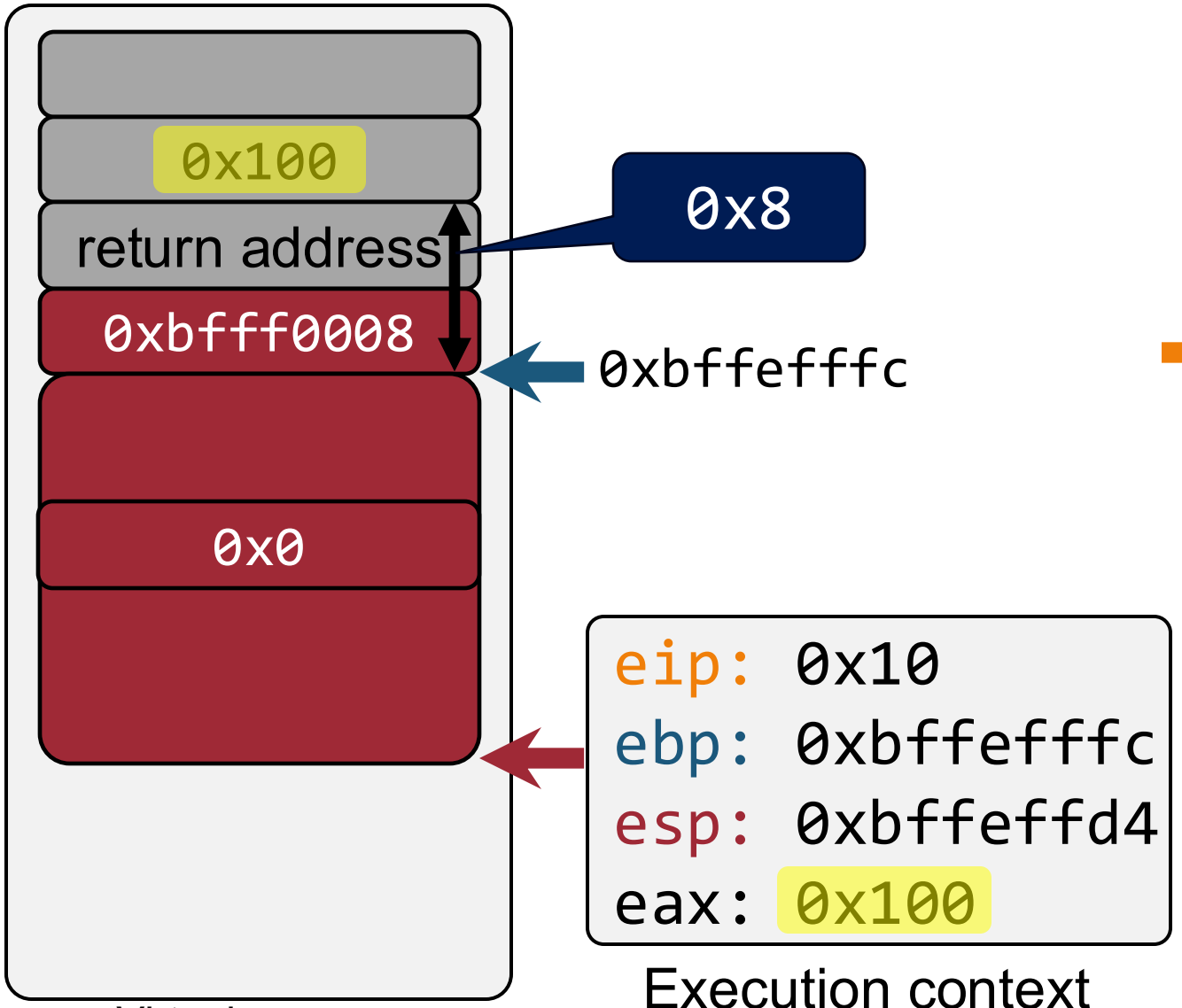

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example




```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

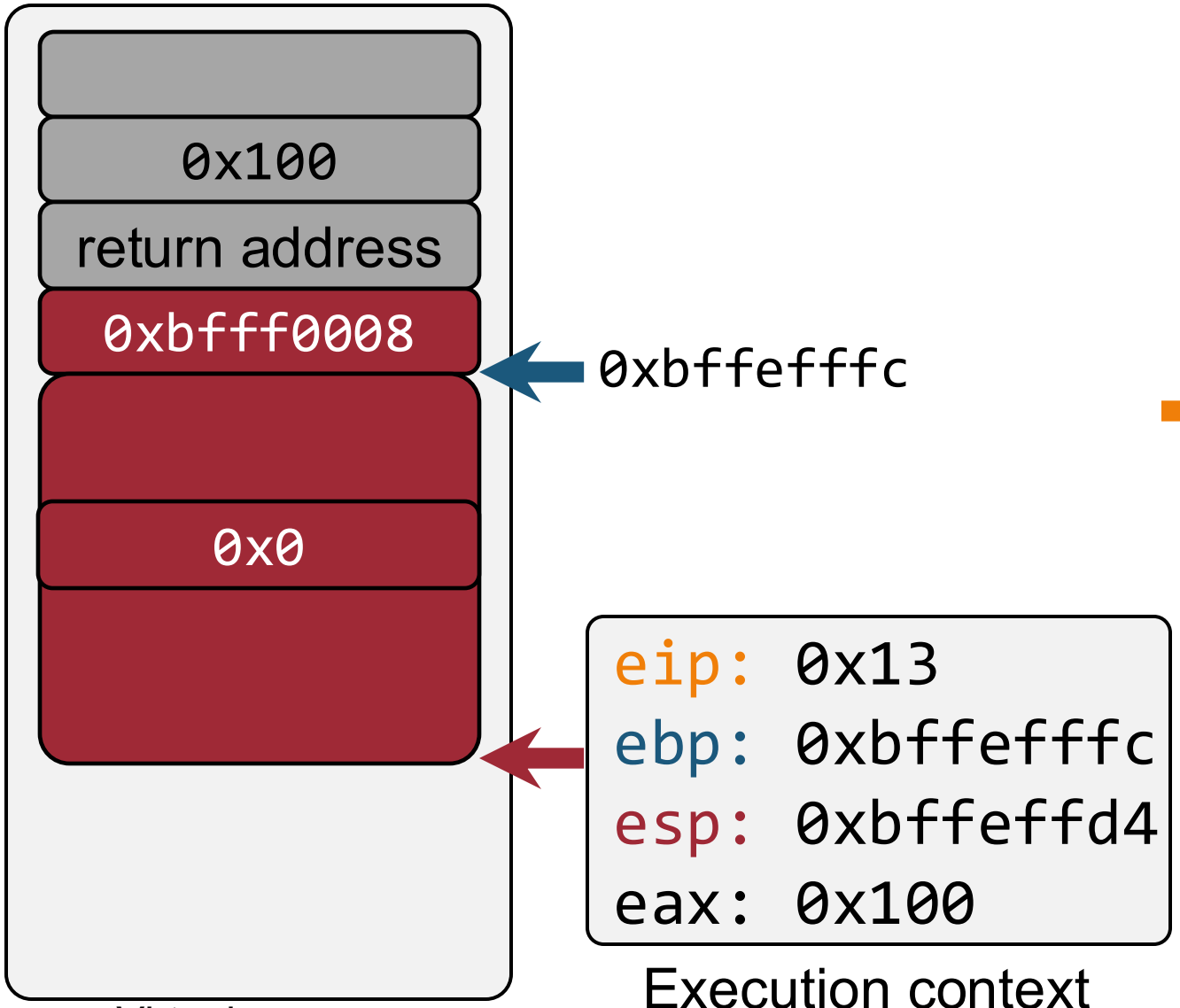
Execution Example




```
int red(int a1) {
    return blue(a1 - 42);
}
```

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example




```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example

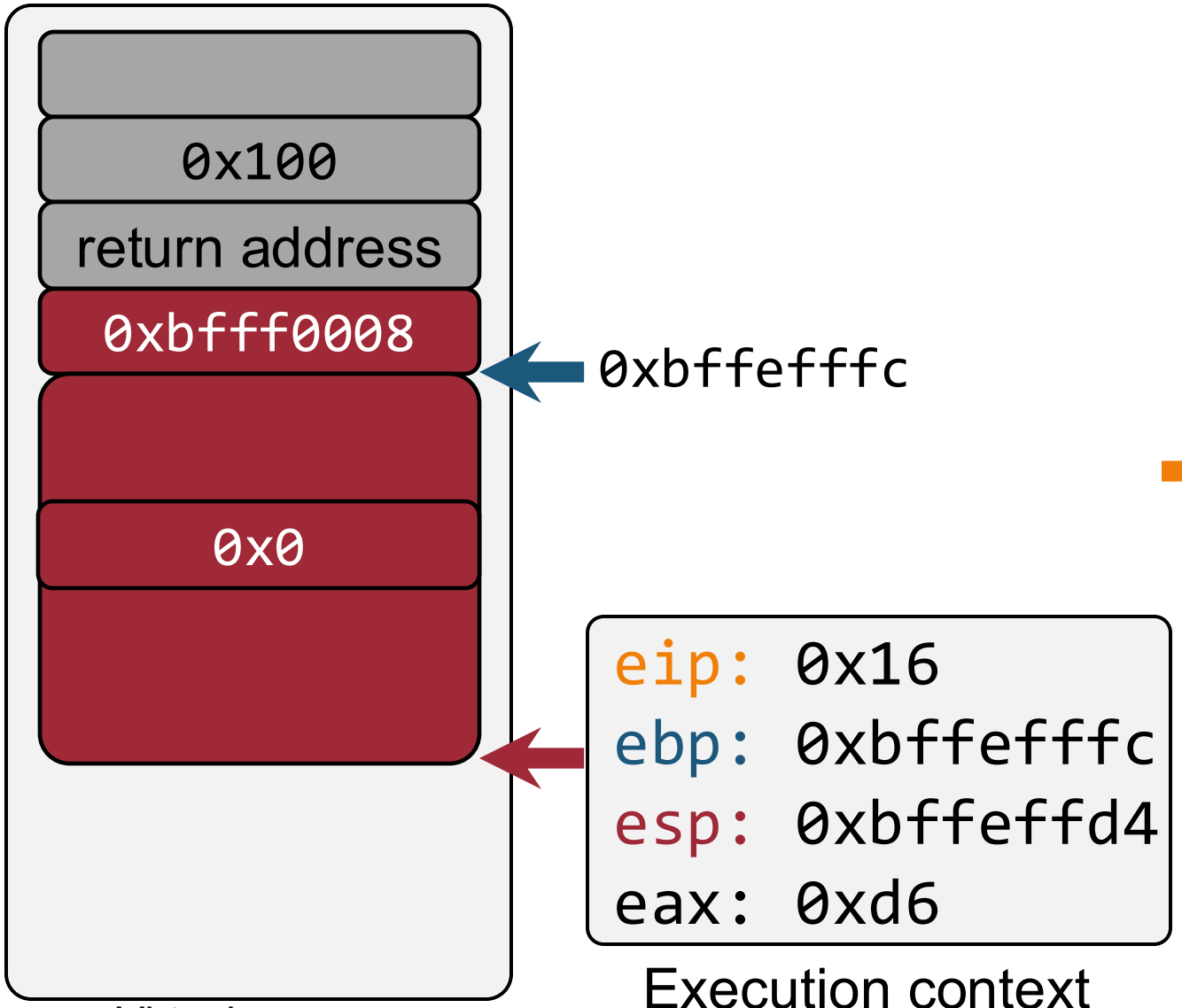

```
int red(int a1) {
    return blue(a1 - 42);
}
```


```
eip: 0x13
ebp: 0xbffefffc
esp: 0xbffeffd4
eax: 0xd6
```

Execution context

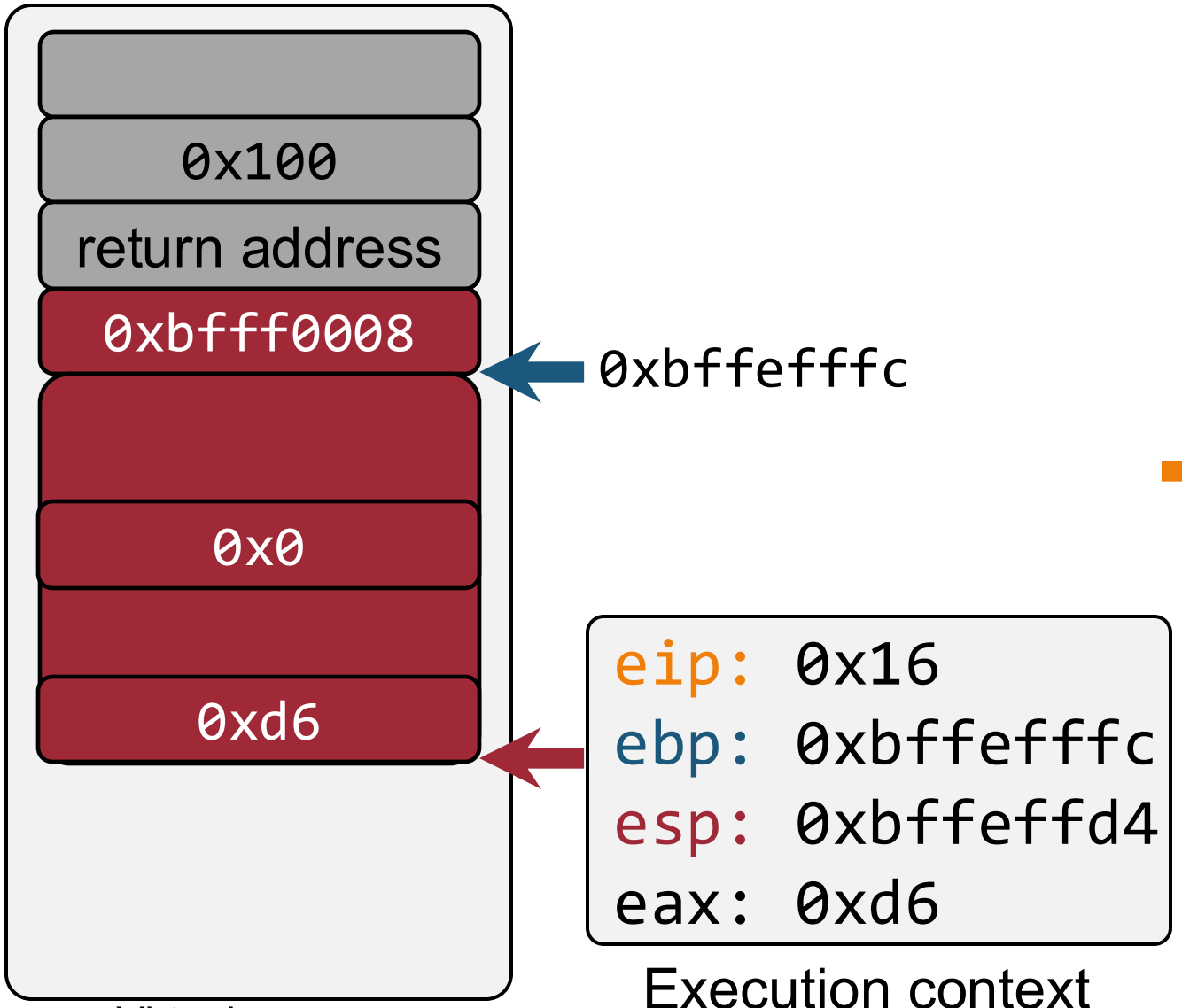
```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example



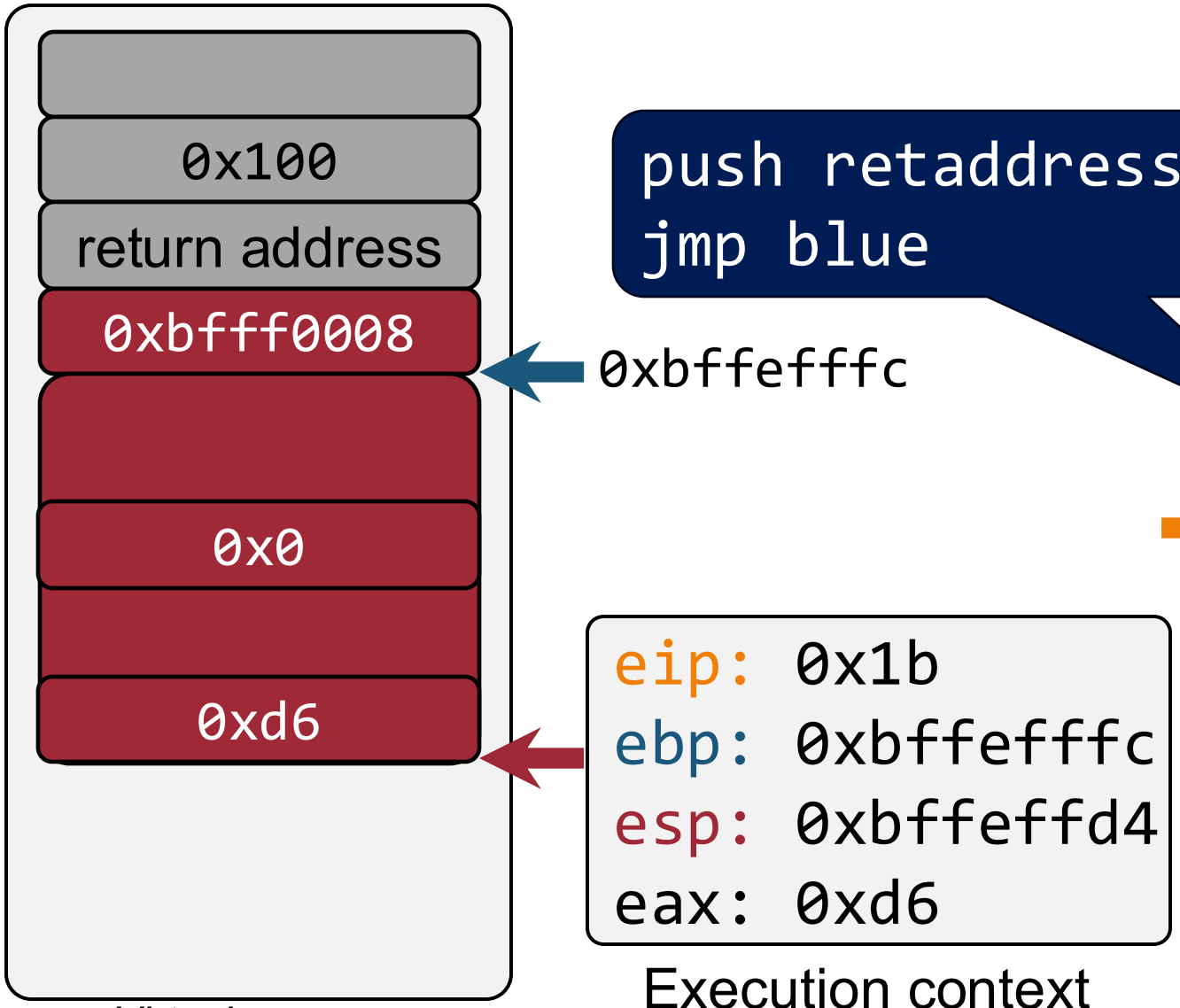

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example



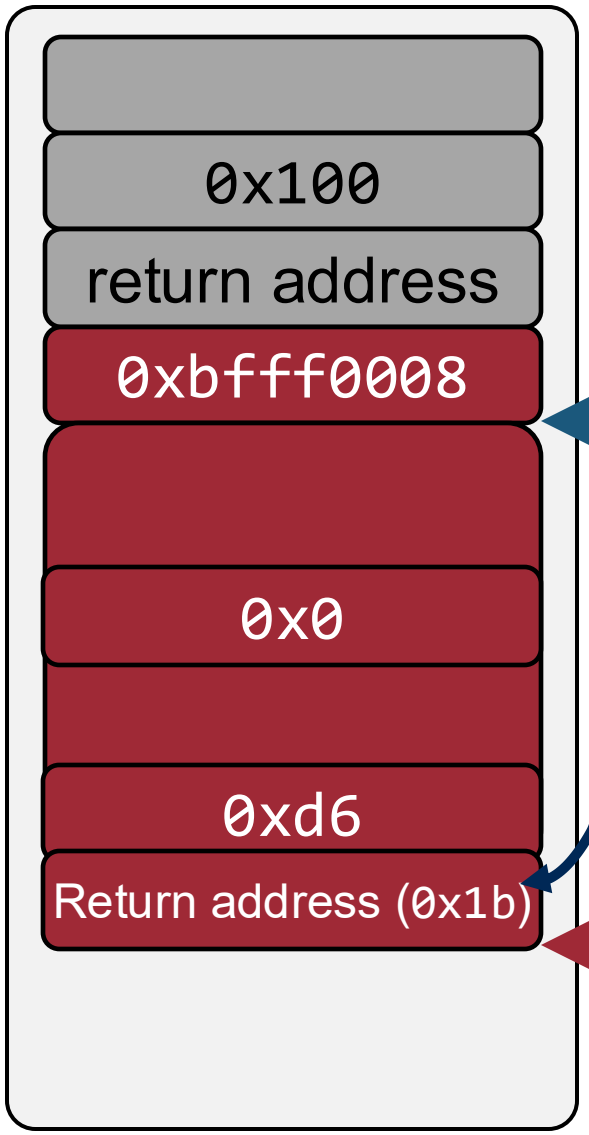

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example




```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example



push retaddress
jmp blue

0xbffefffc

```
eip: 0x22
ebp: 0xbffefffc
esp: 0xbffeffd0
eax: 0xd6
```

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example

0xbffefffc

```
eip: 0x23
ebp: 0xbffefffc
esp: 0xbffeffd0
eax: 0xd6
```

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example

0xbffefffc

eip: 0x23
ebp: 0xbffefffc
esp: 0xbffeffcc
eax: 0xd6

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example

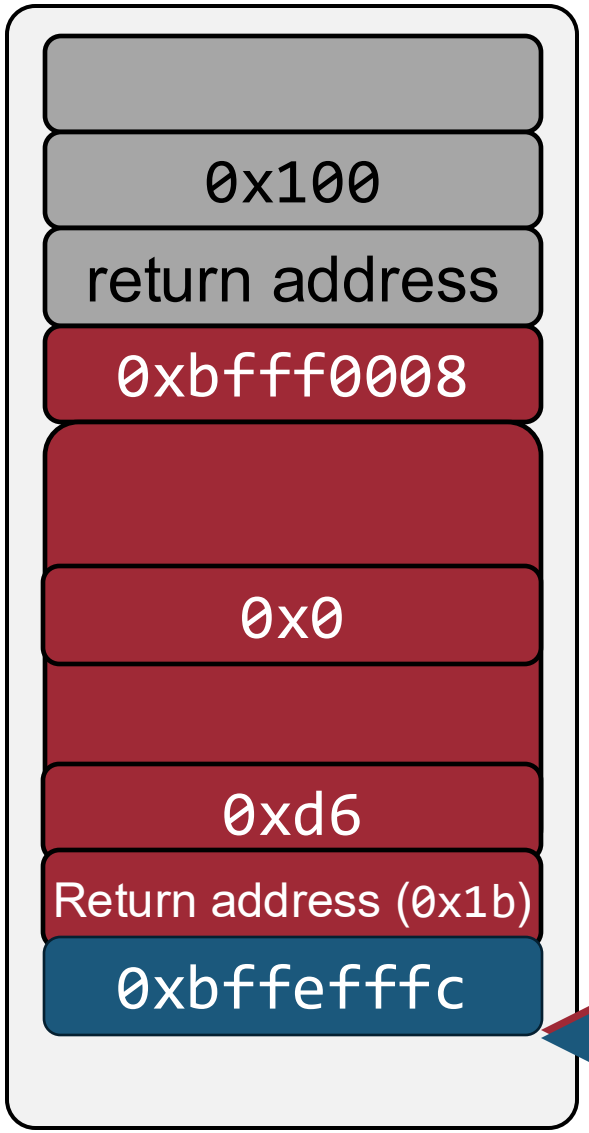
0xbffefffc

eip: 0x25
ebp: 0xbffefffc
esp: 0xbffeffcc
eax: 0xd6

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example



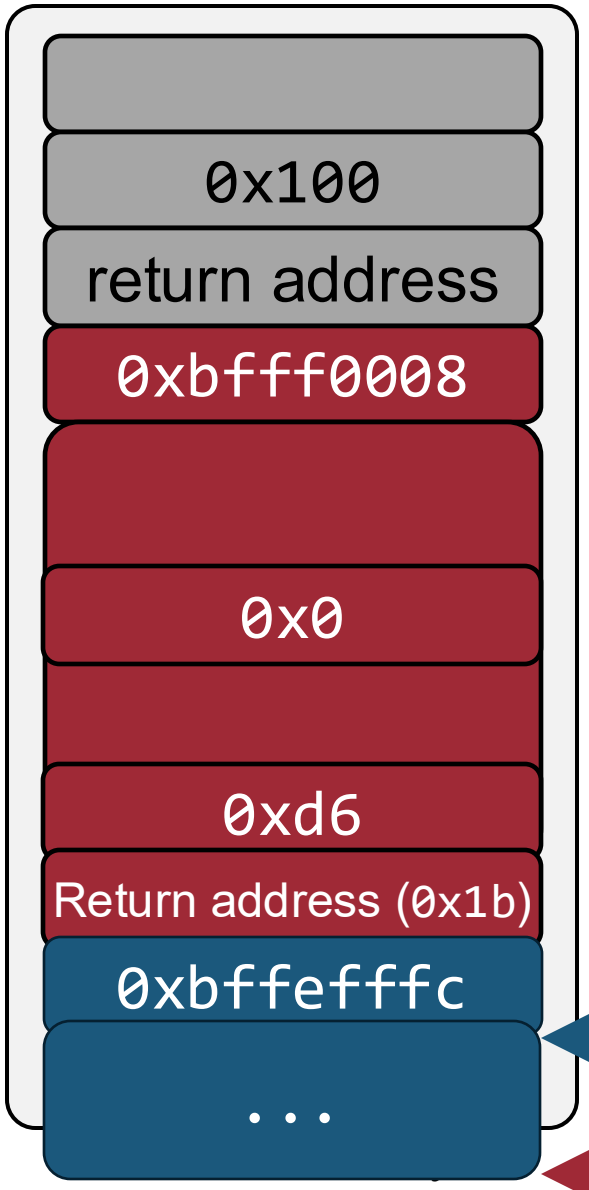
0xbffefffc

eip: 0x25
ebp: 0xbffeffcc
esp: 0xbffeffcc
eax: 0xd6

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

Execution Example



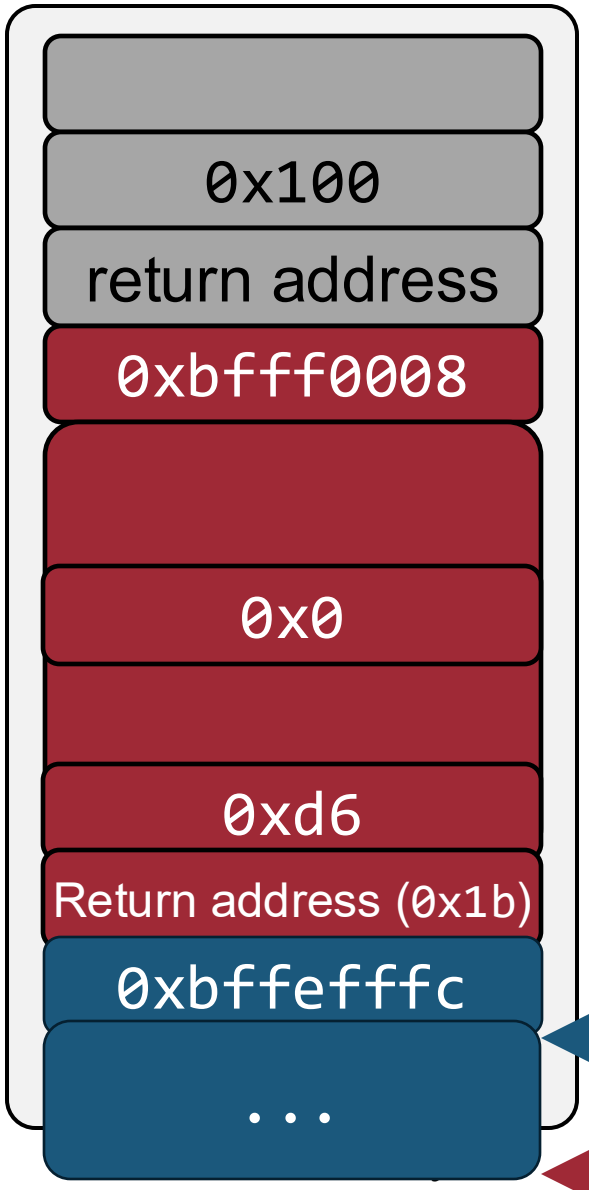
0xbffefffc

eip: 0x46
ebp: 0xbffeffcc
esp: 0xbffeffac

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...                    Skip!
  46:  leave
  47:  ret
```

Execution Example



0xbffefffc

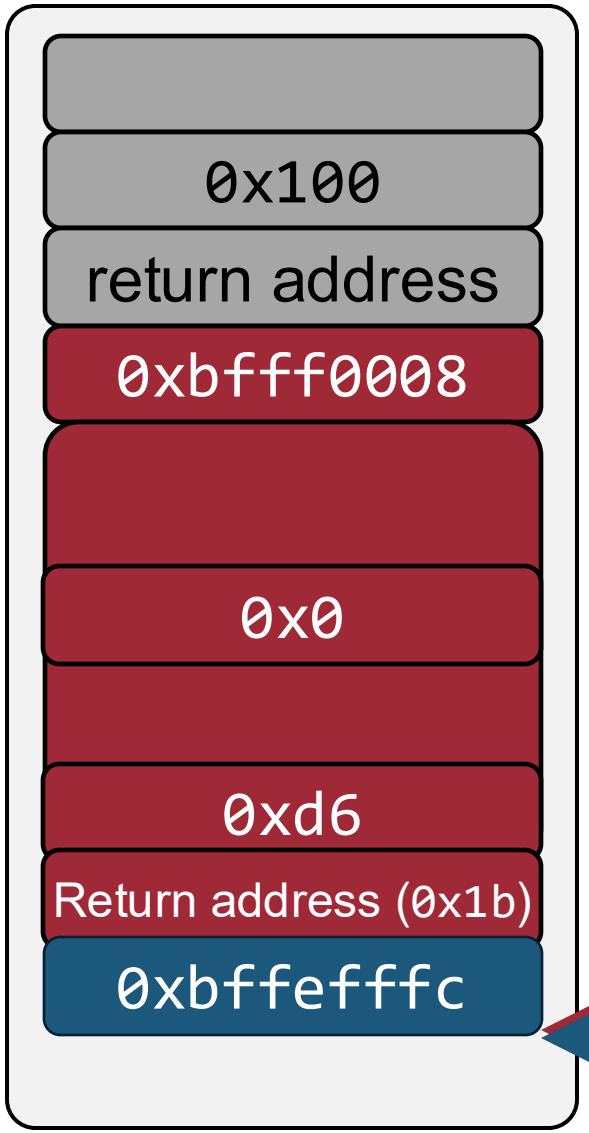
eip: 0x47
ebp: 0xbffeffcc
esp: 0xbffeffac

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

mov esp, ebp
pop ebp

Execution Example



0xbffefffc

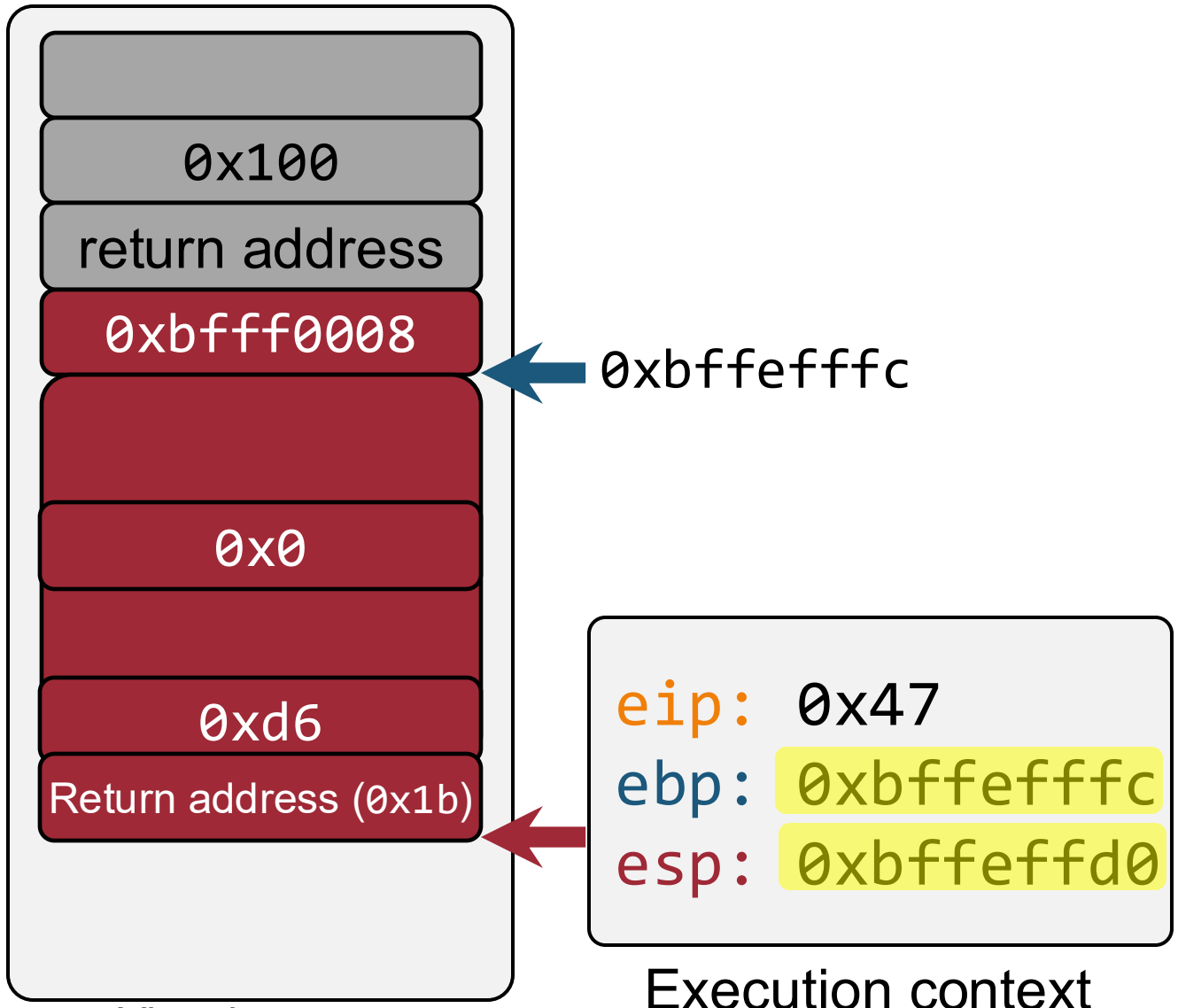
eip: 0x47
ebp: 0xbffeffcc
esp: 0xbffeffcc

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

mov esp, ebp
pop ebp

Execution Example



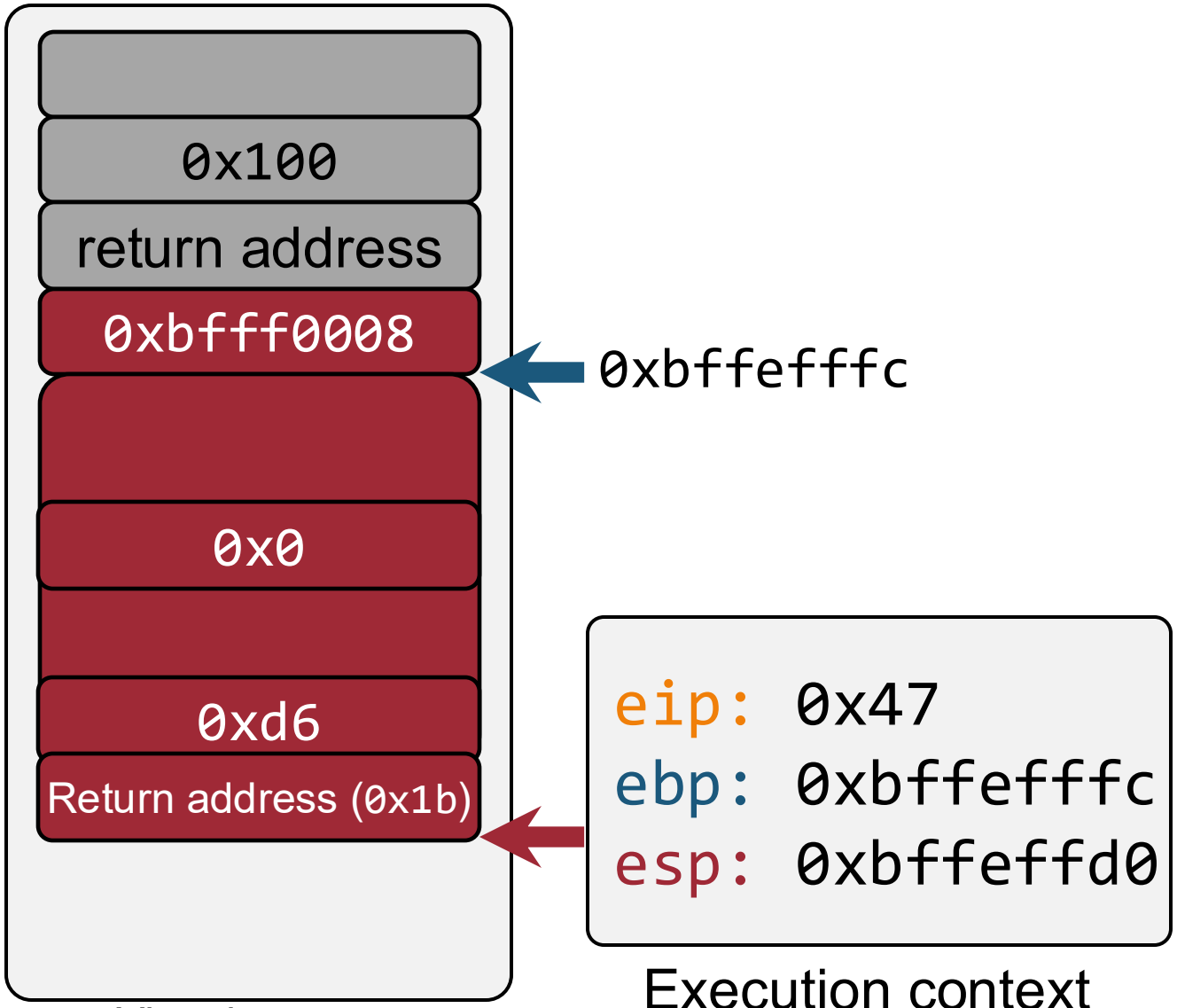

```
eip: 0x47
ebp: 0xbffefffc
esp: 0xbffeffd0
```

Execution context

```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

mov esp, ebp
pop ebp

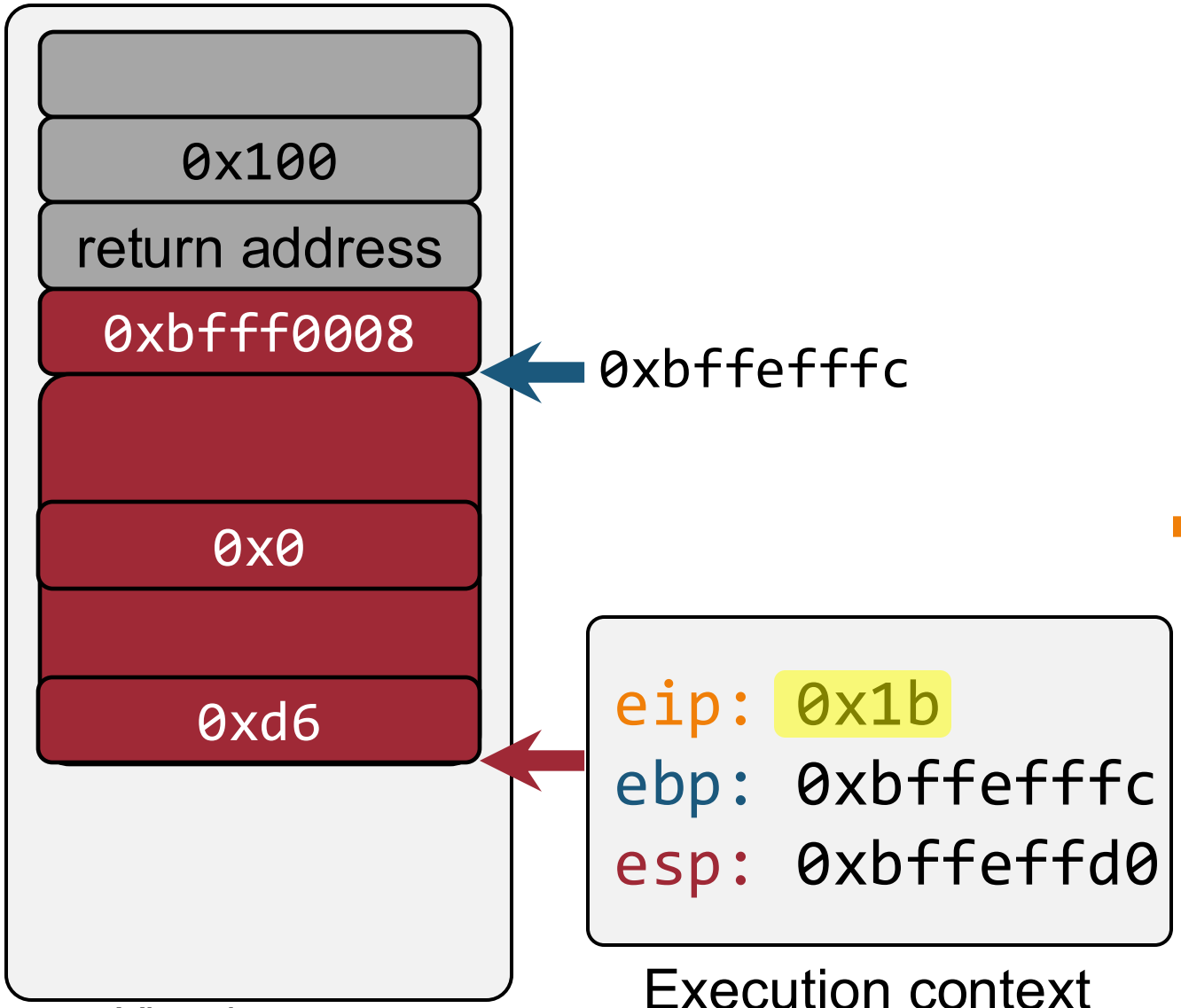
Execution Example




```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

pop eip

Execution Example




```
<red>:
   0:  push   ebp
   1:  mov    ebp,esp
   3:  sub    esp,0x28
   6:  mov    DWORD PTR [ebp-0xc],0x0
   d:  mov    eax,DWORD PTR [ebp+0x8]
  10:  sub    eax,0x2a
  13:  mov    DWORD PTR [esp],eax
  16:  call   blue
  1b:  mov    edx,DWORD PTR [ebp-0xc]
  1e:  add    eax,edx
  20:  leave
  21:  ret

<blue>:
  22:  push   ebp
  23:  mov    ebp,esp
  ...
  46:  leave
  47:  ret
```

pop eip

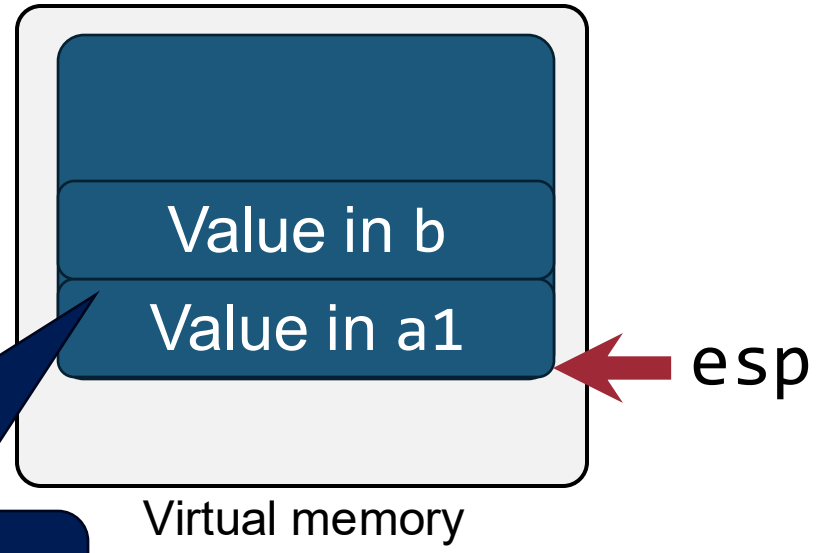
Calling Convention

```
<blue>:
  22:   push   ebp
  23:   mov    ebp,esp
  25:   sub    esp,0x28
  28:   mov    DWORD PTR [ebp-0xc],0x1
  2f:   mov    eax, DWORD PTR [ebp-0xc]
  32:   mov    DWORD PTR [esp+0x4], eax
  36:   mov    eax, DWORD PTR [ebp+0x8]
  39:   mov    DWORD PTR [esp], eax
  3c:   call   purple
  41:   mov    edx, DWORD PTR [ebp-0xc]
  44:   add    eax, edx
  46:   leave
  47:   ret
```

```
int blue(int a1) {
    return 1 + purple(a1, b);
}
```

b

a1



Passing parameter values in a reverse order

Calling Convention


```
<blue>:
  22:   push   ebp
  23:   mov    ebp,esp
  25:   sub    esp,0x28
  28:   mov    DWORD PTR [ebp-0xc],0x1
  2f:   mov    eax, DWORD PTR [ebp-0xc]
  32:   mov    DWORD PTR [esp+0x4], eax
  36:   mov    eax, DWORD PTR [ebp+0x8]
  39:   mov    DWORD PTR [esp], eax
  3c:   call   purple
  41:   mov    edx, DWORD PTR [ebp-0xc]
  44:   add    eax, edx
  46:   leave
  47:   ret
```

```
int blue(int a1) {
    return 1 + purple(a1, b);
}
```

b

a1

Storing a return value in eax

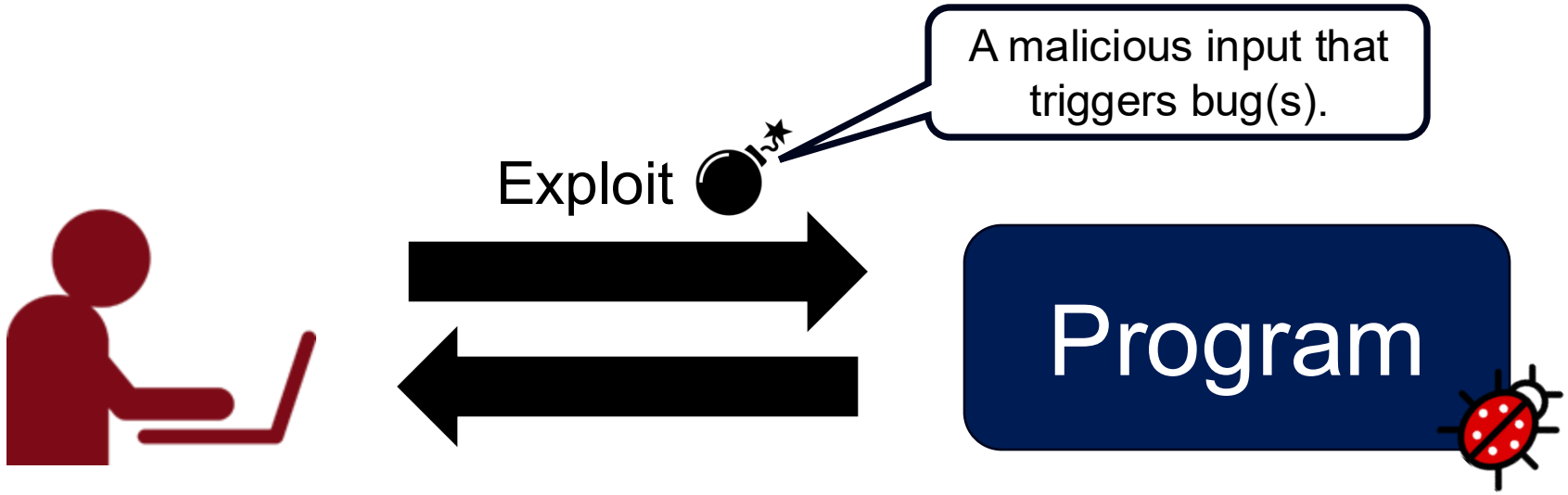
Software Bug

- Software bug is an ***error*** in a program

Q: If you only have time for fixing one bug out of hundred, which bug will you fix first?

Exploitable Bugs

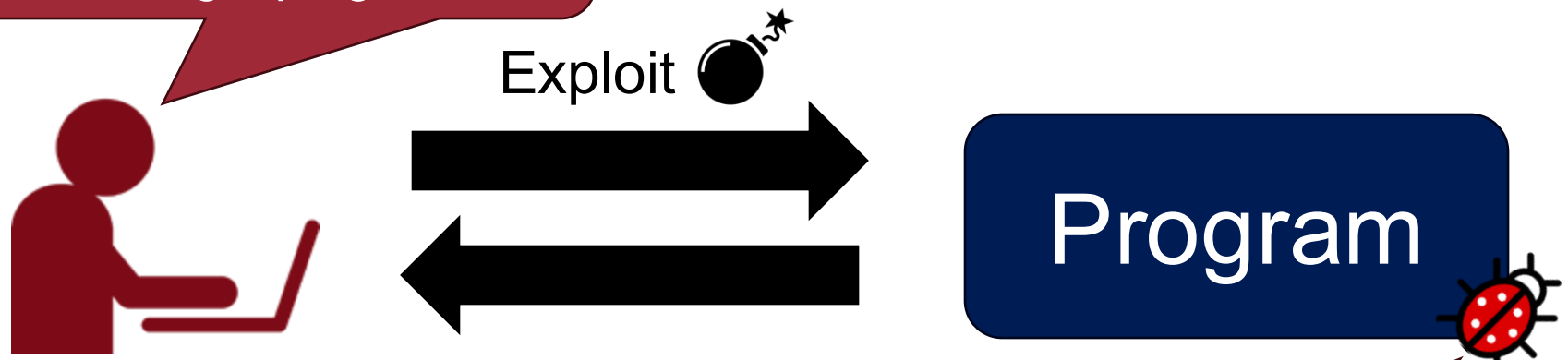
We often call an ***exploitable bug*** as a vulnerability



Exploitable Bugs

We often call an ***exploitable bug*** as a vulnerability

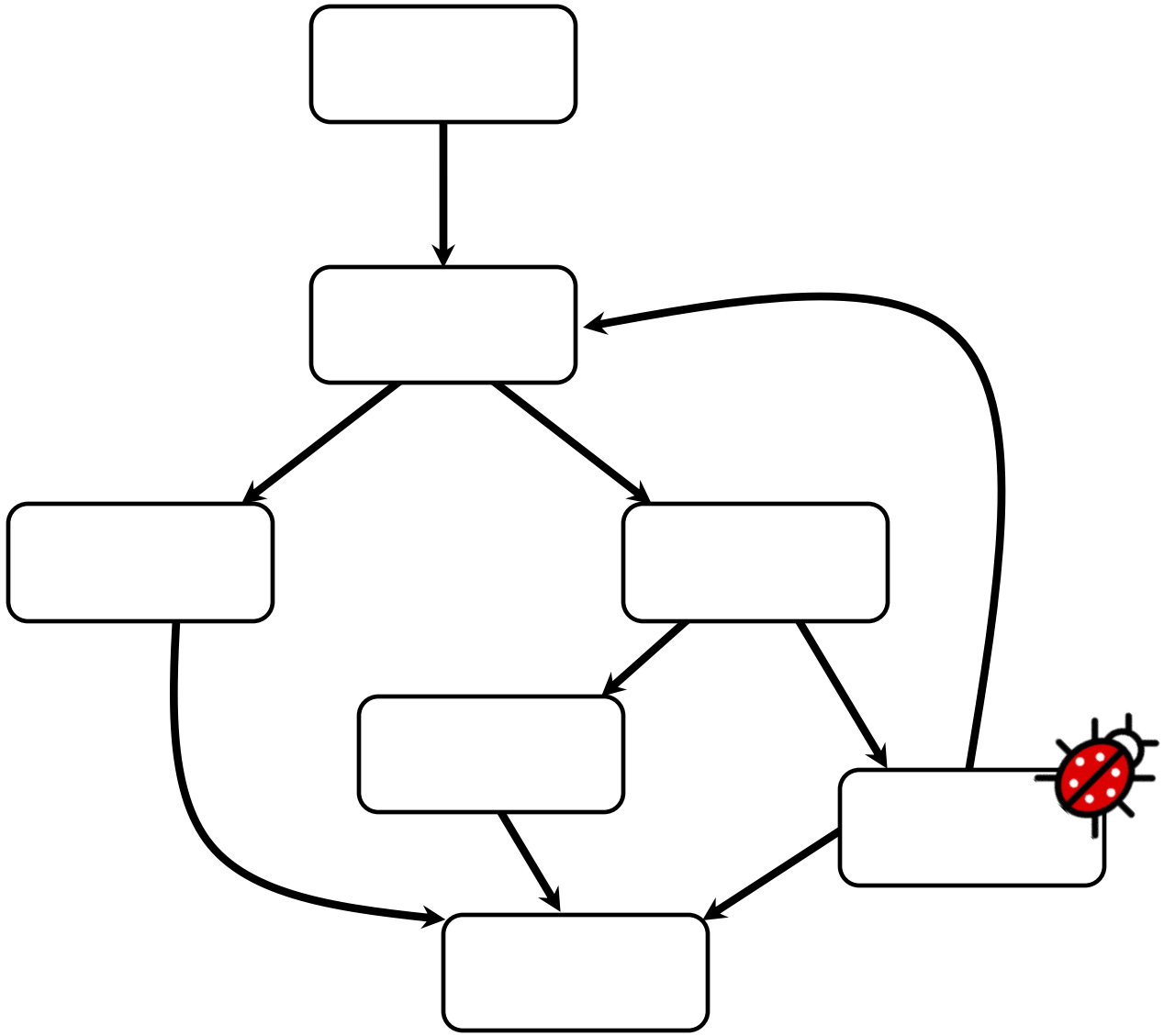
Exploitation is an act of taking advantage of a bug to cause unintended behavior of the target program



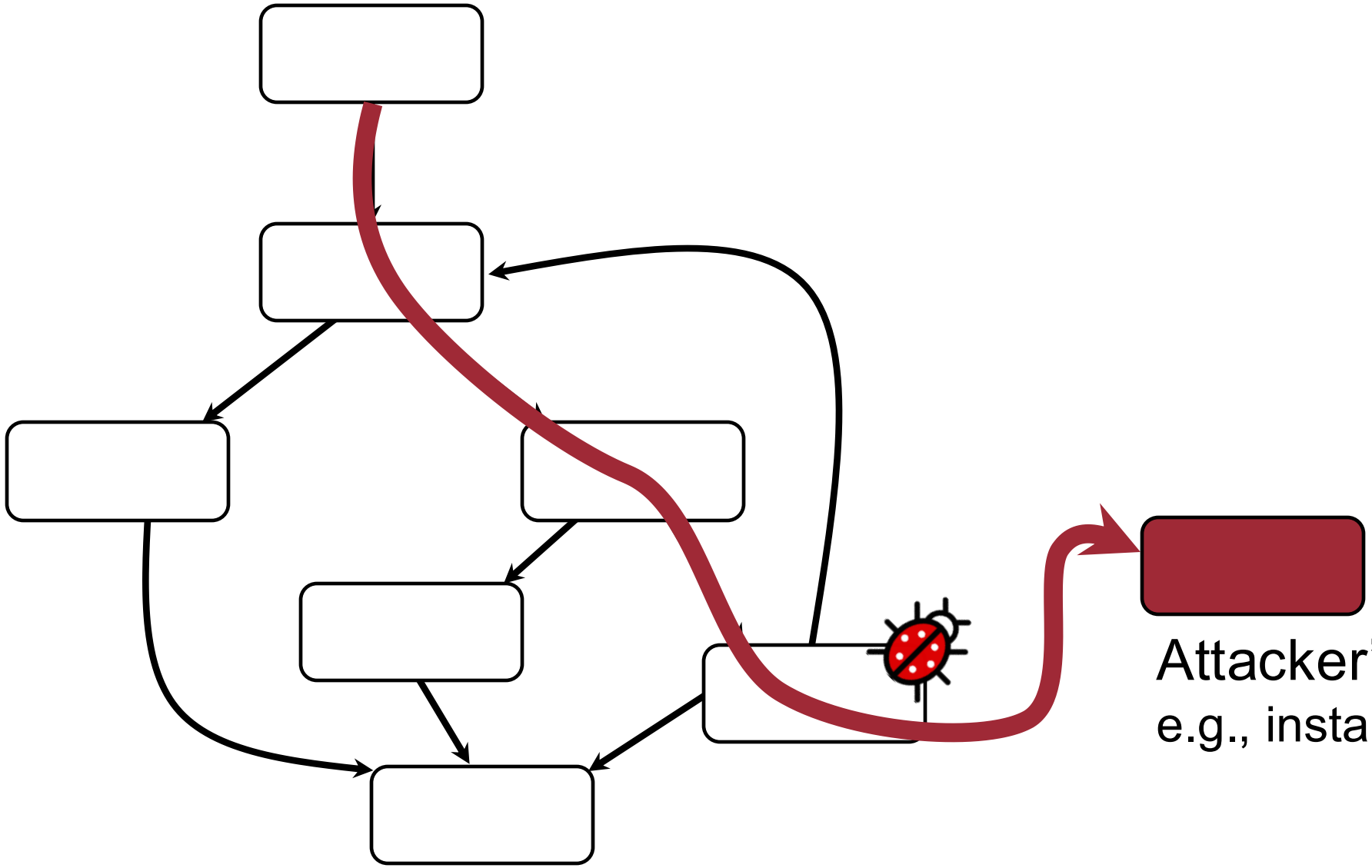
Some vulnerabilities allow an attacker to run any ***arbitrary code*** on victim's machines without their consent

Control Flow Hijack

Control Flow Hijack



Control Flow Hijack



Attacker's own code/logic
e.g., install malicious software

The Classic Exploitation

- The first computer worm (called Morris Worm) was born

Robert Tappan Morris
- Creator of the worm
- Cornell graduate
- Professor at MIT now

Image from https://www.nndb.com/people/466/000027385/

Morris Worm

- Exploited a ***buffer overflow*** vulnerability

```
int main(int argc, char* argv[]) {
  char line[512];
  /* omitted ... */
  gets(line); /* Buffer Overflow! */
  /* omitted ... */
}
```

This simple line allowed the Morris Worm to infect 10% of the internet computers in 1988

Replicating Historic Exploitation


```
int main(int argc, char* argv[]) {
  char line[512];
  gets(line);
  return 0;
}
```

Compile this program with:

```
$ gcc -mpreferred-stack-boundary=2
-O0 -fno-stack-protector -fno-pic
-no-pie -z execstack -o morris
morris.c –m32
```

Compiler Warning (ignore this for now):
morris.c:(.text+0x11): warning: the `gets' function is dangerous and should not be used.

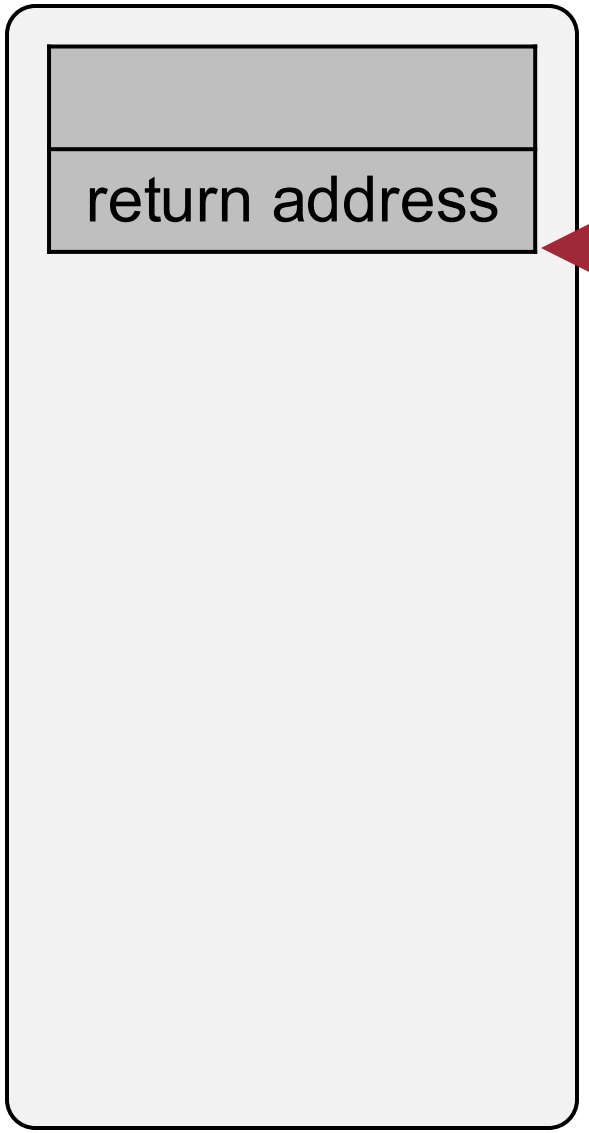
`gets(char *s)`

Reads a line from STDIN into the buffer pointed to by s until a terminating new line or EOF, which it replaces with a NULL byte (‘\0’)

Disassembled Code for the Morris Worm


```
$ objdump -M intel -d morris


08049162 <main>:
 8049162:   55                      push   ebp
 8049163:   89 e5                   mov    ebp,esp
 8049165:   81 ec 00 02 00 00       sub    esp,0x200
 804916b:   8d 85 00 fe ff ff       lea    eax,[ebp-0x200]
 8049171:   50                      push   eax
 8049172:   e8 b9 fe ff ff          call   8049030 <gets@plt>
 8049177:   83 c4 04                add    esp,0x4
 804917a:   b8 00 00 00 00          mov    eax,0x0
 804917f:   c9                      leave
 8049180:   c3                      ret
```

Analyzing the Vulnerability

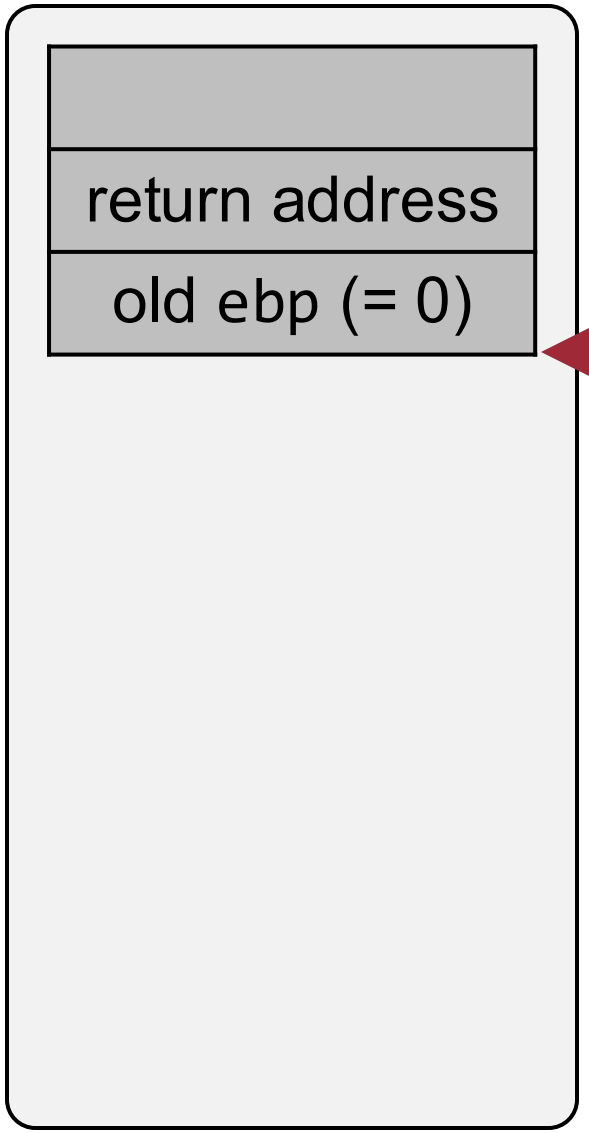



```
eip: 0x8049162
ebp: 0x0
esp: 0xbffff70c
```

Execution context

```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

Analyzing the Vulnerability



0xbffff70c

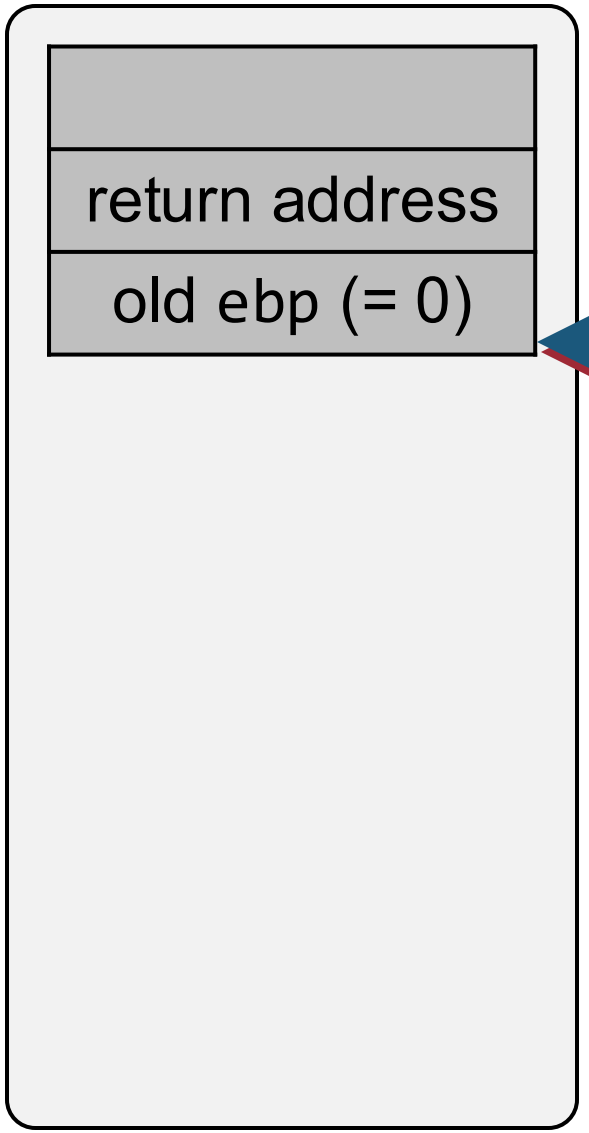
0xbffff708

```
eip:  0x8049163
ebp:  0x0
esp:  0xbffff708
```

Execution context

```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

Analyzing the Vulnerability



0xbffff70c

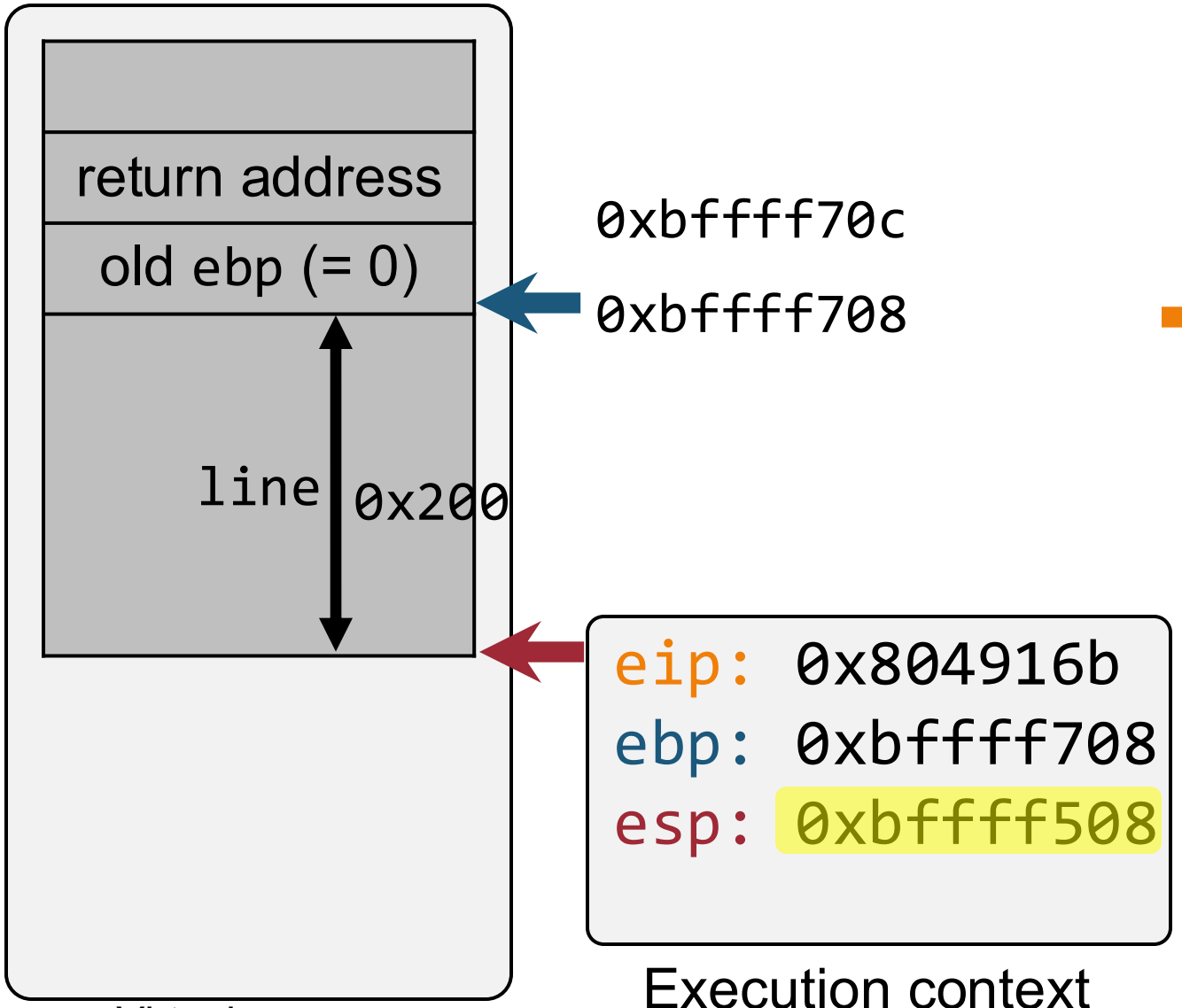
0xbffff708

```
eip: 0x8049165
ebp: 0xbffff708
esp: 0xbffff708
```

Execution context

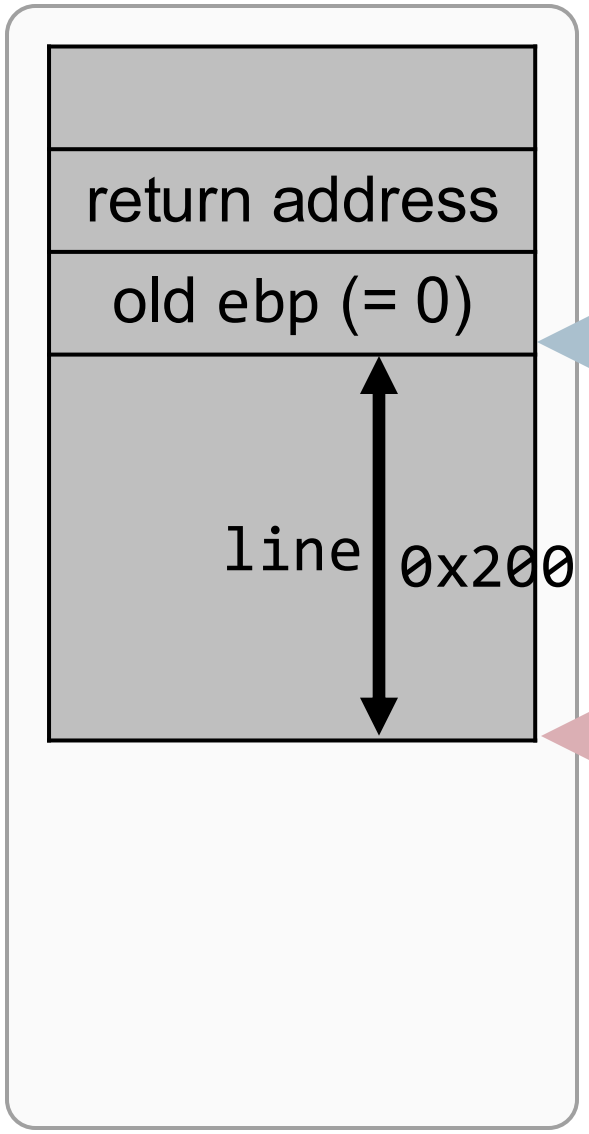
```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

Analyzing the Vulnerability




```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

Analyzing the Vulnerability



0xbffff70c

0xbffff708

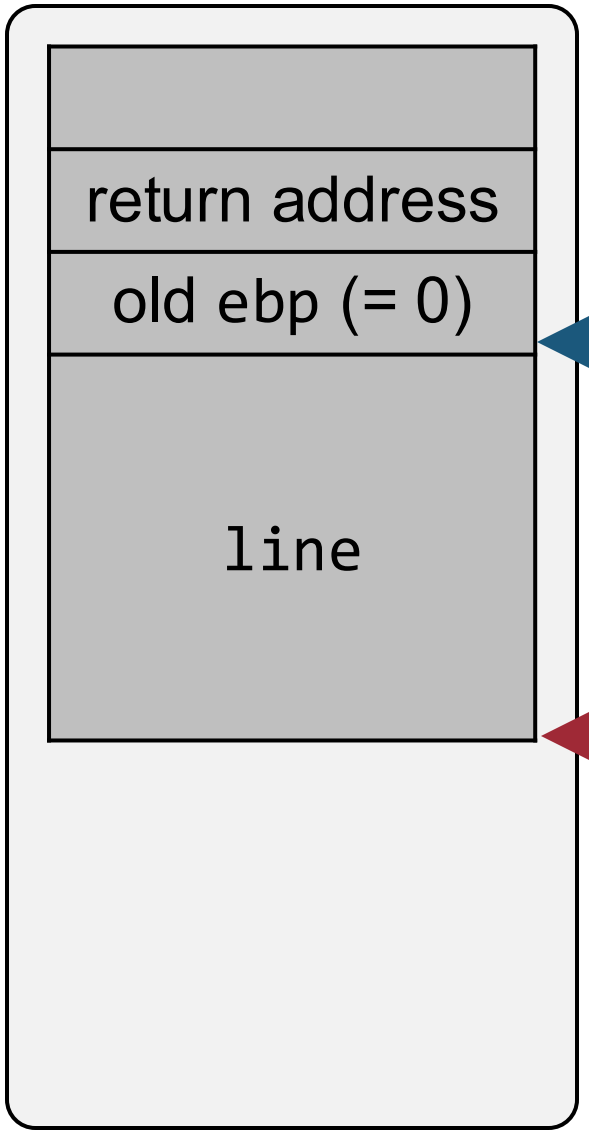
```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
```

```
eip: 0x80
ebp: 0xbf
esp: 0xbf
```

Execution c

```
int main(int argc, char* argv[]) {
  char line[512];
  gets(line);
  return 0;
}
```

Analyzing the Vulnerability



0xbffff70c

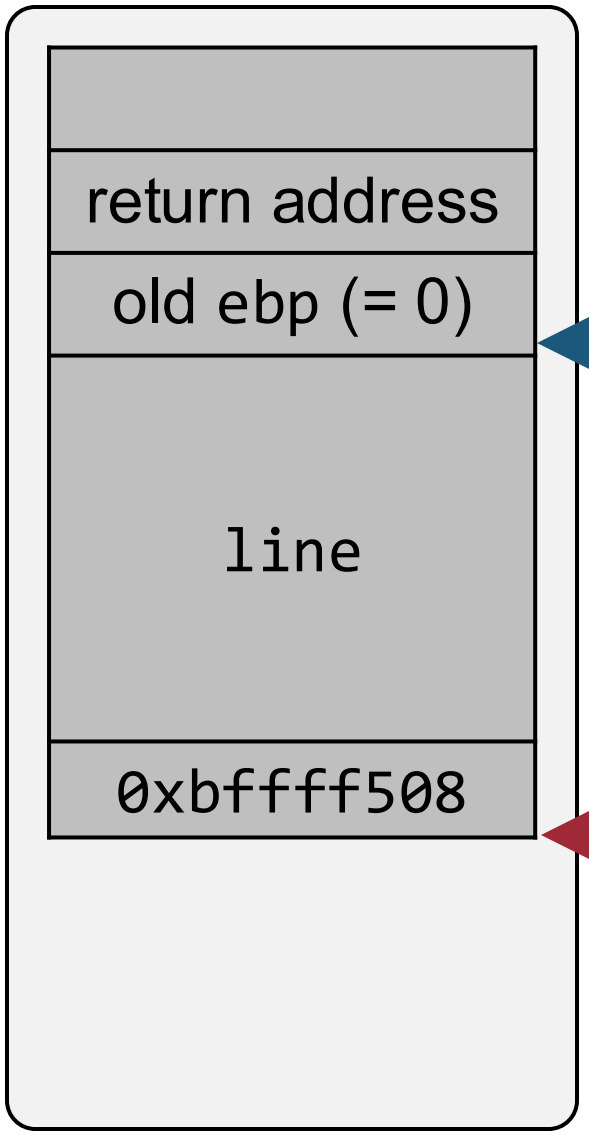
0xbffff708

```
eip: 0x8049171
ebp: 0xbffff708
esp: 0xbffff508
eax: 0xbffff508
```

Execution context

```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

Analyzing the Vulnerability



0xbffff70c

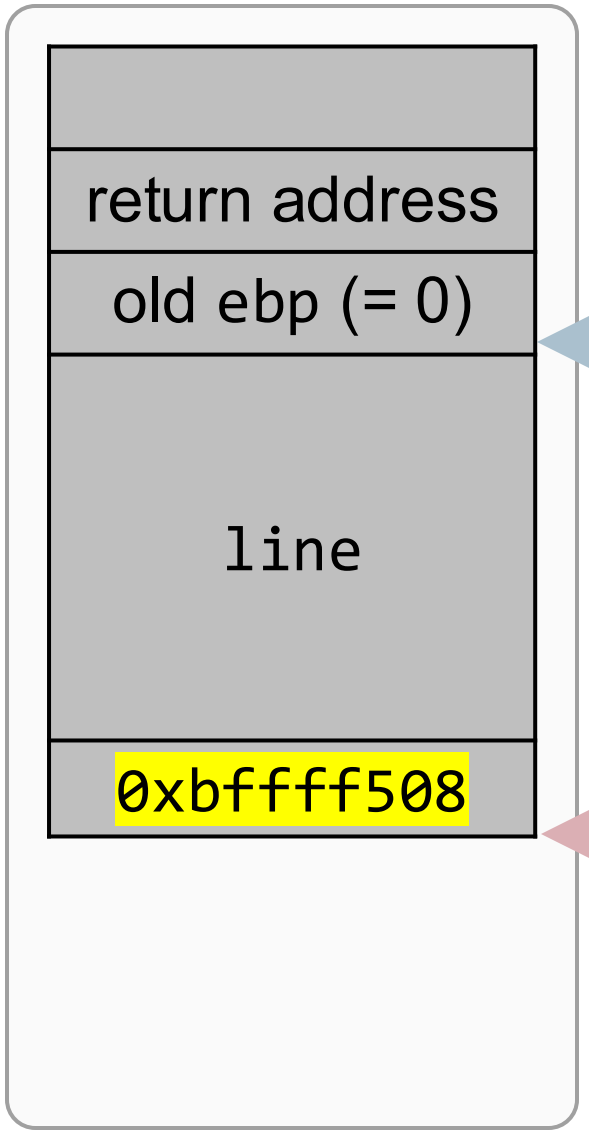
0xbffff708

```
eip:  0x8049172
ebp:  0xbffff708
esp:  0xbffff504
eax:  0xbffff508
```

Execution context

```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

Analyzing the Vulnerability



0xbffff70c

0xbffff708

```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
```

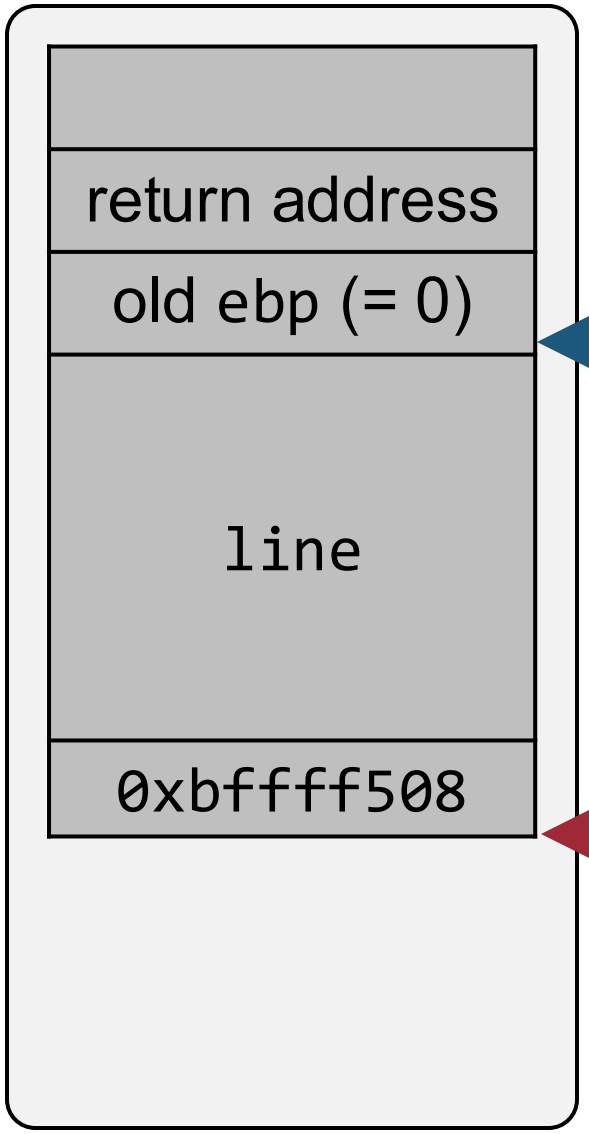
```
eip: 0x80
ebp: 0xbf
esp: 0xbf
eax: 0xbf
```

Execution c

```
int main(int argc, char* argv[]) {
  char line[512];
  gets(line);
  return 0;
}
```

Address of the variable `line`

Analyzing the Vulnerability



0xb

0xbffff708

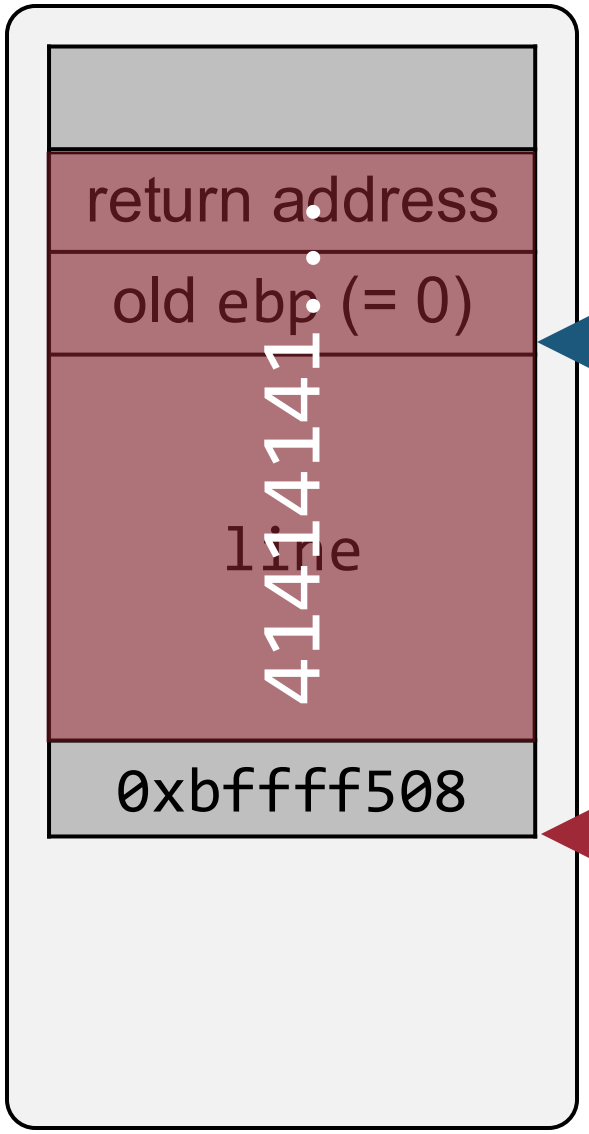
What if user input is 520 consecutive 'A's?

```
08049162 <main>:
   162:   push   ebp
   163:   mov    ebp,esp
   165:   sub    esp,0x200
804916b:  lea    eax,[ebp-0x200]
49171:    push   eax
8049172:  call   8049030 ; gets
8049177:  add    esp,0x4
804917a:  mov    eax,0x0
804917f:  leave
8049180:  ret
```

```
eip: 0x8049177
ebp: 0xbffff708
esp: 0xbffff504
eax: 0xbffff508
```

Execution context

Analyzing the Vulnerability



0xb

0xbffff708

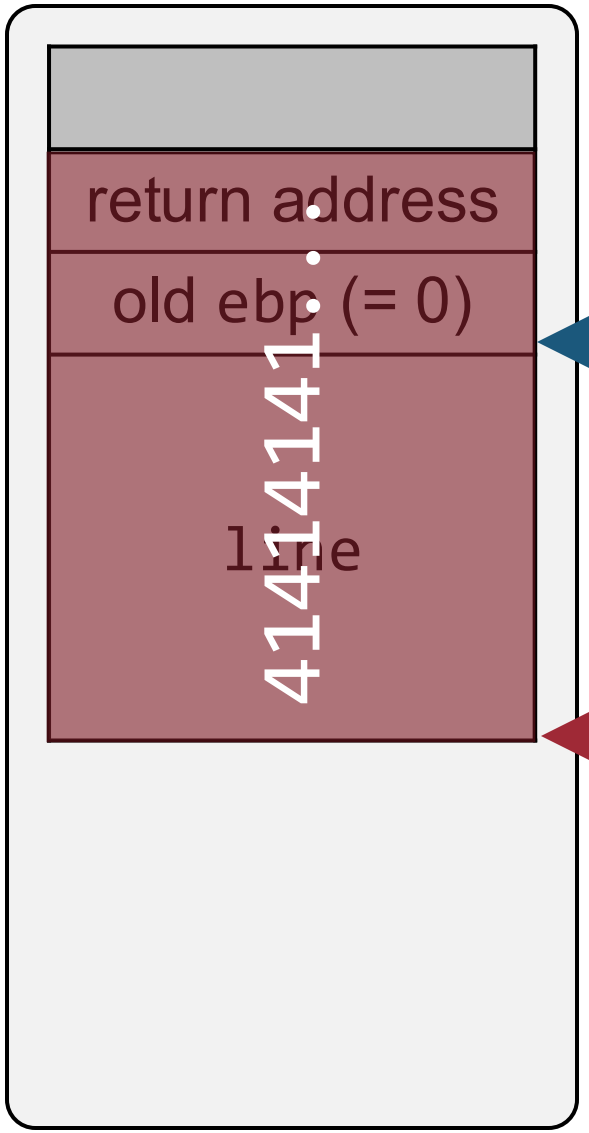
What if user input is 520 consecutive 'A's?

```
08049162 <main>:
   162:   push   ebp
   163:   mov    ebp,esp
   165:   sub    esp,0x200
804916b:  lea    eax,[ebp-0x200]
8049171:  push   eax
8049172:  call   8049030 ; gets
8049177:  add    esp,0x4
804917a:  mov    eax,0x0
804917f:  leave
8049180:  ret
```

```
eip: 0x8049177
ebp: 0xbffff708
esp: 0xbffff504
eax: 0xbffff508
```

Execution context

Analyzing the Vulnerability



0xbffff70c

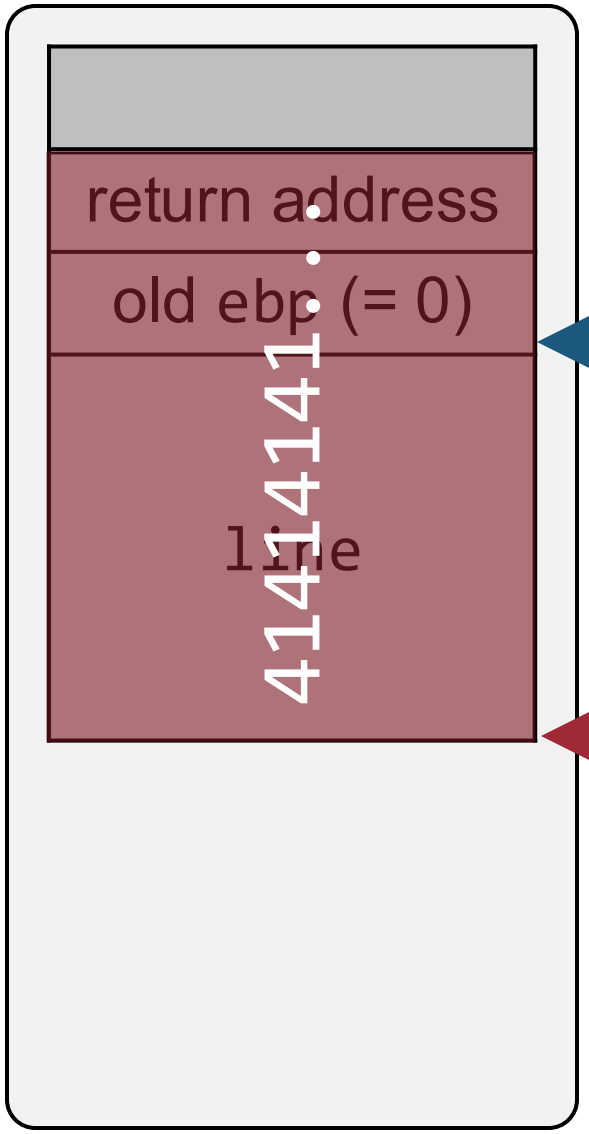
0xbffff708

```
eip: 0x804917a
ebp: 0xbffff708
esp: 0xbffff508
eax: 0xbffff508
```

Execution context

```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

Analyzing the Vulnerability



0xbffff70c

0xbffff708

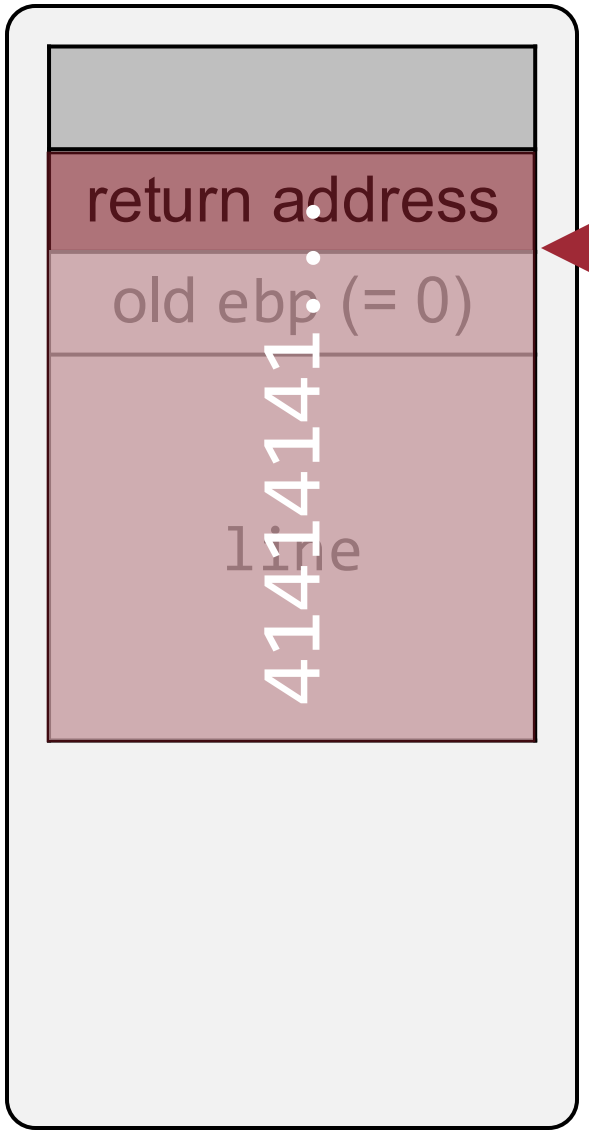
```
eip: 0x804917f
ebp: 0xbffff708
esp: 0xbffff508
eax: 0x0
```

Execution context

```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

mov esp, ebp
pop ebp

Analyzing the Vulnerability



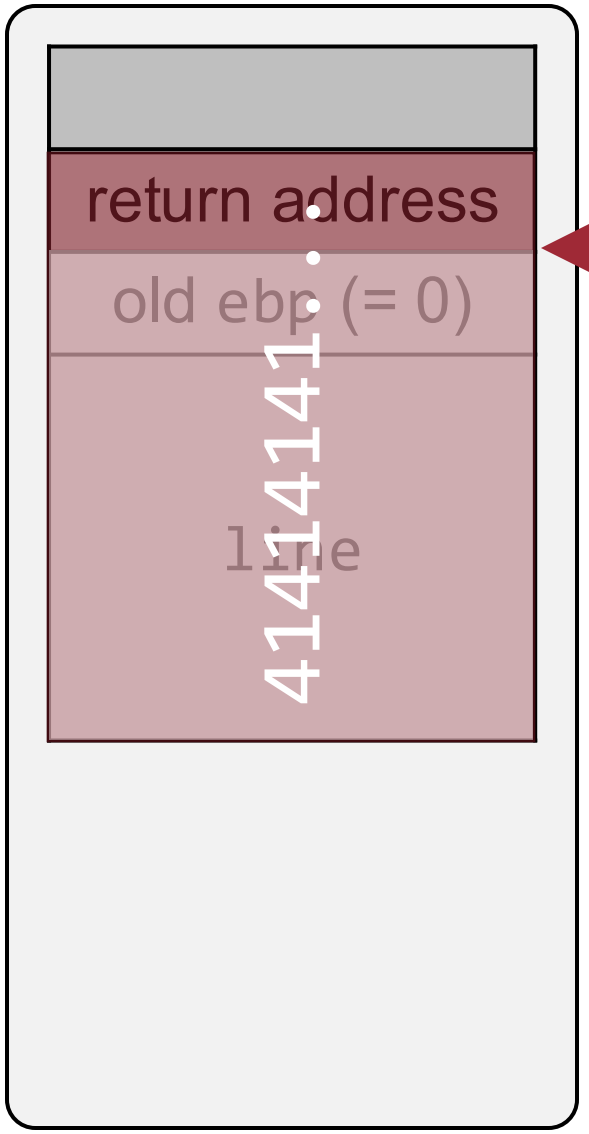
0xbffff70c

```
eip: 0x8049180
ebp: 0x41414141
esp: 0xbffff70c
eax: 0x0
```

Execution context

```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

Analyzing the Vulnerability



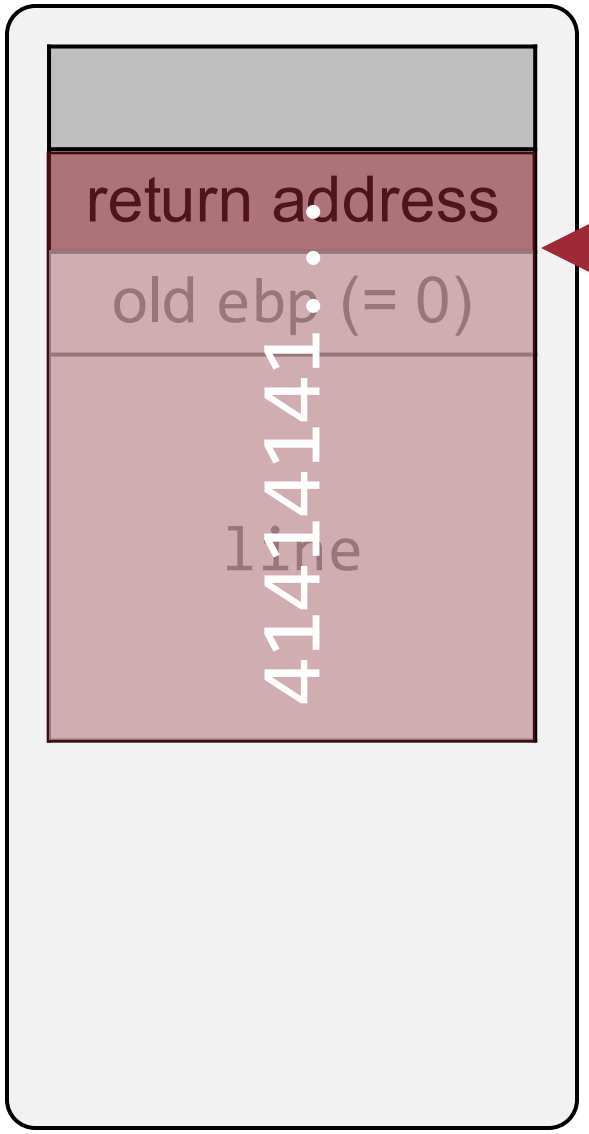

```
eip: 0x8049180
ebp: 0x41414141
esp: 0xbffff70c
eax: 0x0
```

Execution context

```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

pop eip

Analyzing the Vulnerability



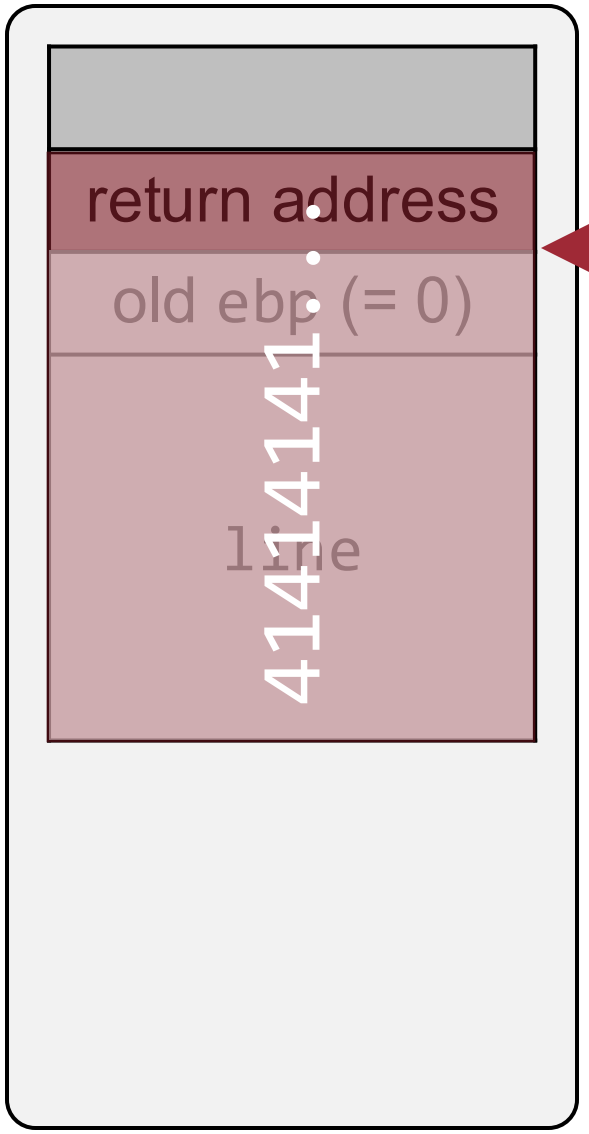

```
eip: 0x41414141
ebp: 0x41414141
esp: 0xbffff70c
eax: 0x0
```

Execution context

```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

pop eip

Analyzing the Vulnerability



0xbffff70c

Control flow hijacked!

```
eip: 0x41414141
ebp: 0x41414141
esp: 0xbffff70c
eax: 0x0
```

Execution context

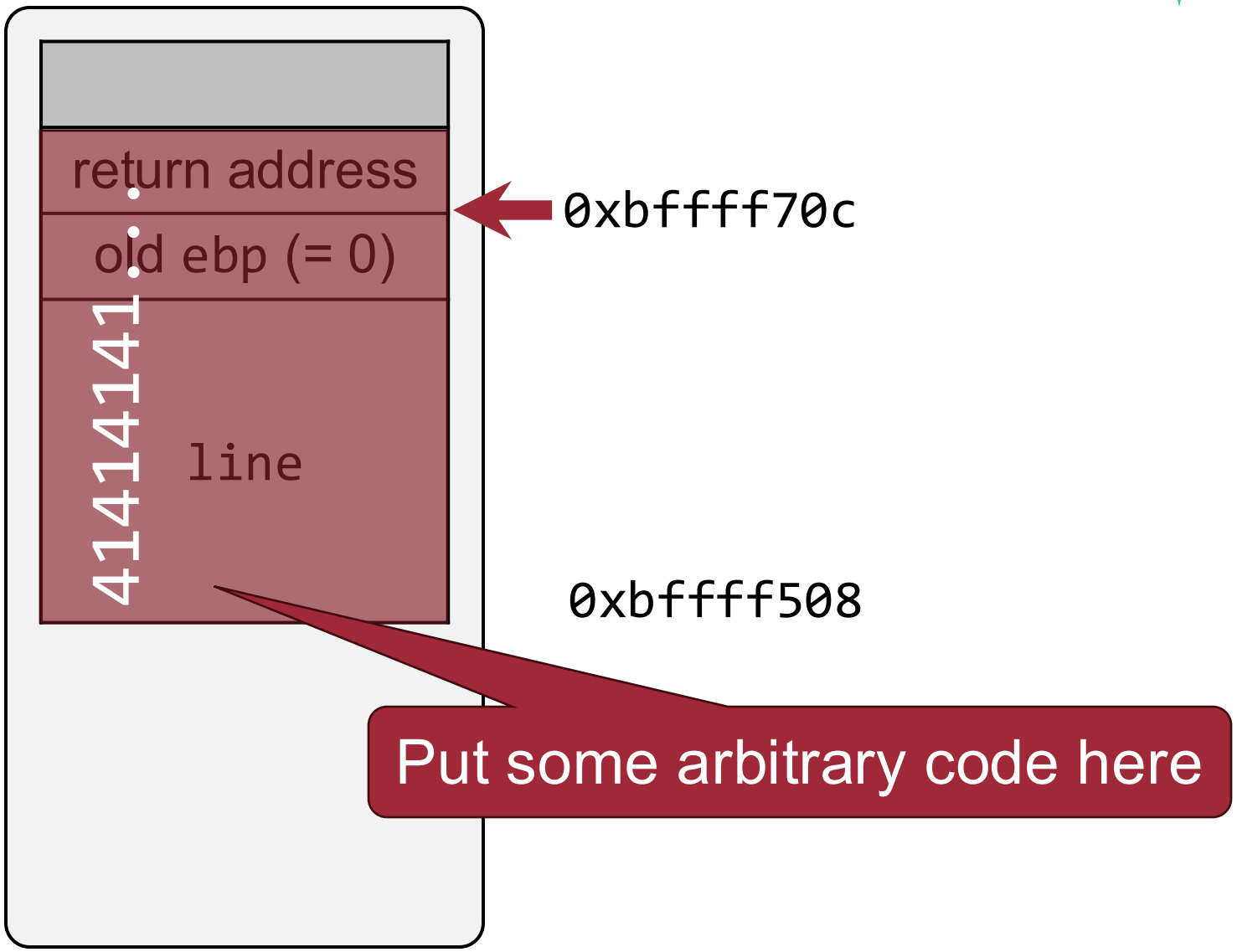
```
08049162 <main>:
8049162:   push   ebp
8049163:   mov    ebp,esp
8049165:   sub    esp,0x200
804916b:   lea    eax,[ebp-0x200]
8049171:   push   eax
8049172:   call   8049030 ; gets
8049177:   add    esp,0x4
804917a:   mov    eax,0x0
804917f:   leave
8049180:   ret
```

pop eip

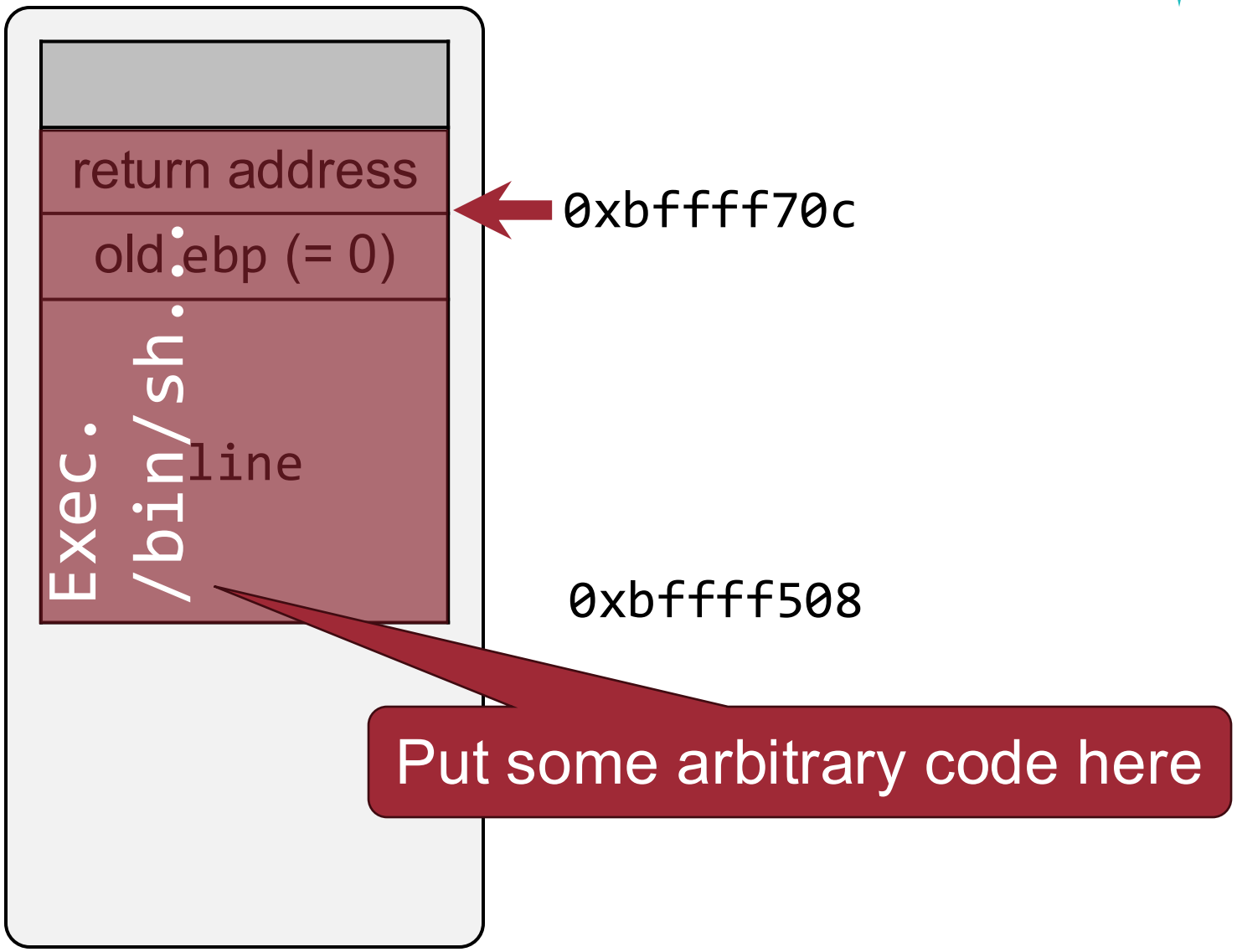
So Far …

- We hijacked the control flow of the program, i.e., we can jump to any where!
- But, where do we jump to?
- We want to inject some ***arbitrary code*** to run!

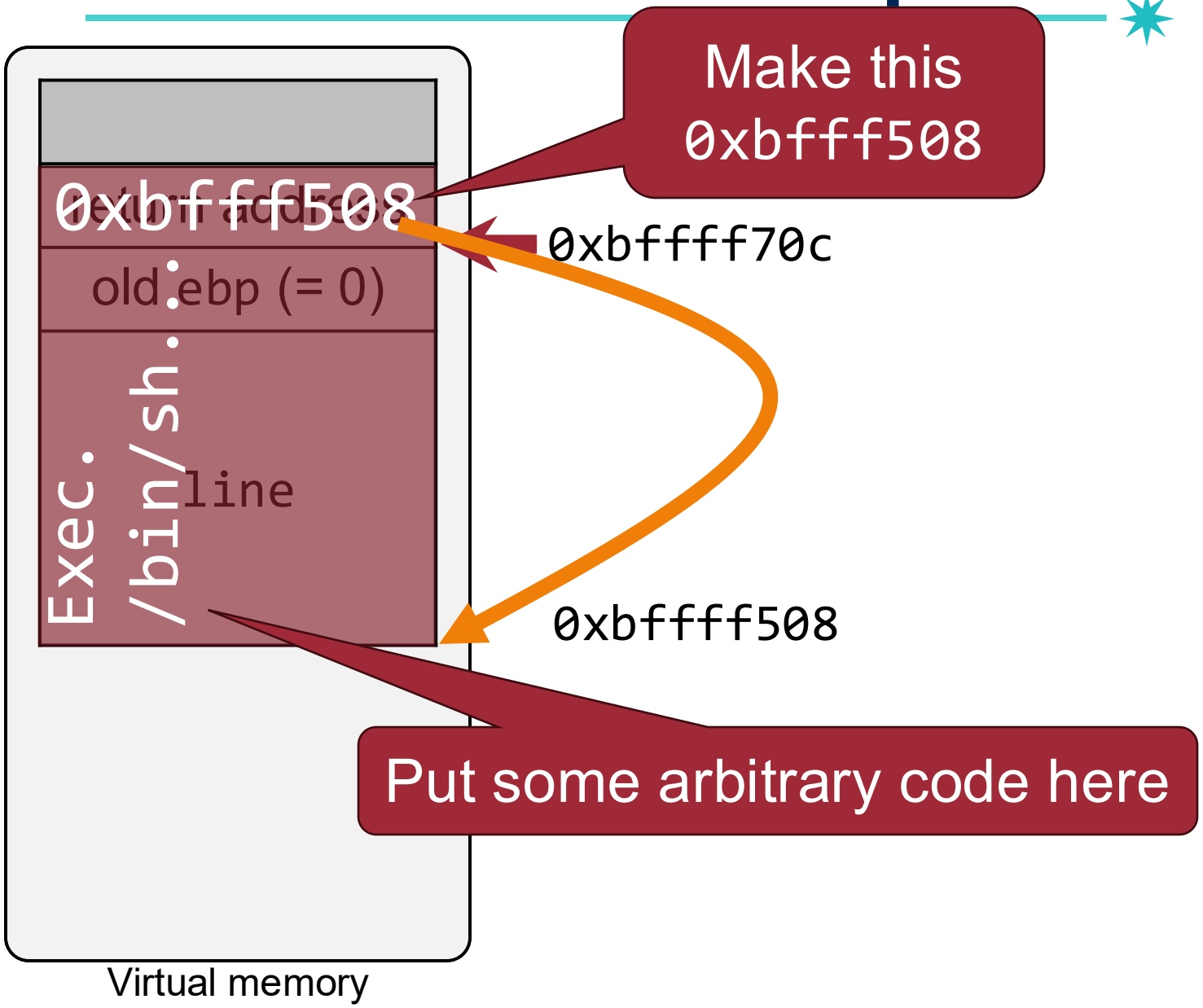
Return-to-Stack Exploit



Return-to-Stack Exploit



Return-to-Stack Exploit



Executing *Shellcode*

- Shellcode can run any arbitrary logic
  - Download /etc/passwd
  - Install malicious software (malware)
  - …
- Typically, executing `/bin/sh` is enough
  - This is the most powerful attack: we can run arbitrary commands
  - You can also achieve this with relatively ***small piece of code***
  - This is the reason why we call it as ***shellcode*** (code that typically runs shell)

Summary

- Only some bugs are exploitable
- Some exploits allow an attacker to hijack the control flow of the program and to run any arbitrary code
- Return-to-stack exploit puts a shellcode into a stack buffer and jumps to it by overwriting the return address
- How we defend against this attack? Next lecture!

Question?